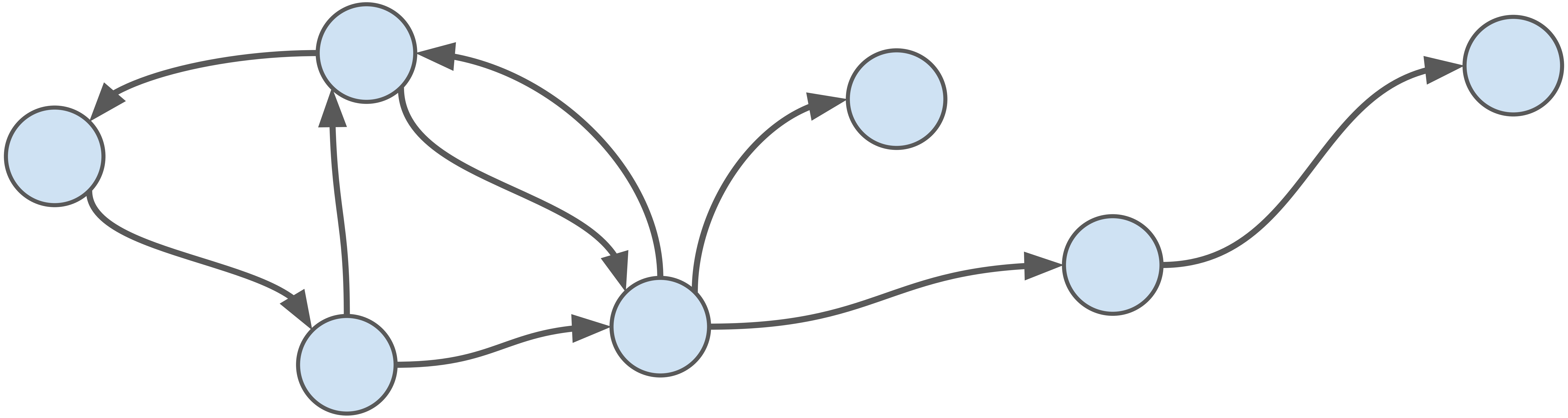
Finding vulnerabilities
by fuzzing, dynamic and static analysis

Brandon Azad
Stanford CS155 guest lecture
April 15, 2021

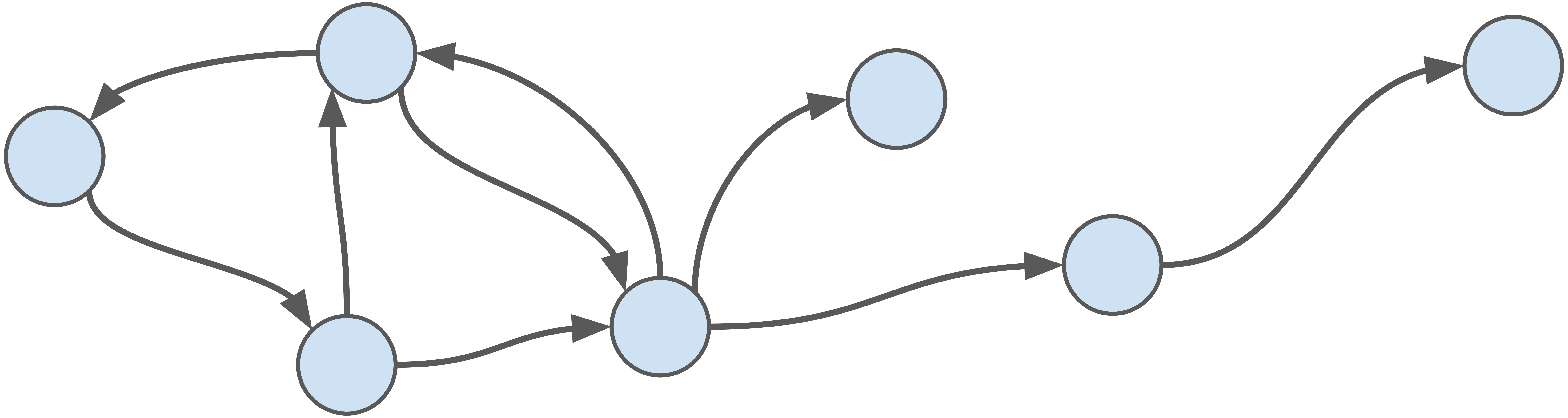
Acknowledgments: Lecture slides are from the Computer Security course taught by Dan Boneh and Zakir Durumeric at Stanford University. When slides are obtained from other sources, a a reference will be noted on the bottom of that slide. A full list of references is provided on the last slide.

Conceptualizing vulnerabilities and exploits

Computer programs: finite state machines

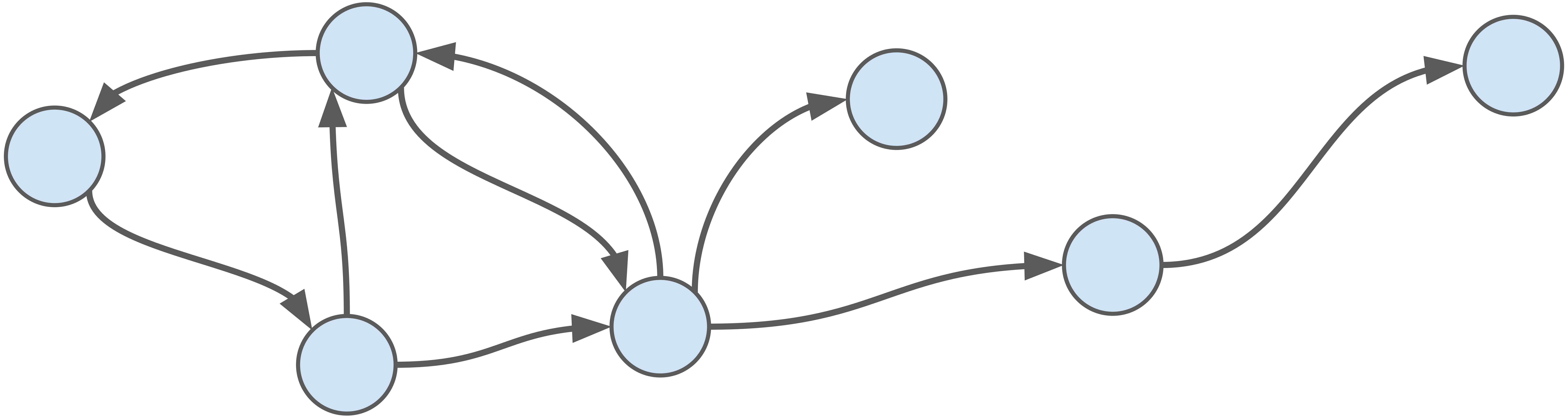


Computer programs: finite state machines



This is a *conceptual* state machine describing the *intended* operation of the program.

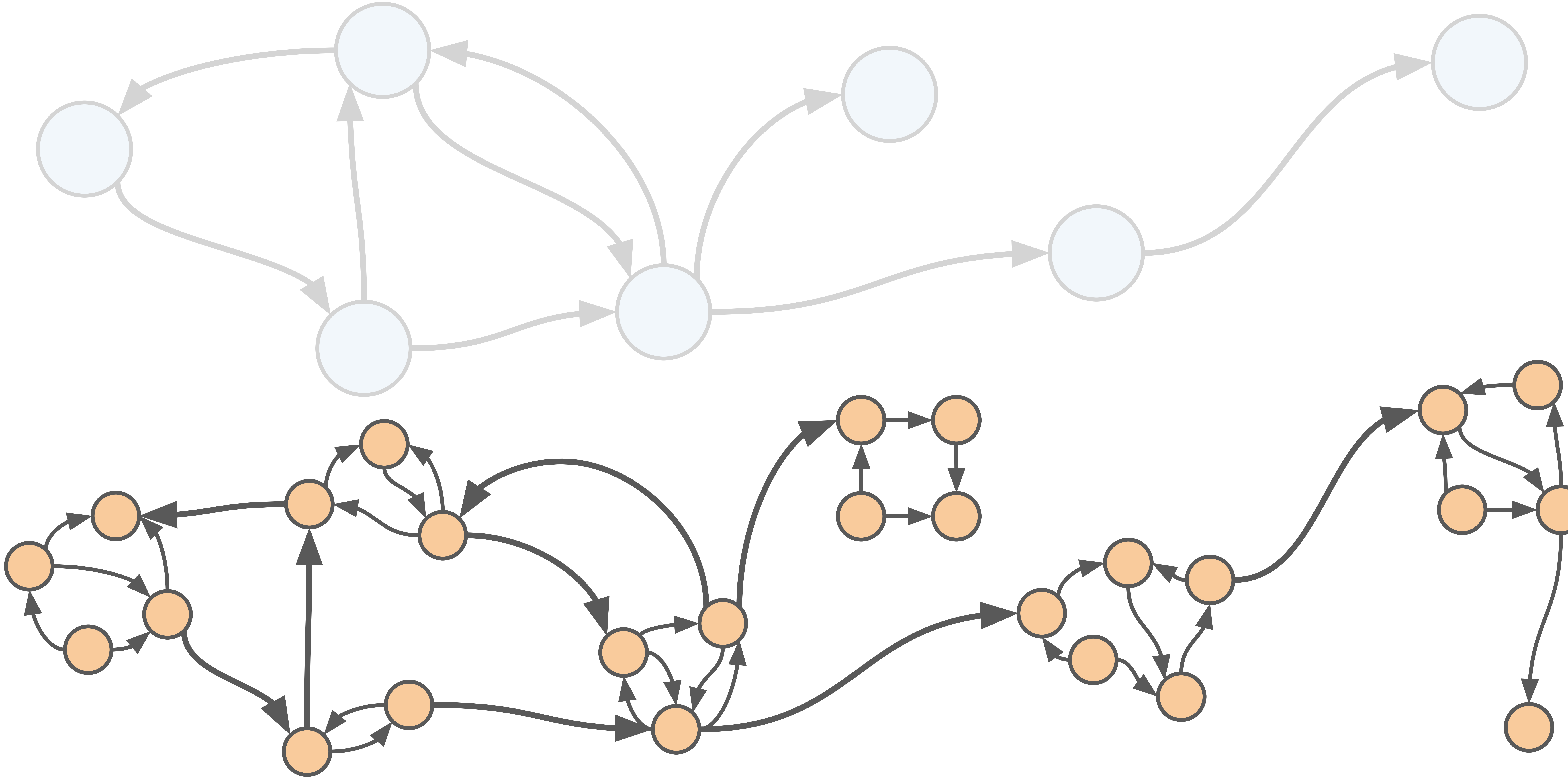
Computer programs: finite state machines



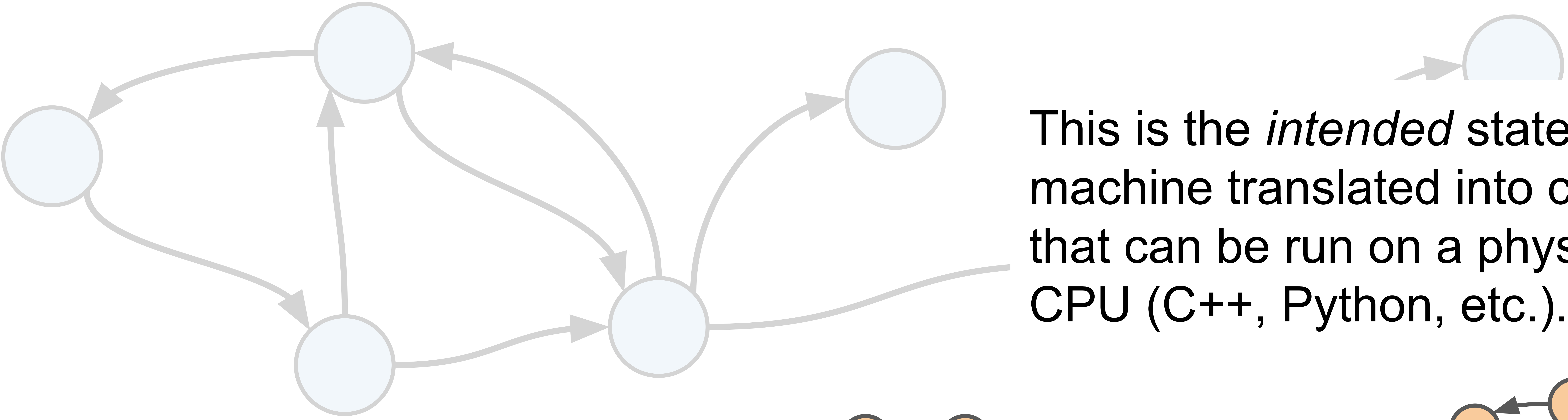
This is a *conceptual* state machine describing the *intended* operation of the program.

A physical CPU cannot directly execute this abstract state machine.

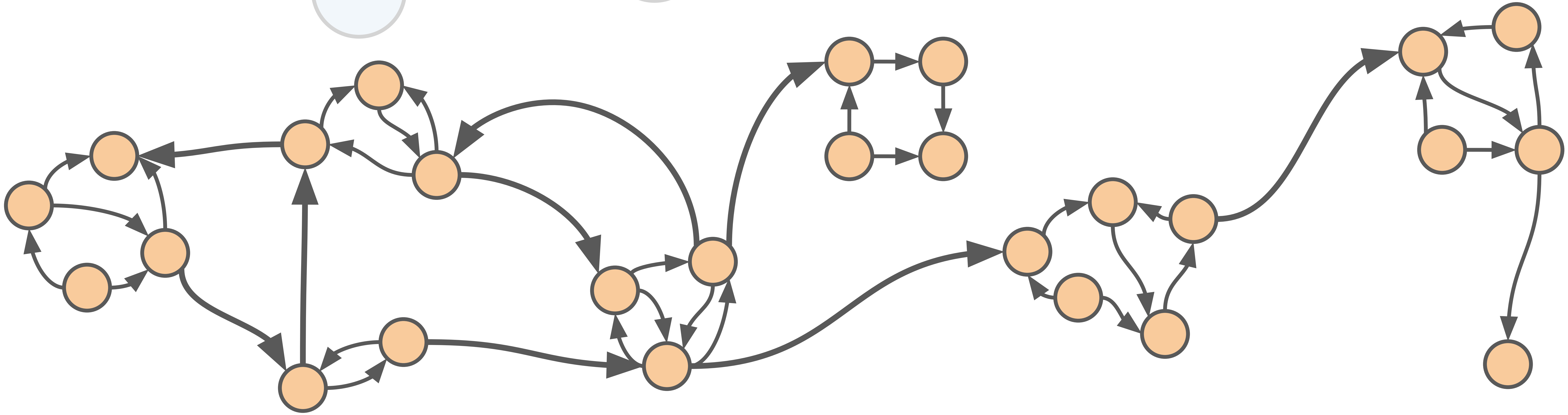
Running code: state machines emulating state machines



Running code: state machines emulating state machines



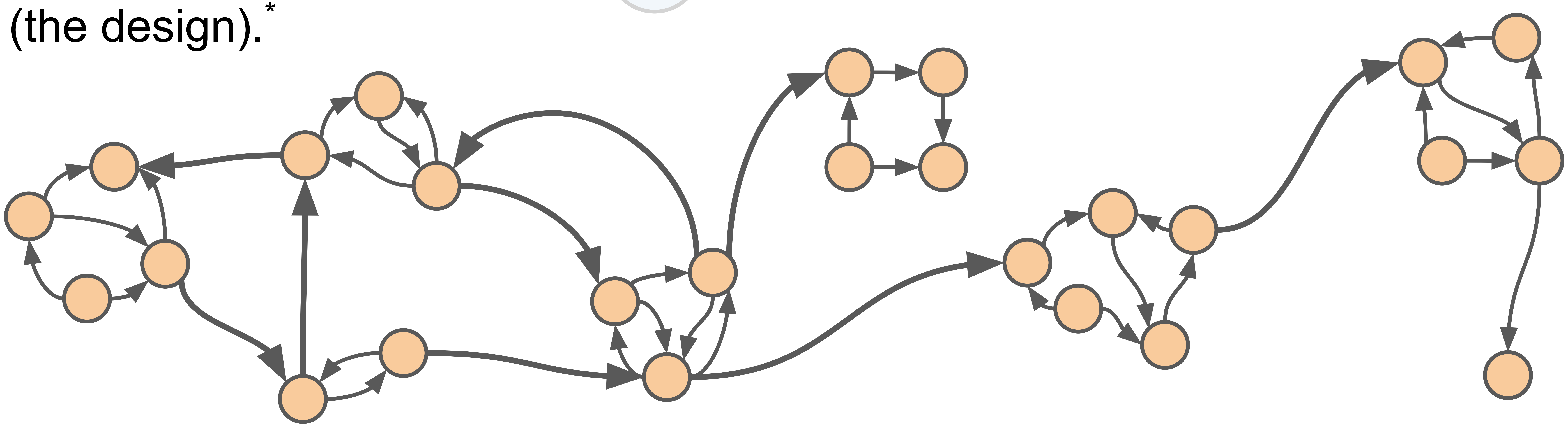
This is the *intended* state machine translated into code that can be run on a physical CPU (C++, Python, etc.).*



* Not quite true: that code still needs to be translated to machine code, which introduces another level of state machines emulating state machines.

Running code: state machines emulating state machines

Bugs occur when there are reachable states in the runnable state machine (the code) that have no corresponding state in the intended state machine (the design).*



* Not the full picture: the initial design itself could have issues (design issues) which still count as software bugs.

Running code: state machines emulating state machines

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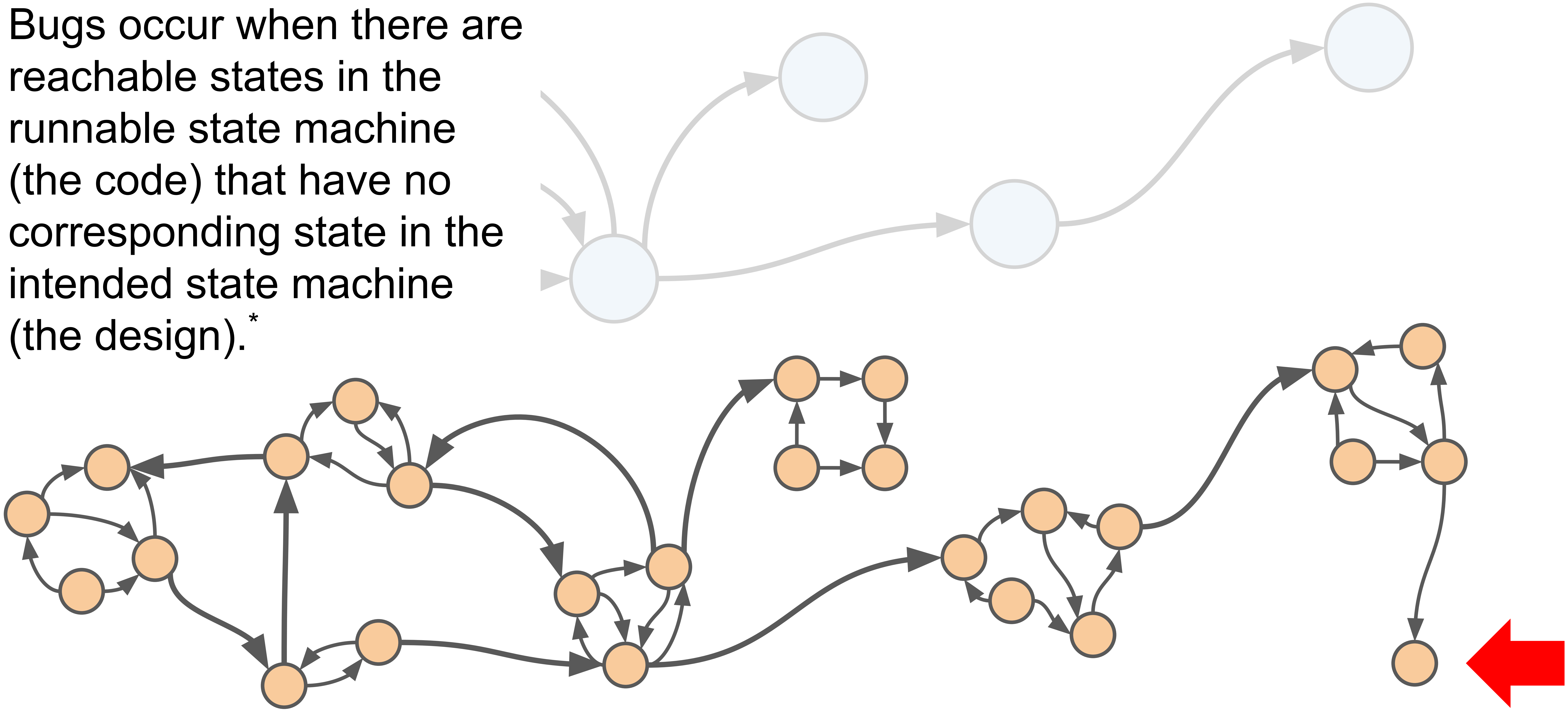
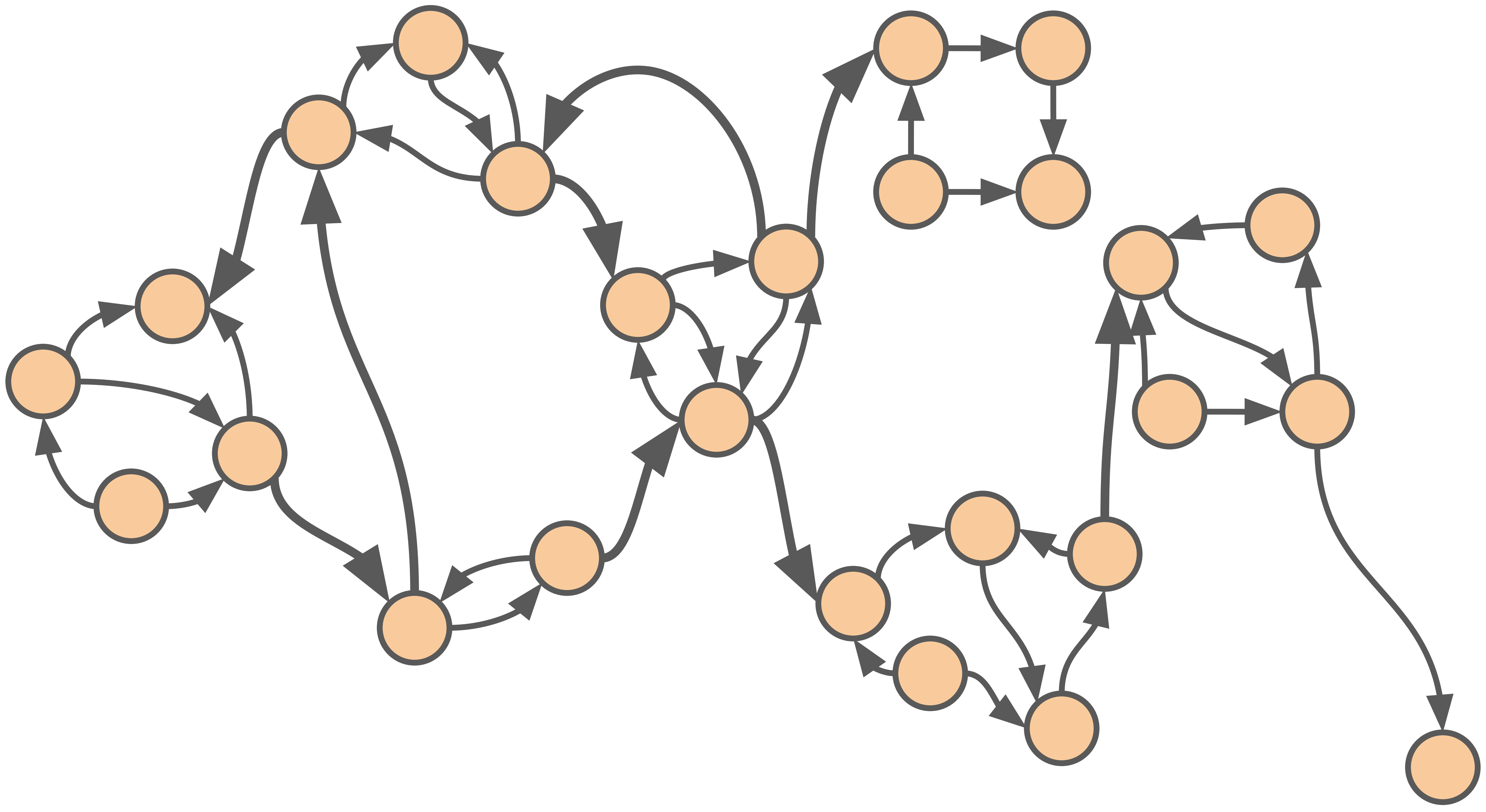


Classifying states



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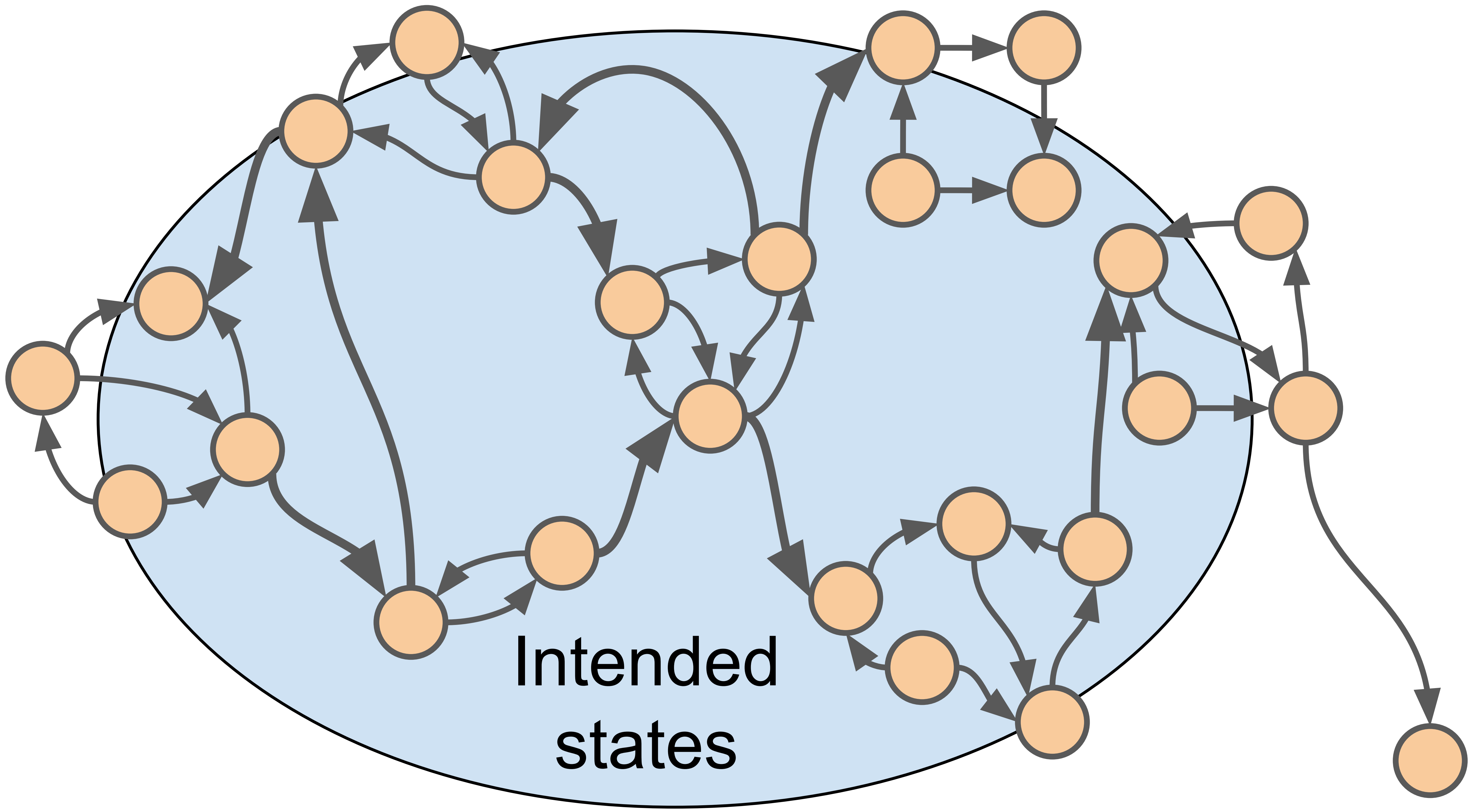

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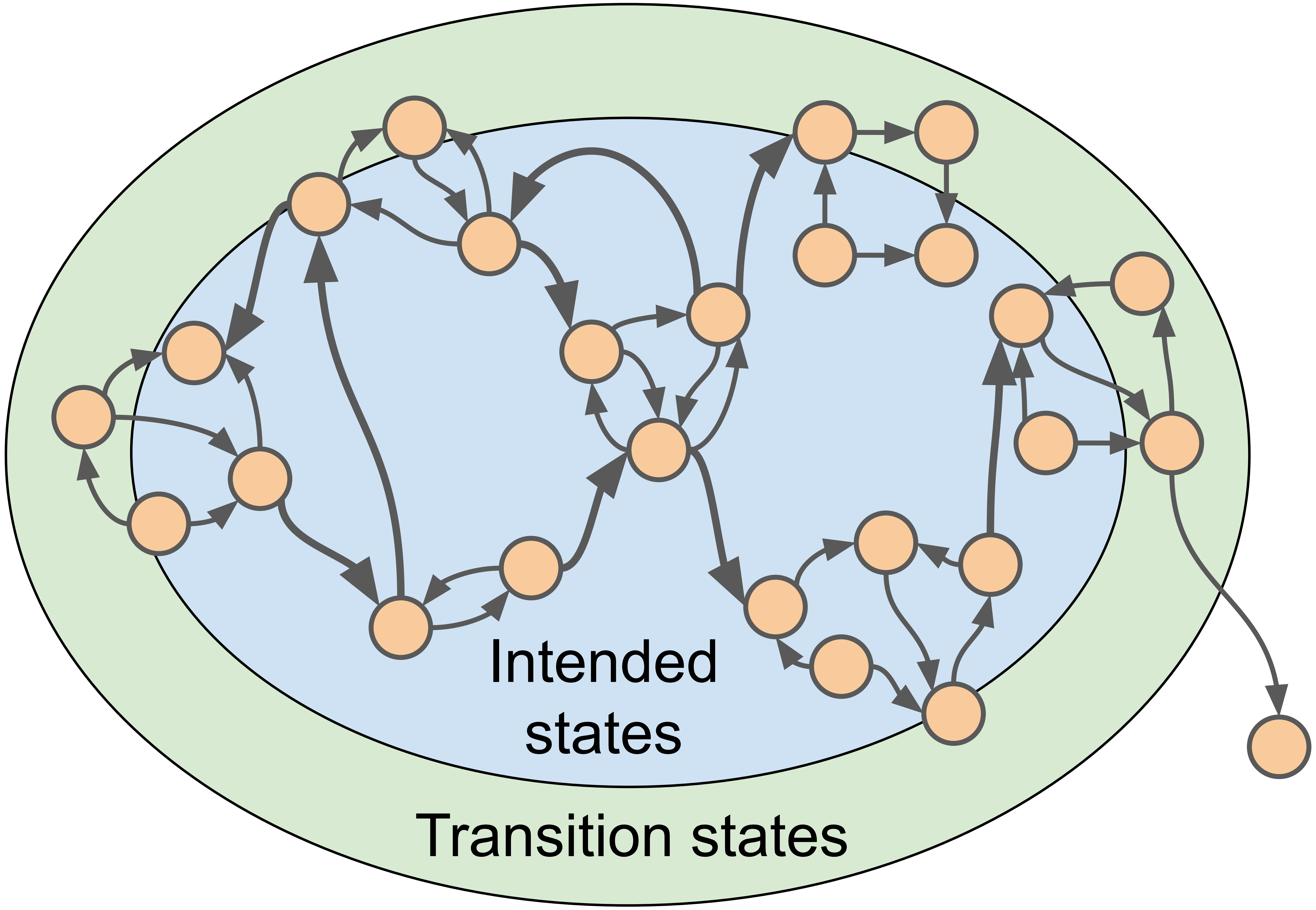
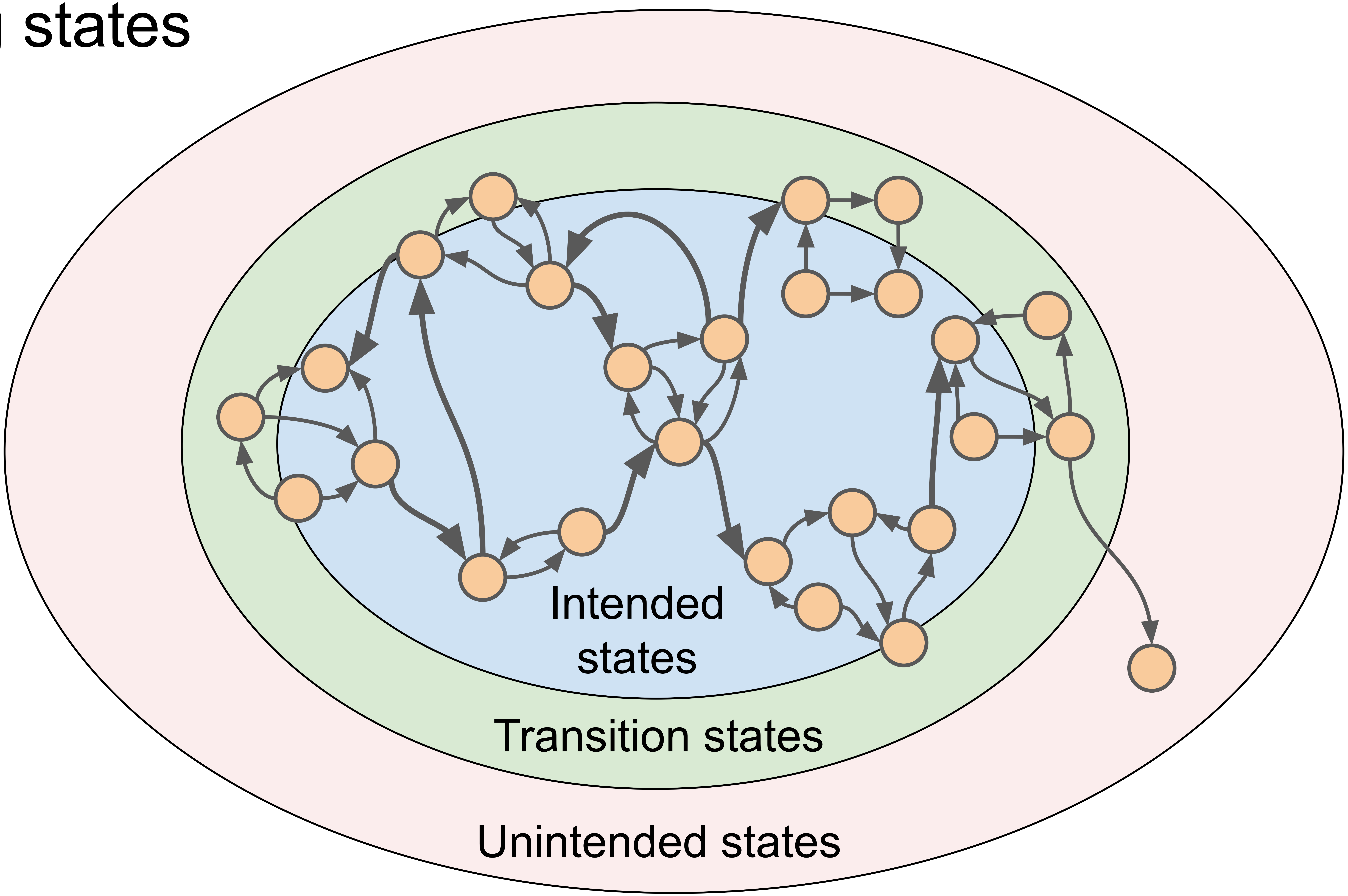
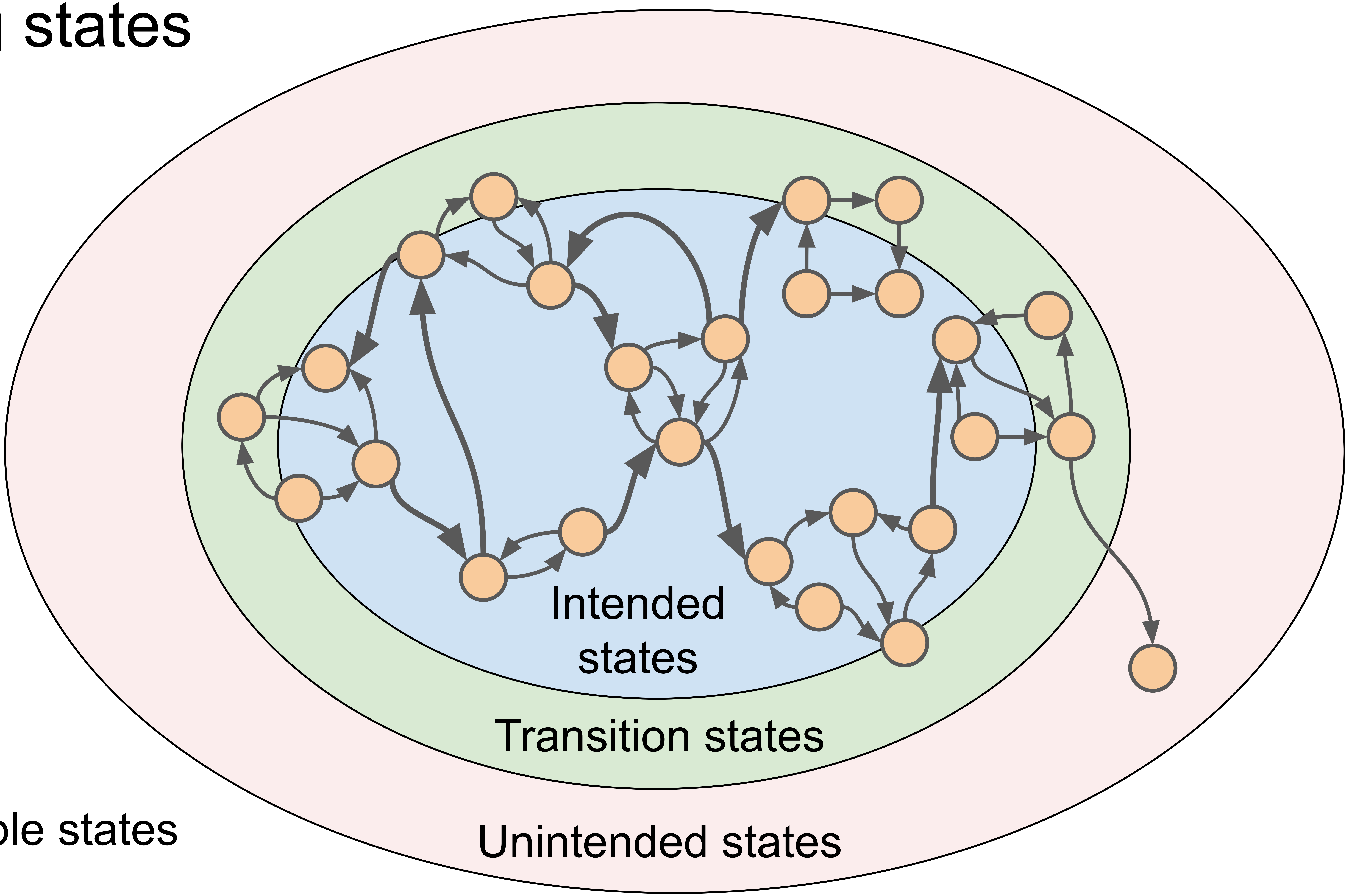


Classifying states

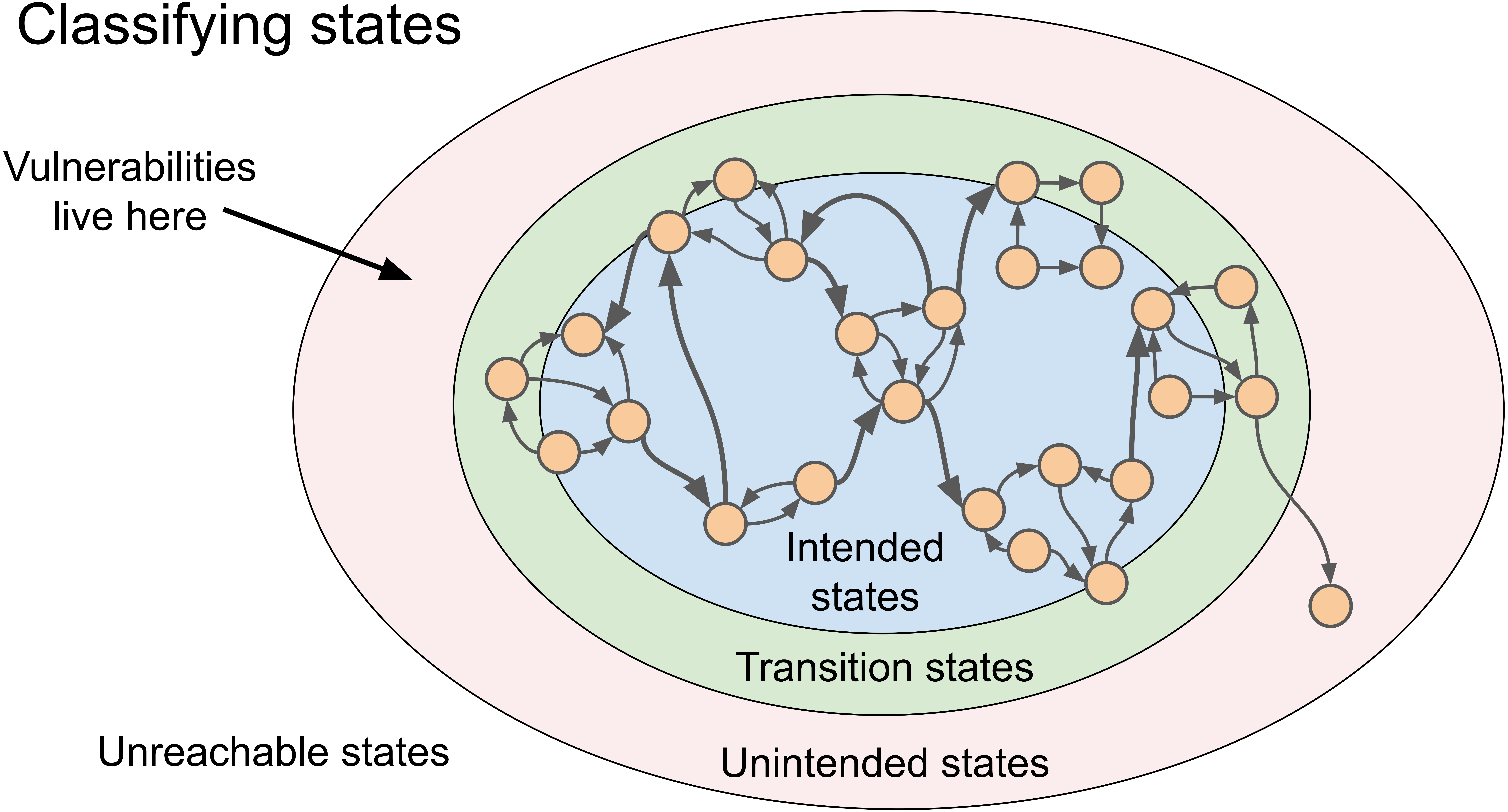


Classifying states



Unreachable states

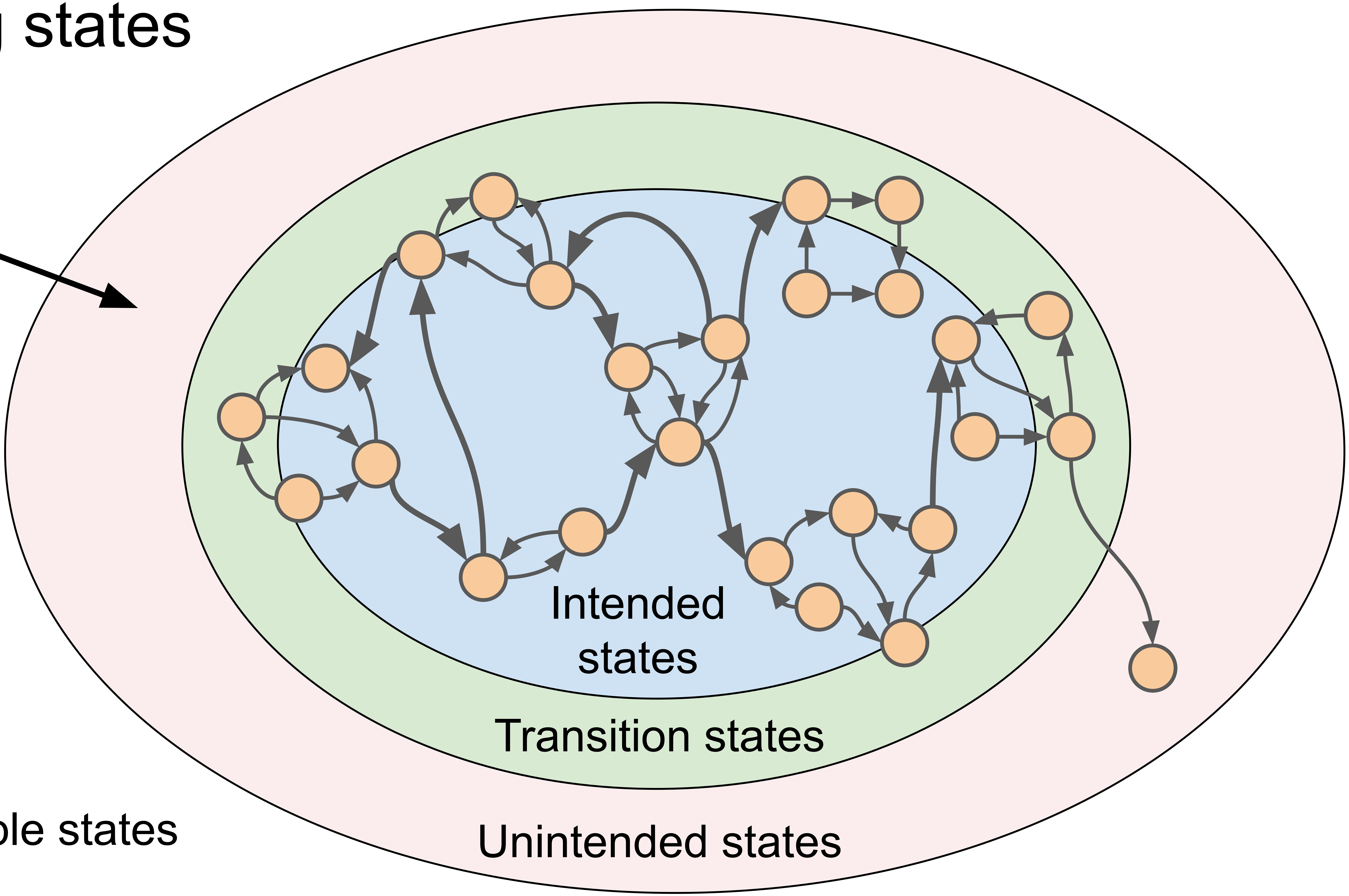
Classifying states



Classifying states

Vulnerabilities live here

Exploitation is making the program do "interesting" transitions in the unintended state space.



Unreachable states

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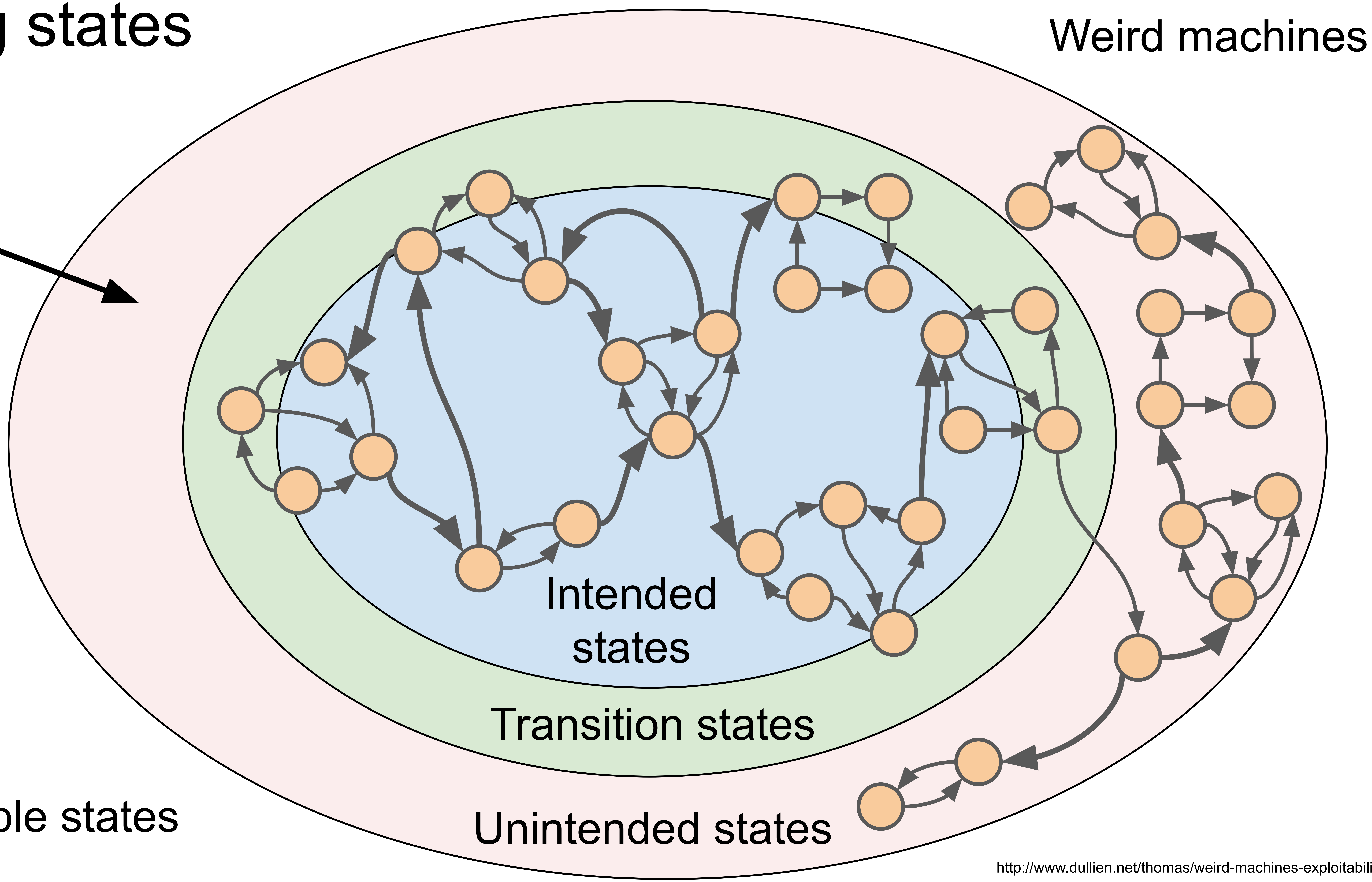


Unreachable states

http://www.dullien.net/thomas/weird-machines-exploitability.pdf

Common categories of software bugs

Design issue: The conceptual state machine does not meet the intended goals

The firewall's remote interface is designed with a hardcoded admin password

Functionality bug: The code has bad transitions but only between validly represented states

The save button code is broken, no transition to "saving the file" state

Implementation bug: Code introduces new states not represented in the conceptual state machine

Lack of length checks introduces new "stack corruption" state

Other ways to reach unintended states

Hardware fault: The hardware suffers a glitch that causes a transition to an unintended state *even if the code is perfect*

A cosmic ray causes a bit flip in a voting machine's memory, causing a state where one candidate has an impossible number of votes

Transmission error: The code is correct but is corrupted in-flight

A program downloaded from the internet suffers packet corruption, so the program that is run has a different state machine from the one that was sent

This list is not intended to be exhaustive; merely to illustrate the myriad ways that unintended states may enter a system; deciding which ones to defend against is one step of proper threat modeling.

For any interesting program, it is essentially impossible to manually explore the full state space to find the unintended states

Fuzzing

Fuzzing

Find bugs in a program by feeding it random, corrupted, or unexpected data

Idea: Random inputs will explore a large part of the state space

- Some unintended states are observable as crashes (**`SIGSEGV`**, **`abort()`**)
- Any crash is a bug, but only some bugs are exploitable

Works best on programs that parse files or process complex input data

Fuzzing example

Fuzzing can be as simple as:

```
cat /dev/random | head -c 512 > rand.jpeg; open rand.jpeg
```

How could we do better?

- Randomly corrupt real JPEG files
- Reference the JPEG spec so that we generate only “JPEG-looking” data
- Measure the JPEG parser to see how deep we’re getting in the code

Common fuzzing strategies

Mutation-based fuzzing

Randomly mutate test cases from some corpus of input files

Generation-based (smart) fuzzing

Generate test cases based on a specification for the input format

Coverage guided fuzzing

Measure code coverage of test cases to guide fuzzing towards new (unexplored) program states

This is not a rigid taxonomy: fuzzers often employ multiple strategies.

Mutation-based fuzzing

Randomly mutate test cases from some corpus of input files

1. Collect a corpus of inputs that explores as many states as possible
2. Perturb inputs randomly, possibly guided by heuristics

    Modify: bit flips, integer increments

    Substitute: small integers, large integers, negative integers

3. Run the program on the inputs and check for crashes
4. Go back to step 2

Can mutation-based “dumb” fuzzing be successful?

In 2010, Charlie Miller fuzzed PDF viewers using the following mutation program:

```
numwrites = random.randrange(math.ceil((float(len(buf)) / FuzzFactor))) + 1
for j in range(numwrites):
    rbyte = random.randrange(256)
    rn = random.randrange(len(buf))
    buf[rn] = "%c"%(rbyte)
```

Found 64 exploitable-looking crashes

Dumb fuzzing is often way more successful than it has any right to be

Mutation-based fuzzing

Advantages

Simple to set up and run

Can use off-the-shelf software (possibly with a harness) for many programs

Limitations

Results depend strongly on the quality of the initial corpus

Coverage may be shallow for formats with checksums or validation

Generation-based (smart) fuzzing

Generate test cases based on a specification for the input format

1. Convert a specification of the input format (RFC, etc.) into a generative procedure
2. Generate test cases according to the procedure and introduce random perturbations
3. Run the program on the inputs and check for crashes
4. Go back to step 2

Syzkaller

A kernel system call fuzzer that uses test case generation and coverage

Test cases are sequences of syscalls generated from syscall descriptions

Runs the test case program in a VM

Kernel crashes in the VM indicate potential Local Privilege Escalation (LPE) vulnerabilities

Raw | Blame

304 lines (235 sloc) | 15.7 KB

Syscall descriptions

`syzkaller` uses declarative description of syscall interfaces to manipulate programs (sequences of syscalls). Below you can see (hopefully self-explanatory) excerpt from the descriptions:

```
open(file filename, flags flags[open_flags], mode flags[open_mode]) fd
read(fd fd, buf buffer[out], count len[buf])
close(fd fd)
open_mode = S_IRUSR, S_IWUSR, S_IXUSR, S_IRGRP, S_IWGRP, S_IXGRP, S_IROTH, S_
```

The descriptions are contained in `sys/$OS/*.txt` files. For example see the sys/linux/dev_snd_midi.txt file for descriptions of the Linux MIDI interfaces.

A more formal description of the description syntax can be found here.

Programs

The translated descriptions are then used to generate, mutate, execute, minimize, serialize and deserialize programs. A program is a sequences of syscalls with concrete values for arguments. Here is an example (of a textual representation) of a program:

```
r0 = open(&(0x7f0000000000)="./file0", 0x3, 0x9)
read(r0, &(0x7f0000000000), 42)
close(r0)
```

https://github.com/google/syzkaller/blob/master/docs/syscall_descriptions.md

Generation-based (smart) fuzzing

Advantages

- Can get deeper coverage faster by leveraging knowledge of the input format
- Input format/protocol complexity is not a limit on coverage depth

Limitations

- Requires a lot of effort to set up
- Successful fuzzers are often domain-specific
- Coverage limited by accuracy of the spec; implementation may diverge

Coverage guided fuzzing

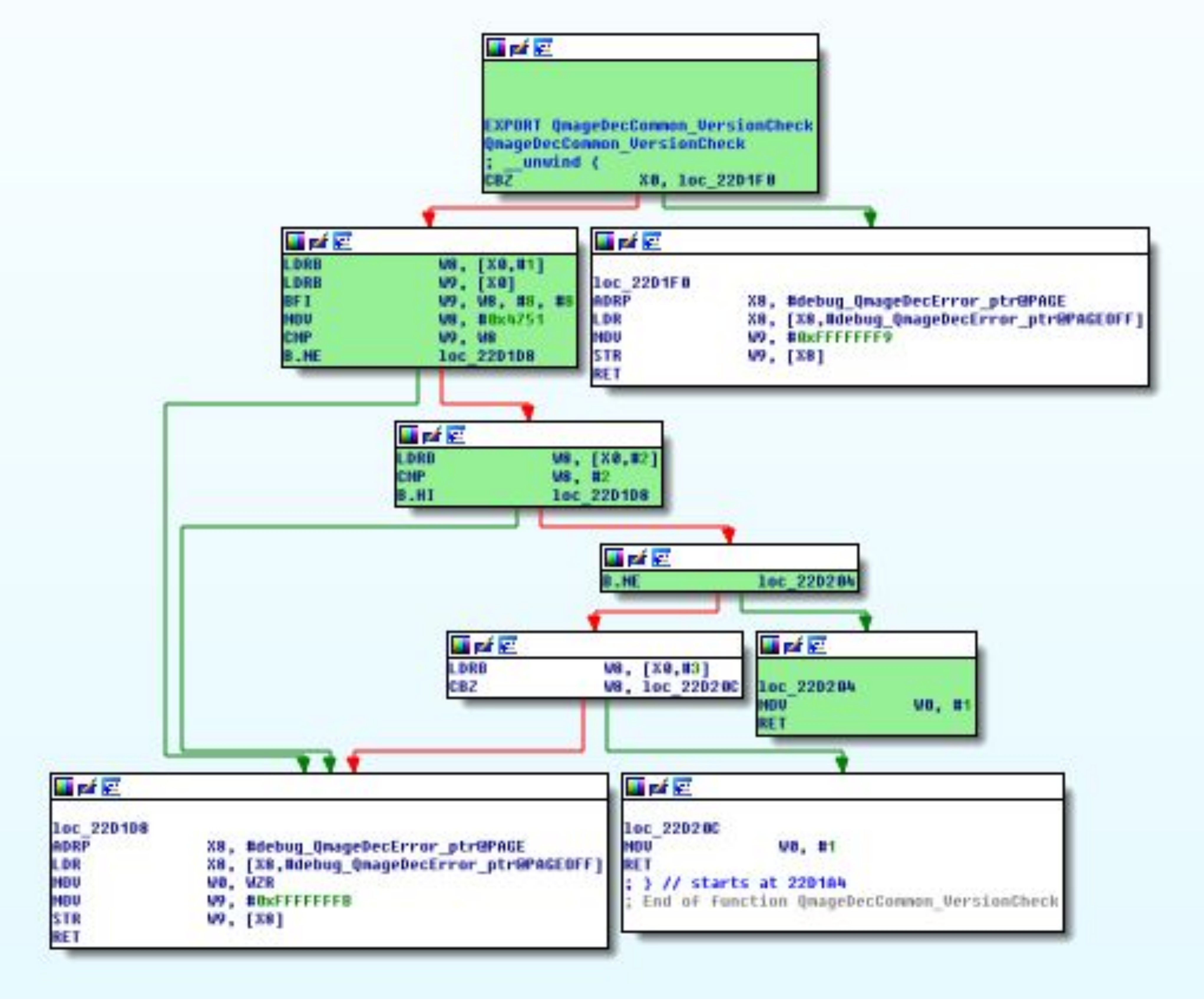
Key insight: code coverage is a useful metric, why not use it as **feedback** to guide fuzzing?

Prefer test cases that reach new states

Basic block coverage: Has this basic block in the CFG been run?

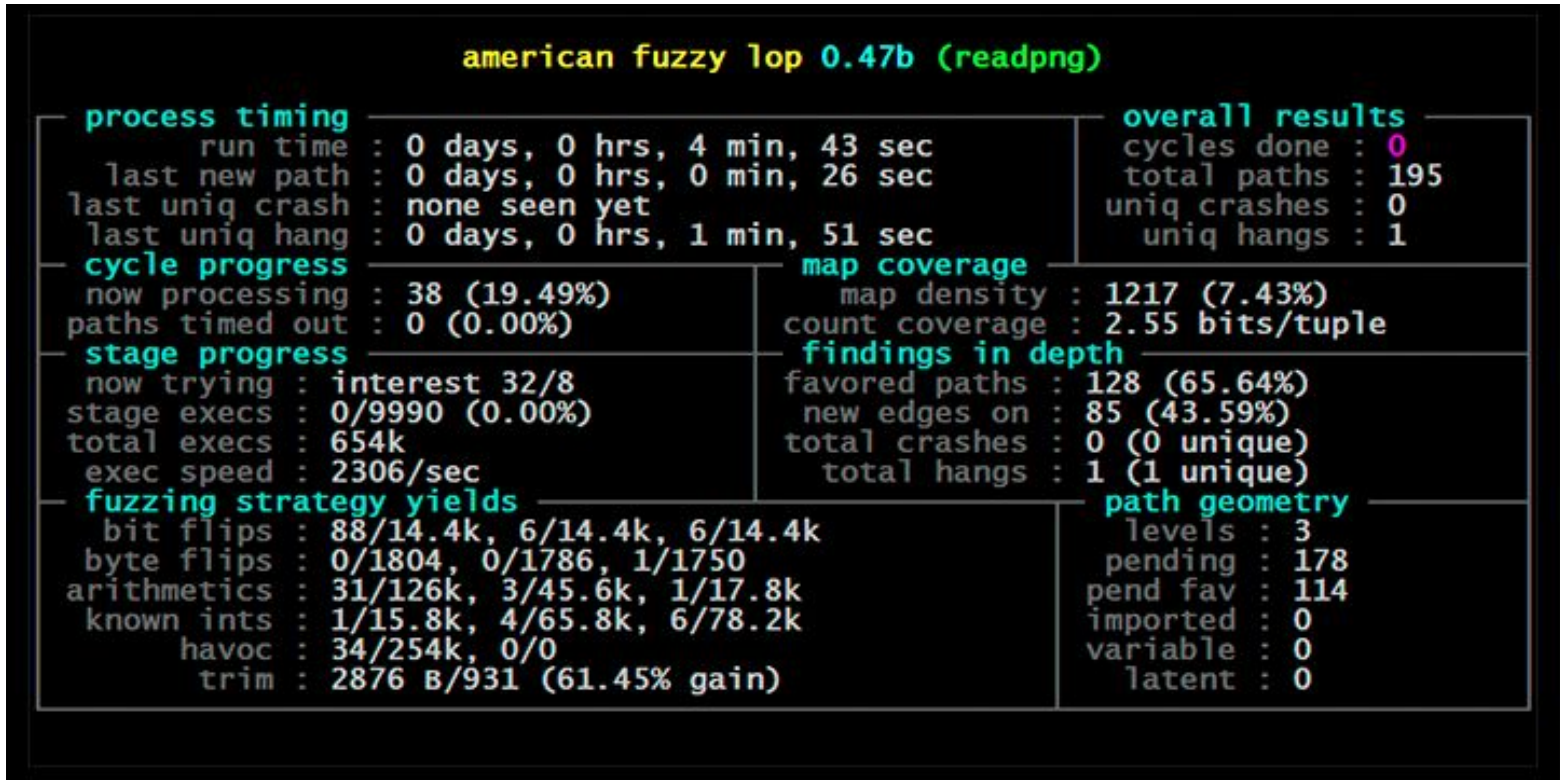
Edge coverage: Has this branch been taken?

Path coverage: Has this particular path through the program been taken?



https://googleprojectzero.blogspot.com/2020/07/mms-exploit-part-2-effective-fuzzing-qmage.html

american fuzzy lop (AFL)



1. Compile the program with instrumentation to measure coverage

2. Trim the test cases in the queue to the smallest size that doesn't change the program behavior

3. Create new test cases by mutating the files in the queue using traditional fuzzing strategies

4. If new coverage is found in a mutated file, add it into the queue

5. Go back to step 2

https://lcamtuf.coredump.cx/afl/README.txt

Coverage guided fuzzing

Advantages

Very good at finding new program states, even if the initial corpus is limited

Combines well with other fuzzing strategies

Wildly successful track record

Limitations

Not a panacea to bypass strong checksums or input validation

Still doesn’t find all types of bugs (e.g. race conditions)

Real world example: Fuzzing the Samsung Qmage codec

Thursday, July 23, 2020

MMS Exploit Part 2: Effective Fuzzing of the Qmage Codec

Posted by Mateusz Jurczyk, Project Zero

This post is the second of a multi-part series capturing my journey from discovering a vulnerable little-known Samsung image codec, to completing a remote zero-click MMS attack that worked on the latest Samsung flagship devices. New posts will be published as they are completed and will be linked here when complete.

- MMS Exploit Part 1: Introduction to the Samsung Qmage Codec and Remote Attack Surface
- [this post]
- MMS Exploit Part 3: Constructing the Memory Corruption Primitives
- MMS Exploit Part 4: MMS Primer, Completing the ASLR Oracle
- MMS Exploit Part 5: Defeating Android ASLR, Getting RCE

Introduction

In Part 1, I discussed how I discovered the "Qmage" image format natively supported on all modern Samsung phones, and how I traced its roots to Android boot animations and even some pre-Android phones. At this stage of the story, we also know that the codec seems very fragile and is likely affected by bugs, and that it constitutes a zero-click remote attack surface via MMS and the default Samsung Messages app. I was at this point of the project in early December 2019. The next logical step was to thoroughly fuzz it – the code was definitely too extensive and complex to approach with a manual audit, especially without access to the original source or expertise of the inner workings of the format. As a big fan of fuzzing, I hoped to be able to run it in accordance with the current state of the art: efficiently (without unnecessary overhead), at scale, with code coverage information, reliable reproducibility and effective deduplication. But how to achieve all this with a codec that is part of Android, accessible only through Skia image API, and precompiled for the ARM/ARM64 architectures only? Read on to find out!

Writing the test harness

The fuzzing harness is usually one of the most critical pieces of a successful fuzzing session, and it was the first thing I started working on. I published the end result of my work as SkCodecFuzzer on GitHub, and it can be used as a reference while reading this post. My initial goal with the loader was to write a Linux command-line program that could run on physical Android devices, and use the Skia SkCodec interface to load and decode an input image file in exactly the same way (or at least as closely as

In 2019, Mateusz Jurczyk discovered the Qmage image codec included on Samsung smartphones

- Reachable via zero-click MMS

The code looks fragile but the library is closed source

- Few examples of Qmage files

Mateusz developed a harness to enable large-scale coverage-guided fuzzing of the Qmage codec

https://googleprojectzero.blogspot.com/2020/07/mms-exploit-part-2-effective-fuzzing-qmage.html

Fuzzing the Samsung Qmage image codec: harness

A **fuzzing harness** was written to call the interesting functions in the library and supply the test case input from the fuzzer

```
d2s:/data/local/tmp $  ./loader accessibility_light_easy_off.qmg
[+] Detected image characteristics:
[+] Dimensions:      344 x 344
[+] Color type:      4
[+] Alpha type:      3
[+] Bytes per pixel: 4
[+] codec->GetAndroidPixels() completed successfully
d2s:/data/local/tmp $
```

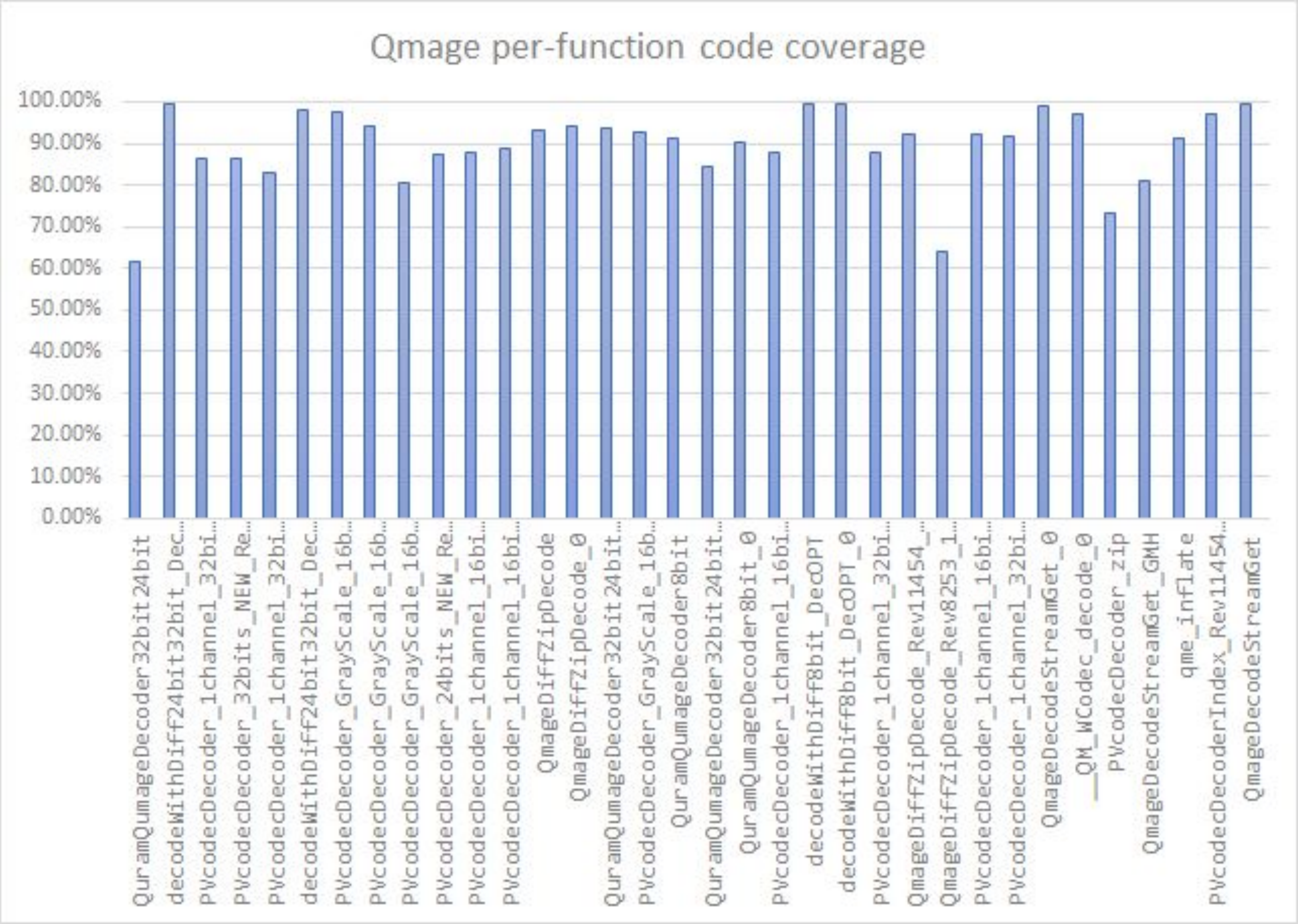
An emulator (qemu-aarch64) was used to run the harness and Qmage library on a Linux machine

Easier to get 1000 Linux cores than 1000 Samsung Galaxy phones

Fuzzing the Samsung Qmage image codec: coverage

Code coverage was collected by modifying qemu-aarch64 to trace executed PC addresses

- Coverage feedback compensated for the small number of initial test cases



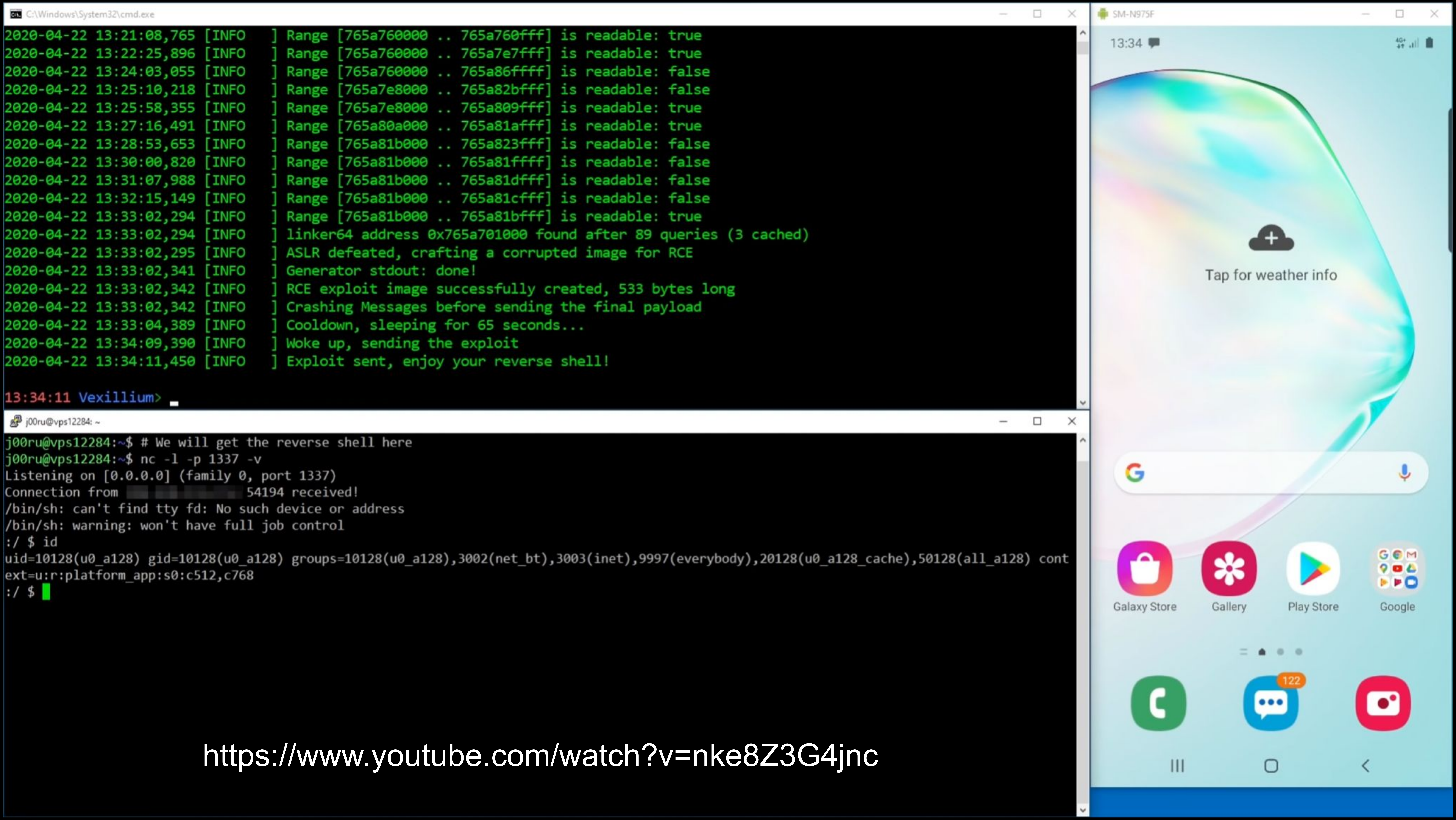
Fuzzing the Samsung Qmage image codec: results

Category	Count	Percentage
write	174	3.33%
read-memcpy	124	2.38%
read-vector	18	0.34%
read-32	3	0.06%
read-16	52	1.00%
read-8	34	0.65%
read-4	703	13.47%
read-2	393	7.53%
read-1	3322	63.66%
sigabrt	3	0.06%
null-deref	392	7.51%

4 weeks of fuzzing

87.3% coverage of the Qmage codec

5218 unique crashes

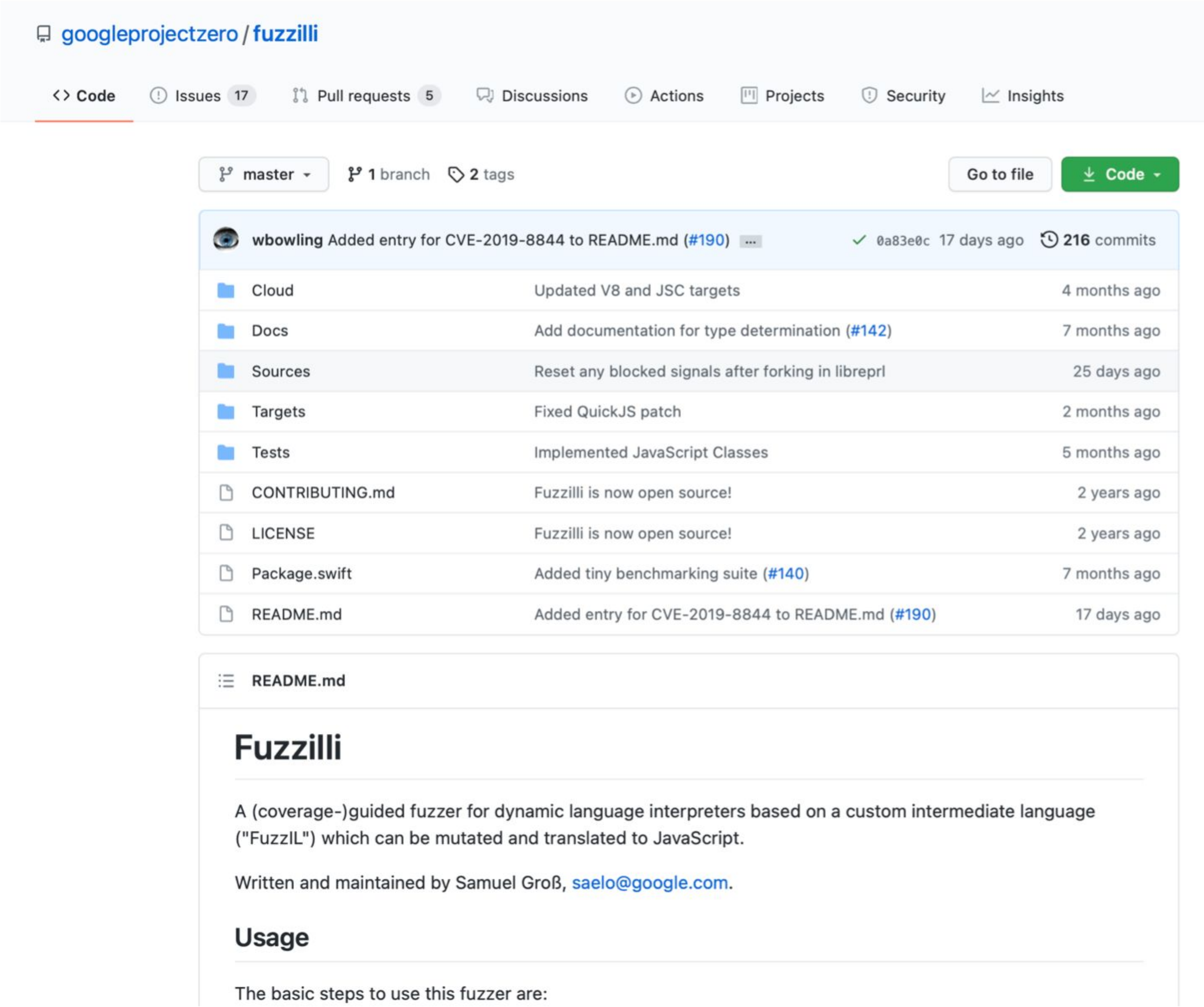


https://www.youtube.com/watch?v=nke8Z3G4jnc

Another cool fuzzer: Fuzzilli

Very successful JavaScript fuzzer

Principle: Translate JavaScript to a dense Intermediate Language (IL), and fuzz the IL



https://github.com/googleprojectzero/fuzzilli

Fuzzing summary

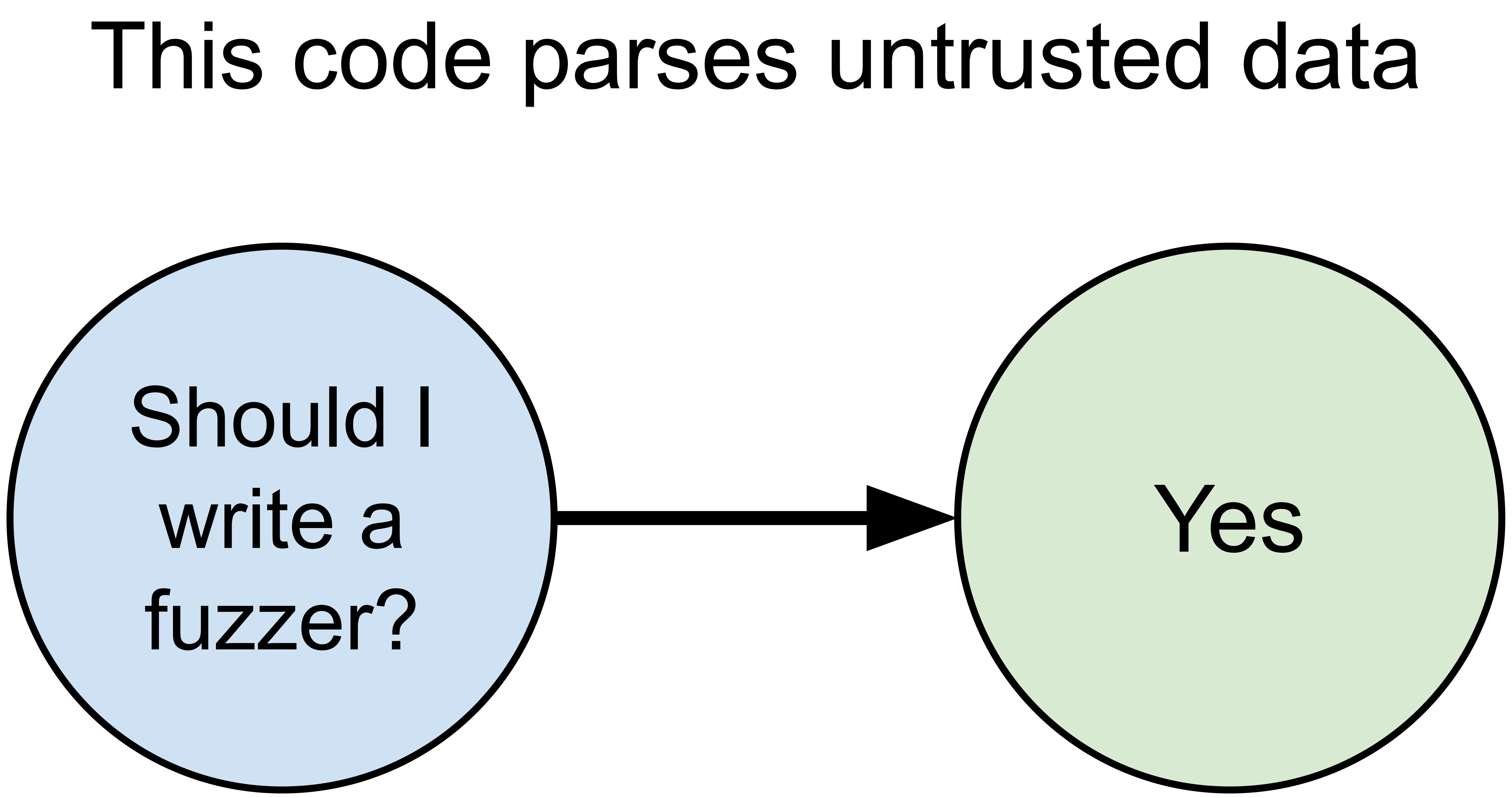
Off-the-shelf fuzzers are excellent at finding bugs

Custom fuzzers are also excellent at finding bugs

Different fuzzers often find different bugs

Relatively easy to get started

Fuzzing doesn't find all types of bugs



Dynamic analysis

Dynamic analysis

Analyze a program's behavior by actually running its code

- May be combined with compile-time modifications like instrumentation
- Can modify the program's behavior dynamically
  - Useful for rapid experimentation

Often complements fuzzing very well

Running A Program Under Valgrind

Like the debugger, Valgrind runs on your executable, so be sure you have compiled an up-to-date copy of your program. Run it like this, for example, if your program is named `memoryLeak`:

```
$ valgrind ./memoryLeak
```

Valgrind will then start up and run the specified program inside of it to examine it. If you need to pass command-line arguments, you can do that as well:

```
$ valgrind ./memoryLeak red blue
```

When it finishes, Valgrind will print a summary of its memory usage. If all goes well, it'll look something like this:

```
==4649== ERROR SUMMARY: 0 errors from 0 contexts
==4649== malloc/free: in use at exit: 0 bytes in 0 blocks.
==4649== malloc/free: 10 allocs, 10 frees, 2640 bytes allocated.
==4649== For counts of detected errors, rerun with: -v
==4649== All heap blocks were freed -- no leaks are possible.
```

This is what you're shooting for: no errors and no leaks. Another useful metric is the number of allocations and total bytes allocated. If these numbers are the same ballpark as our sample (you can run solution under valgrind to get a baseline), you'll know that your memory efficiency is right on target.

Finding Memory Errors

Memory errors can be truly evil. The more overt ones cause spectacular crashes, but even then it can be hard to pinpoint how and why the crash came about. More insidiously, a program with a memory error can still seem to work correctly because you manage to get "lucky" much of the time. After several "successful" outcomes, you might wishfully write off what appears to be a spurious catastrophic outcome as a figment of your imagination, but depending on luck to get the right answer is not a good strategy. Running under valgrind can help you track down the cause of visible memory errors as well as find lurking errors you don't even yet know about.

https://web.stanford.edu/class/cs107/resources/valgrind.html

AddressSanitizer (ASan)

Fast memory error detector for C/C++ using compiler instrumentation and a runtime library that replaces **`malloc()`** to surround allocations with redzones

- Out-of-bounds accesses
- Use-after-free
- Use-after-return
- Use-after-scope
- Double-free, invalid free
- Memory leaks

Typically 2x slowdown

```
==9901==ERROR: AddressSanitizer:heap-use-after-free on address 0x60700000dfb5 at pc 0x45917b
bp 0x7fff4490c700 sp 0x7fff4490c6f8
READ of size 1 at 0x60700000dfb5 thread T0
    #0 0x45917a in main use-after-free.c:5
    #1 0x7fce9f25e76c in __libc_start_main /build/buildd/eglibc-2.15/csu/libc-start.c:226
    #2 0x459074 in _start (a.out+0x459074)
0x60700000dfb5 is located 5 bytes inside of 80-byte region [0x60700000dfb0,0x60700000e000)
freed by thread T0 here:
    #0 0x4441ee in __interceptor_free projects/compiler-rt/lib/asan/asan_malloc_linux.cc:64
    #1 0x45914a in main use-after-free.c:4
    #2 0x7fce9f25e76c in __libc_start_main /build/buildd/eglibc-2.15/csu/libc-start.c:226
previously allocated by thread T0 here:
    #0 0x44436e in __interceptor_malloc projects/compiler-rt/lib/asan/asan_malloc_linux.cc:74
    #1 0x45913f in main use-after-free.c:3
    #2 0x7fce9f25e76c in __libc_start_main /build/buildd/eglibc-2.15/csu/libc-start.c:226
SUMMARY: AddressSanitizer: heap-use-after-free use-after-free.c:5 main
```

https://github.com/google/sanitizers/wiki/AddressSanitizer

AddressSanitizer (ASan)

Fast memory error detector for C/C++ using compiler instrumentation and a runtime library t… redzones

- Out-of-bour…
- Use-after-fr…
- Use-after-re…
- Use-after-s…
- Double-free, invalid free
- Memory leaks

> Pro tip: Once coverage guided fuzzing plateaus, run the generated corpus under ASan to find bugs the fuzzer missed!

```
ss 0x60700000dfb5 at pc 0x45917b

ibc-2.15/csu/libc-start.c:226

x60700000dfb0,0x60700000e000)

ib/asan/asan_malloc_linux.cc:64
    #1 0x45914a in main use-after-free.c:4
    #2 0x7fce9f25e76c in __libc_start_main /build/buildd/eglibc-2.15/csu/libc-start.c:226
previously allocated by thread T0 here:
    #0 0x44436e in __interceptor_malloc projects/compiler-rt/lib/asan/asan_malloc_linux.cc:74
    #1 0x45913f in main use-after-free.c:3
    #2 0x7fce9f25e76c in __libc_start_main /build/buildd/eglibc-2.15/csu/libc-start.c:226
SUMMARY: AddressSanitizer: heap-use-after-free use-after-free.c:5 main
```

Typically 2x slowdown

ThreadSanitizer (TSan)

Data race detector for C/C++

- Similar in principle to AddressSanitizer but for race conditions

High overhead

- 5-10x memory
- 5-15x slowdown

```
WARNING: ThreadSanitizer: data race (pid=19219)
  Write of size 4 at 0x7fcf47b21bc0 by thread T1:
    #0 Thread1 tiny_race.c:4 (exe+0x00000000a360)

  Previous write of size 4 at 0x7fcf47b21bc0 by main thread:
    #0 main tiny_race.c:10 (exe+0x00000000a3b4)

  Thread T1 (running) created at:
    #0 pthread_create tsan_interceptors.cc:705 (exe+0x00000000c790)
    #1 main tiny_race.c:9 (exe+0x00000000a3a4)
```

https://clang.llvm.org/docs/ThreadSanitizer.html

Static analysis

Static analysis

Using a tool to analyze a program's behavior without actually running it

Test whether a certain property holds or find places where it is violated

Static analysis can *prove* some properties about the program that fuzzing and dynamic analysis can't

E.g., can prove that a program is free of NULL pointer dereferences

Despite lots of work in this area, there are countless interesting topics and huge scope for improvements!

Undecidability of static analysis

Goal: Determine whether a given program satisfies a given property

This is theoretically undecidable: it reduces to the halting problem!

```
def solve_halting_problem(P, a):
    def new_P():
        P(a)
        bug()
    return static_analyzer_for_bug(new_P)
```

Soundness and completeness

The best static analyzer can only satisfy one of the following:*

Soundness: Everything that the static analyzer finds is a bug

But some bugs may be missed!

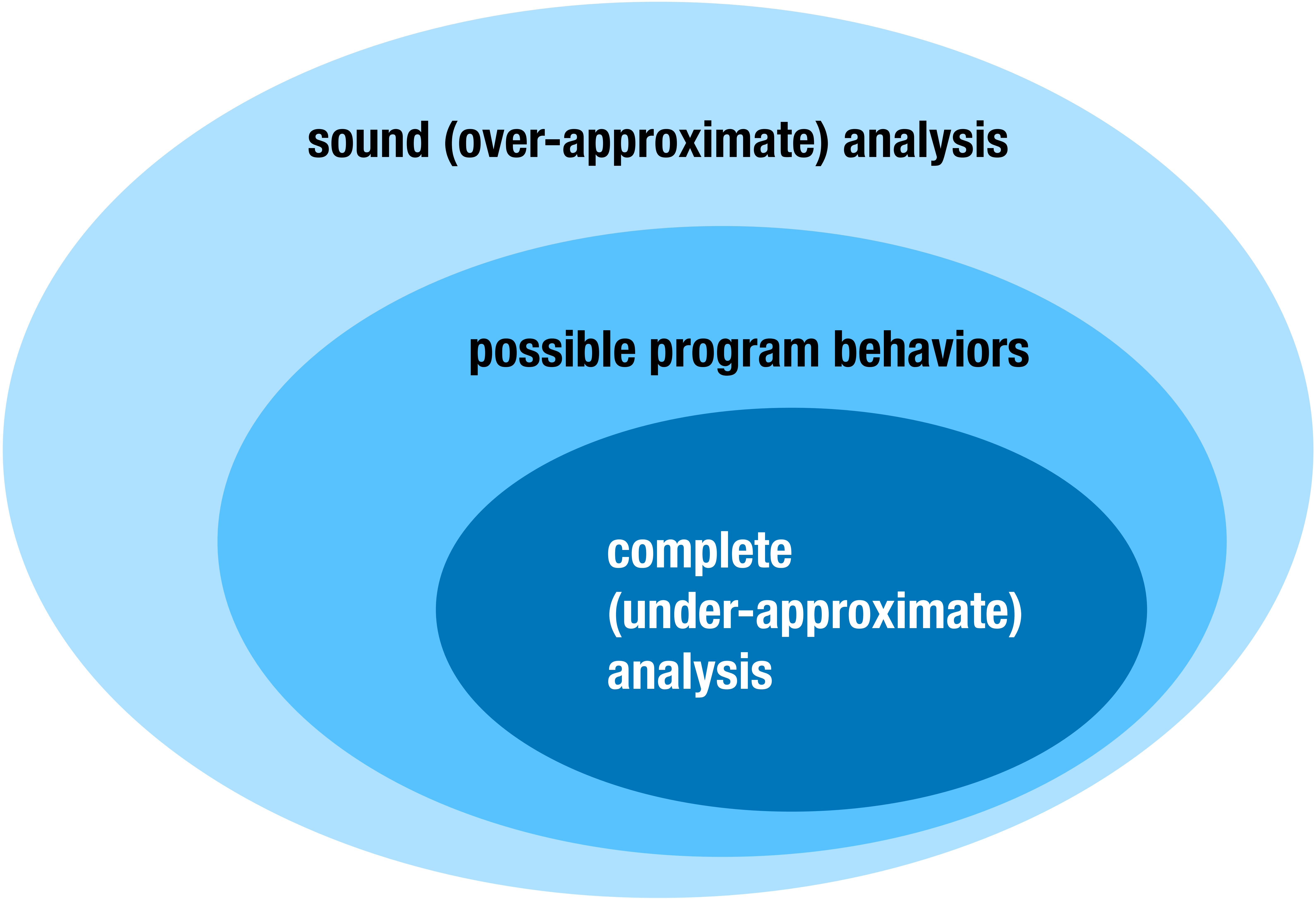
Completeness: The static analyzer finds every bug

But there may be false positives!

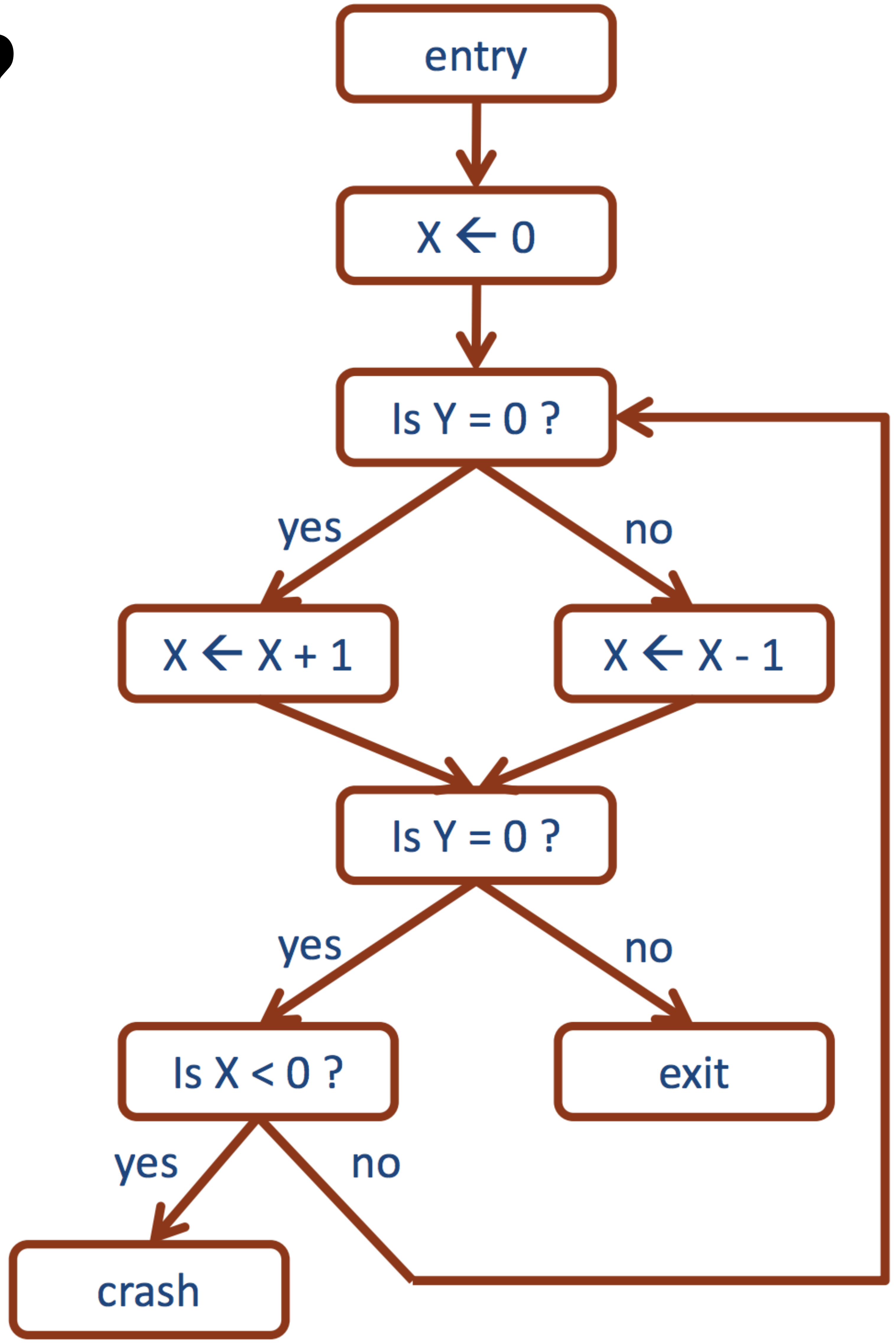
Most static analyzers are neither sound nor complete

* We are assuming termination.

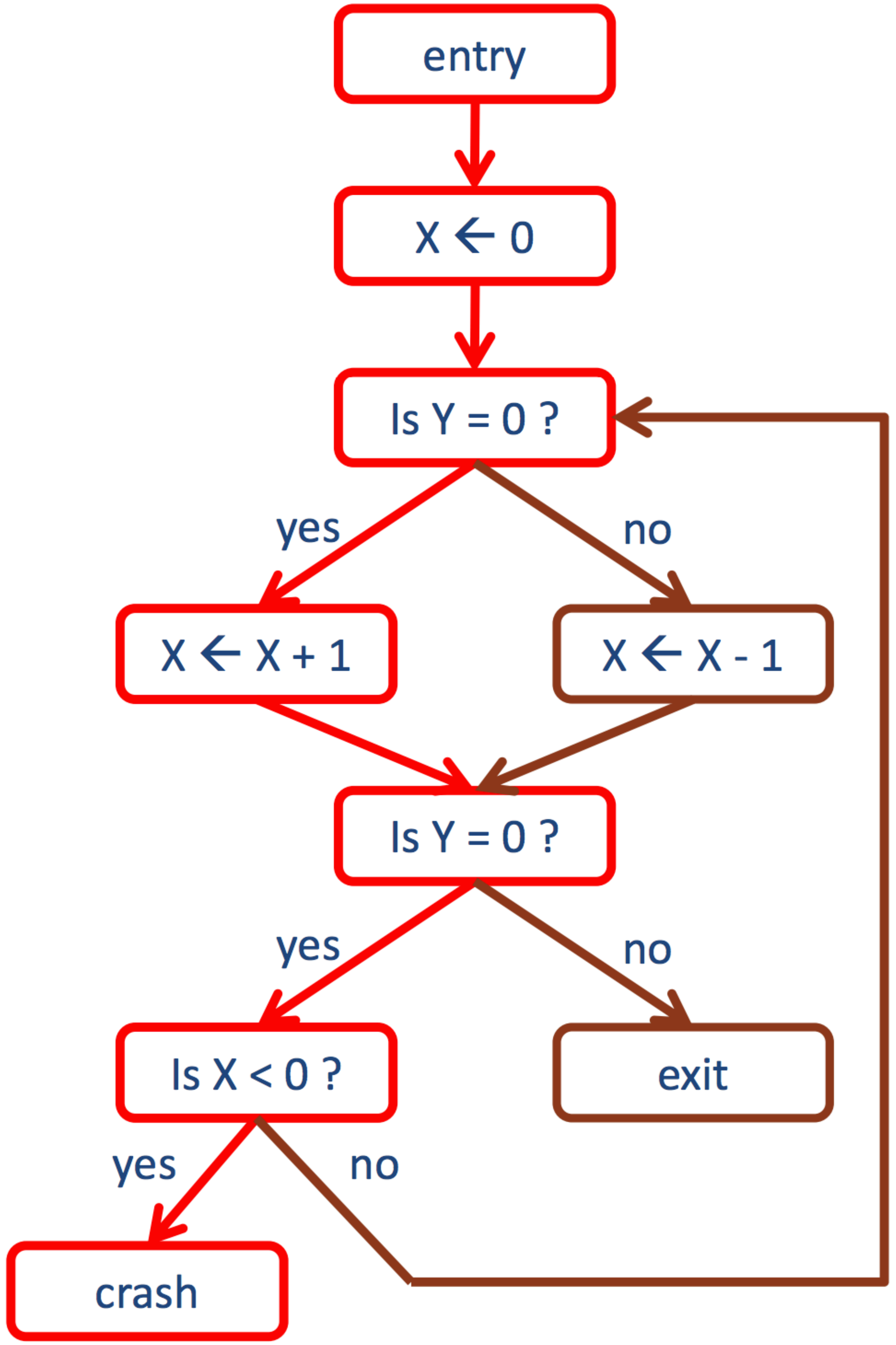
Soundness vs Completeness



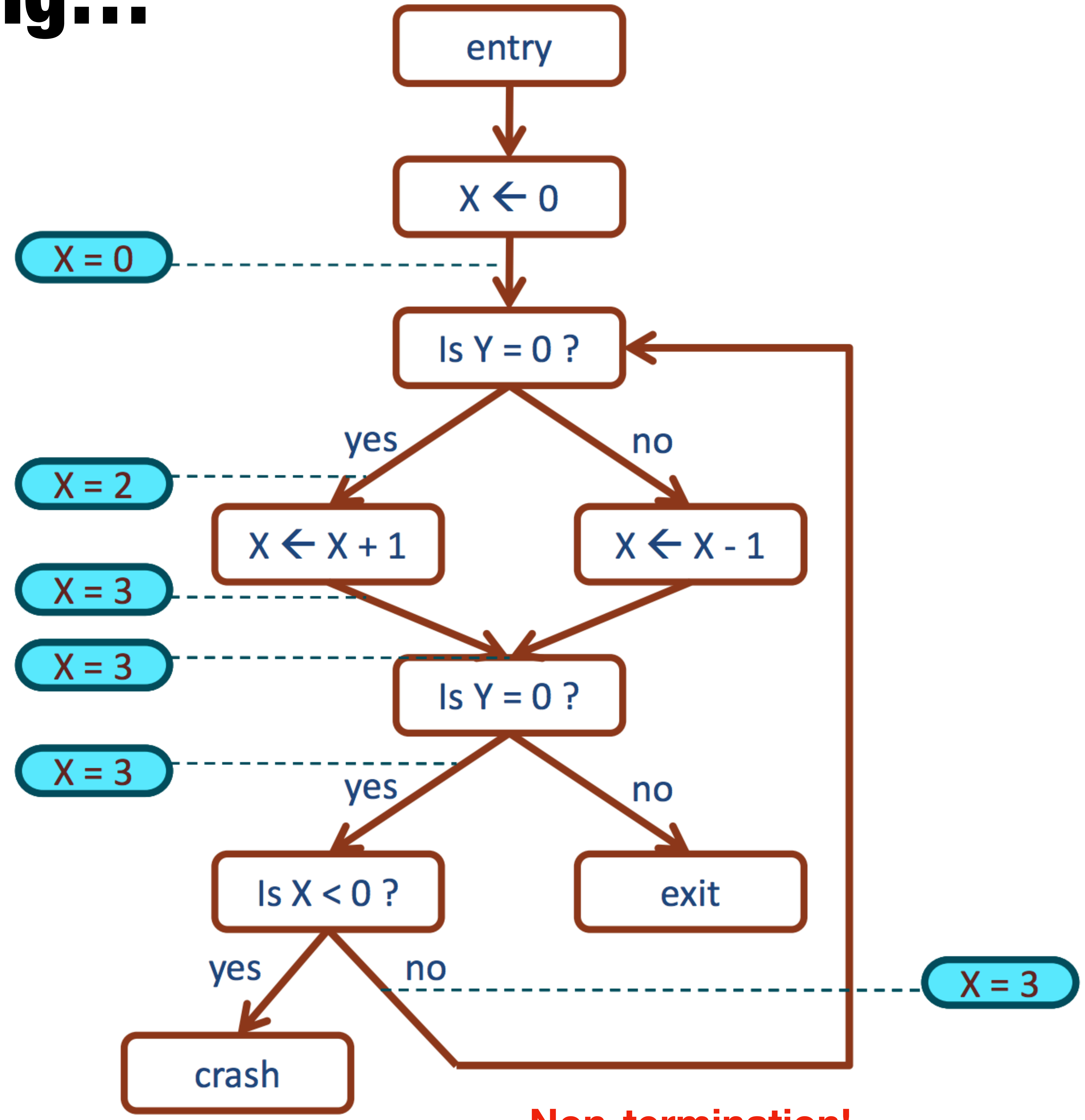
Is this program safe?



Yes, it is safe.
This program will not crash.

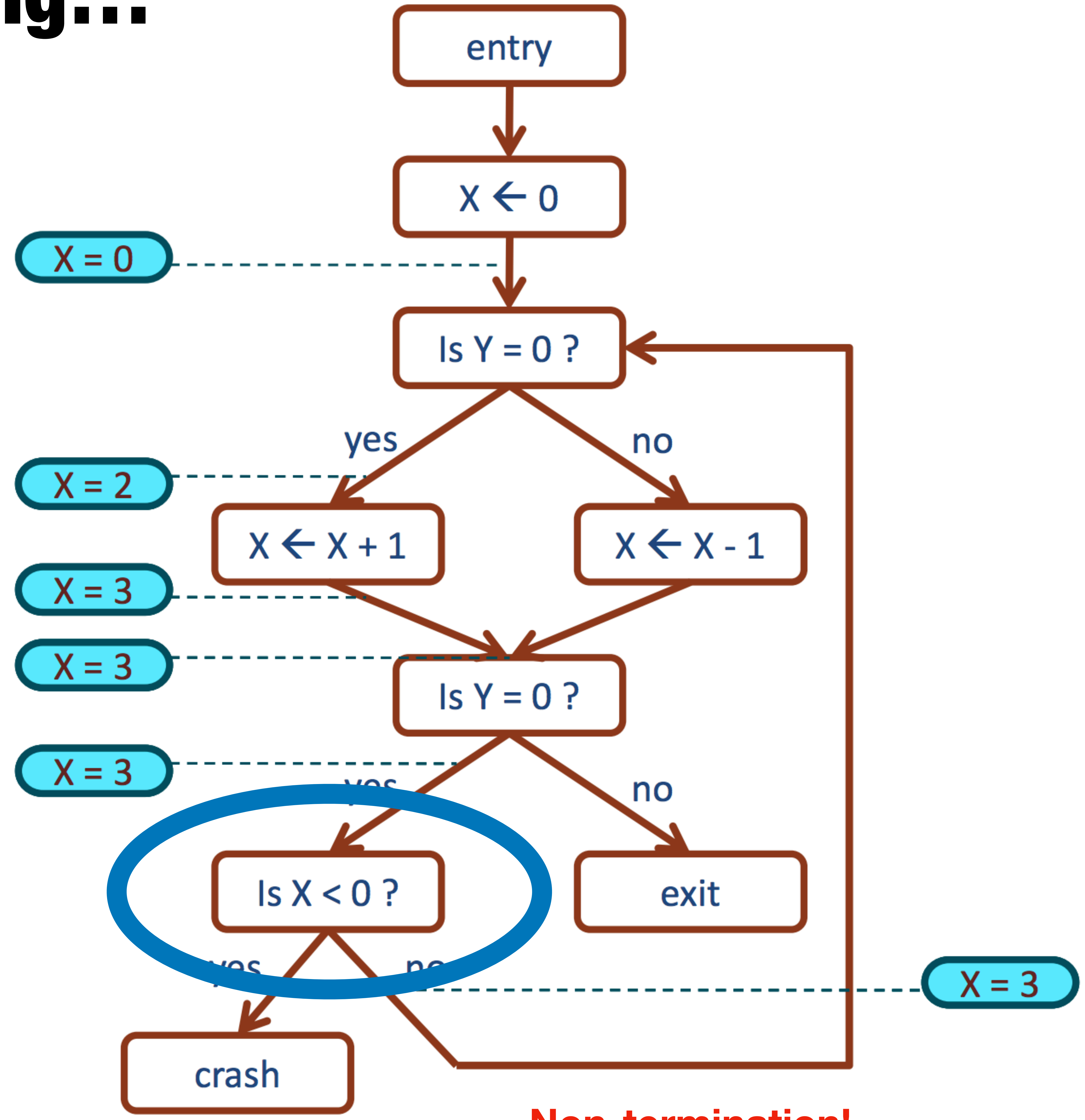


Try analyzing without approximating…



Non-termination!
Therefore, need to approximate

Try analyzing without approximating…



Non-termination!
Therefore, need to approximate

Abstraction

Concrete Domain of Integers

x = 5

x = - 5

x = 0

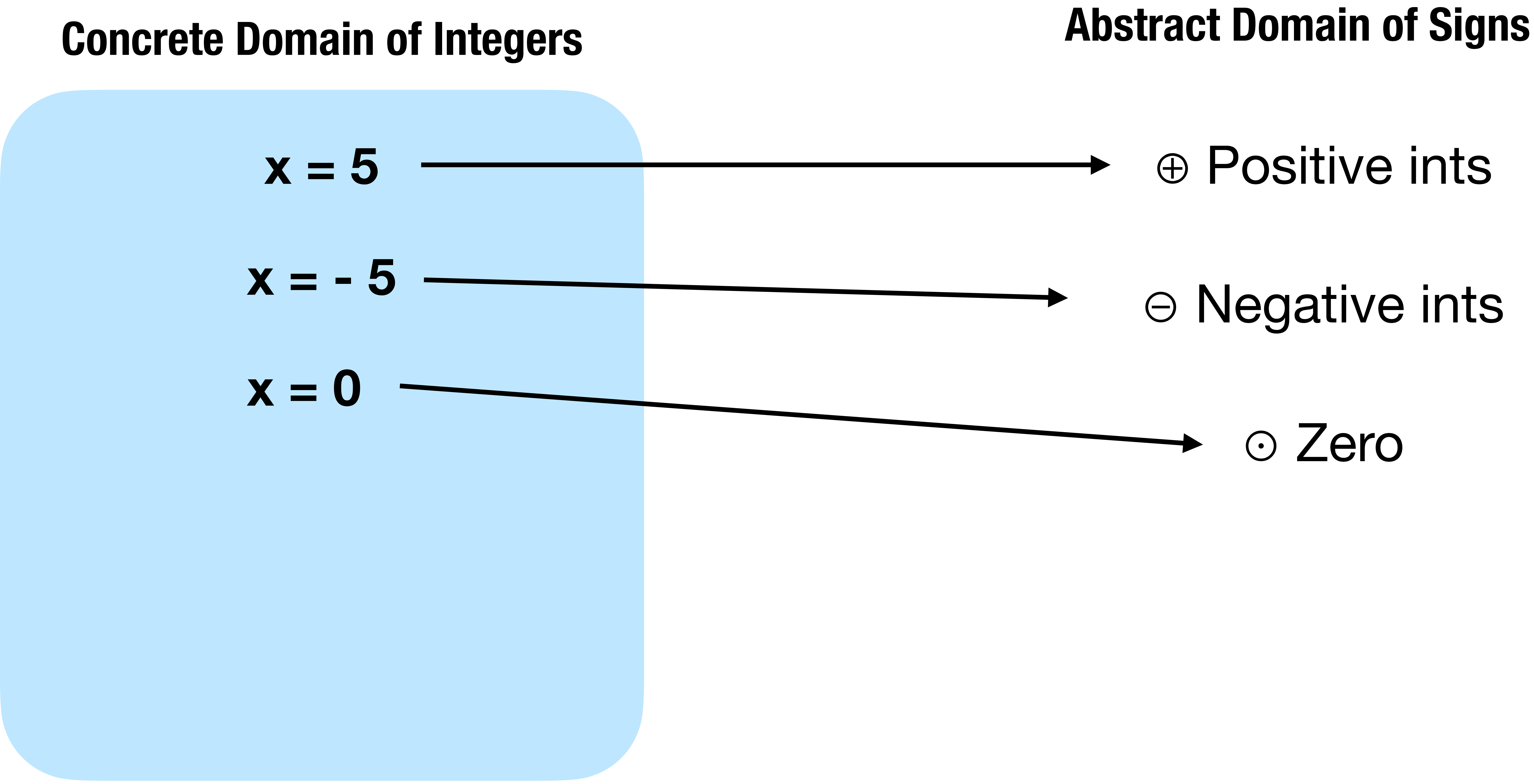
Abstract Domain of Signs

⊕ Positive ints

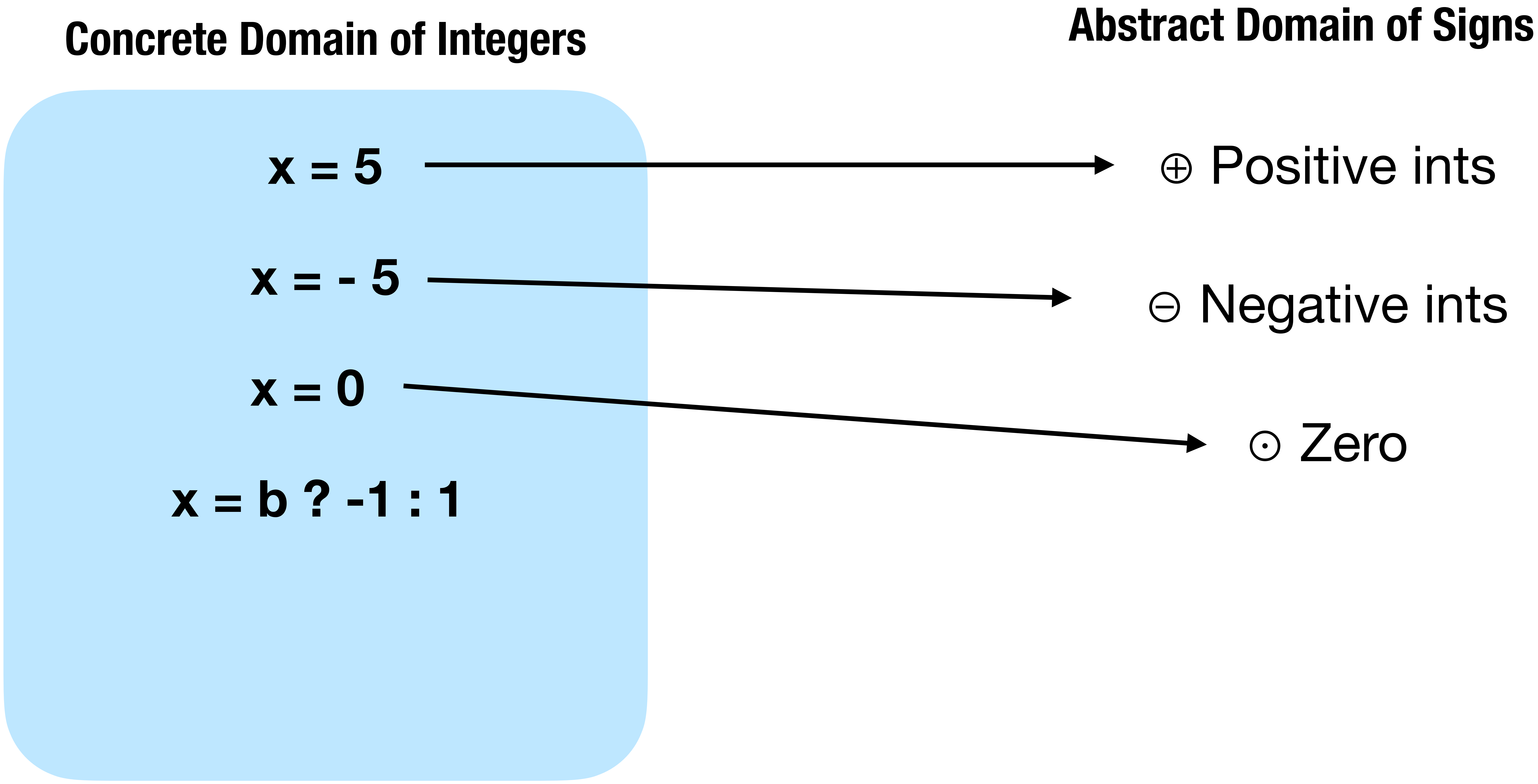
⊖ Negative ints

⊕ Zero

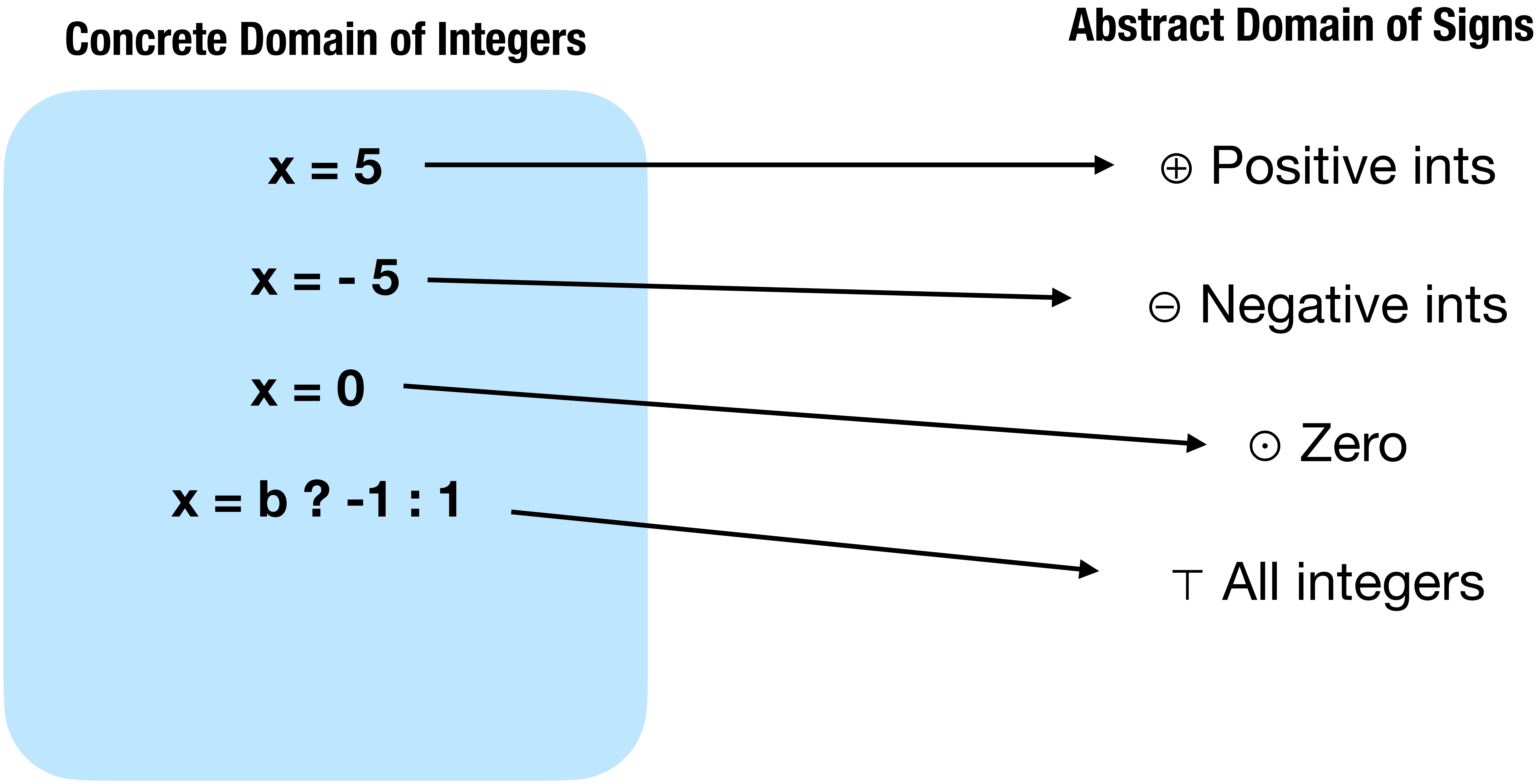
Abstraction



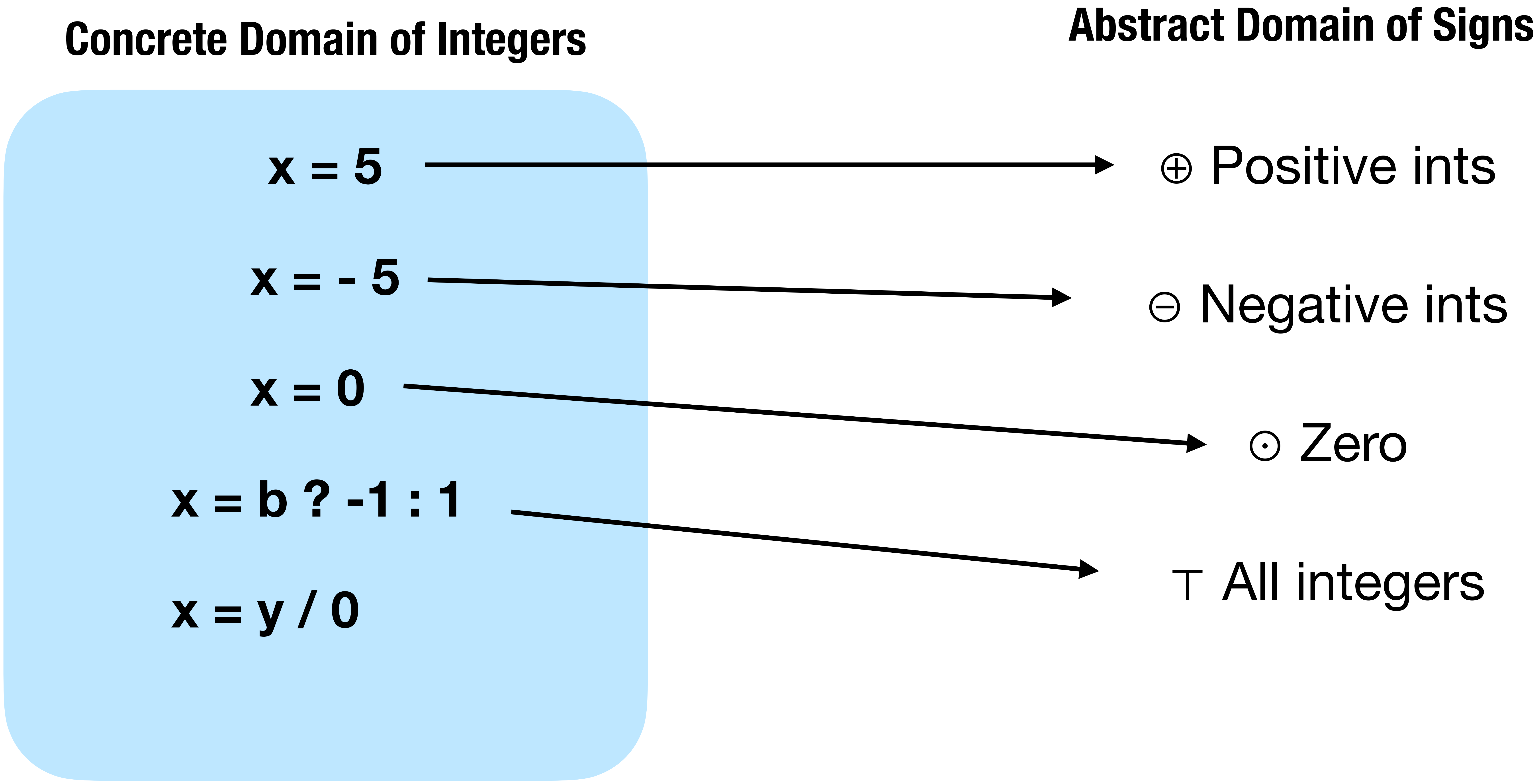
Abstraction



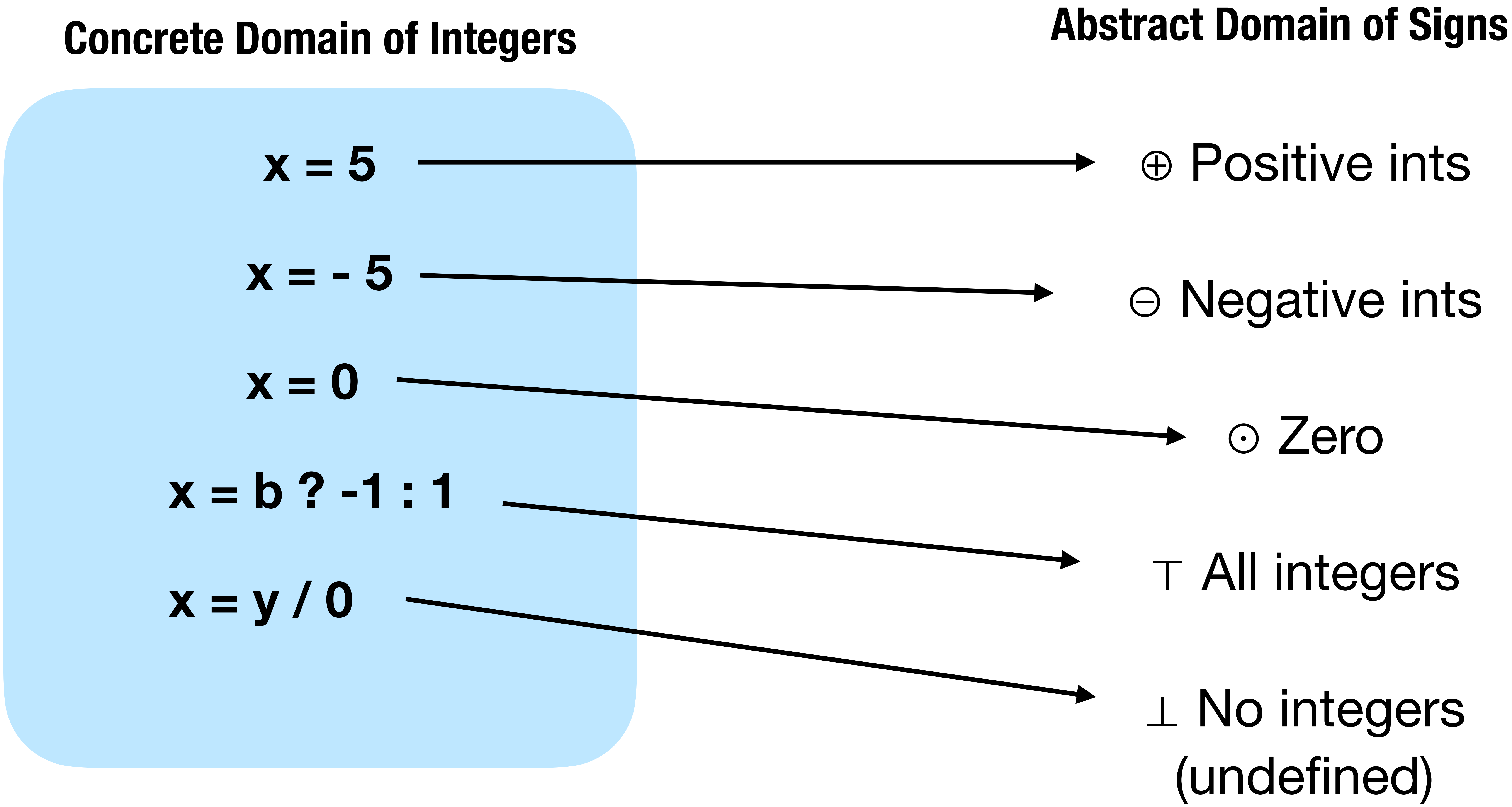
Abstraction



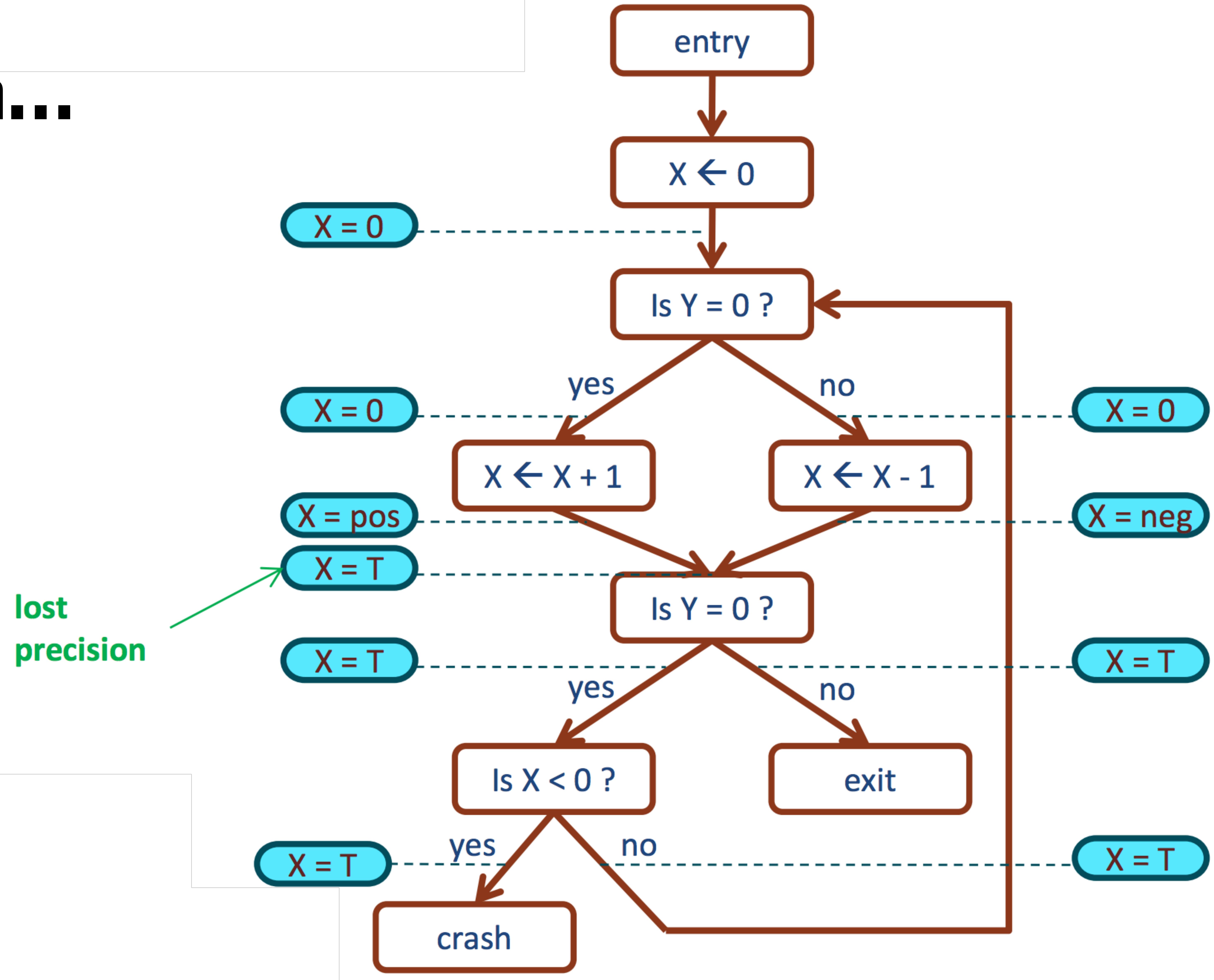
Abstraction



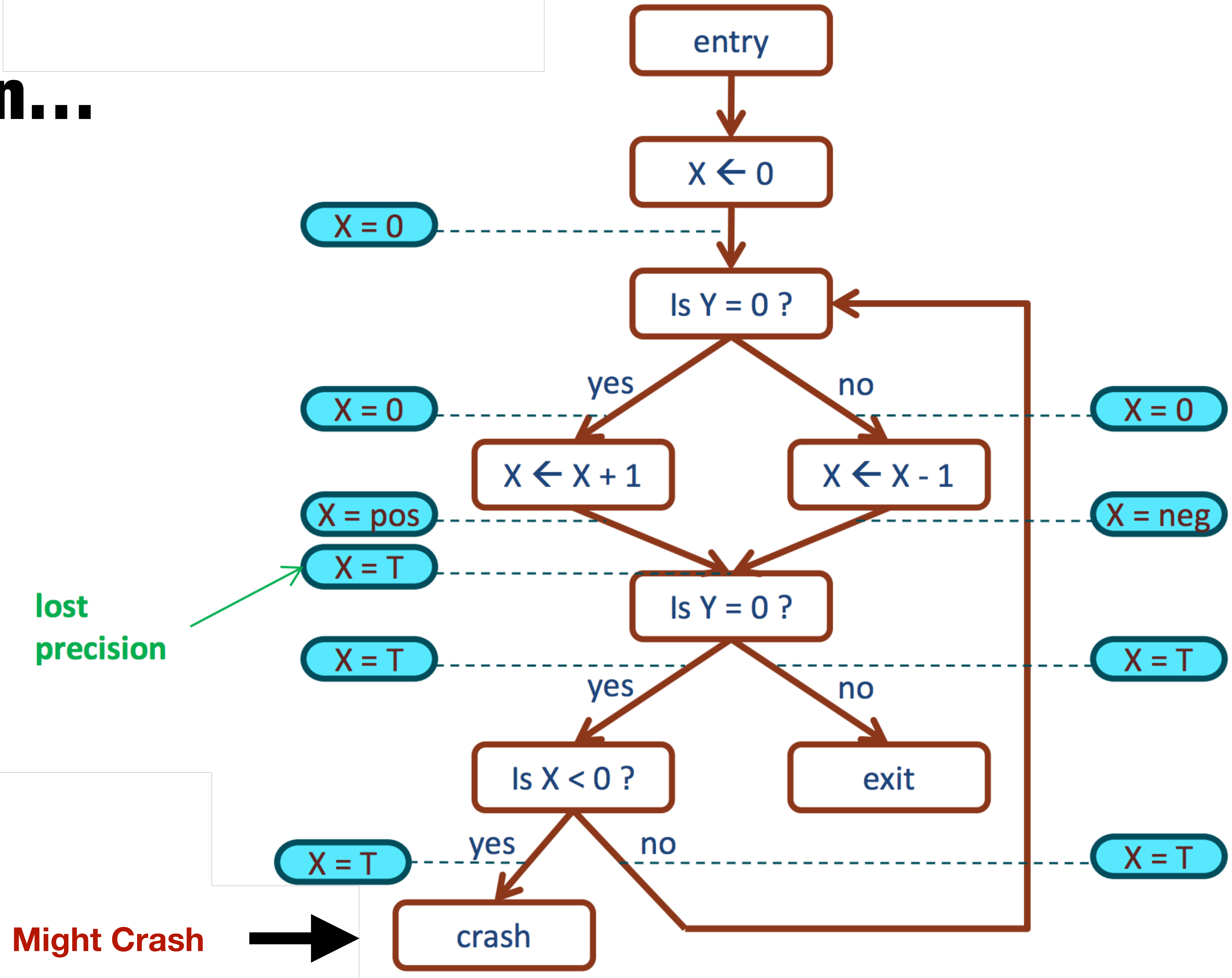
Abstraction



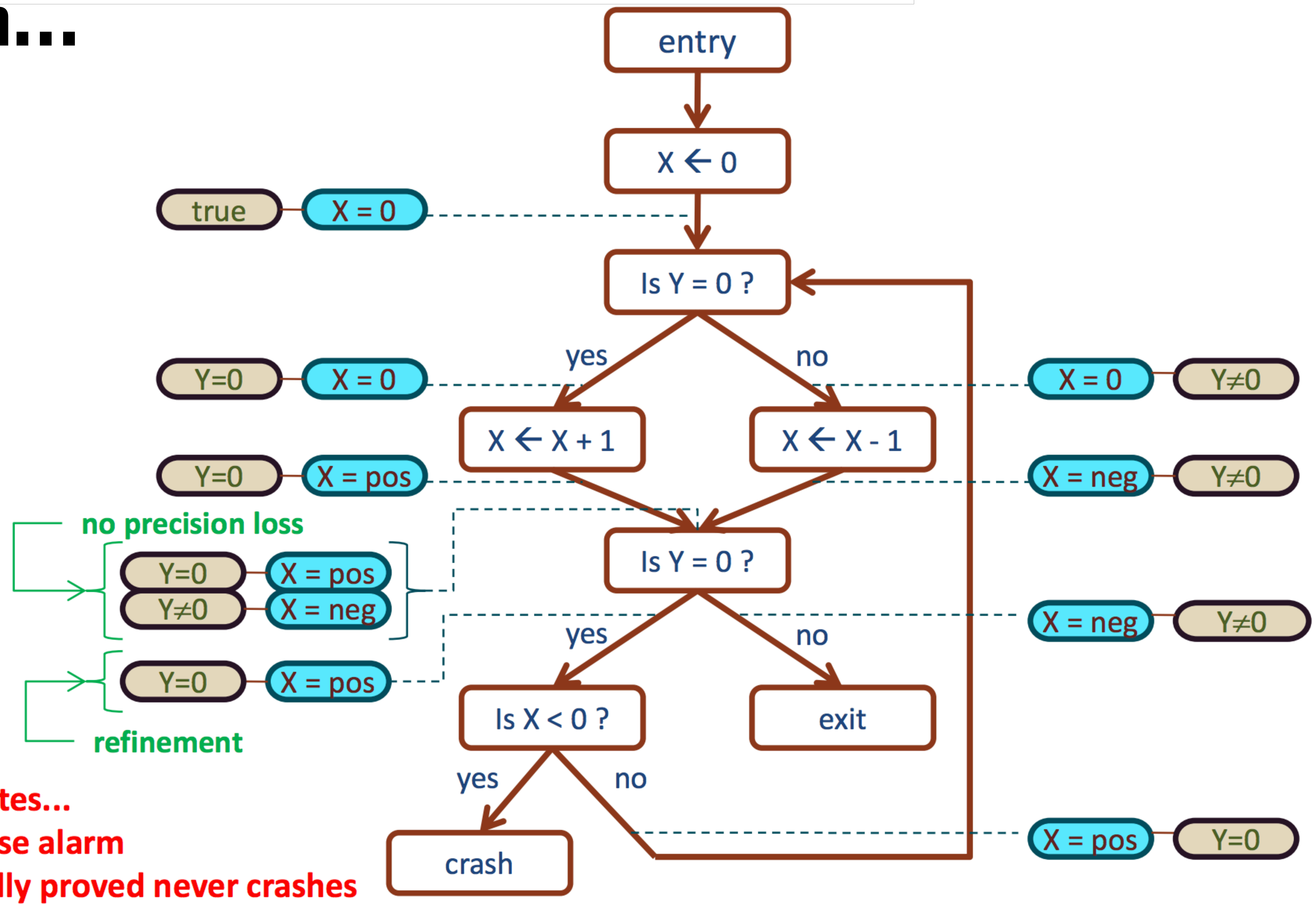
Try analyzing with "signs" approximation…



Try analyzing with "signs" approximation…



Try analyzing with "path-sensitive signs" approximation…

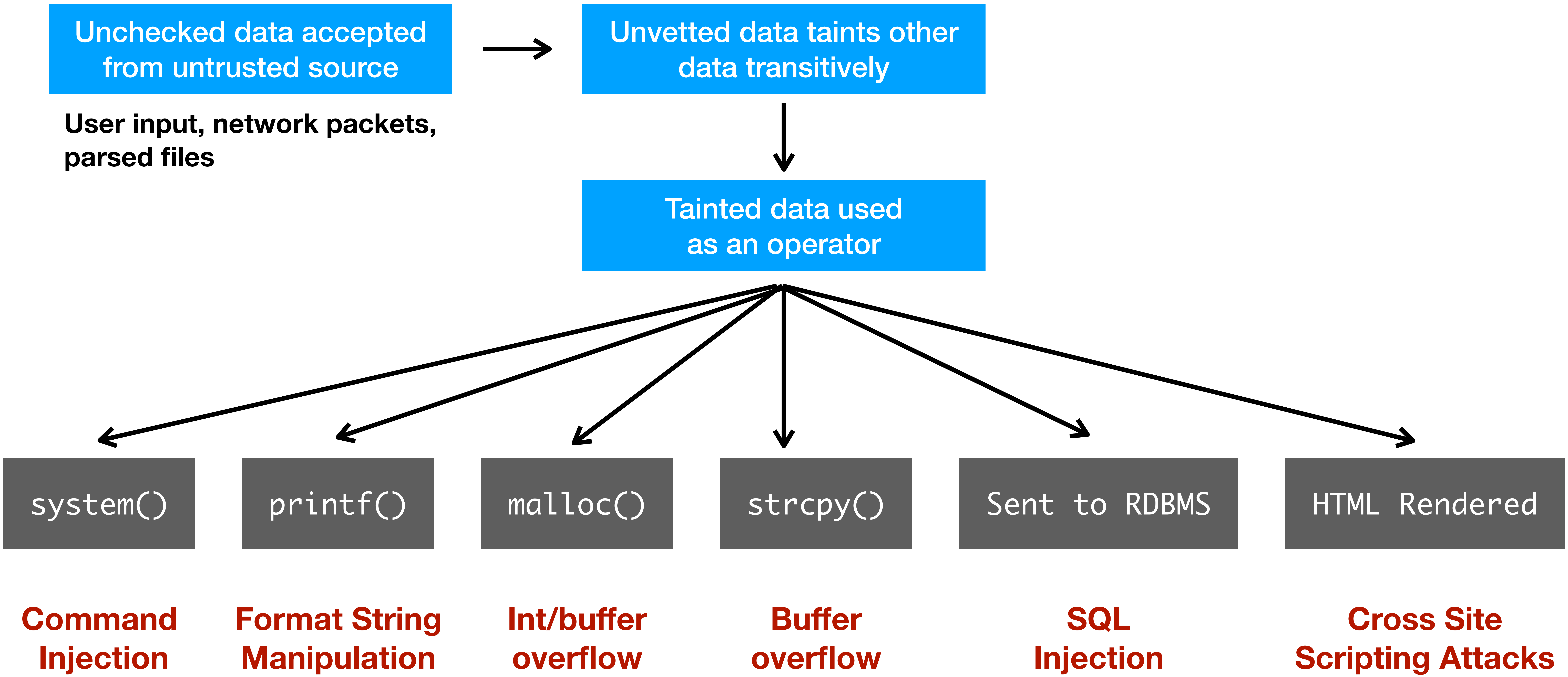


terminates…

… no false alarm

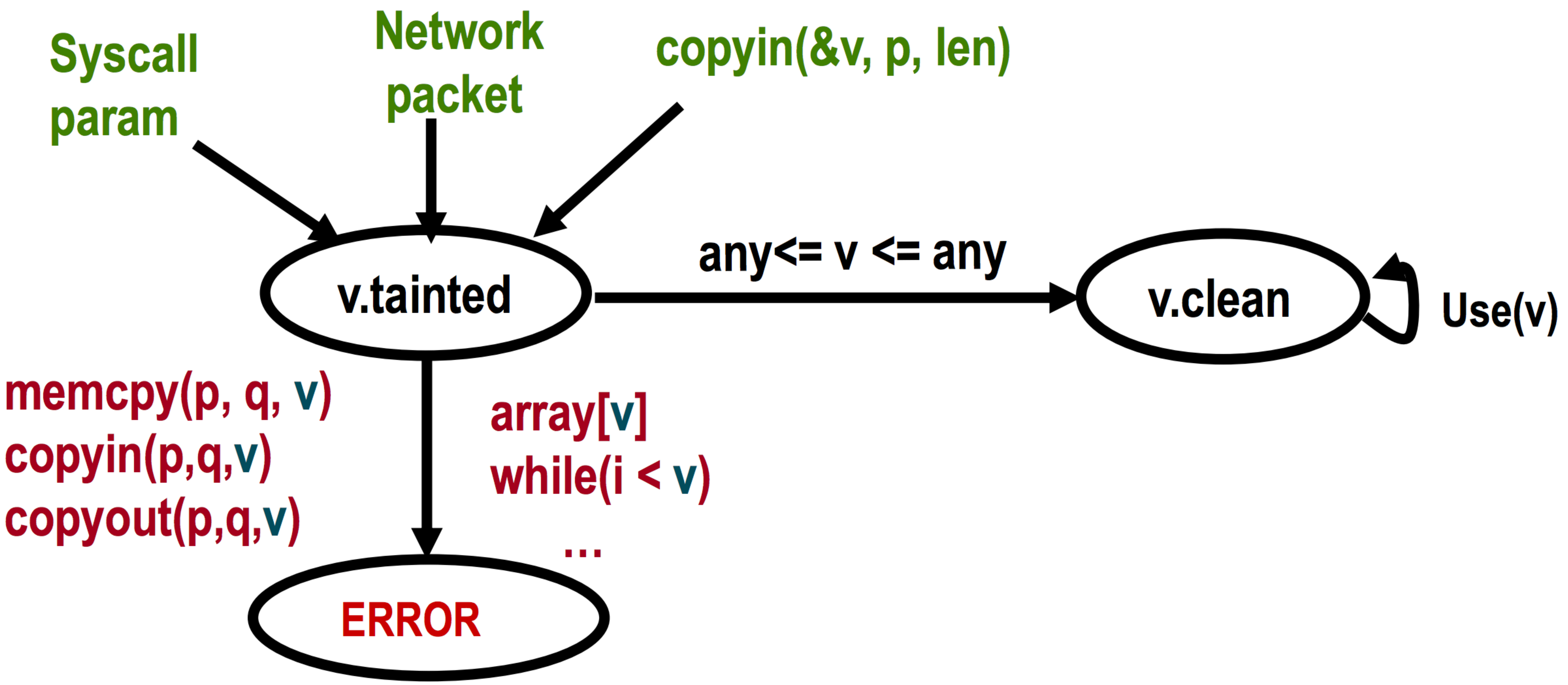
… soundly proved never crashes

Tainting Checkers



Checking for Unsanitized Integers

Warn when unchecked integers from untrusted sources reach trusting sinks



Linux: 125 errors, 24 false; BSD: 12 errors, 4 false

Example Untrusted Integer

Remote exploit, no length checks

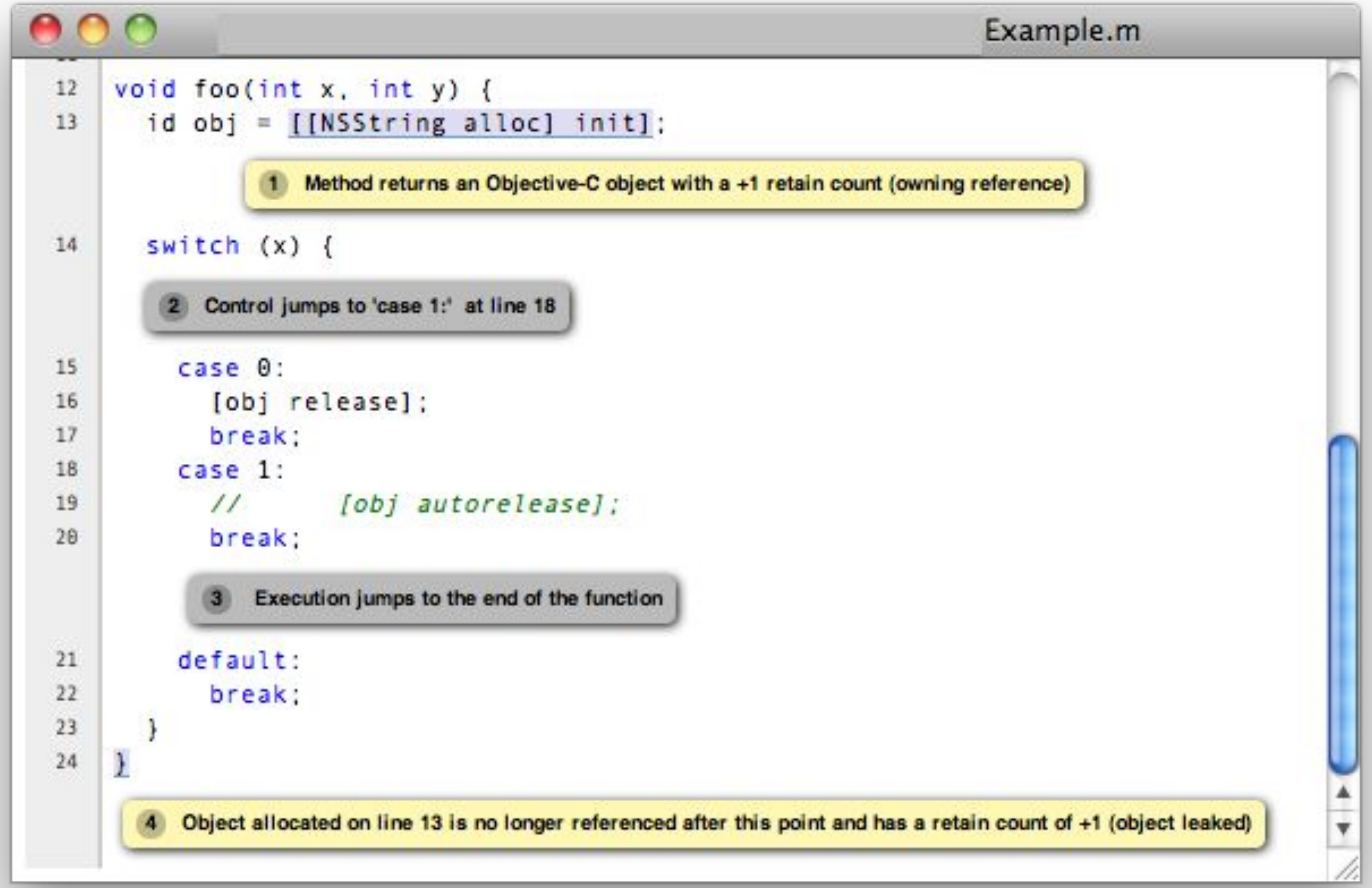
```
/* 2.4.9/drivers/isdn/act2000/capi.c:actcapi_dispatch */
isdn_ctrl cmd;
...
while ((skb = skb_dequeue(&card->rcvq))) {
msg = skb->data;
...
memcpy(cmd.parm.setup.phone,
msg->msg.connect_ind.addr.num,
msg->msg.connect_ind.addr.len - 1);
```

Clang static analyzer

Check for common security issues with a static analysis framework in the compiler

Built in checkers:

- Buffer overflows (with taint)
- Refcount errors
- **`malloc()`** integer overflows
- Insecure API use
- Uninitialized value use



https://clang-analyzer.llvm.org/images/analyzer_html.png

CodeQL (Semmle)

```
class PotentialOverflow extends Expr {
  PotentialOverflow() {
    (this instanceof BinaryArithmeticOperation    // match   x+y x-y x*y
       and not this instanceof DivExpr            // but not x/y
       and not this instanceof RemExpr)           //      or x%y

    or (this instanceof UnaryArithmeticOperation  // match   x++ x-- ++x --x -x
          and not this instanceof UnaryPlusExpr)  // but not +x

    // recursive definitions to capture potential overflow in
    // operands of the operations excluded above
    or this.(BinaryArithmeticOperation).getAnOperand() instanceof PotentialOverflow
    or this.(UnaryPlusExpr).getOperand() instanceof PotentialOverflow
  }
}
```

```
from PotentialOverflow po, SafeInt si
where po.getParent().(Call).getTarget().(Constructor).getDeclaringType() = si
select
    po,
    po + " may overflow before being converted to " + si
```

Query language for finding patterns in large codebases

“SQL for searching code”

Works best when you have a specific bad code pattern in mind

https://msrc-blog.microsoft.com/2018/08/16/vulnerability-hunting-with-semmle-ql-part-1/

Manual analysis

Starred by 4 users

Owner: natashenka@google.com

CC: proje...@google.com

Status: Fixed *(Closed)*

Components: ----

Modified: Dec 2, 2020

Finder-natashenka
Deadline-90
Vendor-Google
CCProjectZeroMembers
Severity-High
Methodology-CodeReview
Product-Duo
Reported-2020-Sep-2
Fixed-2020-Oct-26

Issue 2085: Google Duo: Race condition can cause callee to leak video packets from unanswered call

Code

Reported by natashenka@google.com on Wed, Sep 2, 2020, 5:02 PM PDT

Project Member

When Duo accepts an incoming call, it starts the WebRTC connection by calling setLocalDescription on the answer it generates based on the remote offer, and then disables outgoing video traffic by disabling all encoders by calling RtpSender.setParameters in an executor from onSetSuccess. This creates a race condition, as the connection gets set up by one thread, but outgoing traffic is disabled on another, so there is no guarantee that outgoing traffic will be disabled before the connection is set up and starts sending traffic.

Usually setting up the connection takes a long time, and disabling traffic is very fast, but it is possible to slow down disabling traffic, because it is run on the same thread queue that processes incoming messages from data channels, so if a lot of data channel traffic occurs at the same time a new SDP offer is received, the method to disable video transmission needs to wait in the queue until the incoming data is processed.

The attached script allows a caller on Duo to receive a small amount of video from the callee even if the call is not answered by the callee user. This could allow an attacker to enable the camera on a remote user's device and take pictures of their surroundings.

To reproduce this issue:

1) run track.py on the attacker device

python3 track.py "Attacking Pixel"

2) run exploit_sender.py on the same attacker device in another window, with exploit_sender.js in the same directory

python3 exploit_sender.py "Attacking Pixel"

3) make a video call to the target device and hang up after one second (this populates some difficult-to-generate memory in the

Reverse engineering

Looking at a compiled program in order to figure out what it does and how it works

- Usually assisted by tools
  - Disassembler
  - Decompiler
  - Strings
- Often aided by dynamic analysis
  - Tracing

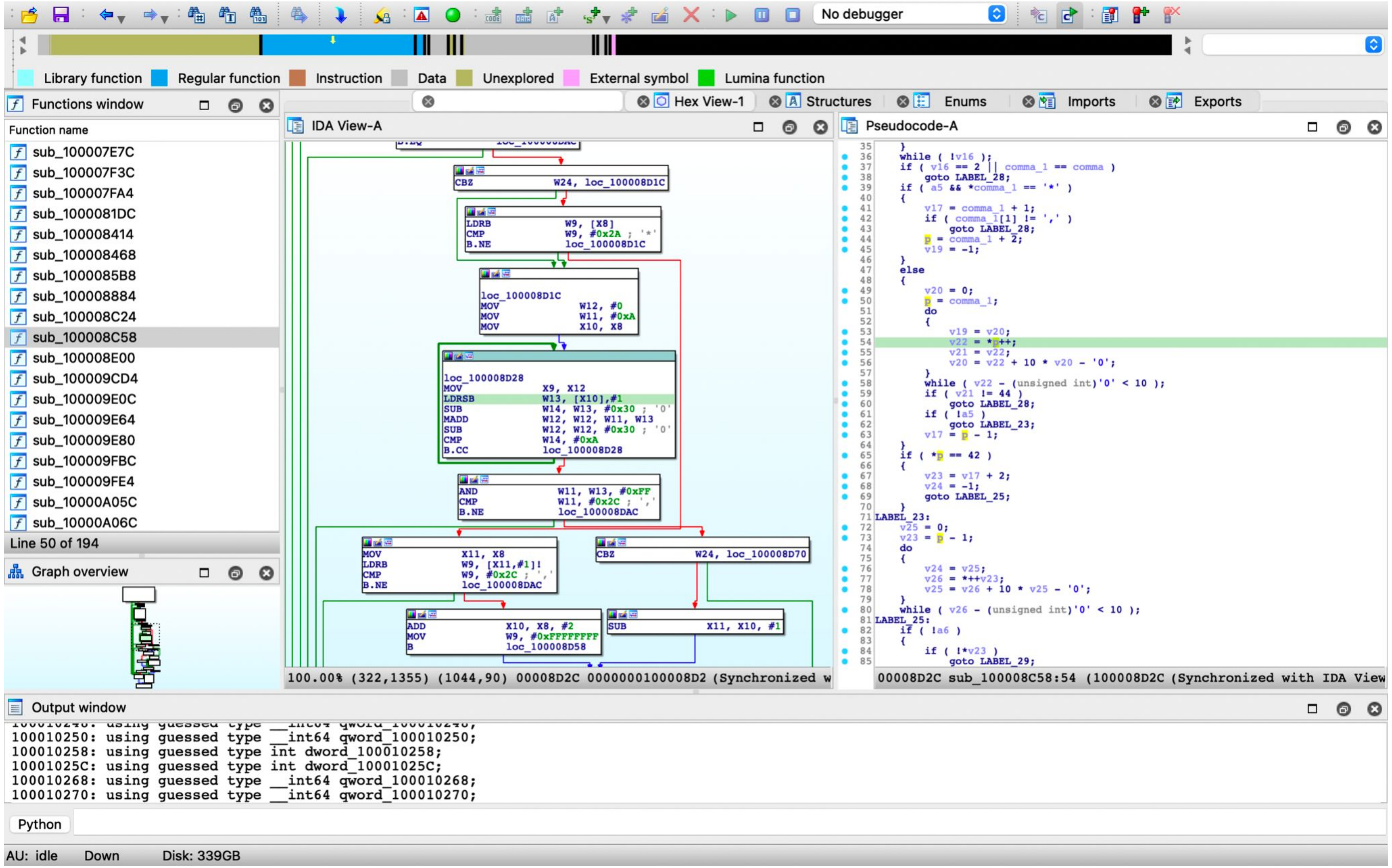
IDA Pro

Disassembly

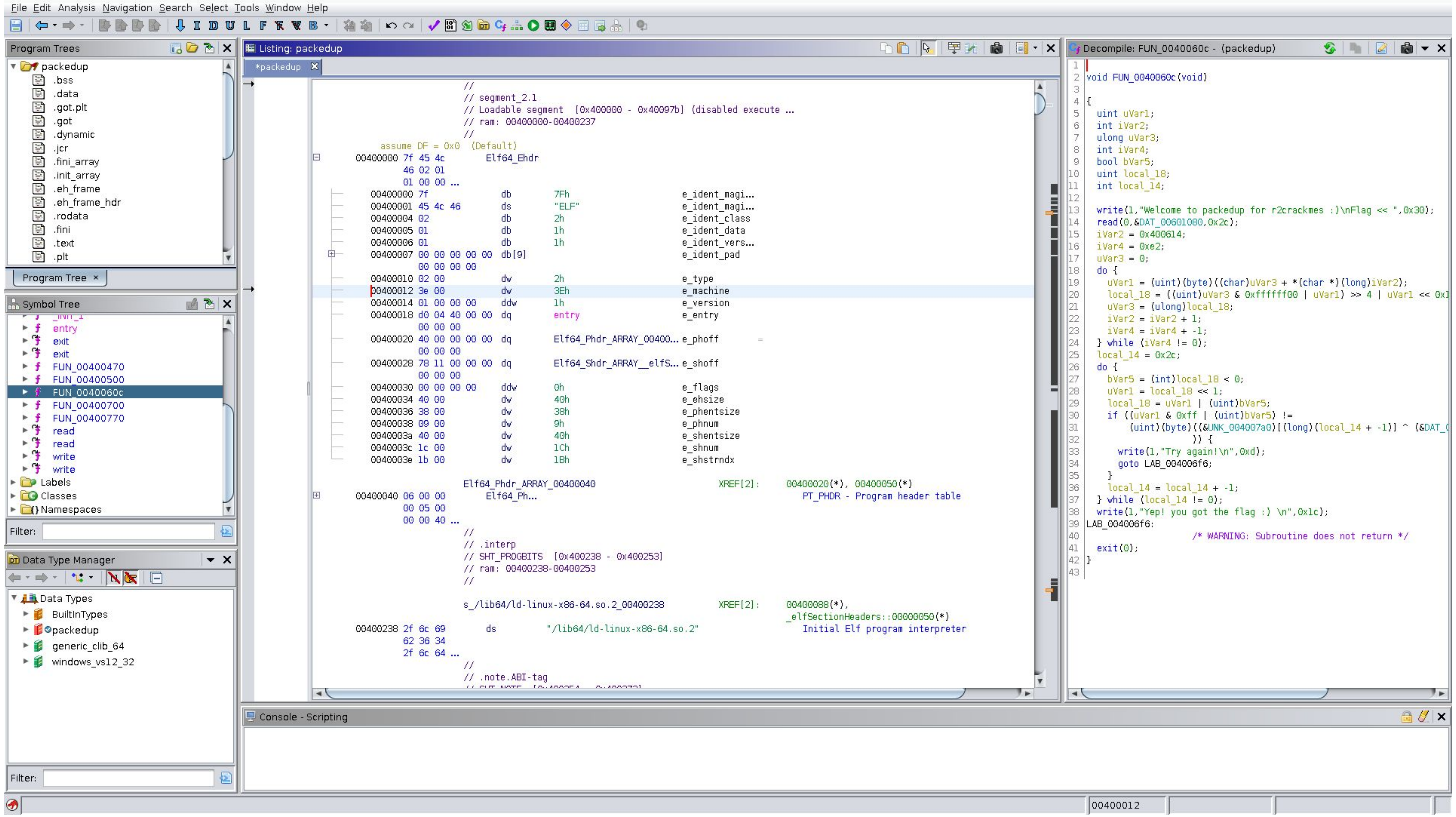
Decompilation

Binary analysis

Scripting



Ghidra



- Similar to IDA
- Open source
- Written by the NSA (no, really)

https://en.wikipedia.org/wiki/Ghidra#/media/File:Ghidra-disassembly,March_2019.png

Tips for writing (more) secure software

Software tests

One of the most effective ways to reduce bugs

Unit tests: Check that each piece of code behaves as expected in isolation

Goal: Unit tests should cover all code, including error handling

So many exploitable bugs would be eliminated with basic unit tests

Regression tests: Check that old bugs haven't been reintroduced

If you don't run regression tests, attackers will run them for you!

Integration tests: Check that modules work together as expected

General tips

Use a modern, memory safe language where possible: Go, Rust, etc.

Understand and document your threat model early in the design process

Treat all input from outside your process adversarially, even if you trust the sender

Use a clean, consistent style throughout the codebase

Thank you!

bazad@cs.stanford.edu