Symbolic Execution

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Why Symbolic Execution?

Real-world applications of this methodology:

- (Software Testing) Bug detection
  e.g., inputs that crash an application

- (Security) Exploit and backdoor identification
  e.g., inputs to bypass authentication code

- (Security) Malware analysis
  e.g., trigger malicious behaviors in evasive or dormant malware

What is Symbolic Execution?

Originally introduced by **James C. King** in a **1976** paper as a static analysis technique for *software testing*.

Key ideas:

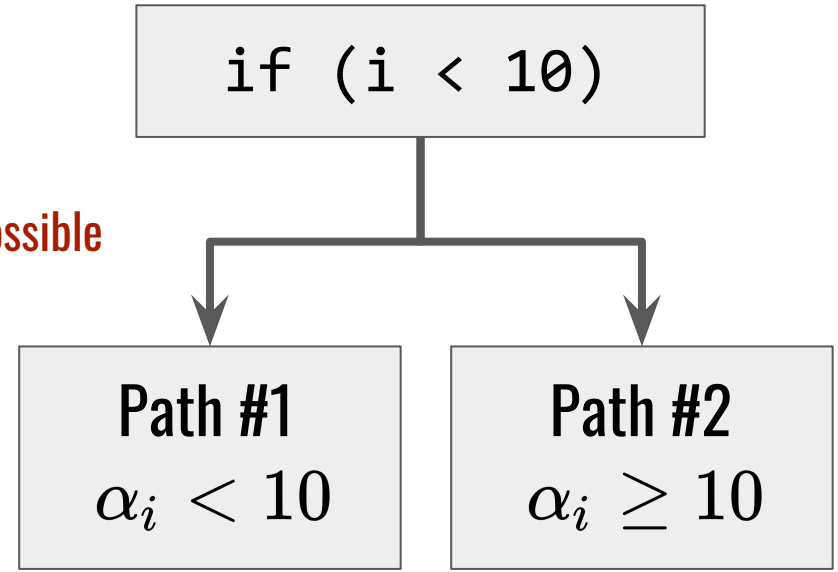
- Each *input* variable is associated to a *symbol*, e.g., $\text{int i} \quad \mapsto \quad \alpha_i$
- Each symbol represents a set of input values, e.g., $\alpha_i \in [0, 2^{32} - 1]$
- Program statements generate formulas over symbols, e.g.,

$$\text{i} * 2 + 5 \quad \mapsto \quad 2 \cdot \alpha_i + 5$$

What about conditional branches?

Symbolic Execution: conditional branch

Fork the execution, considering each possible yet *realizable* path



From now on, we should consider these *path constraints*

Example: find input values that make assertion fail

```
1.  void foobar(int a, int b) {
2.      int x = 1, y = 0;
3.      if (a != 0) {
4.          y = 3+x;
5.          if (b == 0)
6.              x = 2*(a+b);
7.      }
8.      assert(x-y != 0);
9.  }
```

Symbolic Execution can find **all** the inputs leading to the failure.

Can you do the same?

Symbolic Execution: execution state

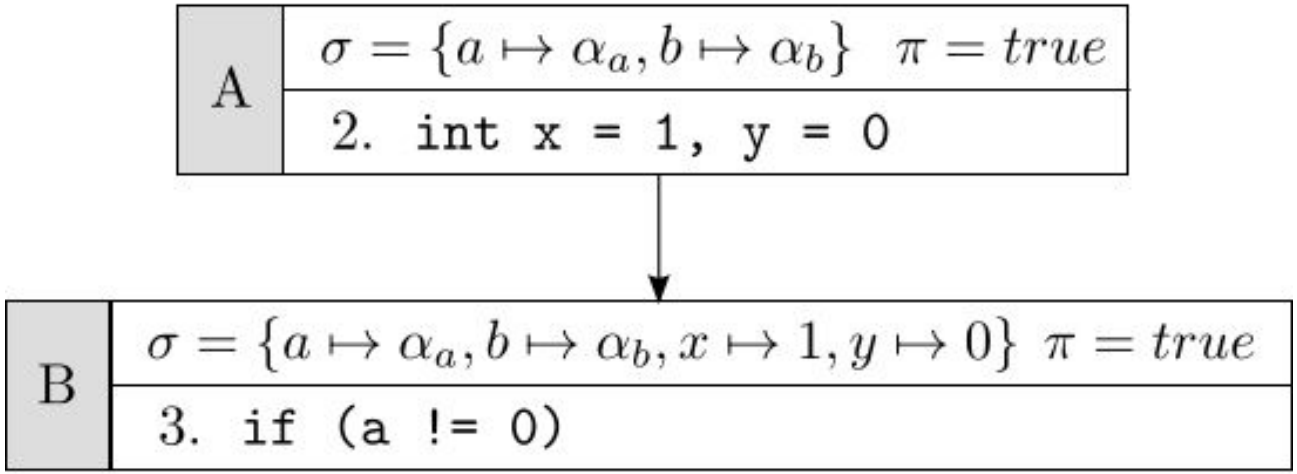
Execution state (stmt, σ, π):

- stmt is the next statement to evaluate
- σ is the *symbolic store* that maps program variables to expressions over concrete values or symbols
- π denotes the path constraints, i.e., assumptions made at branches taken in the execution to reach stmt. Initially, $\pi = true$

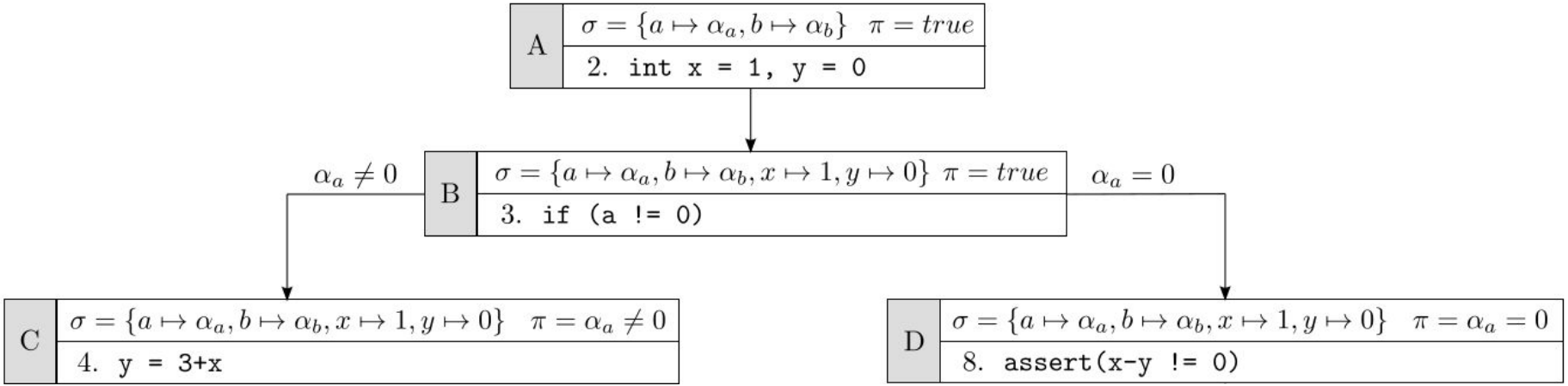
In our example:

A	$\sigma = \{a \mapsto \alpha_a, b \mapsto \alpha_b\}$ $\pi = true$
	2. `int x = 1, y = 0`

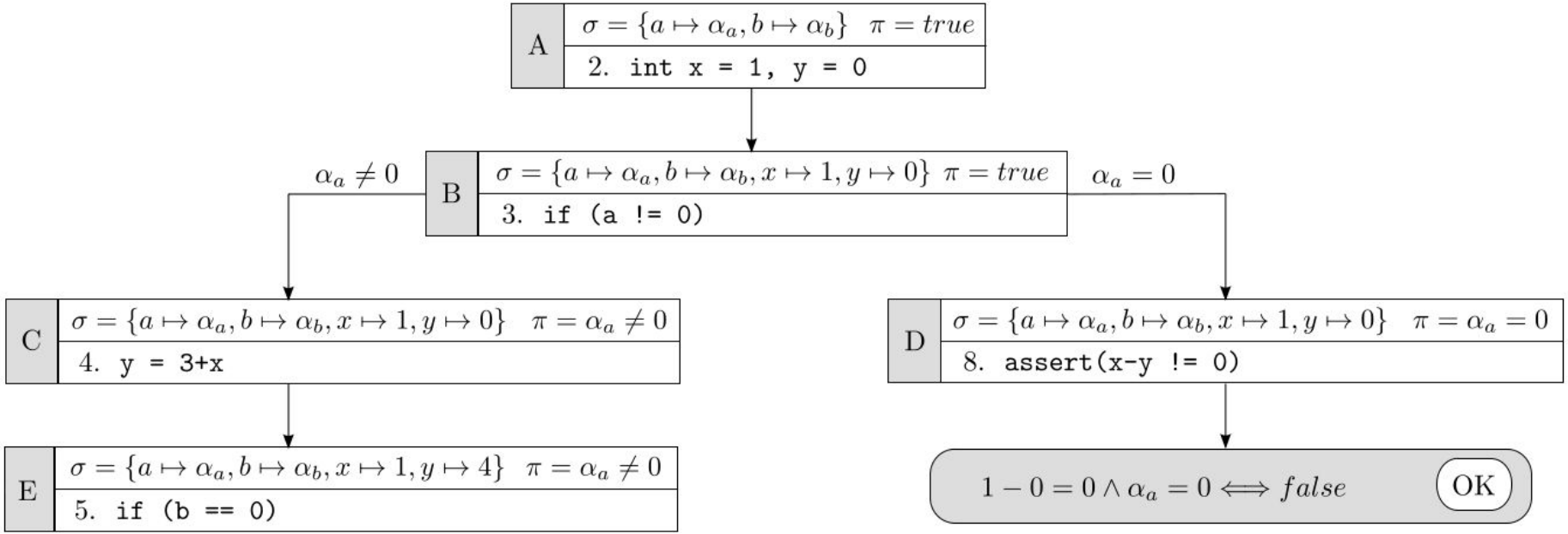
Example: symbolic exploration (1)



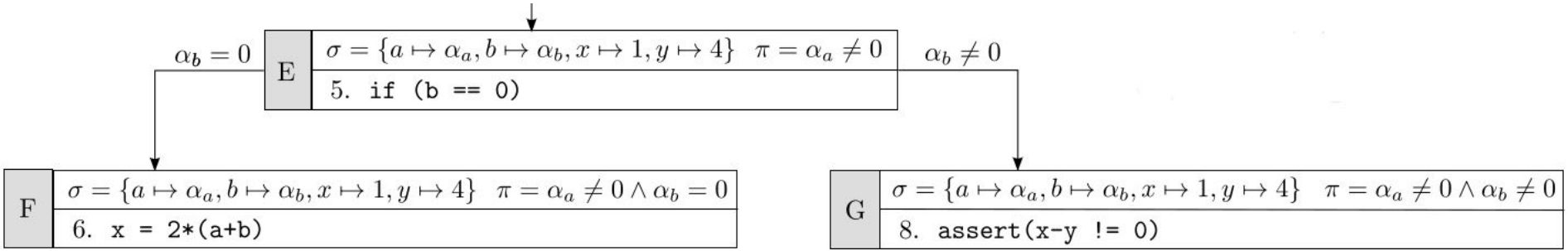
Example: symbolic exploration (2)



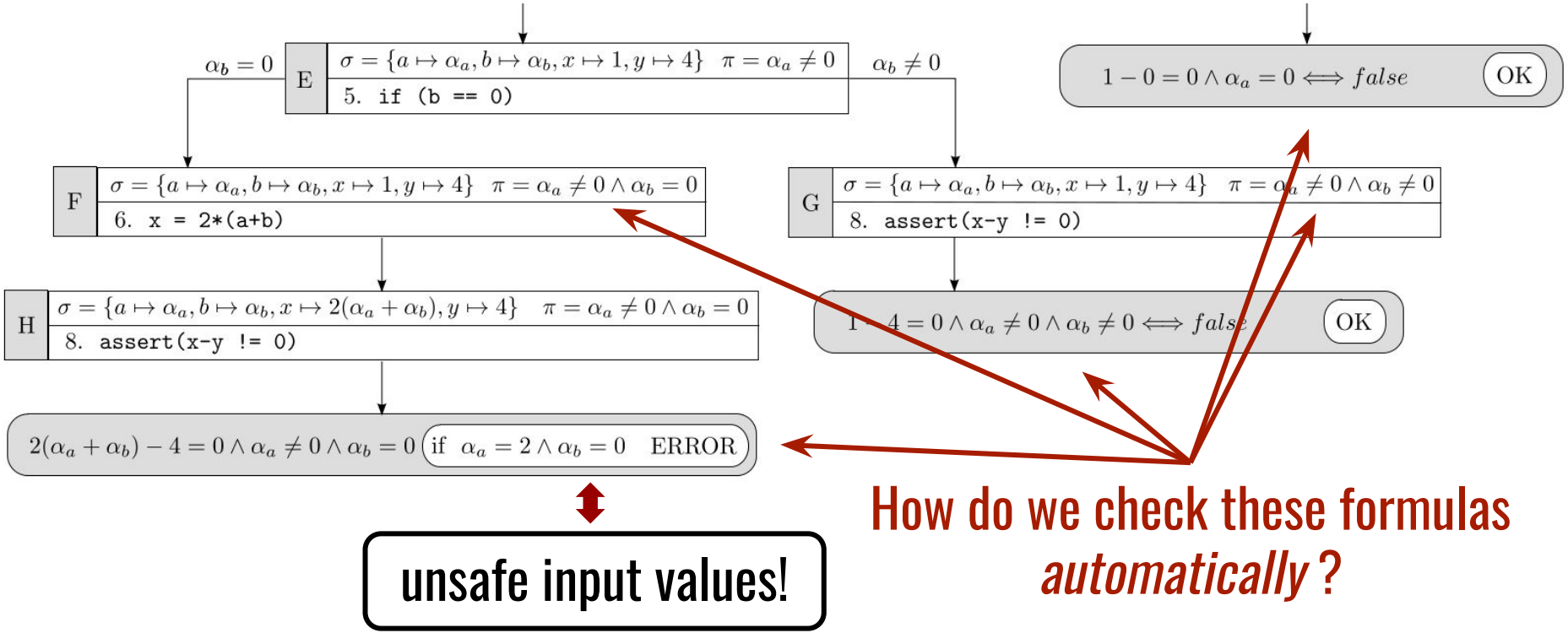
Example: symbolic exploration (3)



Example: symbolic exploration (4)

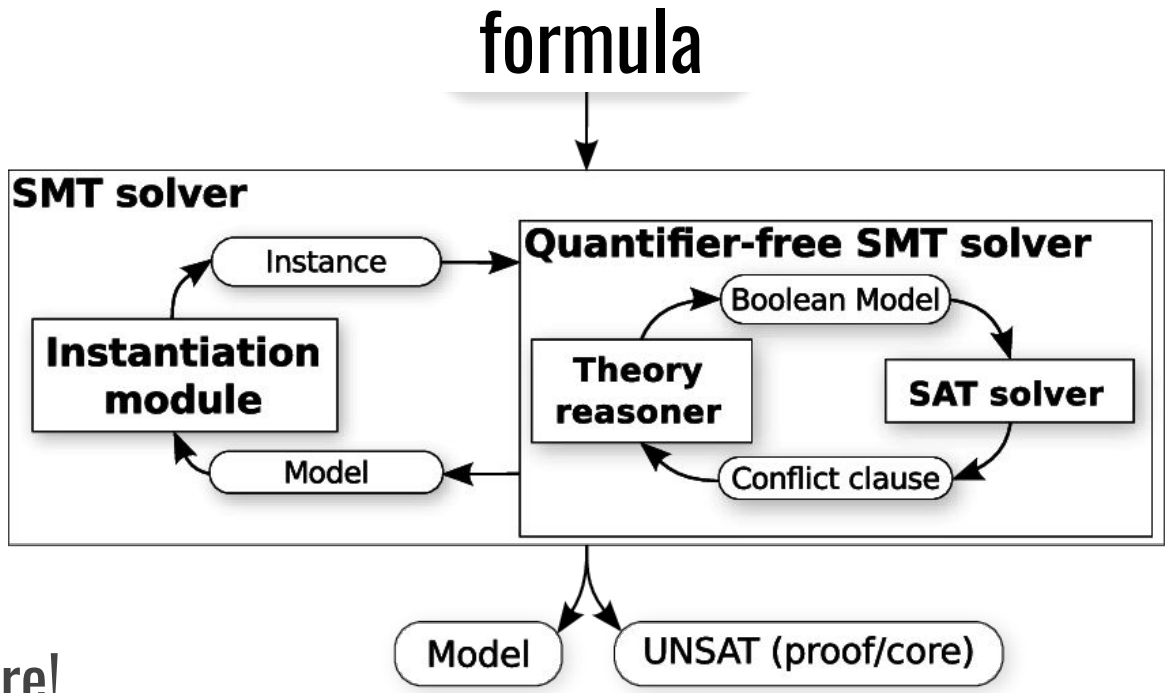


Example: symbolic exploration (4)



How to check a symbolic formula?

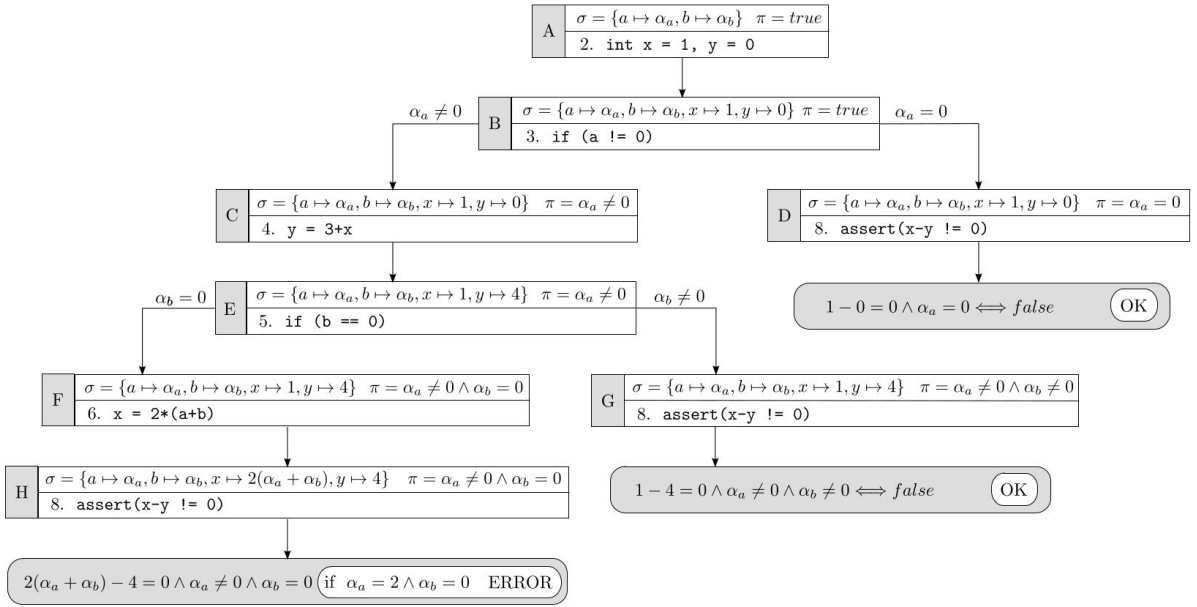
SMT Solvers



SAT is everywhere!

(image credits)

Example: symbolic exploration (5)



We checked **all** possible paths.

Can we prove that no other crash may happen?

Symbolic Execution: soundness and completeness

Can we prove that no other crash may happen?

In theory, yes. In practice, no.

When analyzing programs with Symbolic Execution:

- Constraints may be hard to solve
- Too many paths may be generated
- Tons of details play a role during an execution

Symbolic Execution: is it actually useful?

A quote from “AEG: Automatic Exploit Generation” (T. Avgerinos et al.):

> [...] KLEE is a state-of-the-art forward symbolic execution engine, but in practice is limited to small programs such as /bin/ls.

Pure static symbolic execution hardly scales in practice.

Symbolic Execution: a success story [SAGE NDSS08]

SAGE: Whitebox Fuzzing for Security Testing

SAGE has had a remarkable impact at Microsoft.

Patrice Godefroid, Michael Y. Levin, David Molnar, Microsoft

Most *ACM Queue* readers might think of "program verification research" as mostly theoretical with little impact on the world at large. Think again. If you are reading these lines on a PC running some form of Windows (like 93-plus percent of PC users—that is, more than a billion people), then you have been affected by this line of work—without knowing it, which is precisely the way we want it to be.

Symbolic Execution: a success story (2)

IMPACT OF SAGE

Since 2007, SAGE has discovered many security-related bugs in many large Microsoft applications, including image processors, media players, file decoders, and document parsers. Notably, SAGE found roughly *one-third* of all the bugs discovered by file fuzzing during the development of Microsoft's Windows 7. Because SAGE is typically run last, those bugs were missed by everything else, including static program analysis and blackbox fuzzing.

Finding all these bugs has saved millions of dollars to Microsoft, as well as to the world in time and energy, by avoiding expensive security patches to more than 1 billion PCs. The software running on *your* PC has been affected by SAGE.

Since 2008, SAGE has been running 24/7 on an average of 100-plus machines/cores automatically fuzzing hundreds of applications in Microsoft security testing labs. This is more than 300 machine-years and the *largest computational usage ever for any SMT (Satisfiability Modulo Theories) solver*, with more than 1 billion constraints processed to date.

SAGE is so effective at finding bugs that, for the first time, we faced "bug triage" issues with dynamic test generation. We believe this effectiveness comes from being able to fuzz large applications (not just small units as previously done with dynamic test generation), which in turn allows us to find bugs resulting from problems across multiple components. SAGE is also easy to deploy, thanks to x86 binary analysis, and it is fully automatic. SAGE is now used daily in various groups at Microsoft.

Symbolic execution: challenges

Some of the challenges that symbolic execution has to face:

1. memory model
2. path explosion
3. environment interaction
4. constraint solver

Depending on the goals, different choices and trade-offs must be made in order to effectively use symbolic execution.

Symbolic Execution: memory model

How do we handle symbolic loads or symbolic writes?

```
int array [N] = { 0 };
array [i] = 10;          // i symbolic
assert(array[j] != 0); // j symbolic
```

Approaches:

1. **fully symbolic**:
   consider any possible outcome
2. **fully concrete**:
   consider one possible outcome
3. **partial**: concretize writes,
   concretize loads when hard

N states
accurate but not scale

1 state
scale but not accurate

K states
scale but (in)accurate

Symbolic Execution: path explosion

When possible, pre-constrain your symbolic inputs:

- ➔ none
- ➔ known size
- ➔ known prefix
- ➔ concrete values

Exploit knowledge from the application domain to limit path explosion!

For instance: some fields of a packet in a protocol are constant,
other fields can assume a restricted set of values, etc.

Symbolic Execution: path explosion (2)

State scheduling to prioritize interesting paths. Common strategies:

- depth first search: minimize resource consumption
- random path selection: minimize starvation
- coverage optimized search: maximize coverage
- buggy path first: aims at vulnerability detection

The search heuristic depends on the goal that you are trying to achieve!

Symbolic Execution: environment interaction

How to deal with library/system calls?

1. **fully symbolic:** symbolically execute OS → accurate but not scale
2. **fully concrete:** concretize & execute OS → scale but not accurate
3. **approximation:** API models describe effects on the state → scale but manpower costly and error-prone

Environment is often a source of input.
Approximation is often used in practice.

Symbolic Execution: concolic execution

Concolic execution: concrete + symbolic. A mixed static/dynamic approach.

Key idea:

1. Run code concretely and record instruction trace
2. Symbolically analyze trace
3. Choose one branch, negate it, and generate new input values
4. Restart from (1) using the new inputs

Symbolic Execution: concolic execution (2)

Some of the benefits:

1. Symbolic execution is driven by a concrete execution
   - ➡ easier to detect false positives (divergences)
   - ➡ one solver query for each path
2. Exploit concrete values to solve hard constraints:

```
if (a == (b * b % 50))
```

Hard to solve when `a` and `b` are fully symbolic
Easy to solve when `b` is concrete and `a` is symbolic

Do you want to know more about Symbolic Execution?

Check out our survey!

Roberto Baldoni, Emilio Coppa, Daniele Cono D'Elia, Camil Demetrescu, Irene Finocchi. A Survey of Symbolic Execution Techniques. ACM Computing Surveys (ACM CSUR), 51(3), 2018.
DOI: 10.1145/3182657
PDF: [URL]

A Survey of Symbolic Execution Techniques

ROBERTO BALDONI, EMILIO COPPA, DANIELE CONO D'ELIA, CAMIL DEMETRESCU, and IRENE FINOCCHI, Sapienza University of Rome

Many security and software testing applications require checking whether certain properties of a program hold for any possible usage scenario. For instance, a tool for identifying software vulnerabilities may need to rule out the existence of any backdoor to bypass a program's authentication. One approach would be to test the program using different, possibly random inputs. As the backdoor may only be hit for very specific program workloads, automated exploration of the space of possible inputs is of the essence. Symbolic execution provides an elegant solution to the problem, by systematically exploring many possible execution paths at the same time without necessarily requiring concrete inputs. Rather than taking on fully specified input values, the technique abstractly represents them as symbols, resorting to constraint solvers to construct actual instances that would cause property violations. Symbolic execution has been incubated in dozens of tools developed over the last four decades, leading to major practical breakthroughs in a number of prominent software reliability applications. The goal of this survey is to provide an overview of the main ideas, challenges, and solutions developed in the area, distilling them for a broad audience.

CCS Concepts: • **Software and its engineering** → **Software verification**; *Software testing and debugging*; • **Security and privacy** → Software and application security;

Additional Key Words and Phrases: Symbolic execution, static analysis, concolic execution, software testing

ACM Reference Format:
Roberto Baldoni, Emilio Coppa, Daniele Cono D'Elia, Camil Demetrescu, and Irene Finocchi. 2018. A Survey of Symbolic Execution Techniques. *ACM Comput. Surv.* 51, 3, Article 0 (2018), 37 pages. https://doi.org/0000001.0000001

"Sometimes you can't see how important something is in its moment, even if it seems kind of important. This is probably one of those times."

(Cyber Grand Challenge highlights from DEF CON 24, August 6, 2016)

1 INTRODUCTION

Symbolic execution is a popular program analysis technique introduced in the mid '70s to test whether certain properties can be violated by a piece of software [16, 58, 67, 68]. Aspects of interest could be that no division by zero is ever performed, no NULL pointer is ever dereferenced, no backdoor exists that can bypass authentication, etc. While in general there is no automated way to decide some properties (e.g., the target of an indirect jump), heuristics and approximate analyses can prove useful in practice in a variety of settings, including mission-critical and security applications.

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Hands-on Session

angr: a python framework for analyzing binaries

http://angr.io

Support for:

- CFG reconstruction
- (Static) Symbolic Execution
- Static Binary Analysis
- ...a lot more...

Extremely easy to prototype new ideas (e.g., novel program analyses) with angr!

angr @ DARPA CGC

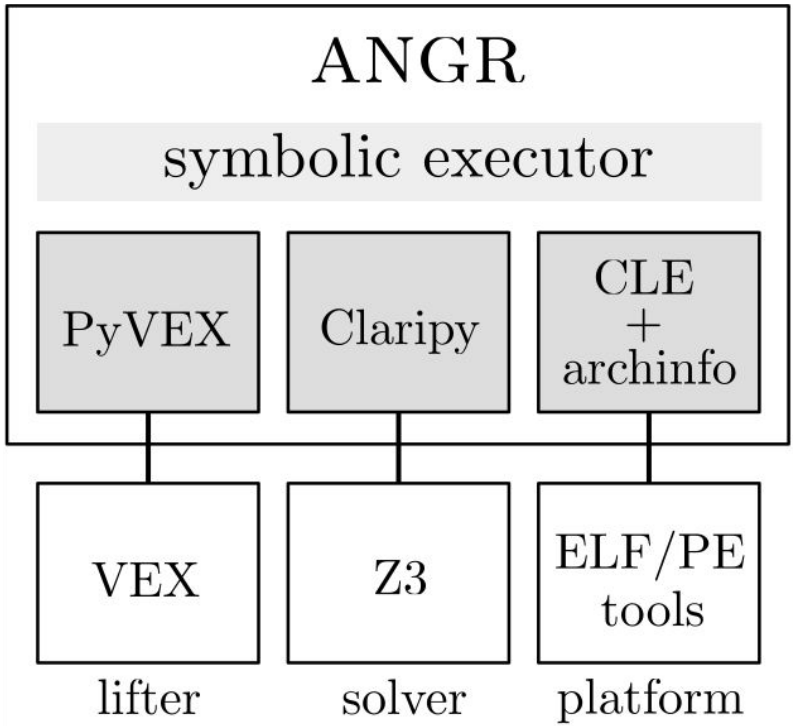
angr was the core of the MechaPhish CRS that played at the DARPA Cyber Grand Challenge.

This was a competition where fully autonomous systems have to detect, patch, and exploit software.

More details: phrack.org/papers/cyber_grand_shellphish.html

MechaPhish and angr are developed by the Computer Security Lab @ UC Santa Barbara. This is the research group of Giovanni Vigna!

angr: architecture



Components:

- PyVEX: lifter based on VEX (valgrind) for reasoning on binary code. Makes angr architecture-independent!
- Claripy: solver abstraction. Support for Microsoft Z3 solver.
- CLE/archinfo: ELF/PE loaders. It handles platform details.

angr: let's start using it!

Installation on BIAR VM v1.6.5:

```
> python2 -m pip install --upgrade --user pip
> python2 -m pip install --user angr
```

angr has been recently ported to Python 3. Avoid it for now.

angr: how to use it?

To symbolic execute a binary, you need to:

1. choose exploration targets:
   a. [start target] where (code address) start the execution
   b. [find target] where (code address) stop the execution
   c. [avoid targets] which paths (code addresses) ignore

2. Define the symbolic inputs

angr does not know what is symbolic and what is concrete. User has to mark it explicitly.

Unlikely that angr will reach the find target if the start target is the binary entry point!
Avoid targets are needed to limit path explosion!

Exercise #1: analyze our initial example [assertion fail]

```
> cd ~/Desktop/
> git clone
https://github.com/ercoppa/symbolic-execution-tut
orial.git
> cd symbolic-execution-tutorial/slide-example
> objdump -d example
```

If you want to use IDA on Windows, download the binary at:
https://github.com/ercoppa/symbolic-execution-tutorial/raw/master/slide-example/example

Exercise #1: target addresses and symbolic inputs

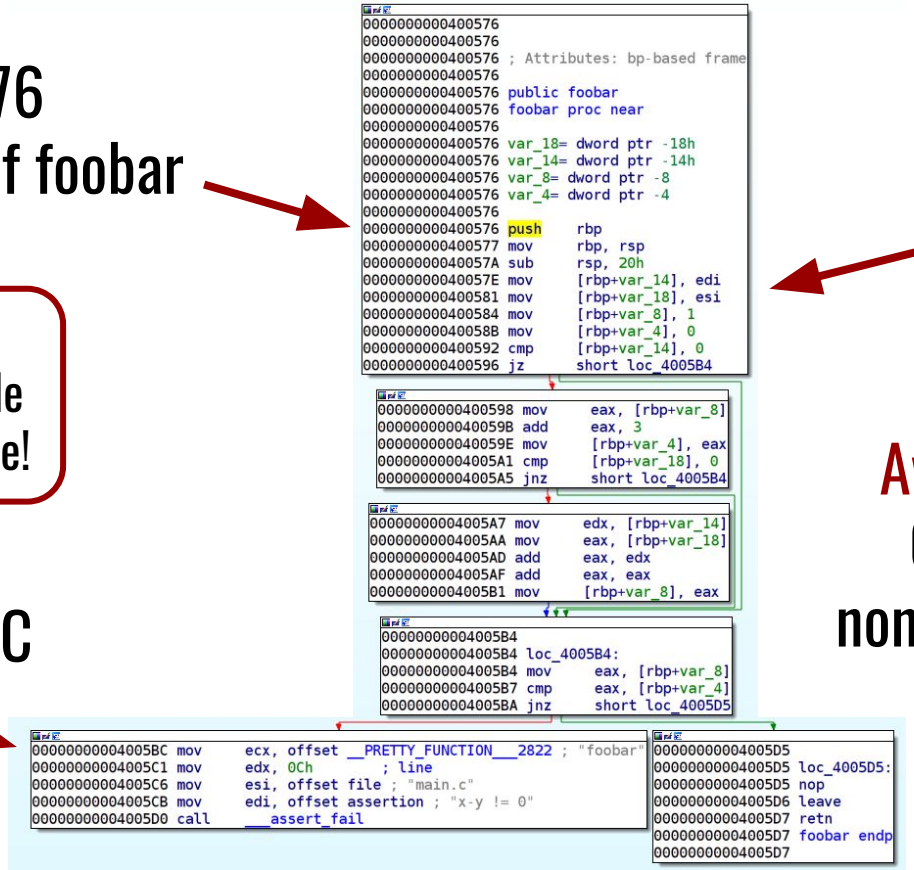
Start target: 0x400576
first instruction of foobar

Inputs:
function args

Target addresses may change if you re-compile the example.c source file!

Find target: 0x4005BC
assert block

Avoid target:
0x4005D5
non assert block



Exercise #1: angr script solve-example.py (1)

```
import angr


proj = angr.Project('example')

start = XXX     # foobar
avoid = [YYY]   # non assert block
end = ZZZ       # assert block

# blank_state since arbitrary point
state = proj.factory.blank_state(addr=start)

# arguments are inside registers in x86_64
a = state.regs.edi
b = state.regs.esi
```

Exercise #1: angr script solve-example.py (2)

```
sm = proj.factory.simulation_manager(state)
while len(sm.active) > 0:
    print sm # info
    sm.explore(avoid=avoid, find=end, n=1)
    if len(sm.found) > 0: # Bazinga!
       print "\nReached the target\n"
       state = sm.found[0].state
       print "%edi = " + str(state.se.eval_upto(a, 10))
       print "%esi = " + str(state.se.eval_upto(b, 10))

       break
```

Exercise #1: run it!

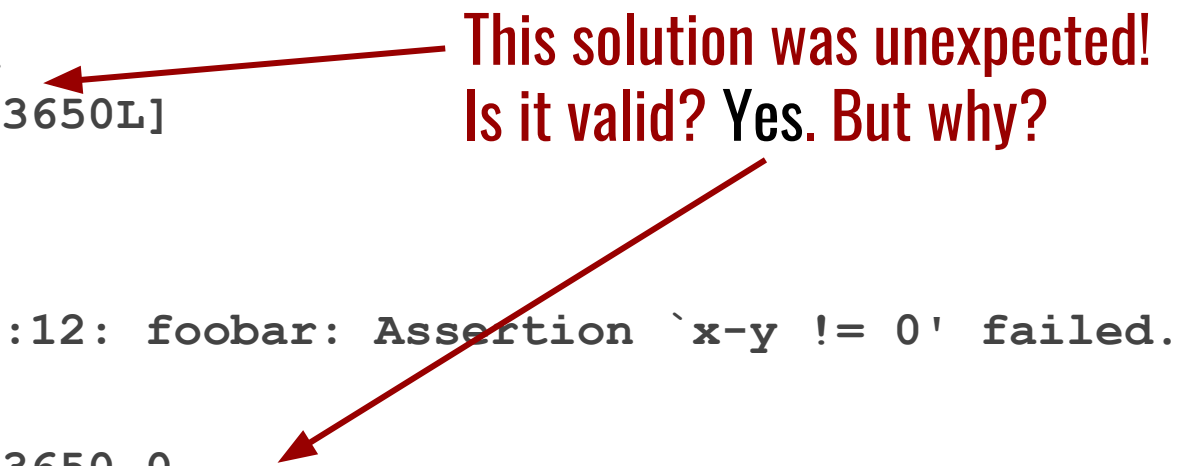
```
> python solve-example.py

<SimulationManager with 1 active>
<SimulationManager with 2 active>
<SimulationManager with 3 active>
<SimulationManager with 3 active, 1 avoid>

Reached the target
%edi = [2L, 2147483650L]
%esi = [0]

> ./example 2 0
example: example.c:12: foobar: Assertion `x-y != 0' failed.
Aborted

> ./example 2147483650 0
example: example.c:12: foobar: Assertion `x-y != 0'
failed.Aborted
```



angr: useful API

Expressions:

- symbolic value: `state.se.BVS(label, size_in_bits)`
- concrete value: `state.se.BVV(value, size_in_bits)`
- operators:

```
state.se.{Concat, Extract, Or, And, Not}
{+, -, *, /, ==, <, <=, >, >=, !=}
state.se.Reverse(expr) // swaps byte to
                       // fix endianness
```

angr: useful API (2)

Exploration:

- create project: `p = angr.Project('binary')`
- blank state: `state = p.factory.blank_state(addr=start)`
- entry state: `state = p.factory.entry_state()`
- simulation engine:

```
sm = proj.factory.simulation_manager(state) # create it
sm.explore(avoid=avoid, find=end, n=1) # explore 1 BB
sm.explore(avoid=avoid, find=end)
sm.active # list of active states
sm.found  # list of found states
sm.avoid  # list of avoided states
```

angr: useful API (3)

Registers:

- get expr from a register: `expr = state.regs.eax`
- put expr into a register: `state.regs.eax = expr`

Memory: keep in mind the endianness!

- read bytes from memory: `expr = state.memory.load(0xABC, 4)`
- store expr into a register: `state.memory.store(0xABC, expr, 4)`

Stack pop expr: `expr = state.stack_pop()`
Stack push expr: `state.stack_push(expr)`

angr: useful API (4)

Constraint solver:

- add a constraint: `state.add_constraints(expr)`
- get a numeric solution: `val = state.se.eval(expr)`
- get K numeric solutions: `v_list = state.se.eval_upto(expr, K)`
- get a solution as string: `s = state.se.eval(arg, cast_to=str)`

angr: useful API (5)

Hook:

```
def custom_hook(state):
    state.regs.eax = state.se.BVS('input', 32)
    state.add_constraints(state.se.And(state.regs.eax > 0, state.regs.eax < 10))

proj.hook(0x4011BE, hook=custom_hook, length=5)
```

custom_hook will be executed when instruction pointer is at 0x4011BE
Since length=5, angr will skip 5 bytes from the code when executing the hook, recovering execution from 0x4011BE+0x5.

Hooks helps bypassing complex functions/instrs or OS interactions.
To write robust API models, angr offers SimProcedures (see documentation)

Exercise #2: logic bomb

It's the same logic bomb that you have already solved in a prev training lecture. You can run it on Windows or Linux (after installing `wine`).

Binary: bomb/bomb.exe

Logic behind each phase:

Exercise #2: phase 1

```
> cd ../bomb
> wine ./bomb # Run it on Windows. It's easier!
Welcome to my fiendish little bomb. You have 6 phases with
which to blow yourself up. Have a nice day!

TEST_TEST_TEST

BOOM!!!
The bomb has blown up.
```

typed the wrong solution

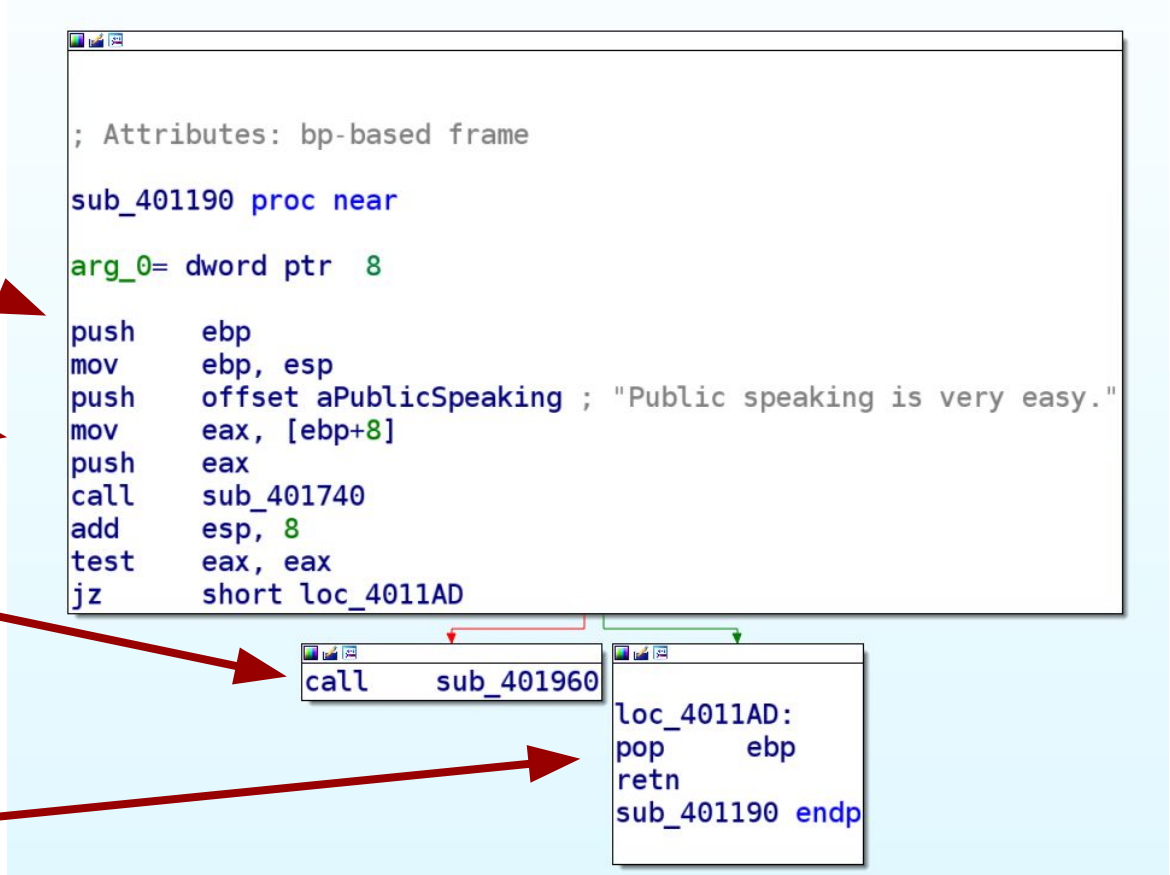
Exercise #2: target addresses and input

start target: begin of phase_1()

Input: first argument, pointer to a string

avoid target: block calling bomb_explode()

find target: block returning to main function



Exercise #2: discussion script of phase #1 (solution)

Exploration targets:

```
start = 0x401190     # addr of phase_1()
avoid = [0x401960]   # addr of explode_bomb()
end = [0x4011AD]     # last block of
                      phase_1 (before ret)
```

Exercise #2: new angr bits from phase-1.py

```
# a symbolic input string with a length up to 128 bytes
arg = state.se.BVS("input_string", 8 * 128)
# an ending byte
arg_end = state.se.BVV(0x0, 8)

# concat arg and arg_end
arg = state.se.Concat(arg, arg_end)

bind_addr = 0x603780 # read_line() is storing here the input string

# store the symbolic string at this address
state.memory.store(bind_addr, arg)

# push string address into the stack
state.stack_push(state.se.BVV(bind_addr, 32))
state.stack_push(state.se.BVV(0x0, 32))
```

Alternative approach:

```
arg_end = state.se.BVS("end_input_string", 8)
state.add_constraints(arg_end == 0x0)
```

Exercise #2: phase #1 (execution)

```
> python phase-1.py
<SimulationManager with 1 active>
[...] // after 2 minutes

Reached the target
<SimulationManager with 1 found, 35 active, 101 avoid>
Solution: Public speaking is very easy.

> ./bomb.exe # you can run it on Linux using wine
Welcome to my fiendish little bomb. You have 6 phases with
which to blow yourself up. Have a nice day!

Public speaking is very easy.

Phase 1 defused. How about the next one? [...]
```

Exercise #2: now move on to other phases!

Hints:

1. use phase-1.py as a template to edit for other phases
2. check previous slides on angr API
3. detect start/find/avoid target addresses
4. try to avoid OS interactions
5. understand the execution context of each phase: where the input is expected to be found, what assumptions can be made on it to help SE