Finding vulnerabilities

CS642: Computer Security

Spring 2019

Finding vulnerabilities

Manual analysis

Simple example: double free

Fuzzing tools

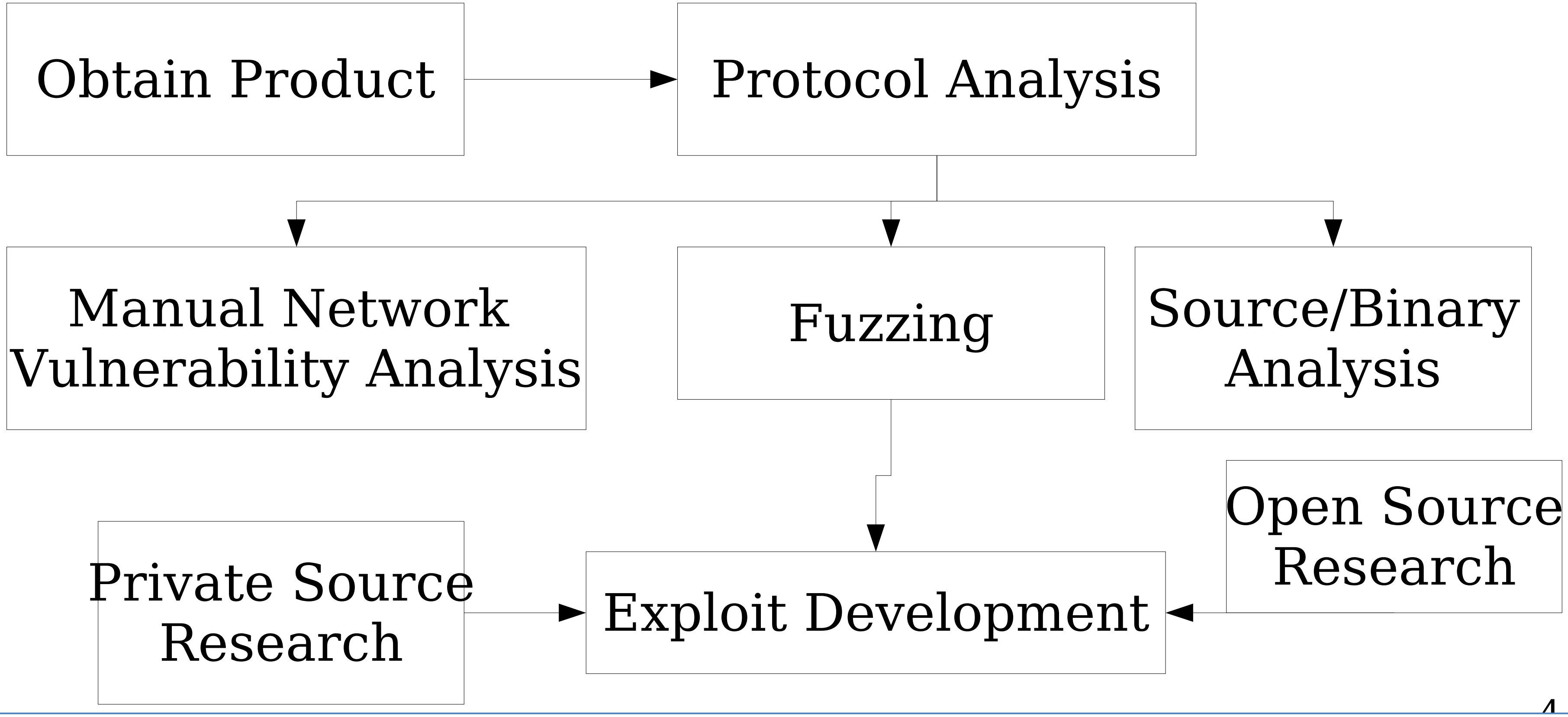
Static analysis, dynamic analysis

…

Hackers use People, Processes and Technology to obtain a singular goal: Information dominance

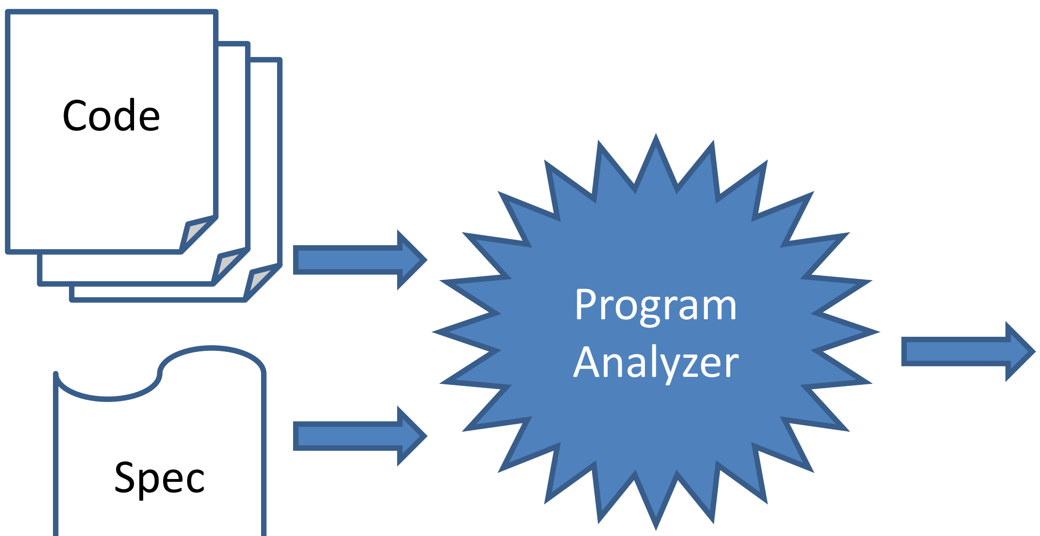
From “How Hackers Look for Bugs”, Dave Aitel

Take a sample product X and attack it remotely



From “How Hackers Look for Bugs”, Dave Aitel

Program analyzers



Report	Type	Line
1	mem leak	324
2	buffer oflow	4,353,245
3	sql injection	23,212
4	stack oflow	86,923
5	dang ptr	8,491
…	…	…
10,502	info leak	10,921

Report 2: false alarm

Report 5: false alarm

analyze large code bases

potentially reports many warnings

may emit false alarms

Slide credit: Prof Mitchell Stanford's CS 155

Example program analyzers

- Manual analysis (you are the analyzer!)
- Static analysis (do not execute program)
  - Scanners
  - Abstract interpretation
  - Symbolic execution
- Dynamic analysis (execute program)
  - Debugging
  - Fuzzers
  - Ptrace

<u>Do you have source code?</u>
Yes: lucky you
No: can still do things, but not as easily
(missing a lot of context about program)

Program analysis: Soundness and completeness

Property	Definition
Soundness	If the program contains an error, the analysis will report a warning. “Sound for reporting correctness”
Completeness	If the analysis reports an error, the program will contain an error. “Complete for reporting correctness”

Slide credit: Prof Mitchell Stanford’s CS 155

	Complete	Incomplete
Sound	Reports all errors Reports no false alarms No false positives No false negatives **Undecidable**	Reports all errors May report false alarms No false negatives False positives **Decidable**
Unsound	May not report all errors Reports no false alarms False positives No false negatives **Decidable**	May not report all errors May report false alarms False negatives False positives **Decidable**

Slide credit: Prof Mitchell Stanford’s CS 155

Manual analysis

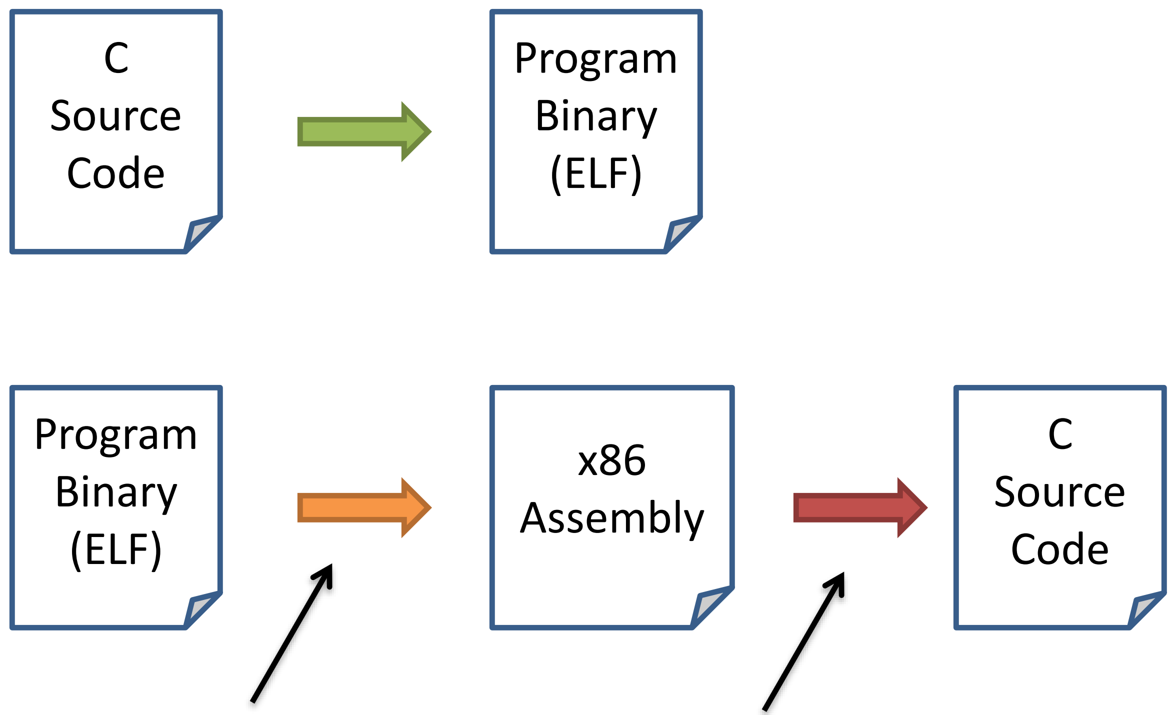
- You get a binary or the source code
- You find vulnerabilities

- Experienced analysts accoding to Aitel:
  - 1 hour of binary analysis:
    - Simple backdoors, coding style, bad API calls (strcpy)
  - 1 week of binary analysis:
    - Likely to find 1 good vulnerability
  - 1 month of binary analysis:
    - Likely to find 1 vulnerability *no one else will ever find*

Disassembly and decompiling

The normal compilation process

What if we start with binary?

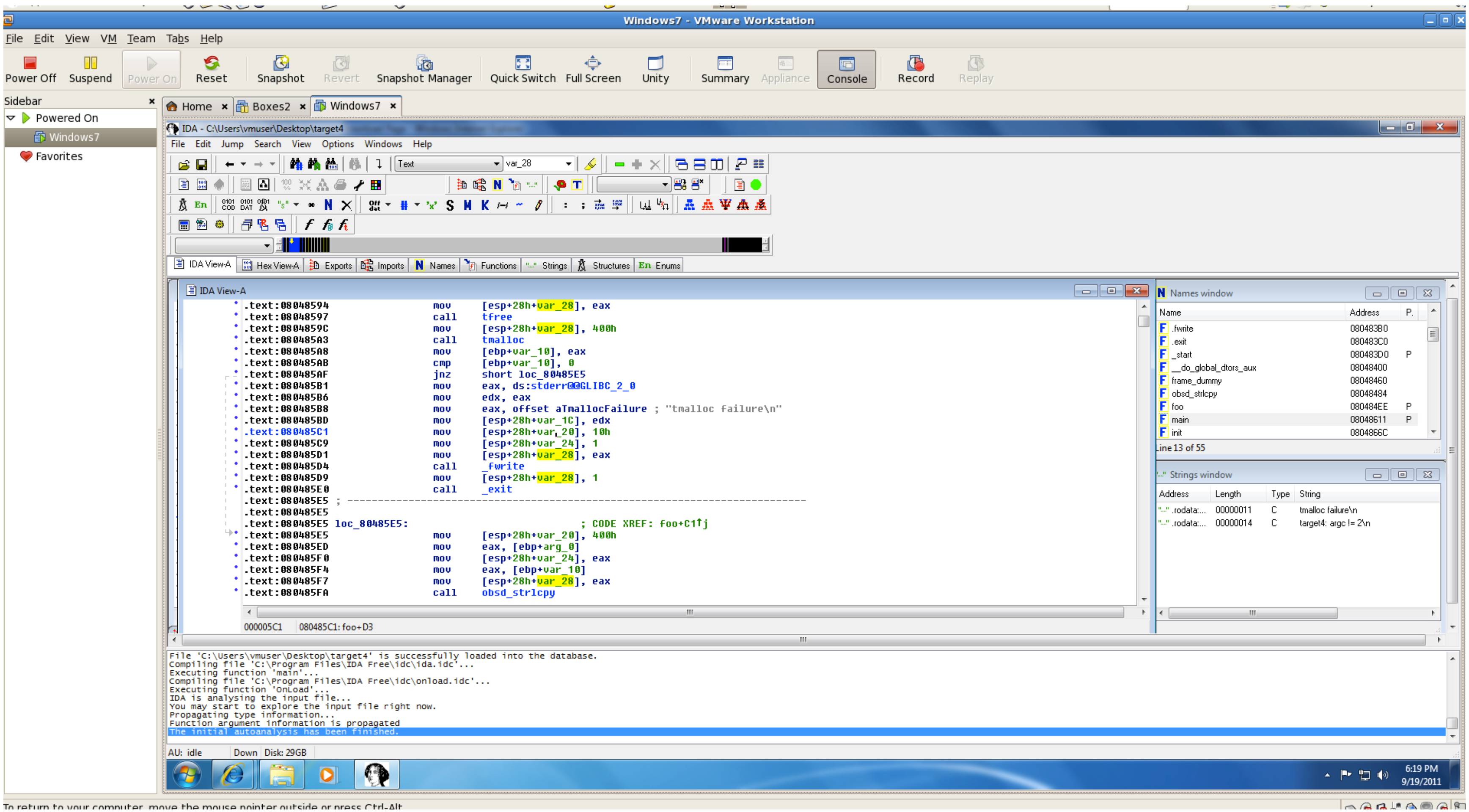


Disassembler
(gdb, IDA Pro, OllyDebug)

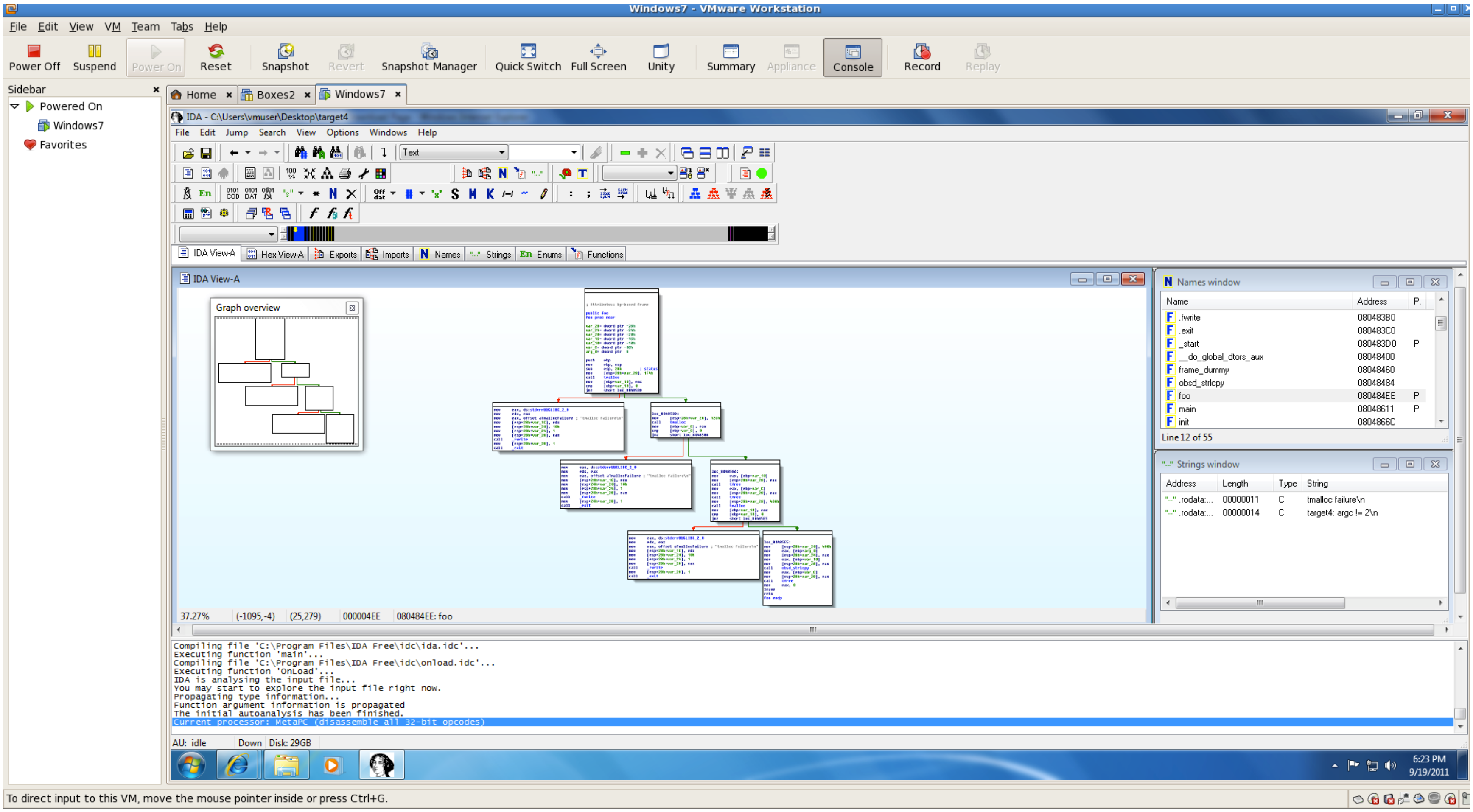
Decompiler
(IDA Pro has one)

Very complex, usually poor results

Tool example: IDA Pro



Tool example: IDA Pro



```
movl   $0xf8,(%esp)
call   0x8048364 <malloc@plt>
mov    %eax,0x14(%esp)
movl   $0xf8,(%esp)
call   0x8048364 <malloc@plt>
mov    %eax,0x18(%esp)
mov    0x14(%esp),%eax
mov    %eax,(%esp)
call   0x8048354 <free@plt>
mov    0x18(%esp),%eax
mov    %eax,(%esp)
call   0x8048354 <free@plt>
movl   $0x200,(%esp)
call   0x8048364 <malloc@plt>
mov    %eax,0x1c(%esp)
mov    0xc(%ebp),%eax
add    $0x4,%eax
mov    (%eax),%eax
movl   $0x1ff,0x8(%esp)
mov    %eax,0x4(%esp)
mov    0x1c(%esp),%eax
mov    %eax,(%esp)
call   0x8048334 <strncpy@plt>
mov    0x18(%esp),%eax
mov    %eax,(%esp)
call   0x8048354 <free@plt>
mov    0x1c(%esp),%eax
mov    %eax,(%esp)
call   0x8048354 <free@plt>
leave
ret
```

What type of vulnerability might this be?

```
main(  int argc, char* argv[] ) {
  char* b1;
  char* b2;
  char* b3;

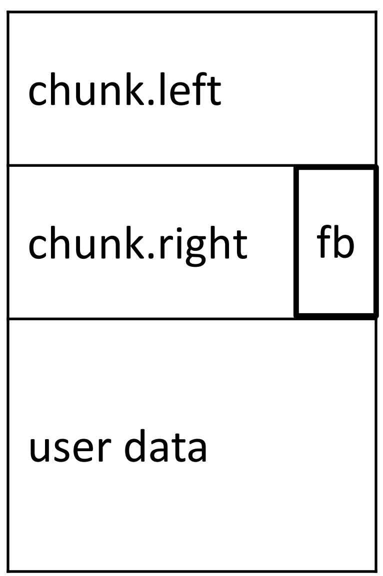
  if( argc != 3 ) then return 0;
  if( argv[2] != 31337 )
      complicatedFunction();
  else {
      b1 = (char*)malloc(248);
      b2 = (char*)malloc(248);
      free(b1);
      free(b2);
      b3 = (char*)malloc(512);
      strncpy( b3, argv[1], 511 );
      free(b2);
      free(b3);
   }
}
```

Double-free vulnerability

Double-free vulnerabilities

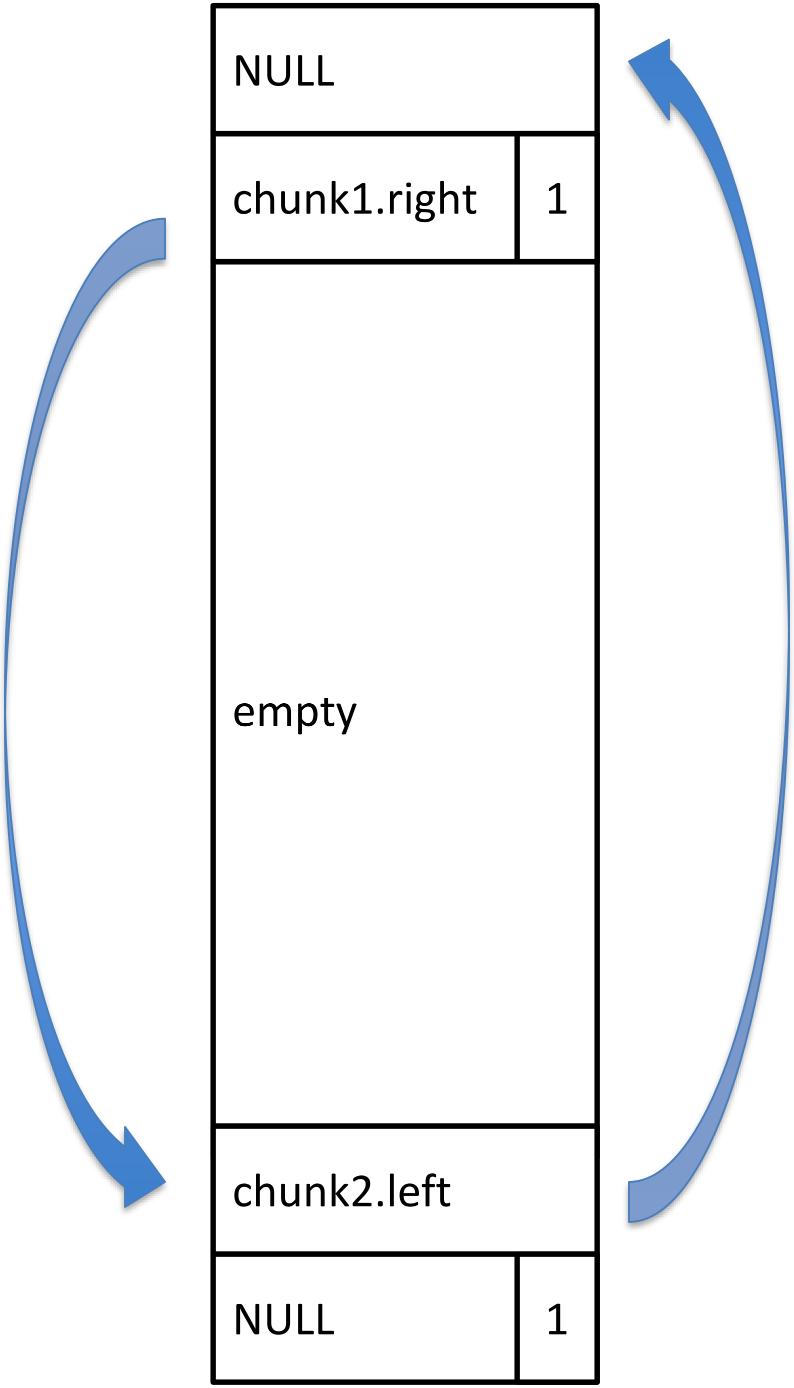
Can corrupt the state of the heap management

Say we use a simple doubly-linked list malloc implementation with control information stored alongside data



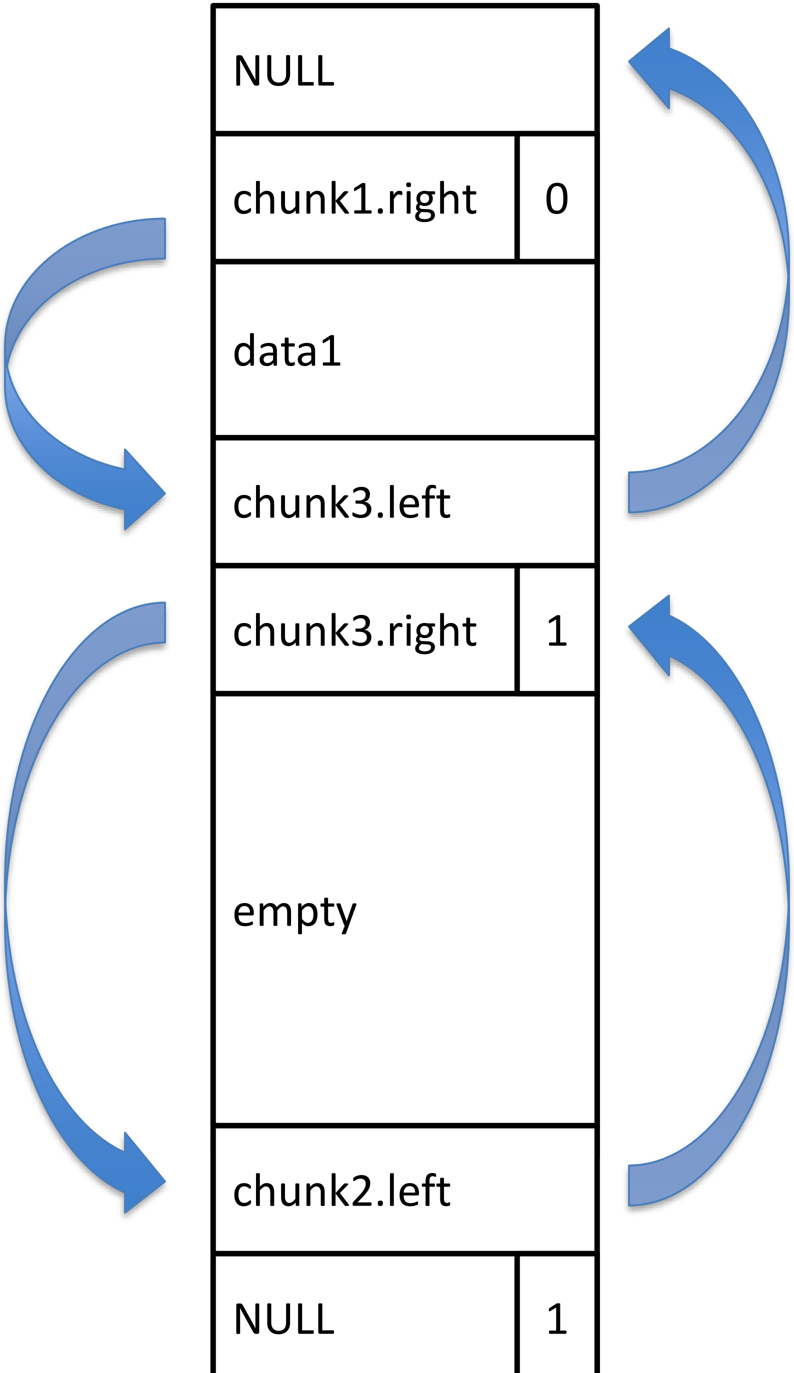
Chunk has:

1) left ptr (to previous chunk)
2) right ptr (to next chunk)
3) free bit which denotes if chunk is free
   this reuses low bit of right ptr
   because we will align chunks
4) user data



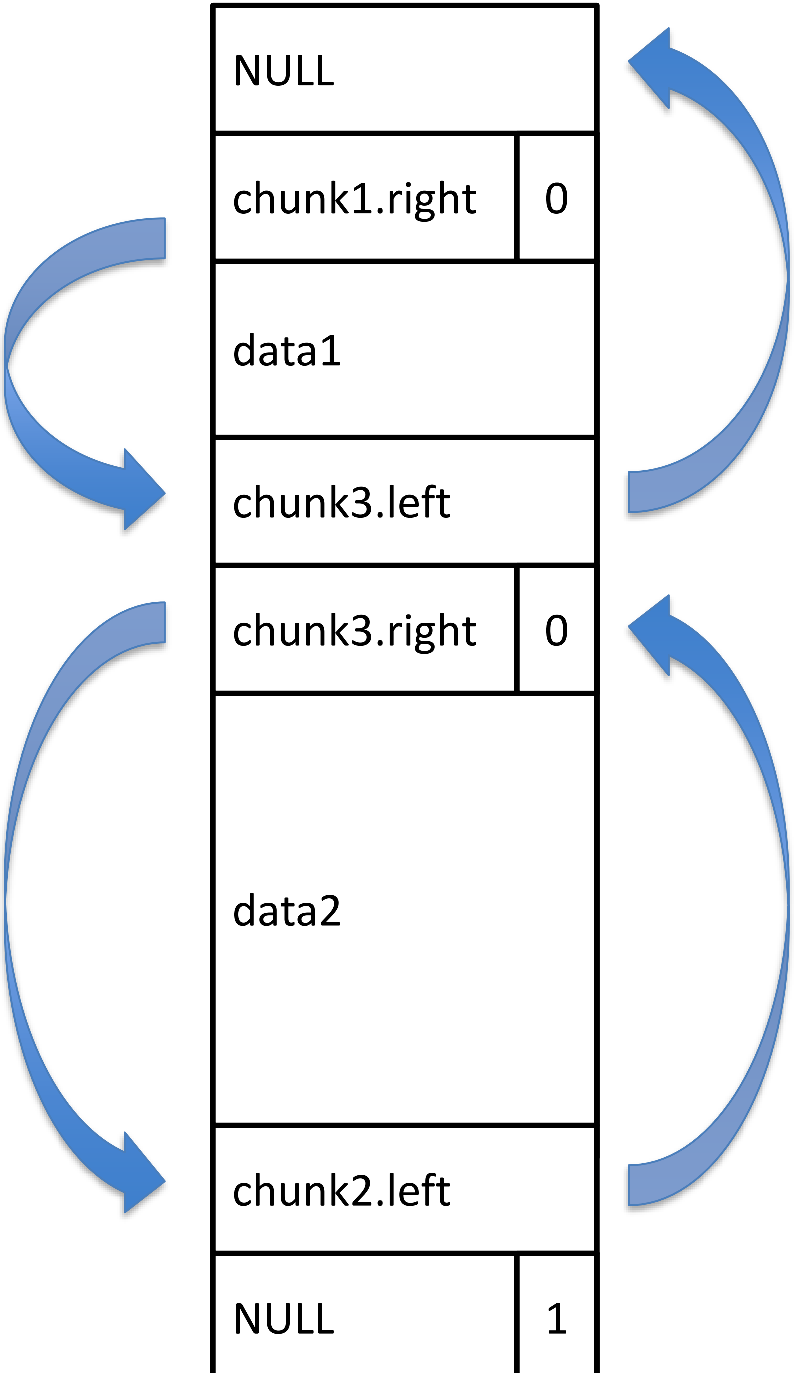
malloc()

- search left-to-right for free chunk
- modify pointers



malloc()
- search left-to-right for free chunk
- modify pointers

b1 = malloc(BUF_SIZE1);



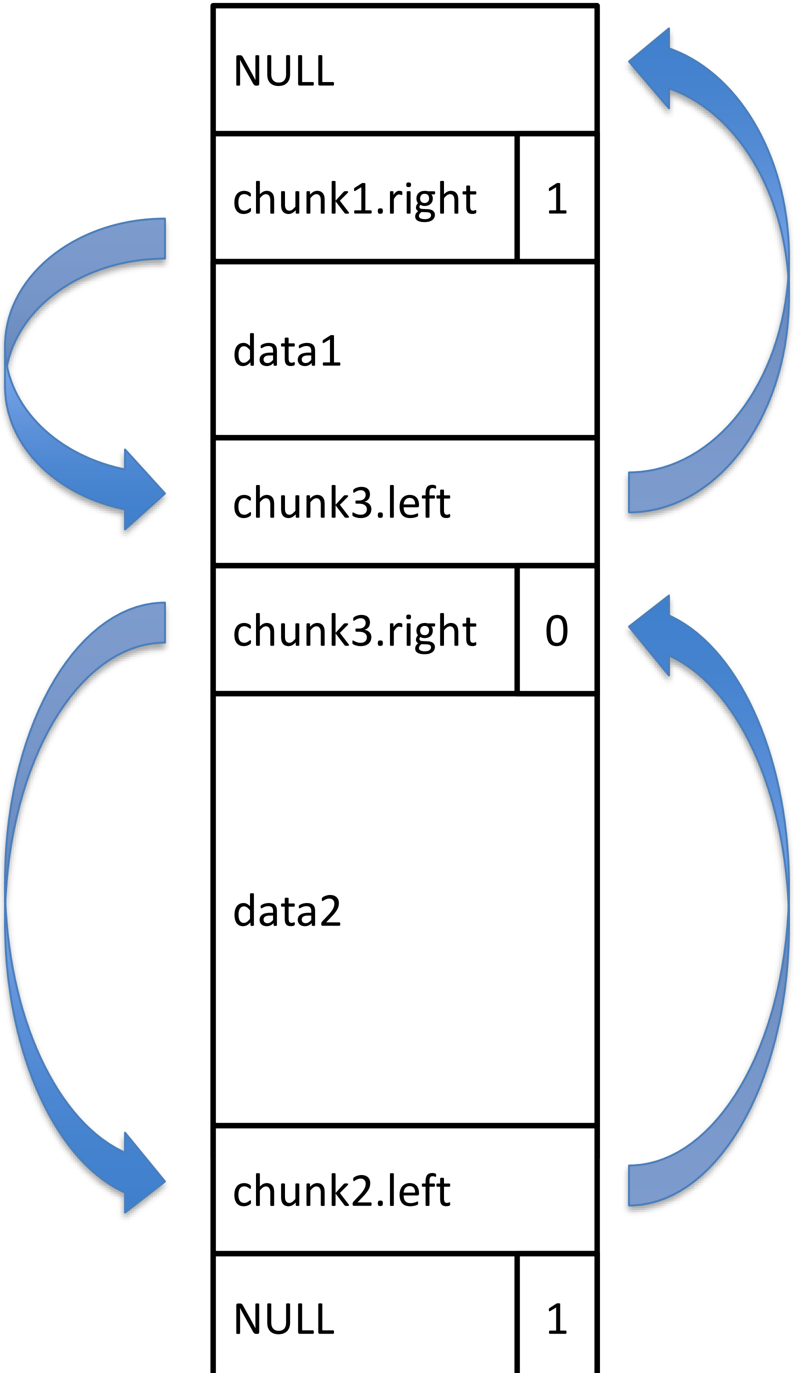
malloc()

- search left-to-right for free chunk
- modify pointers

b1 = malloc(BUF_SIZE1)
b2 = malloc(BUF_SIZE2)

free()

- Consolidate with free neighbors



malloc()

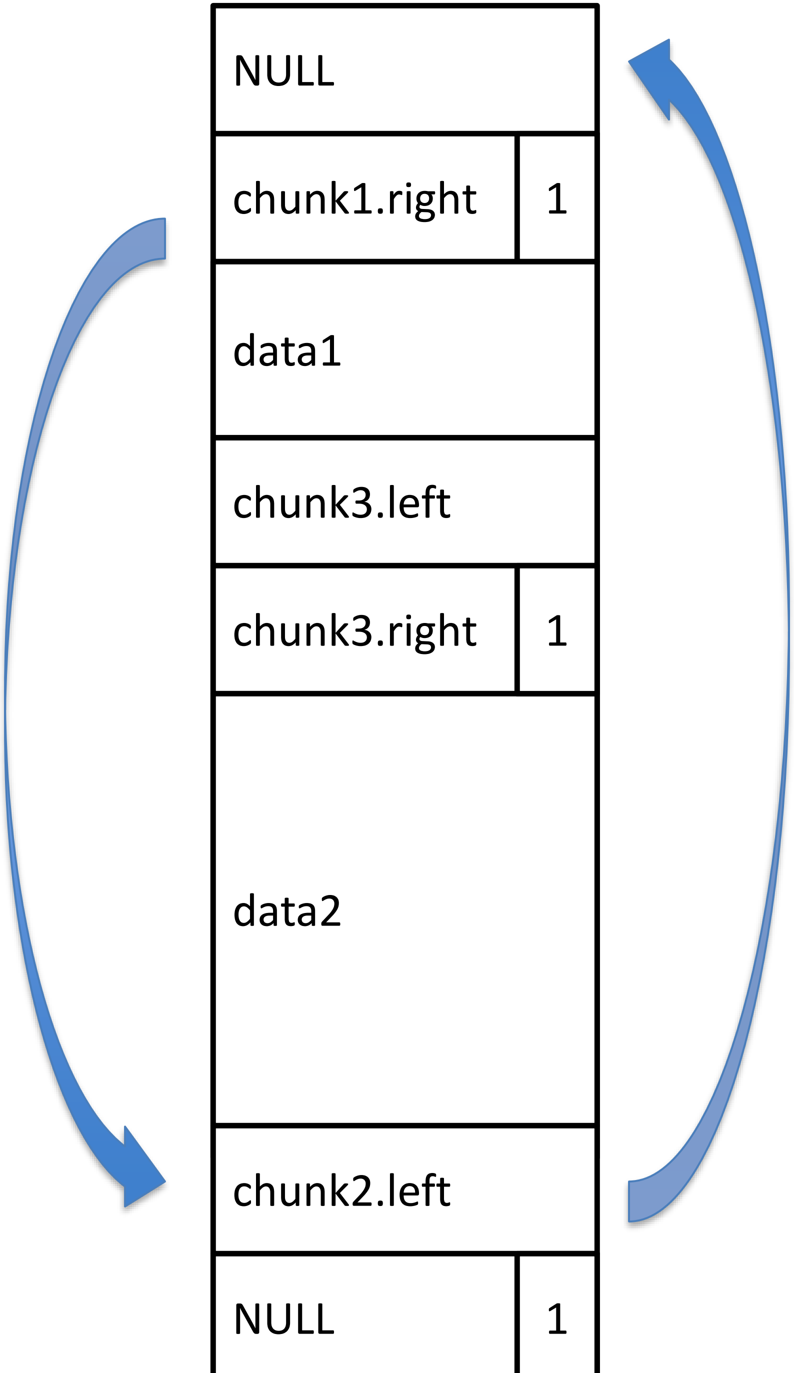
- search left-to-right for free chunk
- modify pointers

b1 = malloc(BUF_SIZE1)
b2 = malloc(BUF_SIZE2)

free()

- Consolidate with free neighbors

free(b1)

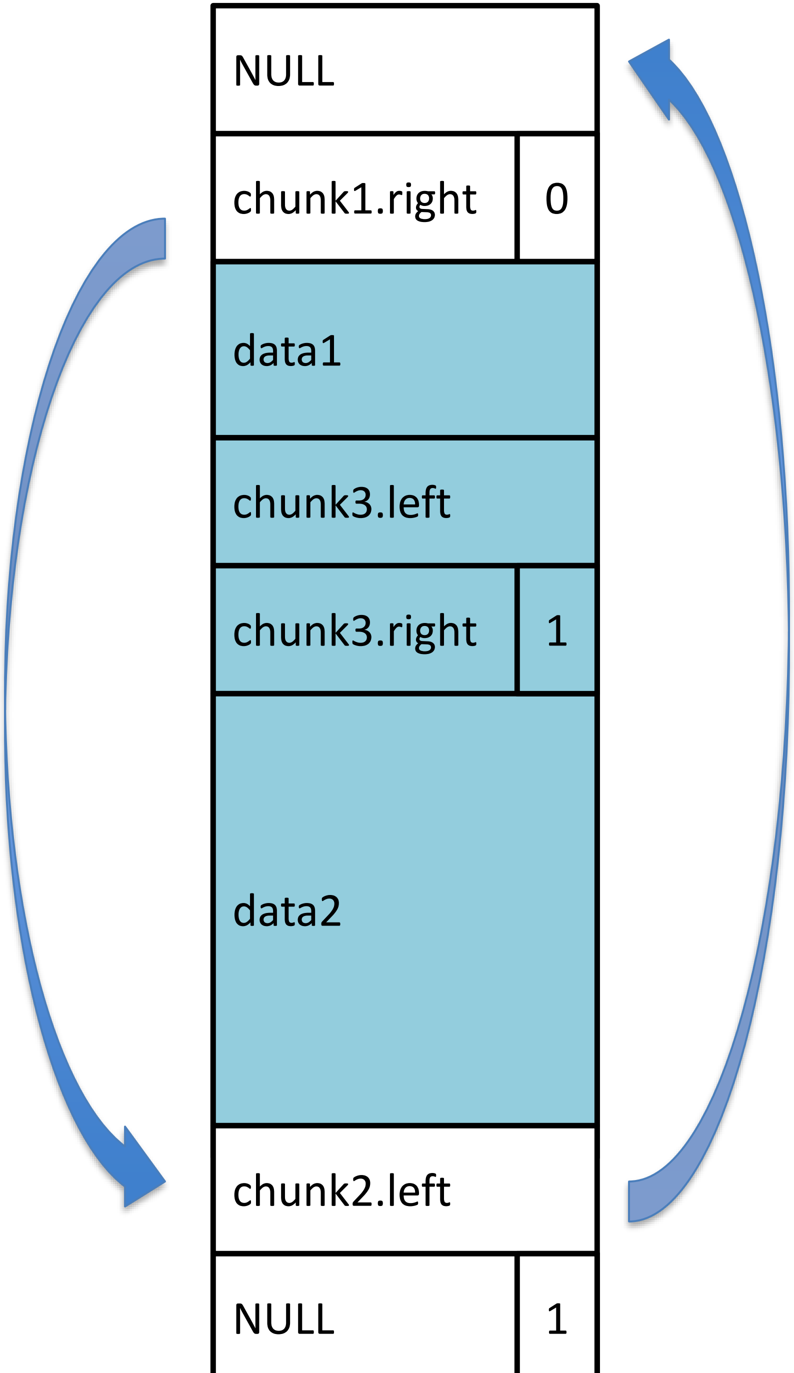


malloc()
- search left-to-right for free chunk
- modify pointers

b1 = malloc(BUF_SIZE1)
b2 = malloc(BUF_SIZE2)

free()
- Consolidate with free neighbors

free(b1)
free(b2)



malloc()

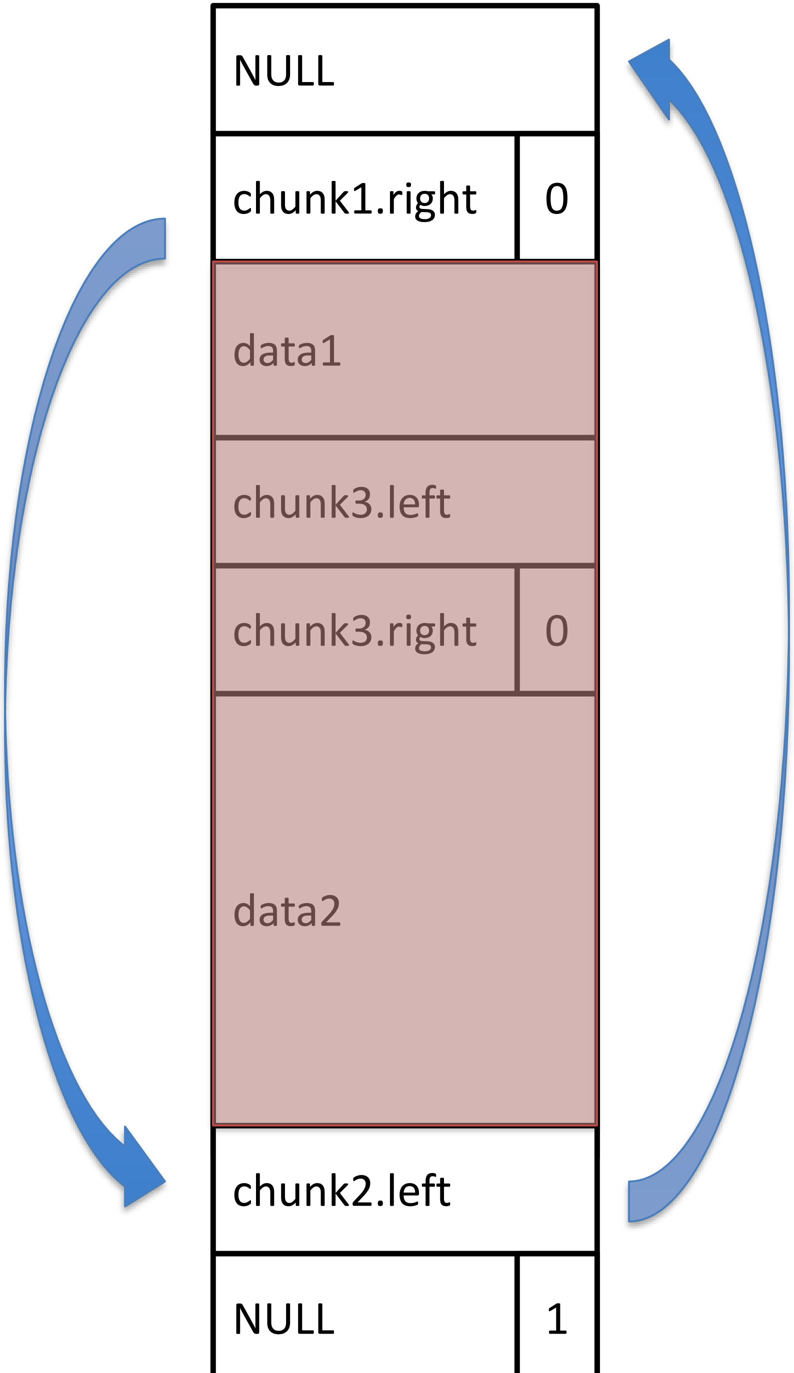
- search left-to-right for free chunk
- modify pointers

b1 = malloc(BUF_SIZE1)
b2 = malloc(BUF_SIZE2)

free()

- Consolidate with free neighbors

free(b1)
free(b2)
b3 = malloc(BUF_SIZE1 + BUF_SIZE2)



malloc()

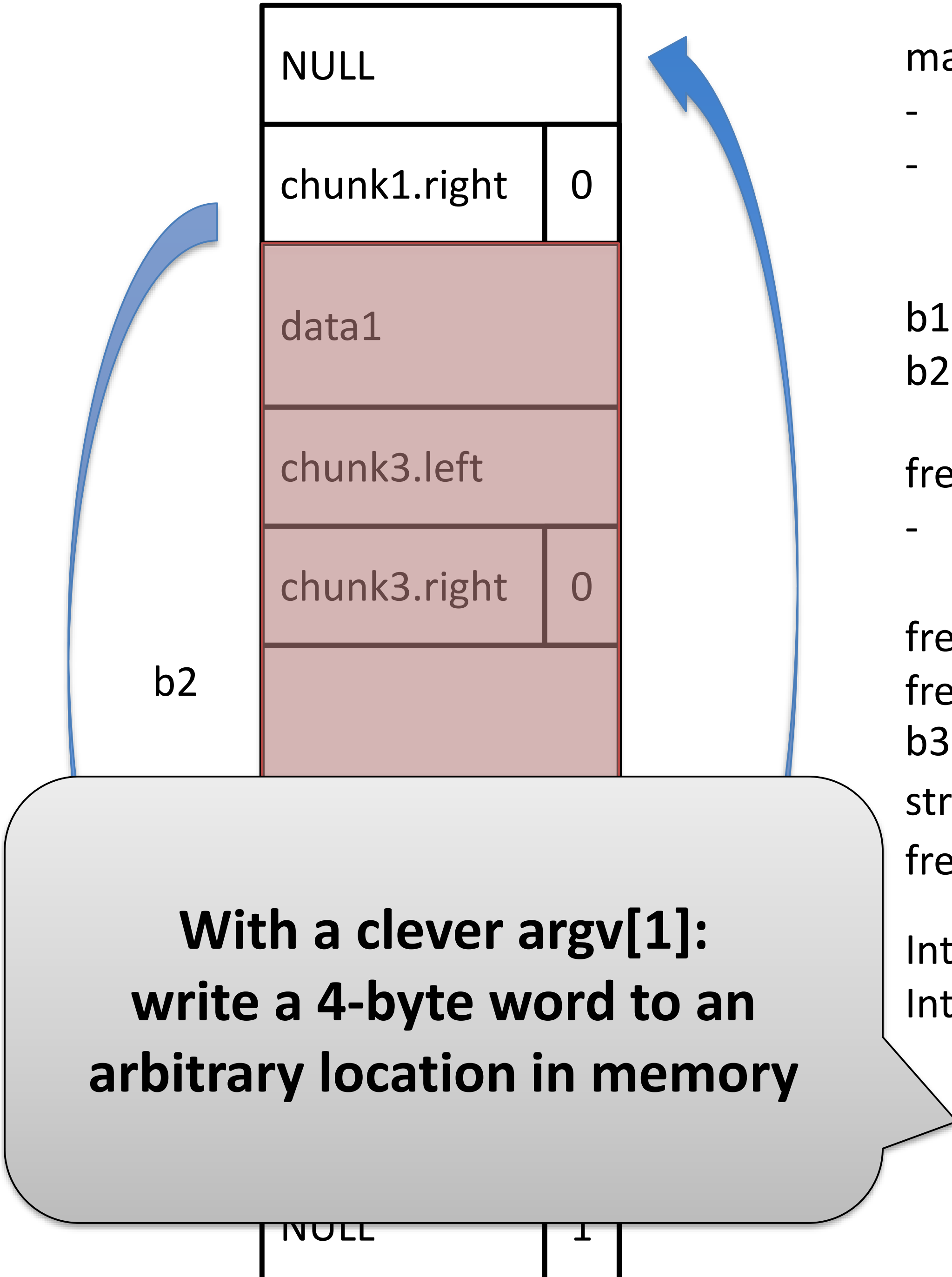
- search left-to-right for free chunk
- modify pointers

b1 = malloc(BUF_SIZE1)
b2 = malloc(BUF_SIZE2)

free()

- Consolidate with free neighbors

free(b1)
free(b2)
b3 = malloc(BUF_SIZE1 + BUF_SIZE2)
strncpy(b3, argv[1], BUF_SIZE1+BUF_SIZE2-1)



malloc()

- search left-to-right for free chunk
- modify pointers

b1 = malloc(BUF_SIZE1)
b2 = malloc(BUF_SIZE2)

free()

- Consolidate with free neighbors

free(b1)
free(b2)
b3 = malloc(BUF_SIZE1 + BUF_SIZE2)
strncpy(b3, argv[1], BUF_SIZE1+BUF_SIZE2-1)
free(b2)

Interprets b2-8 as a chunk3.left
Interprets b2-4 as a chunk3.right

(b2 - 8)->left->right = (b2-8)->right
(b2 - 8)->right->left = (b2-8)->left

```
movl   $0xf8,(%esp)
call   0x8048364 <malloc@plt>
mov    %eax,0x14(%esp)
movl   $0xf8,(%esp)
call   0x8048364 <malloc@plt>
mov    %eax,0x18(%esp)
mov    0x14(%esp),%eax
mov    %eax,(%esp)
call   0x8048354 <free@plt>
mov    0x18(%esp),%eax
mov    %eax,(%esp)
call   0x8048354 <free@plt>
movl   $0x200,(%esp)
call   0x8048364 <malloc@plt>
mov    %eax,0x1c(%esp)
mov    0xc(%ebp),%eax
add    $0x4,%eax
mov    (%eax),%eax
movl   $0x1ff,0x8(%esp)
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mov    %eax,(%esp)
call   0x8048334 <strncpy@plt>
mov    0x18(%esp),%eax
mov    %eax,(%esp)
call   0x8048354 <free@plt>
mov    0x1c(%esp),%eax
mov    %eax,(%esp)
call   0x8048354 <free@plt>
leave
ret
```

What type of vulnerability might this be?

This is very simple example. Manual analysis is very time consuming.

Security analysts use a variety of tools to augment manual analysis

Aiding analysts with tools

How can we automatically find the bug?

```
main(  int argc, char* argv[] ) {
 char* b1;
 char* b2;
 char* b3;

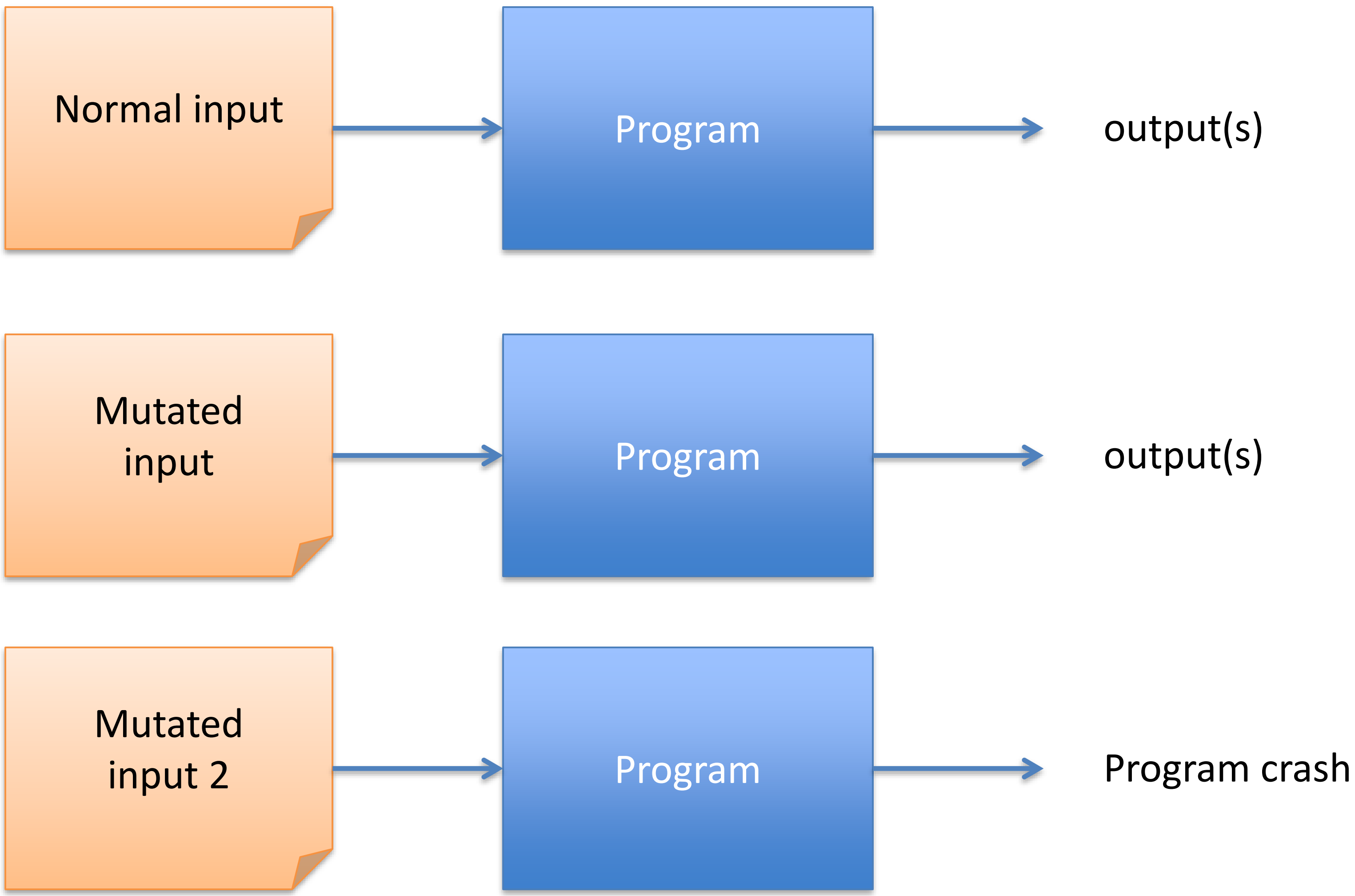
 if( argc != 3 ) then return 0;
 if( argv[2] != 31337 )
     complicatedFunction();
 else {
     b1 = (char*)malloc(248);
     b2 = (char*)malloc(248);
     free(b1);
     free(b2);
     b3 = (char*)malloc(512);
     strncpy( b3, argv[1], 511 );
     free(b2);
     free(b3);
  }
}
```

Start with dynamic analysis: Fuzzing

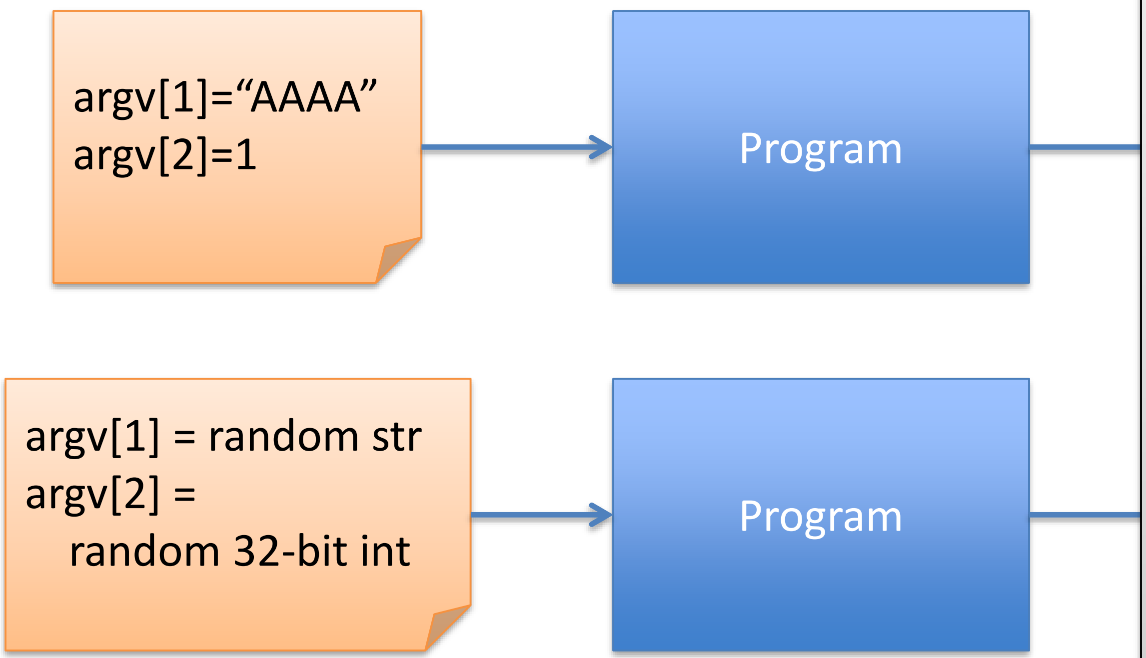
"The term first originates from a class project at the University of Wisconsin 1988 although similar techniques have been used in the field of quality assurance, where they are referred to as robustness testing, syntax testing or negative testing."
Wikipedia
http://en.wikipedia.org/wiki/Fuzz_testing

Choose a bunch of inputs
See if they cause program to misbehave
Example of dynamic analysis

Black-box fuzz testing: the goal



Black-box fuzz testing

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      free(b2);
      b3 = (char*)malloc(512);
      strncpy( b3, argv[1], 511 );
      free(b2);
      free(b3);
   }
}
```

If x is 32 bits, then probability of crashing is **at most what**?

$1/2^{32}$

Achieving code coverage can be very difficult

Fuzzing is a lot about code coverage

- Code coverage defined in many ways
  - # of basic blocks reached
  - # of paths followed
  - # of conditionals followed
  - gcov is useful standard tool
- Mutation based
  - Start with known-good examples
  - Mutate them to new test cases
    - heuristics: increase string lengths (AAAAAAAAA…)
    - randomly change items
- Generative
  - Start with specification of protocol, file format
  - Build test case files from it
    - Rarely used parts of spec

Manually refine fuzzing (example from Miller slides)

Multiplayer game

Fuzz for remote exploits

- Capture packets during normal use
- Replace some packet contents with random values
- Send to game, determine code coverage

Initial: 614 out of 36183 basic blocks

From Wikipedia:

Freeciv 2.1.0-beta3, with the SDL client

One big switch statement controlled by third byte of packet

Update fuzz rules to exhaust the values of this third byte

Improves coverage by 4x.

Repeat several times to improve coverage.

Heap overflow found.

Example program analyzers

- Manual analysis (you are the analyzer!)
- Static analysis (do not execute program)
  - Scanners
  - Symbolic execution
  - Abstract representations
- Dynamic analysis (execute program)
  - Debugging
  - Fuzzers
  - Ptrace

<u>Do you have source code?</u>
Yes: lucky you
No: can still do things, but not as easily
(missing a lot of context about program)

Source code scanners

Look at source code, flag suspicious constructs

```
…
strcpy( ptr1, ptr2 );
…
```

Warning: Don’t use strcpy

Simplest example: grep

Lint is early example

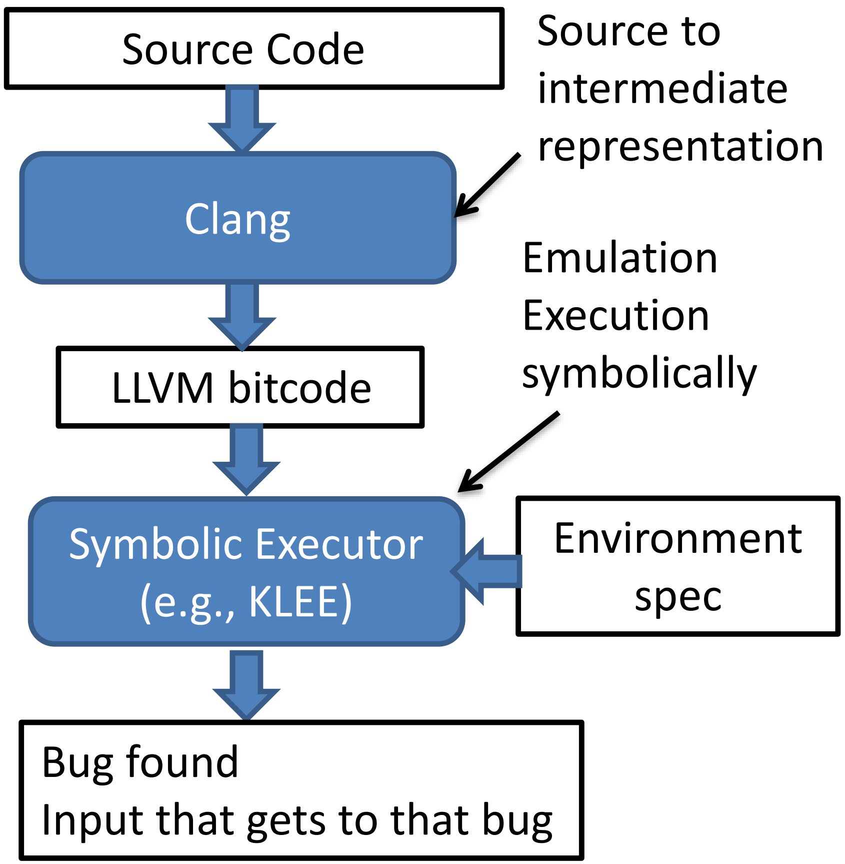
RATS (Rough auditing tool for security)

ITS4 (It’s the Software Stupid Security Scanner)

Circa 1990’s technology:

shouldn’t work for reasonable modern codebases

Symbolic execution



- Technique for statically analyzing code paths and finding inputs
- Associate to each input variable a special symbol
  - called symbolic variable
- Simulate execution symbolically
  - Update symbolic variable's value appropriately
  - Conditionals add constraints on possible values
- Cast constraints as satisfiability, and use SAT solver to find inputs

Symbolic execution

```
main(  int argc, char* argv[] ) {
  char* b1;
  char* b2;
  char* b3;

  if( argc != 3 ) then return 0;
  if( argv[2] != 31337 )
     complicatedFunction();
  else {
     b1 = (char*)malloc(248);
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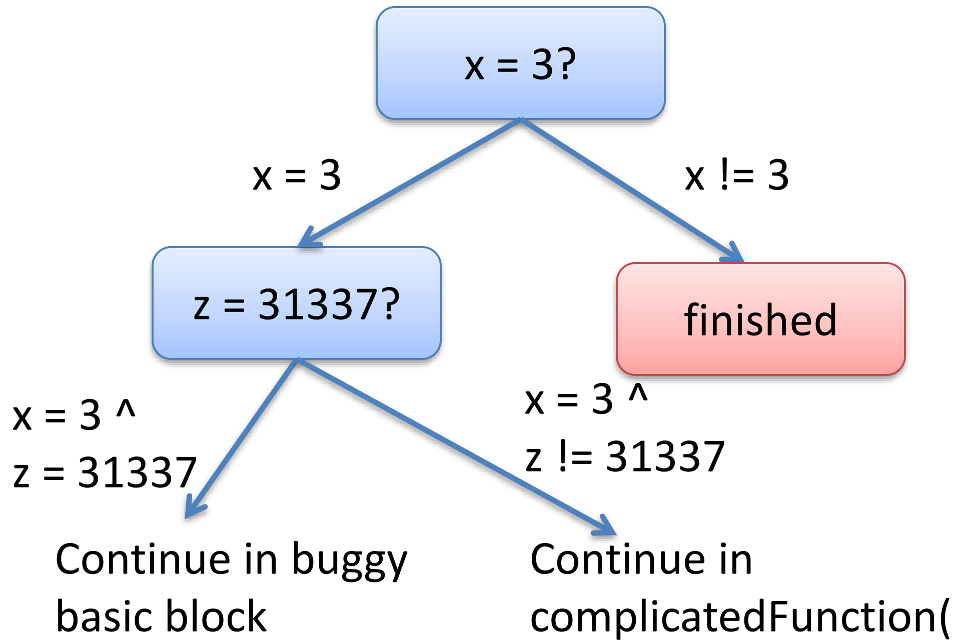
     free(b1);
     free(b2);
     b3 = (char*)malloc(512);
     strncpy( b3, argv[1], 511 );
     free(b2);
     free(b3);
   }
}
```

Initially:

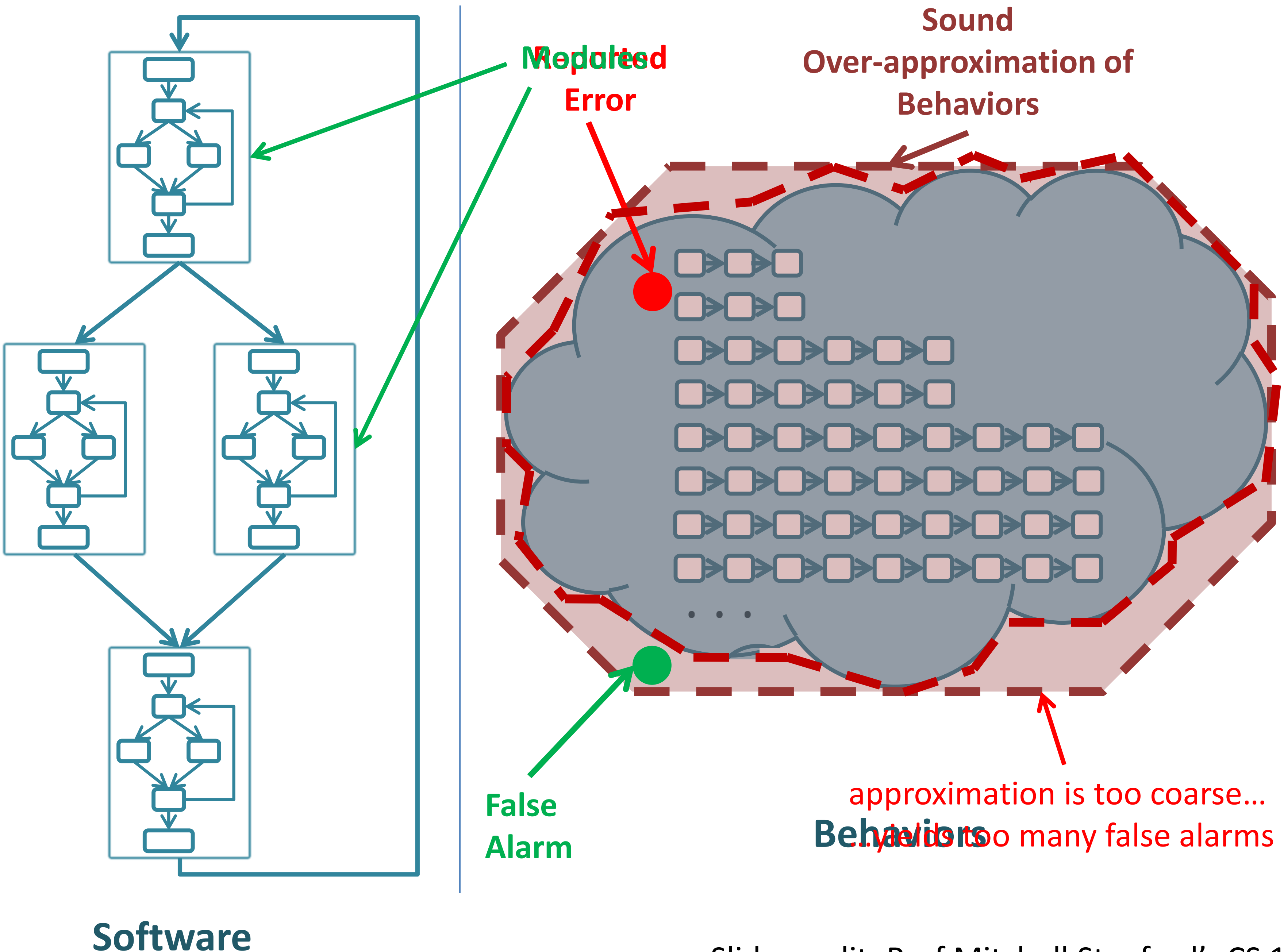
argc = x (unconstrained int)
argv[2] = z (memory array)



- Eventually emulation hits a double free
- Can trace back up path to determine what x, z must have been to hit this basic block

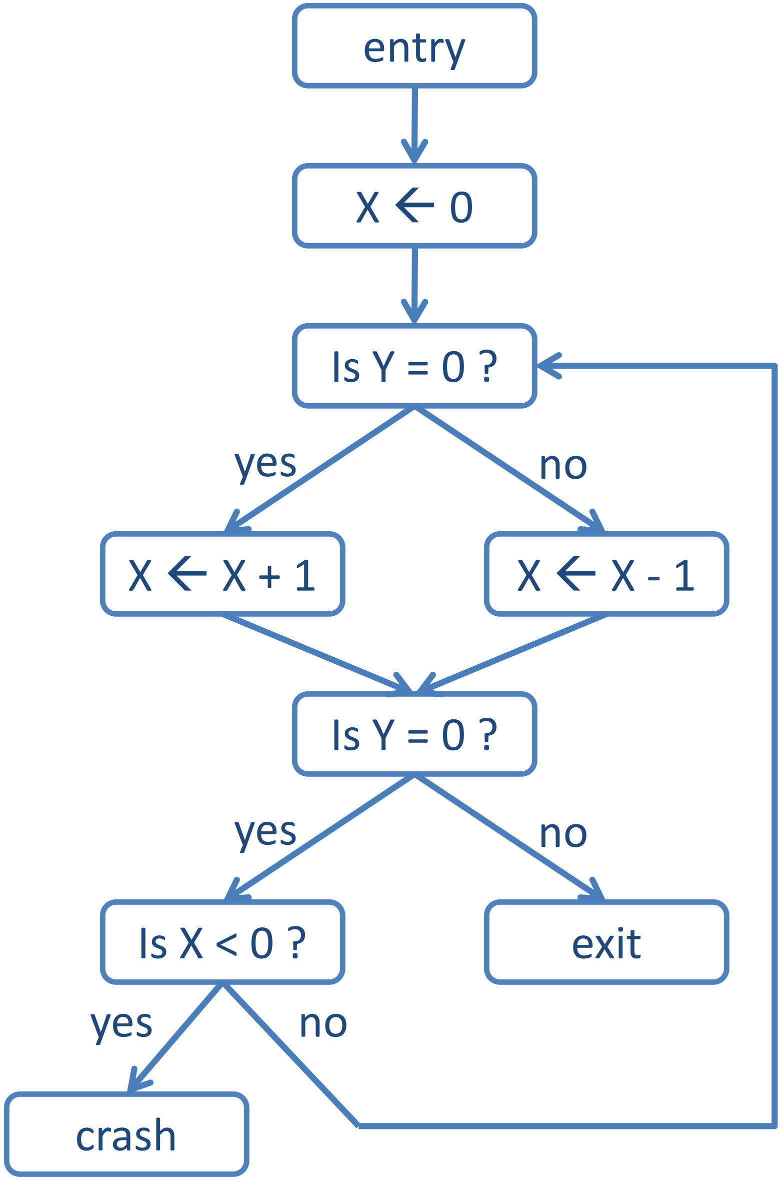
Symbolic execution challenges

- Can we complete analyses?
  - Yes, but only for very simple programs
  - Exponential # of paths to explore
- Path selection
  - Might get stuck in complicatedFunction()
- Encoding checks on symbolic states
  - Must include logic for double free check
  - Symbolic execution on binary more challenging (lose most memory semantics)



Slide credit: Prof Mitchell Stanford's CS 155

Does this program ever crash?



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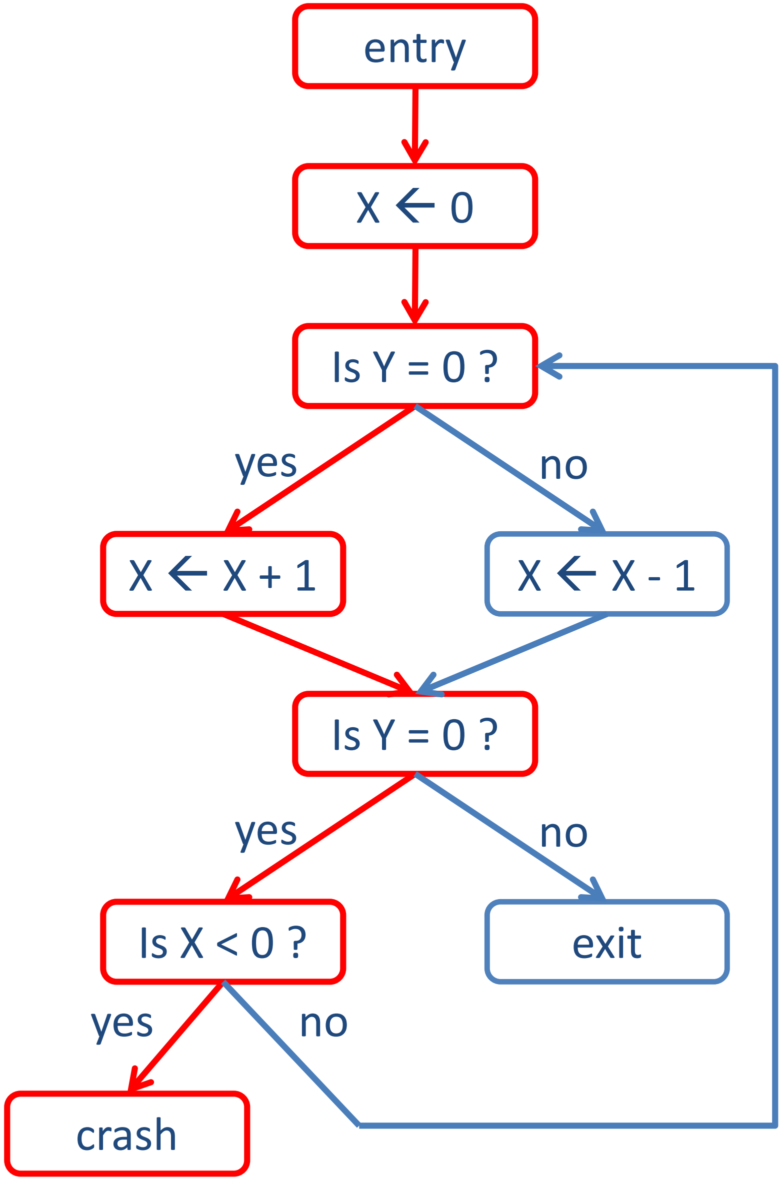
Does this program ever crash?

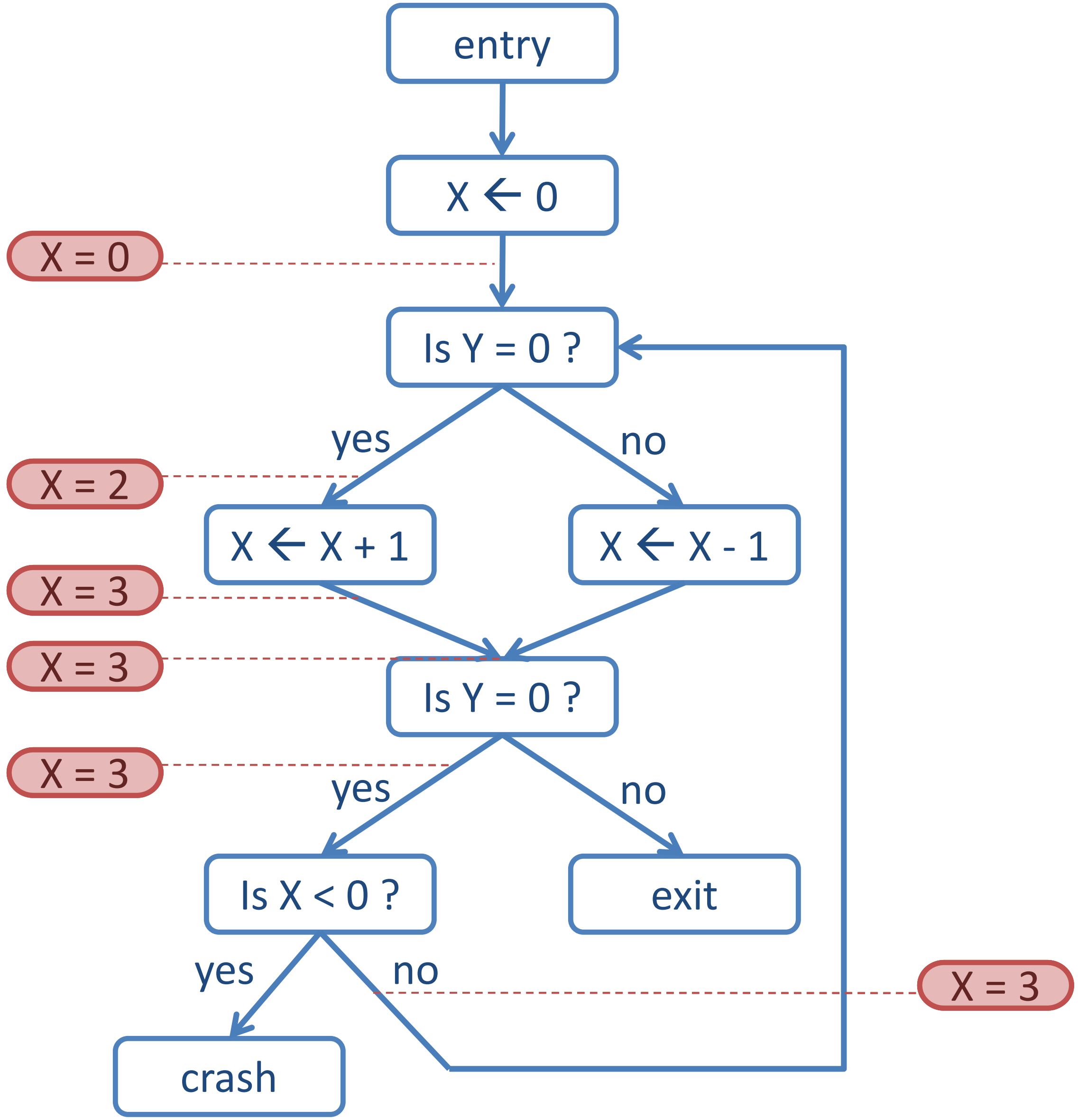


infeasible path!

… program will never crash

Slide credit: Prof Mitchell Stanford's CS 155

Try analyzing without approximating…

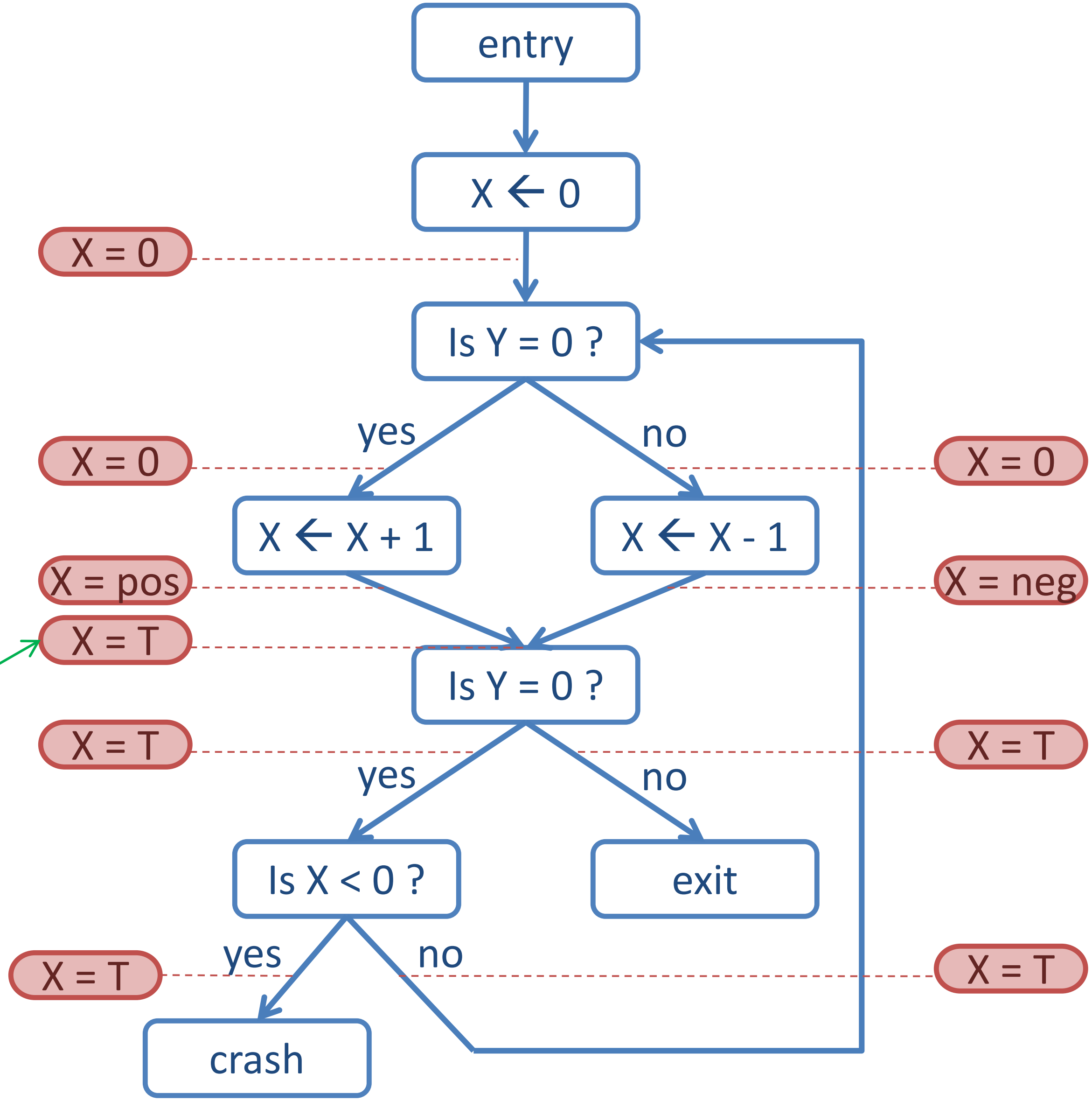


non-termination!

… therefore, need to approximate

Slide credit: Prof Mitchell Stanford's CS 155

Try analyzing with “signs” approximation…

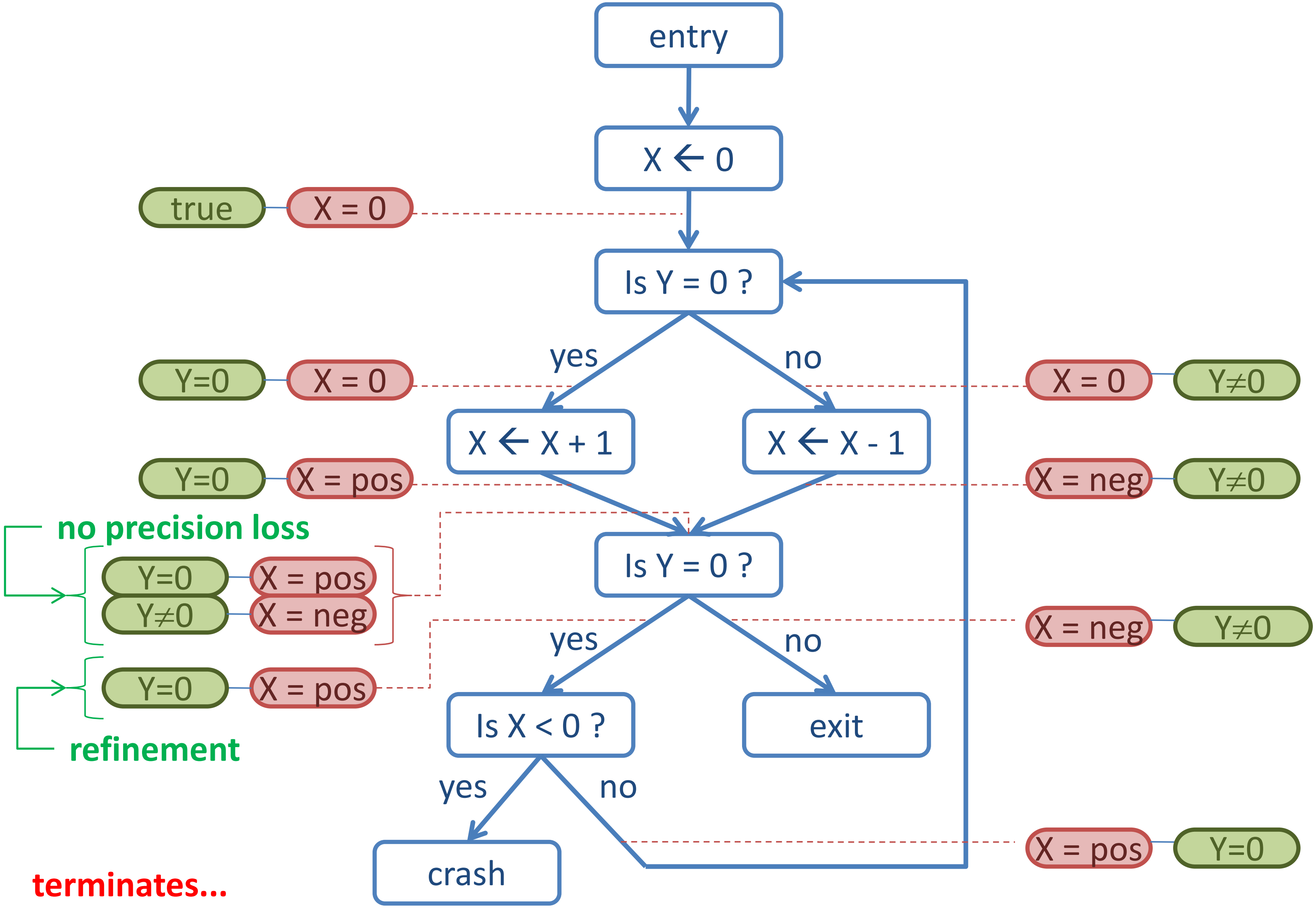


lost precision

terminates…
… but reports false alarm
… therefore, need more precision

Slide credit: Prof Mitchell Stanford’s CS 155

Try analyzing with "path-sensitive signs" approximation...



terminates...

... no false alarm

... soundly proved never crashes

Slide credit: Prof Mitchell Stanford's CS 155

Bug finding is a big business

- Grammatech (Prof Reps here at Wisconsin)
- Coverity (Stanford startup)
- Fortify
- many, many others…

Example program analyzers

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<u>Do you have source code?</u>
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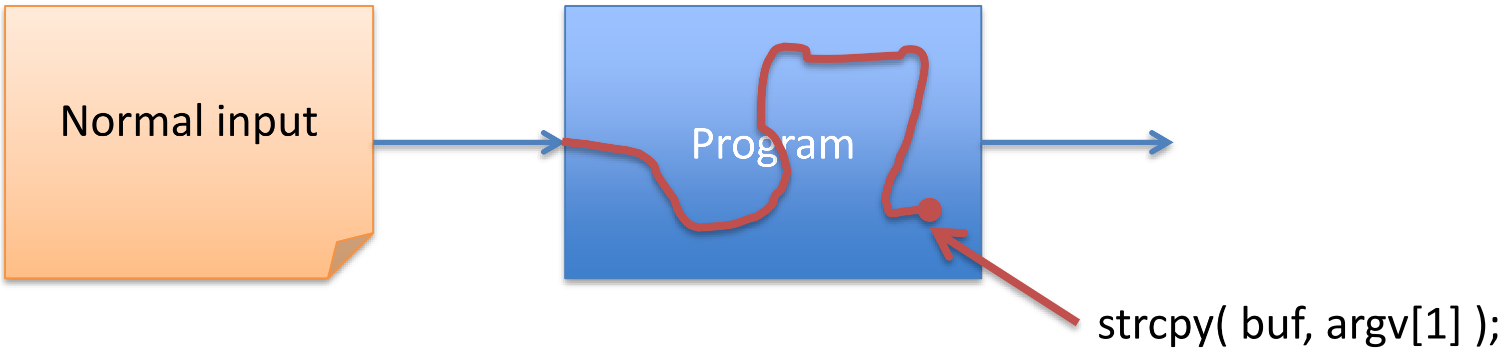
(missing a lot of context about program)

Taint tracking

Track information flow from user input to it’s use

Can be either static or dynamic

Useful to augment manual testing



White-box fuzz testing

- Start with real input and do static analysis
  - Symbolic execution of program
  - Gather constraints (control flow) along way
  - Systematically negate constraints backwards
  - Eventually this yields a new input
- Repeat

Godefroid, Levin, Molnar. “Automated Whitebox Fuzz Testing”

Symbolic execution + fuzzing

```
void top(char input[4]) {
  int cnt=0;
  if (input[0] == 'b') cnt++;
  if (input[1] == 'a') cnt++;
  if (input[2] == 'd') cnt++;
  if (input[3] == '!') cnt++;
  if (cnt >= 3) abort(); // error
}
```

Example from Godefroid et al.

Start with some input.
Run program for real & symbolicly
Say input = “good”

i0 != ‘b’
i1 != ‘a’
i2 != ‘d’
i3 != ‘!’

i0,i1,i2,i3 are all symbolic variables

This gives set of constraints on input
Negate them one at a time to generate a new input that explores new path

Example
i0 != ‘b’ and i1 != ‘a’ and i2 != ‘d’ and i3 = ‘!’
input would be ``goo!’’

Repeat with new input

Dynamic Analysis

- Key idea: add test code to detect memory errors
  - Instrument execution of program
    - what is interesting?
  - Keep extra metadata about what is happening
    - What data can we keep
  - Detect errors when or after they occur
    - How?

Example: Address Sanitizer

- Built into GCC:
  - gcc –fsanitize=address meet.c
- Catches:
  - Out-of-bounds accesses to heap, stack and globals
  - Use-after-free
  - Use-after-return (runtime flag ASAN_OPTIONS=detect_stack_use_after_return=1)
  - Use-after-scope (clang flag -fsanitize-address-use-after-scope)
  - Double-free, invalid free
  - Memory leaks (experimental)

Address Sanitizer approach

- Store 1 byte of metadata for every 8 bytes of memory
  - Metadata = Addr>>3 + Offset
    - Value 0: all 8 bytes accessible
    - Value 1 < n < 7: first n bytes accessible
    - Value < 0: memory in accessible for various reasons
- Instrument memory accesses

```
ShadowAddr = (Addr >> 3) + Offset;
if (*ShadowAddr != 0)
   ReportAndCrash(Addr);
```

Memory Layout

- Heap: Add redzone between allocations – invalid addresses
- Stack/Globals: add redzone between variables

```
void foo() {
  char a[10];
  <function body>
}
```

```
void foo() {
  char rz1[32]
  char arr[10];
  char rz2[32-10+32];
  // set up shadow
  <function body>
```

Demo

- Run on meet.c