Understanding Symbolic Execution

Another step forward to the day when computers do everything humans do but better.

A Simple Capture-the-Flag Level

```
# A simple guessing game.
user_input = raw_input('Enter the password: ')
if user_input == 'hunter2':
  print 'Success.'
else:
  print 'Try again.'
```

There are many solutions:

- Use objdump or readelf to find the string ‘hunter2’.
- Use ltrace to find the comparison.
- Use a debugger and inspect the memory where the password is stored.
- …

A Complex Capture-the-Flag Level

```
# A complex guessing game. Don’t bother to figure out what the code does.
def encrypt(string, amount):
  for i in range(0, len(string)):
    string[i] += amount

user_input = raw_input('Enter the password: ')
if encrypt(user_input, amount=1) == encrypt('hunter2', amount=2):
  print 'Success.'
else:
  print 'Try again.'
```

There are ~~many~~ not as many solutions:

- ~~Use objdump or readelf to find the string ‘hunter2’~~. No, ‘hunter2’ isn’t the password anymore.
- ~~Use ltrace to find the comparison~~. No, the strings it compares aren’t what you entered nor the password.
- ~~Use a debugger and inspect the memory where the password is stored.~~ Nope. Same as above.
- Reverse engineer the encrypt function. Simple in this example, but it could be *really*

Solution: Symbolic Execution

What’s that? It’s a system that walks through all* possible paths of a program.
Let’s work through an example.

We want to find an input that arrives here

```
user_input = raw_input('Enter the password: ')
if user_input == 'hunter2':
  print 'Success.'
else:
  print 'Try again.'
```

*some: for many programs, this would be impossible (even if we decided that a path that never halts is considered the “end” of a branch, the halting problem shows that determining when a branch is considered done is undecidable), and for others it would take longer than the universe has existed so far to traverse all paths.

Step 1: Inject a Symbol

You are here

```
user_input = raw_input('Enter the password: ')
if user_input == 'hunter2':
  print 'Success.'
else:
  print 'Try again.'
```

But first, what is a symbol?

What is a Symbol?

$$x^2 + 2x + 3 = 4$$

Remember high school algebra?

Think of a symbol as x, except that it's a variable in the program.

We don't know what x is. We want to find out. Same with a symbol.

x depends on the equation(s) that constrain it.

A symbol depends on the execution path(s) that constrain it.

…but wait, what is an execution path?

What is an Execution Path?

It’s a possible way to travel through the program.

For example…

```
user_input = raw_input('Enter the password: ')
if user_input == 'hunter2':
  print 'Success.'
else:
  print 'Try again.'
```

…has two possible execution paths. Can you see them?

Execution Path Example

```python
user_input = raw_input('Enter the password: ')
if user_input == 'hunter2':
  print 'Success.'
else:
  print 'Try again.'
```

Path 1: if user_input equals 'hunter2'

```python
user_input = raw_input('Enter the password: ')
↓
if user_input == 'hunter2'   # it is equal!
↓
print 'Success.'
```

Path 2: if user_input does not equal 'hunter2'

```python
user_input = raw_input('Enter the password: ')
↓
if user_input == 'hunter2'   # it's not equal.
↓
print 'Try again.'
```

…okay that makes sense. But how do execution paths act like equations that constrain symbols?

How do execution paths constrain symbols?

```
user_input = λ

if user_input == 'hunter2'

print 'Success.'
```

Look familiar? It’s the same as on the last slide, but user_input is now a symbol.

or this path to be executed, the symbol, λ, must be equal to ‘hunter2

Otherwise, the computer would execute the other path.

Return to Step 1: Inject a Symbol

You just injected a symbol.

You are here

```
1 user_input = λ
2 if user_input == 'hunter2':
3   print 'Success.'
4 else:
5   print 'Try again.'
```

Goal: Find the execution path that reaches line 3, then solve for λ.

Step 2: Branch

You are here

```
user_input = λ
if user_input == 'hunter2':
  print 'Success.'
else:
  print 'Try again.'
```

What happens when you reach an if statement that depends on a symbol? You branch.

...please explain!

What does it mean to branch?

ranching just means to split into the different possible execution path

You are here

```
1 user_input = λ
2 if user_input == 'hunter2':
3   print 'Success.'
4 else:
5   print 'Try again.'
```

Path 1: if user_input equals 'hunter2'

```
user_input = raw_input('Enter the password: ')

if user_input == 'hunter2'   # it is equal!

print 'Success.'
```

Path 2: if user_input does not equal 'hunter2'

```
user_input = raw_input('Enter the password: ')

if user_input == 'hunter2'   # it's not equal.

print 'Try again.'
```

…isn't this is the same slide as before, copied and pasted?

Step 3: Evaluate each Branch

Let’s imagine we picked the ‘user_input does not equal “hunter2”’ branch first.

```
user_input = λ
if user_input == 'hunter2':
  print 'Success.'
else:
  print 'Try again.'
```

You are here

We are at the end of the execution and didn’t find what we wanted. Continue with the other branch!

Step 3: Evaluate each Branch (part 2)

Now we chose the ’user_input equals “hunter2”’ branch.

You are here

```
user_input = λ
if user_input == 'hunter2':
  print 'Success.'
else:
  print 'Try again.'
```

We found what we wanted! We now have an execution path that can constrain the symbol. We can solve for λ to find the password.

A More Complex Example: Part 1

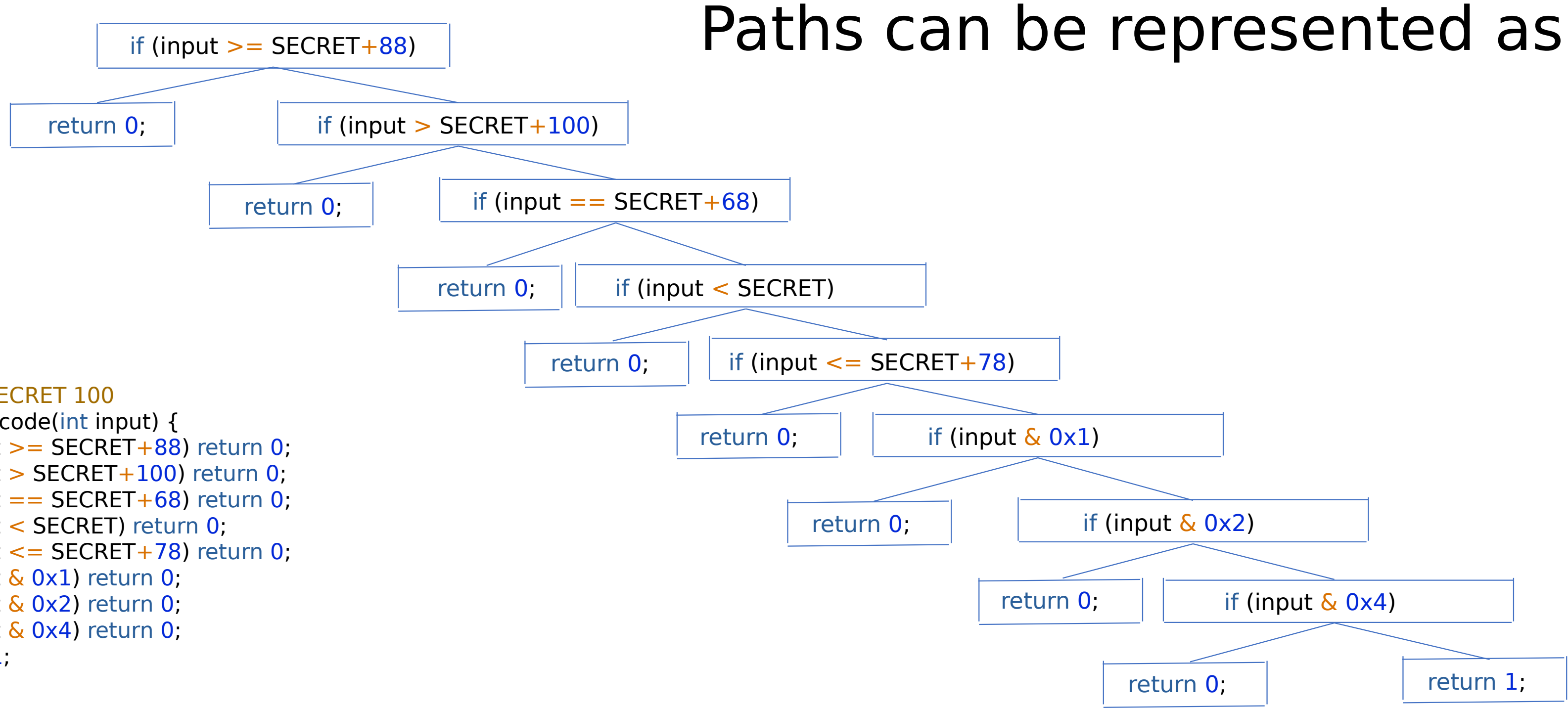
The following is source code from Ch06CAsm_Conditionals:

```
#define SECRET 100
int check_code(int input) {
    if (input >= SECRET+88) return 0;
    if (input > SECRET+100) return 0;
    if (input == SECRET+68) return 0;
    if (input < SECRET) return 0;
    if (input <= SECRET+78) return 0;
    if (input & 0x1) return 0;
    if (input & 0x2) return 0;
    if (input & 0x4) return 0;
    return 1;
}
```

What are the possible paths?

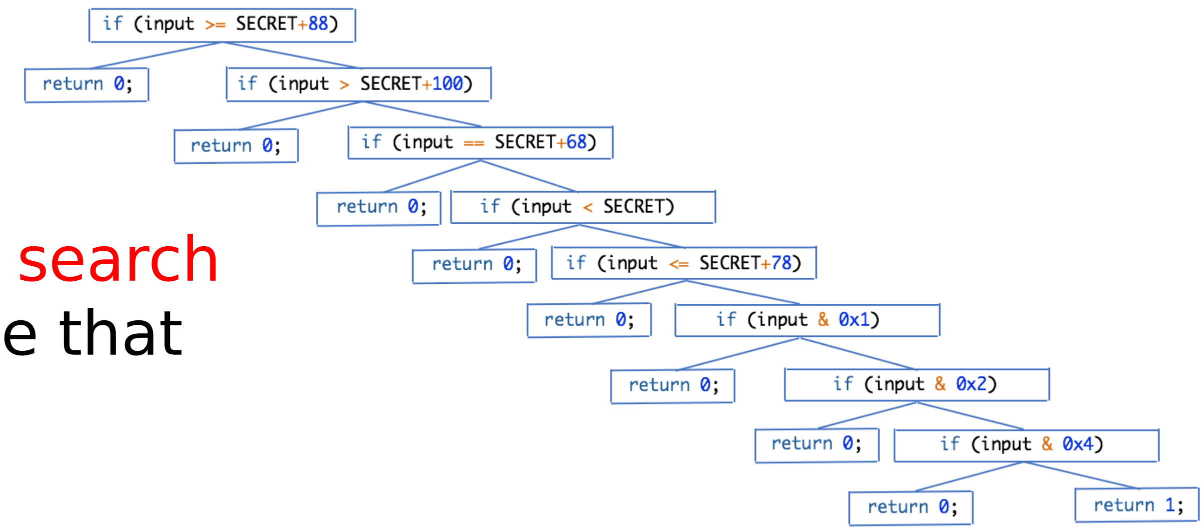
A More Complex Example: Part 2

Paths can be represented as a tree




```
#define SECRET 100
int check_code(int input) {
   if (input >= SECRET+88) return 0;
   if (input > SECRET+100) return 0;
   if (input == SECRET+68) return 0;
   if (input < SECRET) return 0;
   if (input <= SECRET+78) return 0;
   if (input & 0x1) return 0;
   if (input & 0x2) return 0;
   if (input & 0x4) return 0;
   return 1;
}
```

Solving a More Complex Example: Part 1



We can perform any tree search algorithm to find the node that returns 1.

Breadth-first search is a great choice (and, by default, what Angr uses.)

Solving a More Complex Example: Part 2

```
if (input >= SECRET+88)
if (input > SECRET+100)
if (input == SECRET+68)
if (input < SECRET)
if (input <= SECRET+78)
if (input & 0x1)
if (input & 0x2)
if (input & 0x4)
return 1;
```

Once we have a path, we can build an equation that can be solved with a satisfiability modulo theories (SMT) solver:

input >= SECRET+88
∧ input > SECRET+100
∧ input == SECRET68
∧ input < SECRET
∧ input <= SECRET+78
∧ input & 0x1
∧ input & 0x2
∧ input & 0x4

Remember, SECRET = 100.

The Real World™

```
user_input0 = λ0
user_input1 = λ1
user_input2 = λ2
...
if user_input0 == 'hunter2':
  if 2 * user_input1 - 7 * user_input2 < len(user_input0):
    ... # more complex functionality
    print 'Success.'
  else:
    print 'Try again.'
else:
  print 'Try again.'
```

Of course, in the real world, the binaries will be complex. There could be many symbols and many branches. The exponential growth of the complexity of the binary is symbolic execution's largest problem.

How do we step through the program, find the branch we want, and solve for λ?

We let the computer do that! Our friends at UCSB built a powerful tool called Angr to do that for us. It's written in Python and it operates on native binaries (no source code required!).

https://github.com/angr

Symbolic Execution CTF: Part 1

An Introduction to Path Groups

What is Angr?

Angr is a symbolic execution engine*.

It can:

- Step through binaries (and follow any branch)
- Search for a program state that meets a given criteria
- Solve for symbolic variables given path (and other) constraints

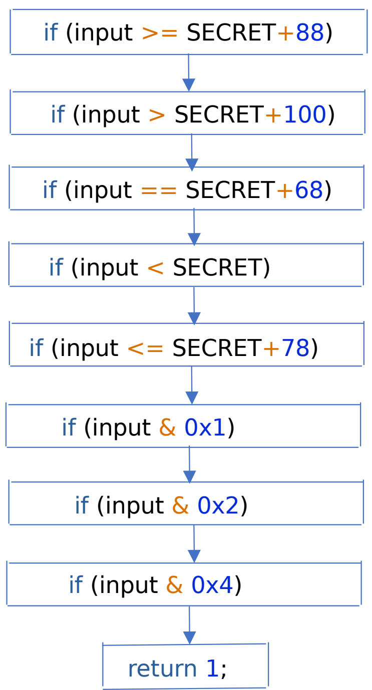
*and more, but use of the included binary analysis tools unrelated to symbolic execution is out of the scope of these slides and the associated CTF.

Recall, the foundation of symbolic execution involves two principles:

1. Execution Paths
2. Symbols

We will begin by discussing execution paths.

An Execution Path in Angr



An execution path represents a possible execution of the program that begins somewhere and ends somewhere else.

A node of an execution path in Angr is represented by a 'SimState' object. As the name suggests, it stores the state of the program, as well as a history of the previous states.

Chaining these SimStates together creates a path.

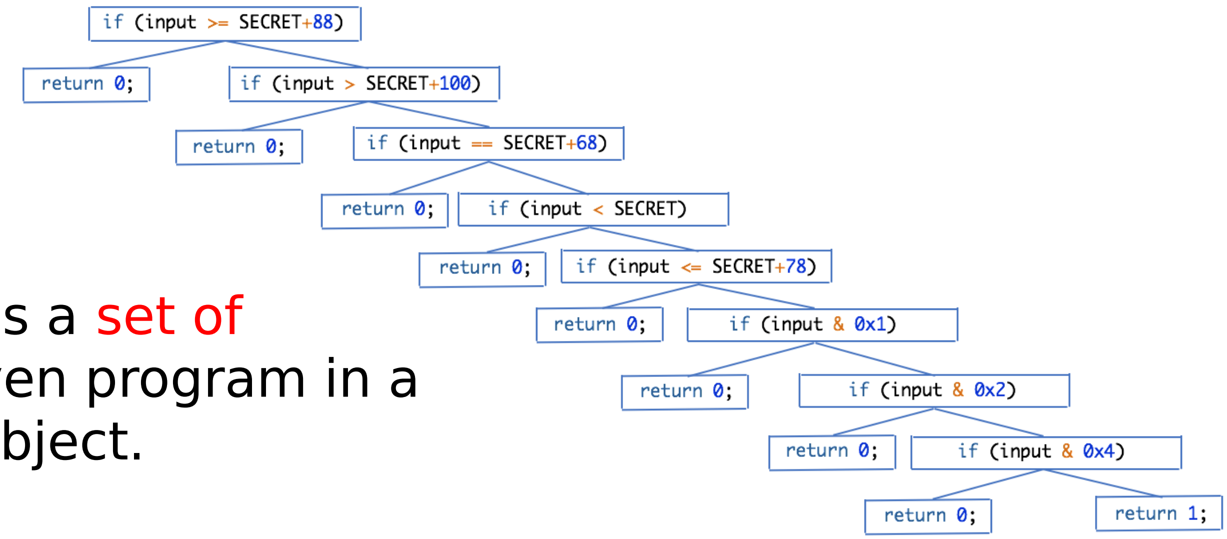
A Set of Execution Paths

A single execution path isn't interesting. We can view one by running the program with a given input without Angr.

Instead, we care about all* (as many as possible) execution paths, so that we can search them to find the one we want.

We'll talk about searching later, but first, how do we represent a set of execution paths in Angr, and how do we build them?

A Simulation Manager (simgr) in Angr



Angr stores and handles a set of possible paths for a given program in a ‘simulation manager’ object.

Simulation managers provide functionality to step through the program to generate possible paths/states.

Building a Set of Paths

1. Angr starts the program wherever you instruct it to start (this is the first active state)

2. Execute instructions in each active (nonterminated) state until we reach a branching point or the state terminates

3. At every branching point, split the state into multiple states, and add them to the set of active states

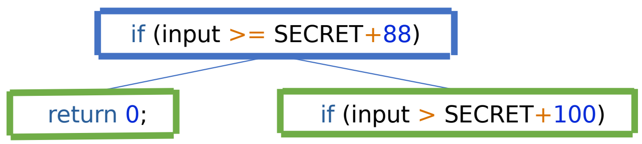
4. Repeat step 2..4 until we find what we want or all states terminate

Animation: Building a Set of Paths

```
if (input >= SECRET+88)
```

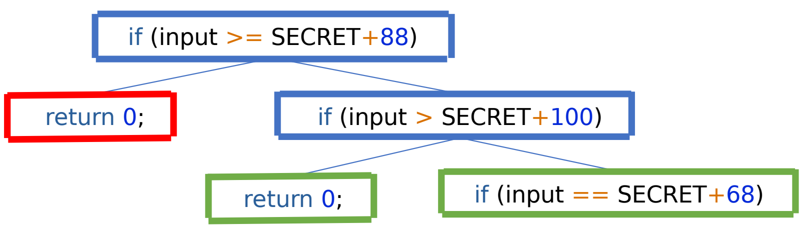
Legend:
Blue = already executed
Green = active
Red = terminated

Animation: Building a Set of Paths



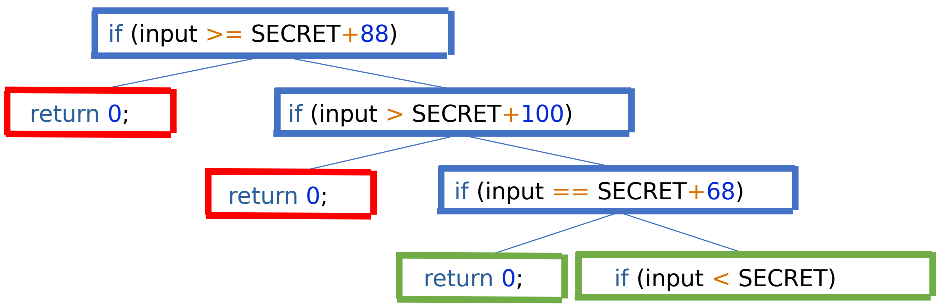
Legend:
Blue = already executed
Green = active
Red = terminated

Animation: Building a Set of Paths



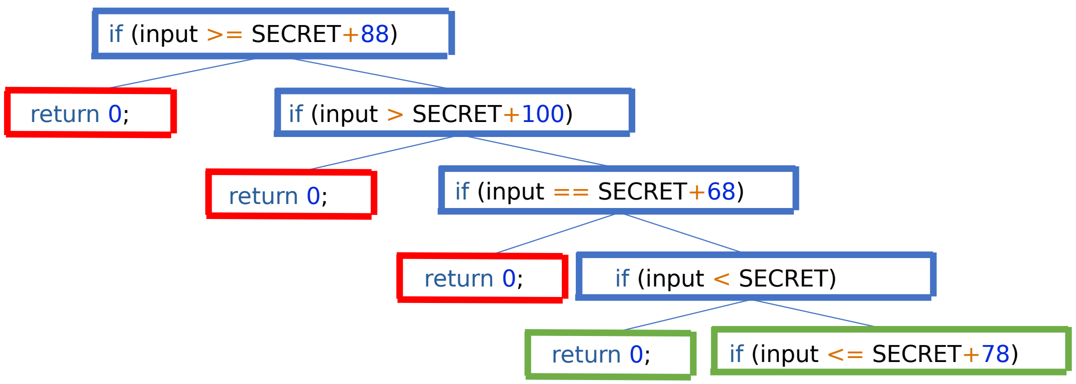
Legend:
Blue = already executed
Green = active
Red = terminated

Animation: Building a Set of Paths



Legend:
Blue = already executed
Green = active
Red = terminated

Animation: Building a Set of Paths



Legend:
Blue = already executed
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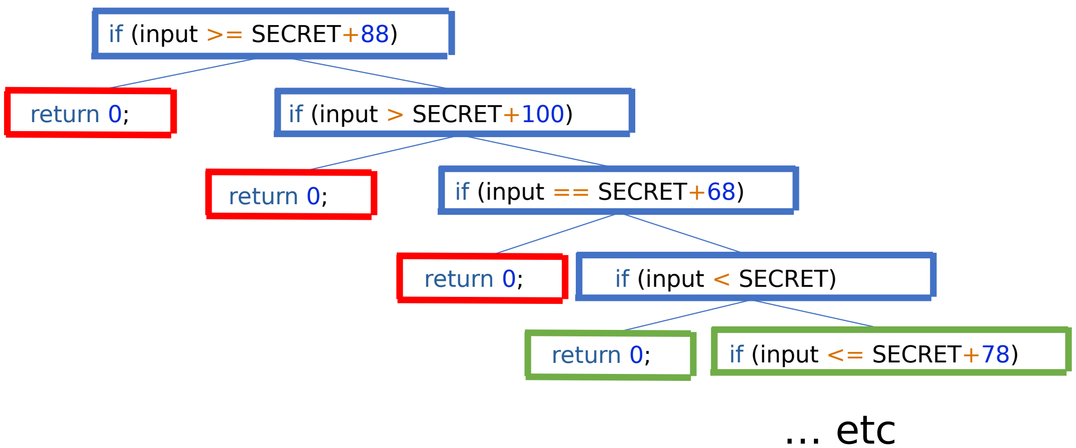
Red = terminated

Animation: Building a Set of Paths



Legend:
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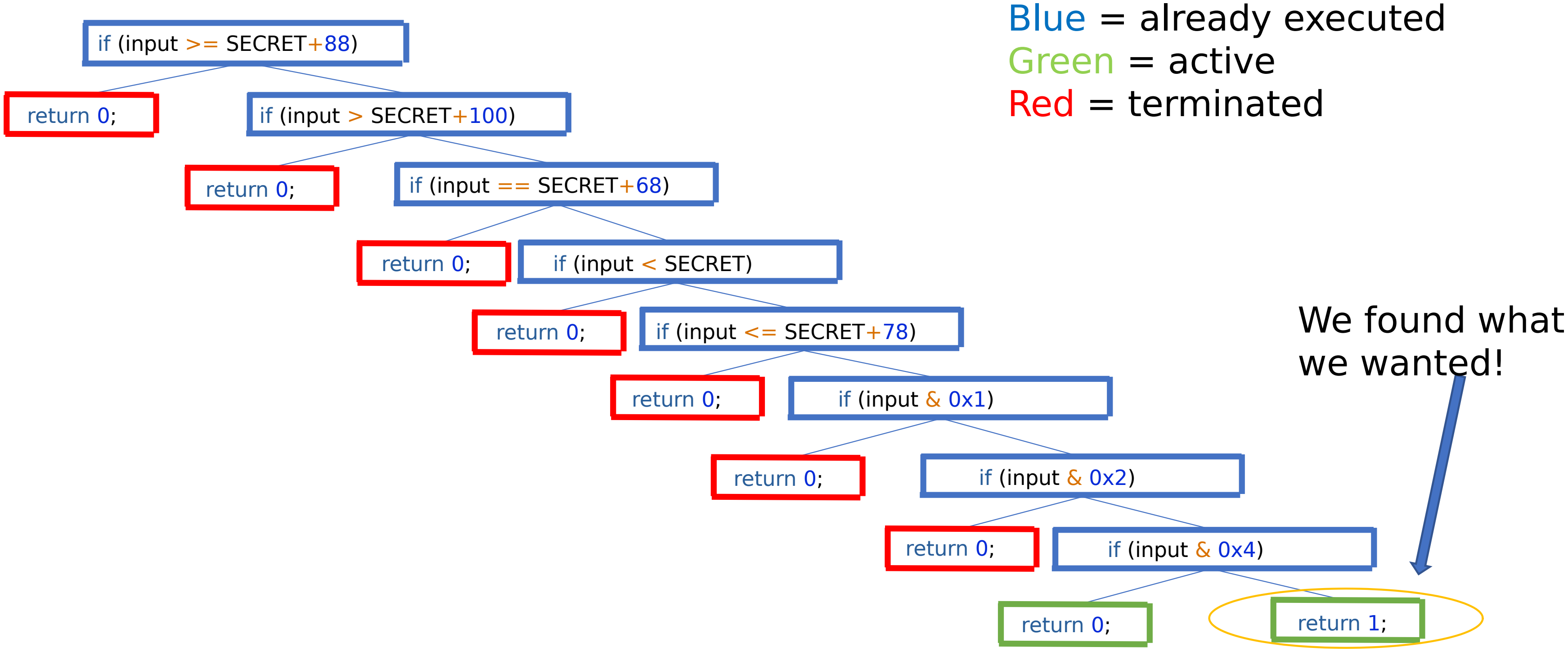
Animation: Building a Set of Paths



Legend:
Blue = already executed
Green = active
Red = terminated

Searching for What We Want

Method 1: Search for an instruction address	Method 2: Search for anything else!

Perhaps we want to find this address.
`804867a:  sub    $0xc,%esp`
`804867d:  push   $0x8048760`
`8048682:  call   8048400 <backdoor@plt>`
`8048687:  add    $0x10,%esp`
	Perhaps we want to find when the variable 'success' is equal to true.
	
	Any arbitrary function that determines if we have reached a state we want would work.

Both of these approaches are trivial! At each step, just check if any active state meets your conditions.

State Explosion (and a Solution?)

A tree representing the paths of a possible program

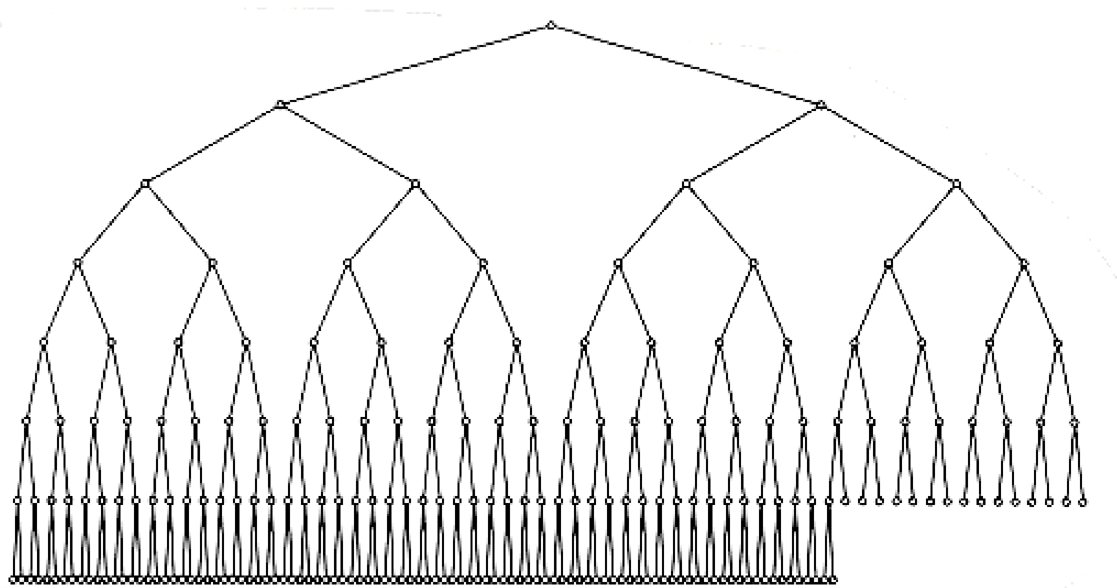


Image source: http://www.icodeguru.com/vc/10book/books/book3/chap6.htm

One of the biggest problems with symbolic execution:

With each if statement, the number of possible branches might double. The growth of the problem is exponential with respect to the size of the program.

There is no known good solution to this problem.

One Good Approach: Avoiding States

If you can identify conditions that would indicate that it is unlikely that continuing would lead to a successful state, you can terminate the path immediately and cross off large sections of the state graph.

Right here a variable is set that tells us that we will not find anything useful down this path.

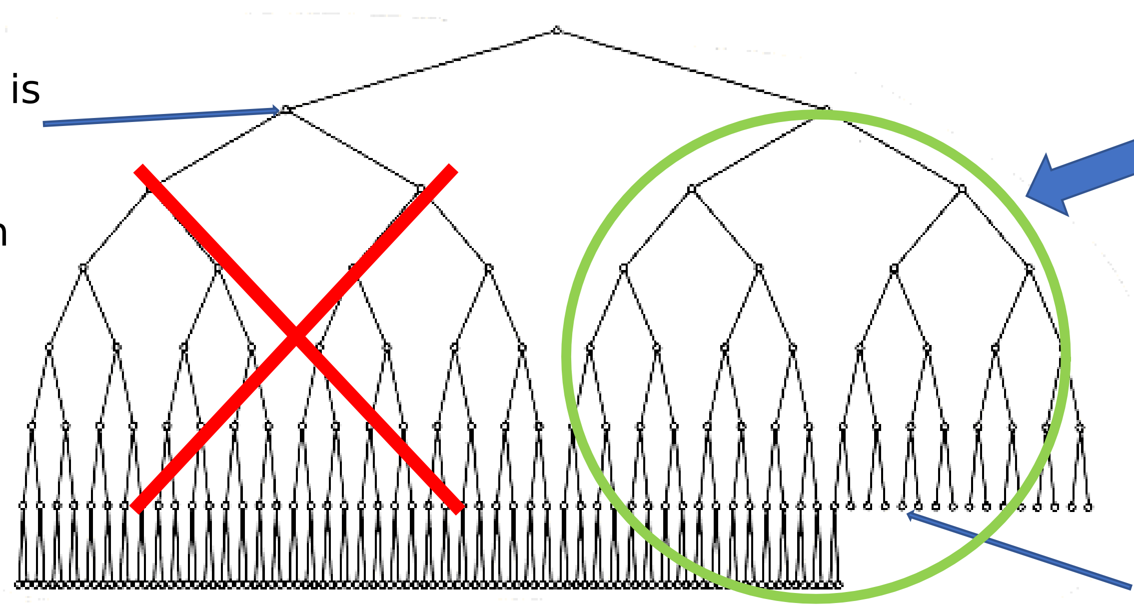


Image source: http://www.icodeguru.com/vc/10book/books/book3/chap6.htm

We only have to search half of the graph! Saves a lot of time.

The successful state is here.

Avoiding Paths

We can avoid states in the exact same way that we accept them as successful.

How do we determine which conditions might lead to a failed state?

Human intuition!

Also, there are various heuristic algorithms that are mostly out of the scope of these notes. We will briefly touch on a method called Veritesting much later.

If you find a better way, publish it!

Summary: Algorithm for Find and Avoid

- Load the binary
- Specify a starting point and create a simulation manager
- While we have not found what we want…
  - Step all active states
  - Run our ‘should_accept_state’ predicate on each active state
    - If one accepts, we found what we wanted! Exit the loop
  - Run our ‘should_avoid_state’ predicate on each active state
    - For each state that is accepted, mark it for

Shortcut: The 'Explore' Method

The previous algorithm is so common that Angr wrote a single function to do it for you, called the 'explore' function:

simulation.explore(find=should_accept_path, avoid=should_avoid_path)

… will add any path that is accepted to the list 'simulation.found'

Additionally, searching or avoiding a specific instruction address is common enough that the find and avoid parameters also accept addresses:

simulation.explore(find=0x80430a, avoid=0x9aa442)

would search for address 0x80430a and terminate anything that

Symbolic Execution CTF: Part 2

Introducing Symbols and Constraints

Injecting Symbols

In some cases, Angr automatically injects a symbols when user input is queried from the stdin file. *

When Angr does not automatically inject a symbol where we want one, we can do so manually.

* It does this with what are called SimProcedures, which we will cover later.

Representation of Symbols: Bitvectors

Angr's symbols are represented by what it calls bitvectors.

Bitvectors have a size, the number of bits they represent.

As with all data in programming, bitvectors can represent any type that can fit. Most commonly, they represent either n-bit integers or strings.

The difference between a bitvector and a typical variable is that, while typical variables store a single value, bitvectors store every value that meet certain constraints.

Bitvector Example

Let the bitvector λ be 8 bits and be constrained by:

$(\lambda > 0, \quad \lambda \leq 4, \quad \lambda \bmod 2 = 0) \vee (\lambda = 1)$

The above is how the bitvector would be stored.

However, if we were to concretize the bitvector (collapse it to a specific value), it could take on any of the following values: 2, 4, or 1.

Between Symbolic and Concrete

Definitions:

A *concrete* bitvector: a bitvector that can take on exactly 1 value.

(Example: { λ: λ = 1 })

A *symbolic* bitvector: a bitvector that can take on more than 1 value.

(Example: { λ: λ > 10 })

An *unsatisfiable* bitvector: a bitvector that cannot take on any values.

(Example: { λ: λ = 10, λ ≠ 10 })

An *unconstrained* bitvector: a bitvector that can take on any

Solving Constraints on Symbols

Angr provides a nice frontend to z3, an open-source constraint solver. It has the following functionality (and more):

- Find any (single) value of a bitvector
- Find up to n possible values of a bitvector
- Find the maximum or minimum possible values of a bitvector
- Determine if a bitvector is ‘true’ or ‘false’
- Determine if a bitvector is satisfiable

Symbols in the Context of a Program State

```
user_input = λ
if user_input == 'hunter2':
  print 'Success.'
else:
  print 'Try again.'
```

We can inject symbols into variables as long as the size of the bitvector is equal to the size of the variable.

Constraints are automatically generated (ex: λ = ‘hunter2’, or, for the other path, λ ≠ ‘hunter2’) as the engine follows a given path.

If we desire, we can manually add constraints to any bitvector at any time during the execution of the program.

Symbol Propagation

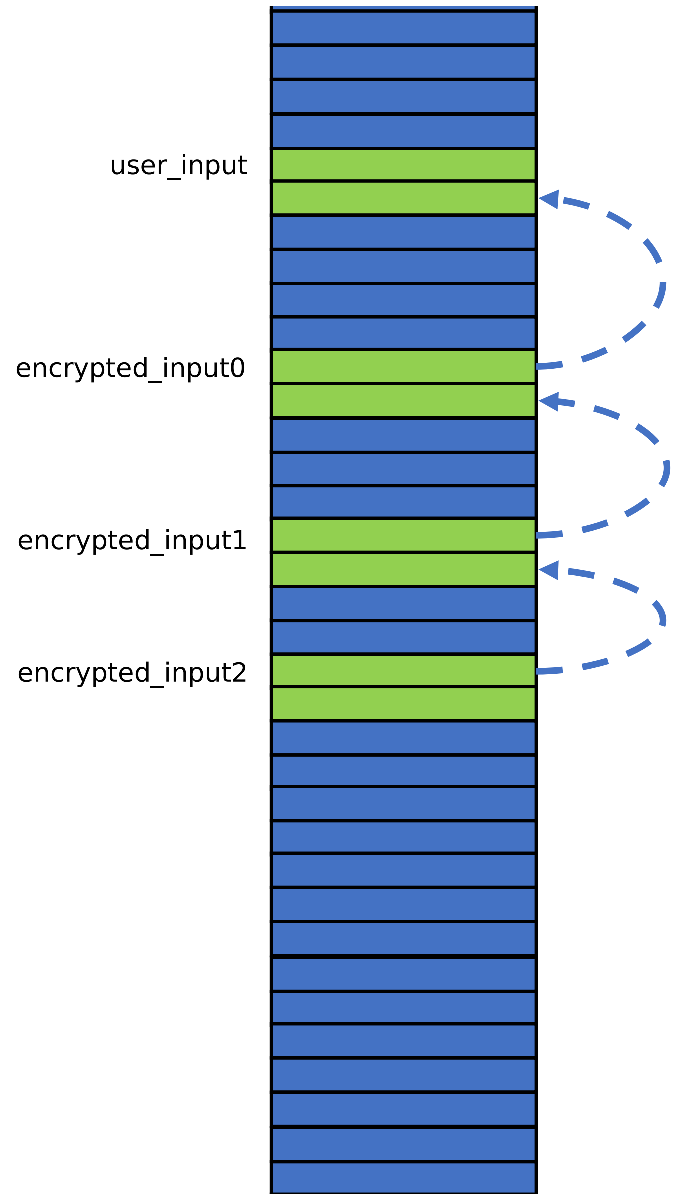
```
user_input = λ
encrypted_input0 = user_input - 3
encrypted_input1 = encrypted_input0 + 15
encrypted_input2 = encrypted_input1 * 7
```

To the right you see the memory, with the variables user_input and encrypted_inputX marked.

All are symbolic, represented by the green.

The variables encrypted_inputX depend entirely on user_input, denoted by the arrow.

Symbols can propagate when values are transferred.



Constraint Propagation

```
user_input = λ
encrypted_input0 = user_input - 3
encrypted_input1 = encrypted_input0 + 15
encrypted_input2 = encrypted_input1 * 7
```

In this example, if we add the constraint: λ = 10, then:

```
user_input = λ = 10
encrypted_input0 = user_input - 3 = 10 – 3 = 7
encrypted_input1 = encrypted_input0 + 15 = 7 + 15 = 22
encrypted_input2 = encrypted_input1 * 7 = 22 * 7 = 154
```

We solved for encrypted_input2!

Constraints propagate through the program.

Constraint Reverse-Propagation

We can add constraints to propagated symbolic values!

```
user_input = λ
encrypted_input0 = user_input - 3
encrypted_input1 = encrypted_input0 + 15
encrypted_input2 = encrypted_input1 * 7
```

In this example, if we add the constraint:
encrypted_input2 = 14, then:

We solved for λ!

```
λ = user_input, λ = -10
user_input - 3 = encrypted_input0 = -13, user_input = -10
encrypted_input0 + 15 = encrypted_input1 = 2, encrypted_input0 = -13
encrypted_input1 * 7 = encrypted_input2 = 14, encrypted_input1 = 2
```

Start here, work backwards

Constraints propagate backwards through the program. We can solve for initial conditions given our desired results in this way.

The NP-Completeness of Constraint Satisfaction and the Inevitable Heat Death of the Universe

A second huge problem with symbolic execution:

It relies on solving complex systems of constraints.

The constraint-satisfaction problem is NP-complete.

Need we say more?

Why are the first three levels of the CTF solved without injecting symbols?

Angr injects them for you!

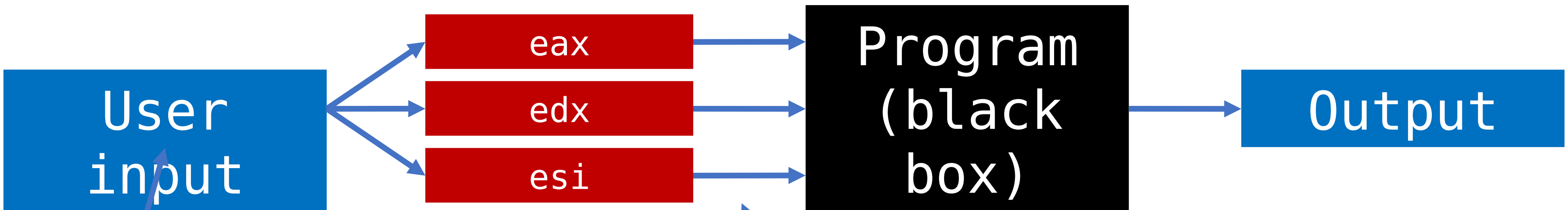
Angr handles simple calls of ‘scanf’ (without complex format strings.)

You will need to inject symbols manually if the input is more complex, for example:

- Complex format string for scanf
- From a file
- From the network
- From interactions with a UI

The following slides have a few examples of

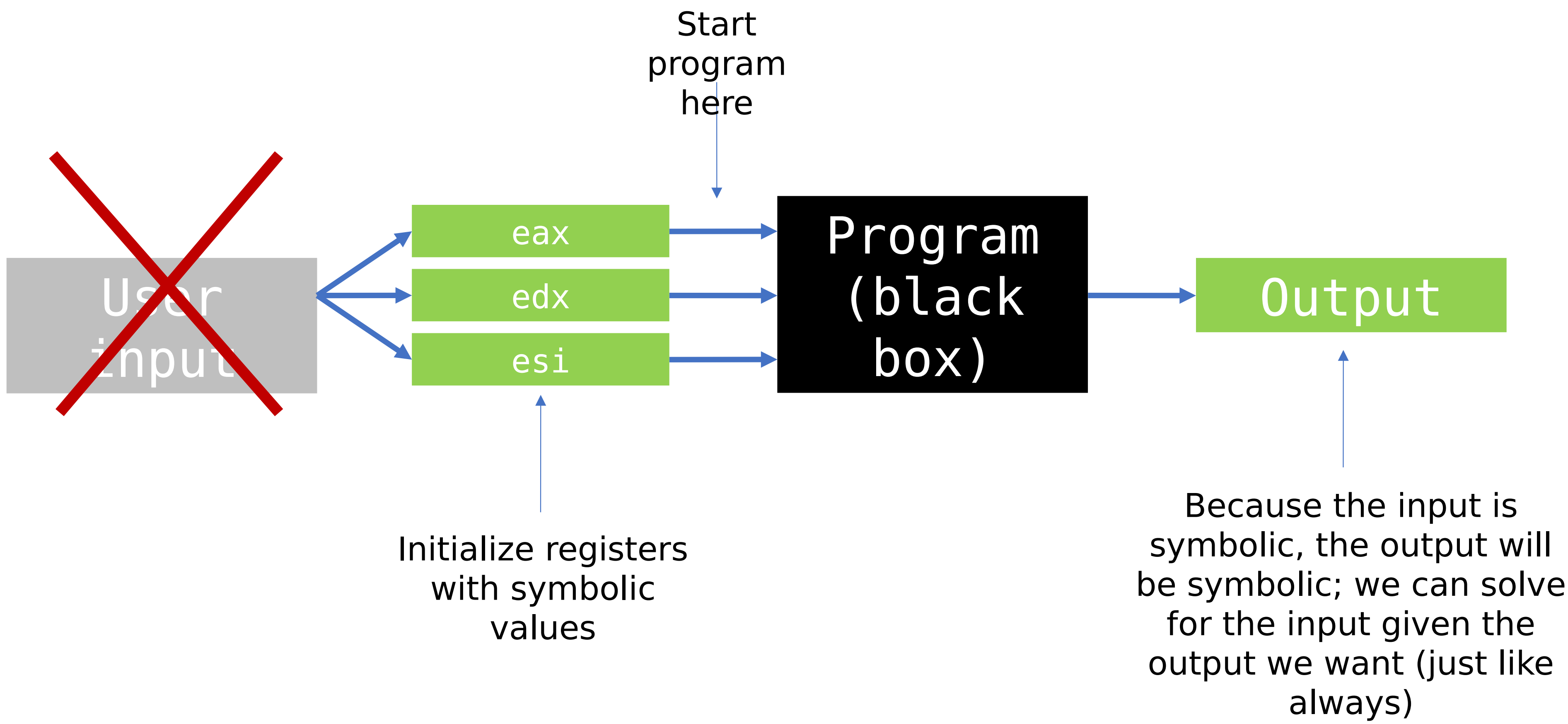
Injecting Symbols Example: Registers



For simple cases, Angr replaces this for us, so that the user input function injects symbolic values into the registers.

For more complex cases, we need to inject the symbols ourselves. We start the program *after* the user input and initialize the registers with a symbolic value.

Injecting Symbols Example: Registers



Injecting Symbols Example: Registers

Situation: The get_user_input function returns values by writing them to registers.

Solution: Instead of calling get_user_input, write symbolic values to the registers.

Start immediately after the call, here.

```
call   80487a5 <get_user_input>
mov    %eax,-0xc(%ebp)
mov    %ebx,-0x8(%ebp)
mov    %ecx,-0x4(%ebp)
```

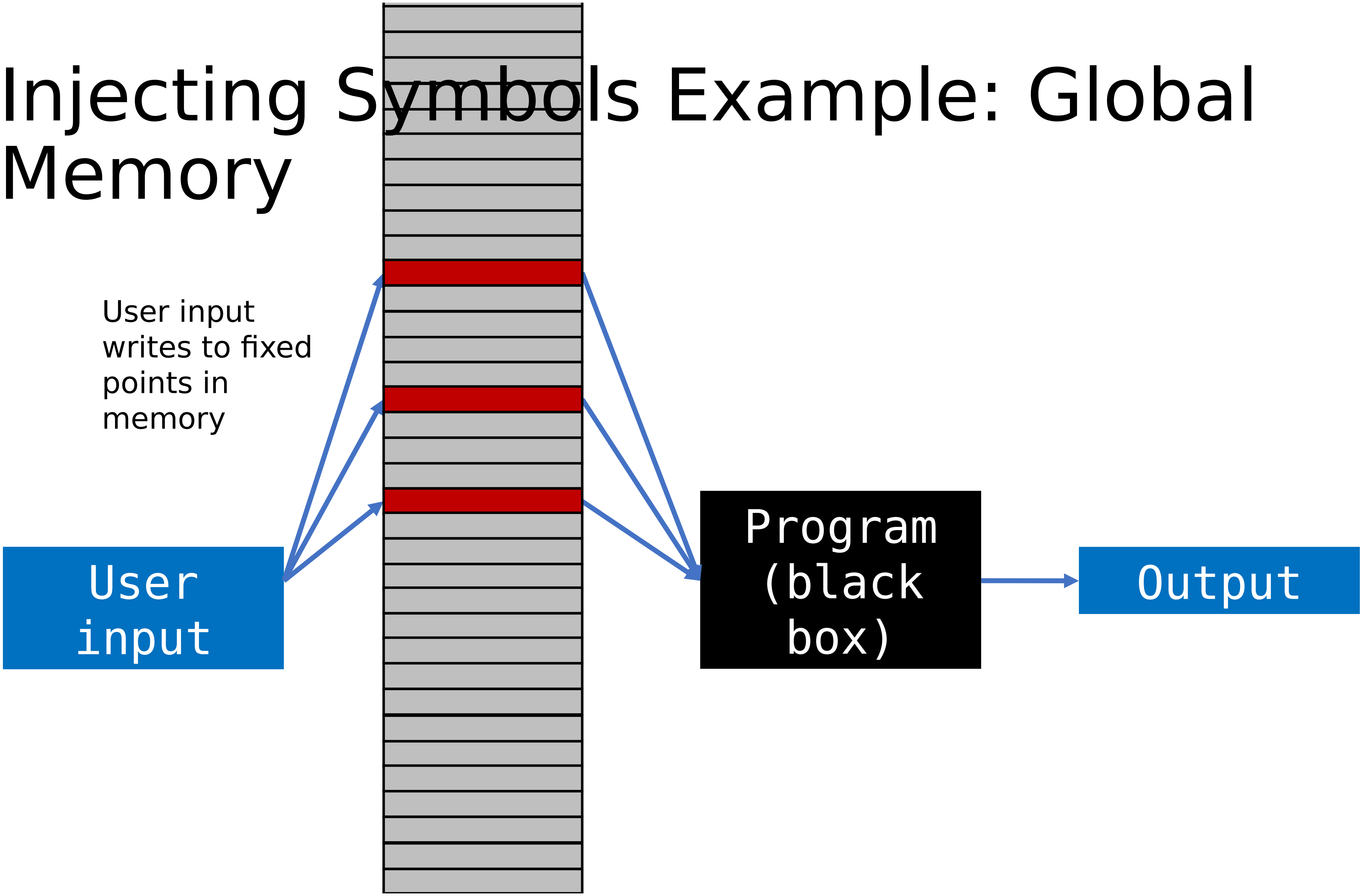
Evidence that the get_user_input function returned the user input on the registers.

In Angr, you can write to a register with either a concrete or a symbolic value:

`state.regs.eax = my_bitvector`

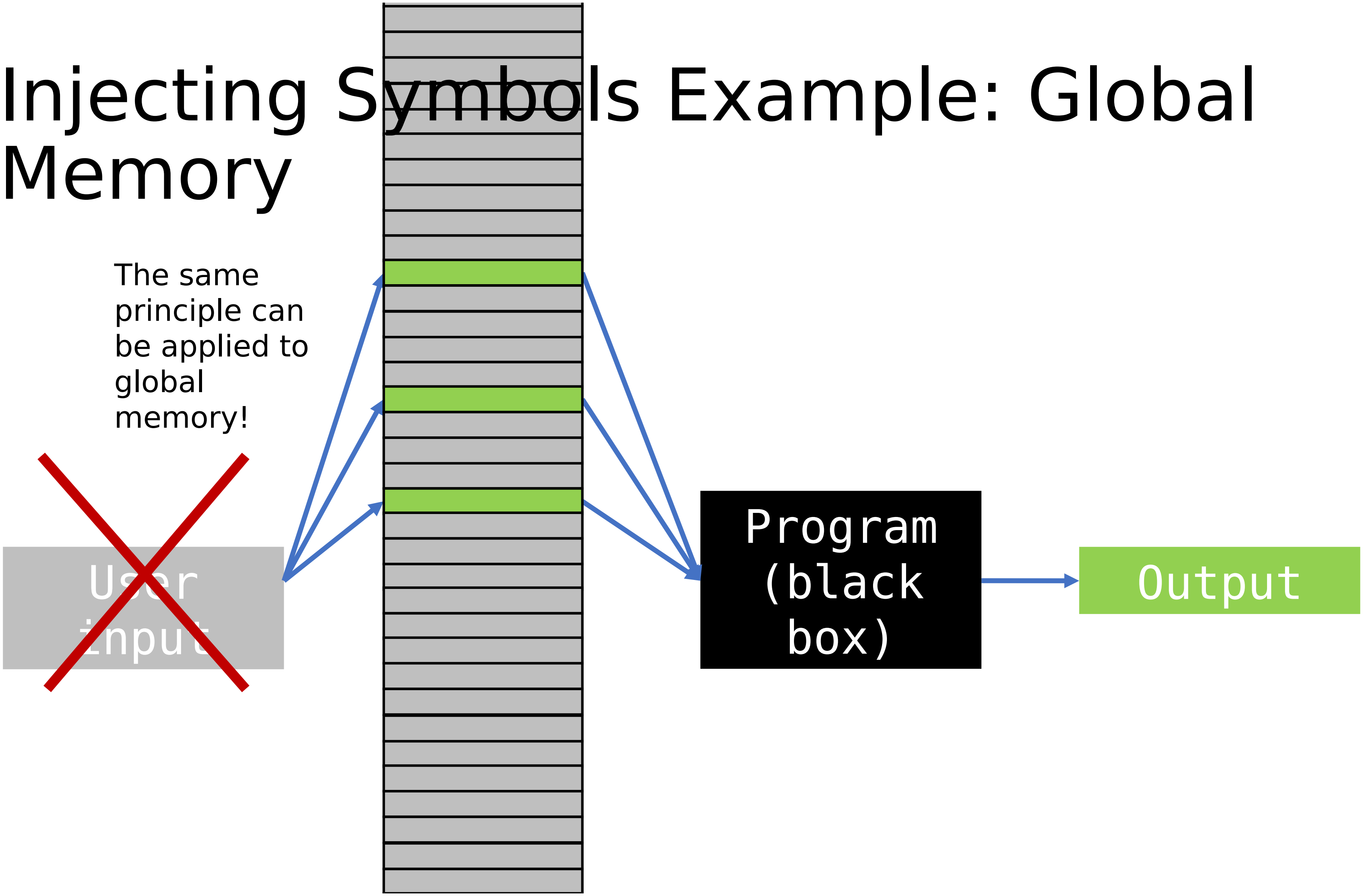
will write the value of `my_bitvector` to eax.

Injecting Symbols Example: Global Memory



Injecting Symbols Example: Global Memory

The same principle can be applied to global memory!



Injecting Symbols Example: Global Memory

Situation: The get_user_input function returns values by writing them to addresses determined at compile time.

Solution: Instead of calling get_user_input, write symbolic values to the addresses.

`scanf("%u %u", &a, &b)`

```
push   $0xaf84128
push   $0xaf84120
push   $0x8048733
call   8048400
<scanf@plt>
```

Parameters (scanf will write user input to these addresses)

Format string "%u %u"

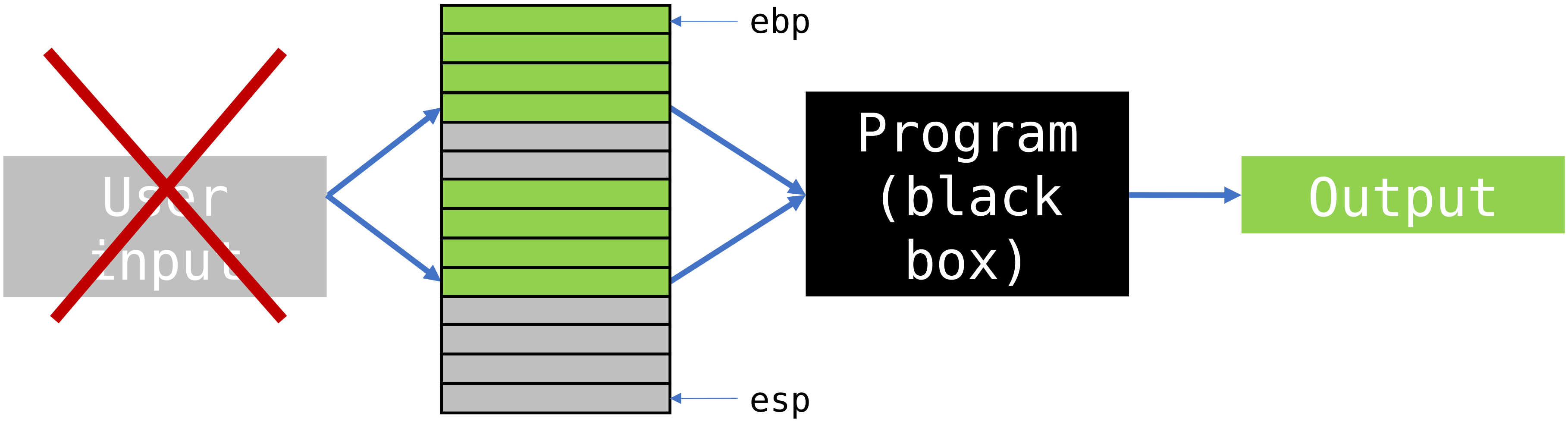
In Angr, you can write to an address with either a concrete or a symbolic value:

`state.memory.store(0xaf84120, my_bitvector)`

will write the value of `my_bitvector` to `0xaf84120`.

Injecting Symbols Example: The Stack

... and, of course, the stack!



Injecting Symbols Example: The Stack

What about the stack?

Allocate memory for local variables

```
sub     $0x20,%esp
lea     -0x8(%ebp),%eax
push    %eax
push    $0x80489c3
call    8048370 <scanf@plt>
```

Format string

Specify a specific local variable as a parameter to scanf

In Angr, you can push to the stack with either a concrete or a symbolic value:

`state.stack_push(my_bitvector)`

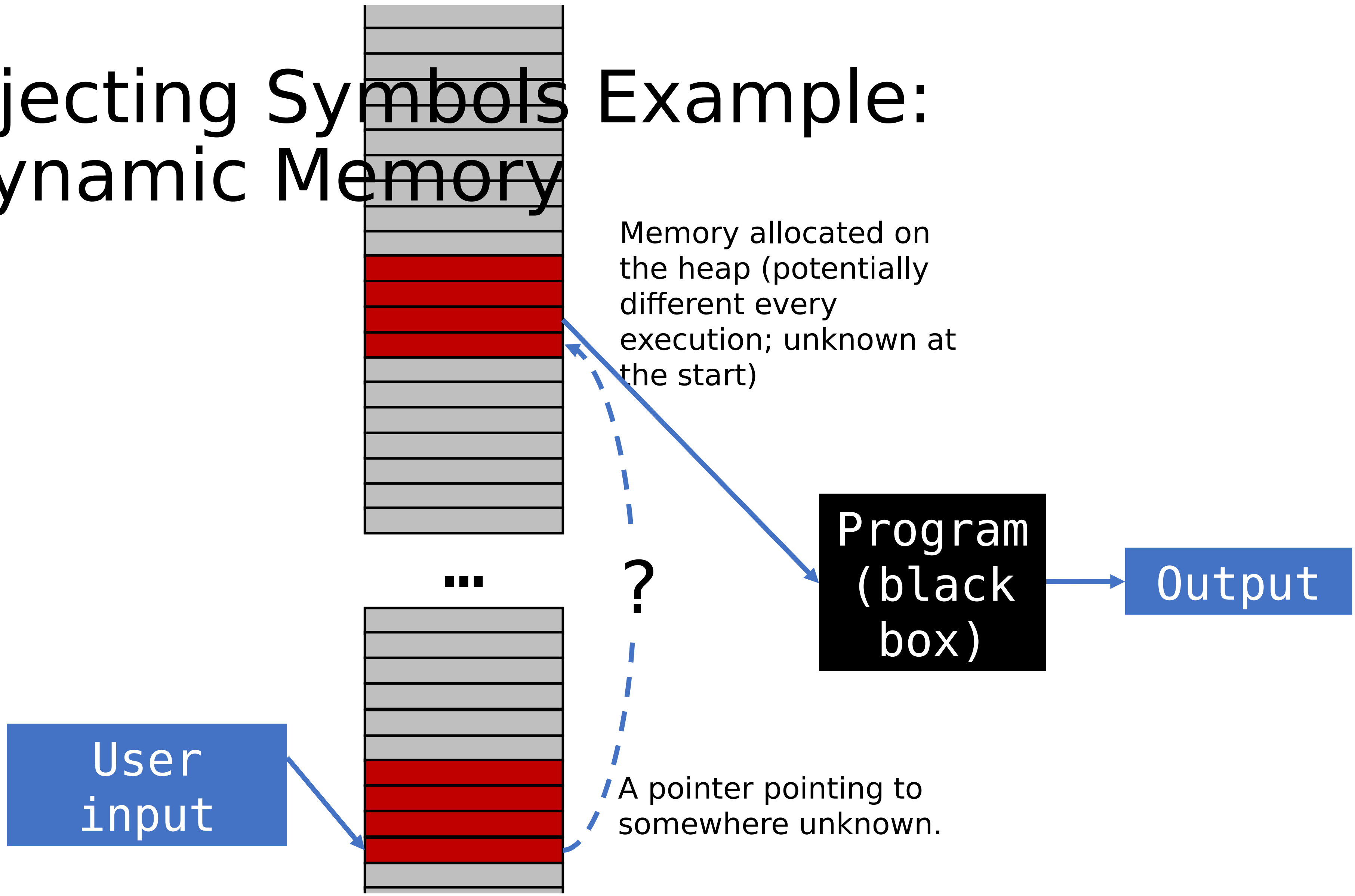
will push the value of `my_bitvector` to the top of the stack.

You may need to account for anything you don’t care about at the beginning of the stack by adding padding:

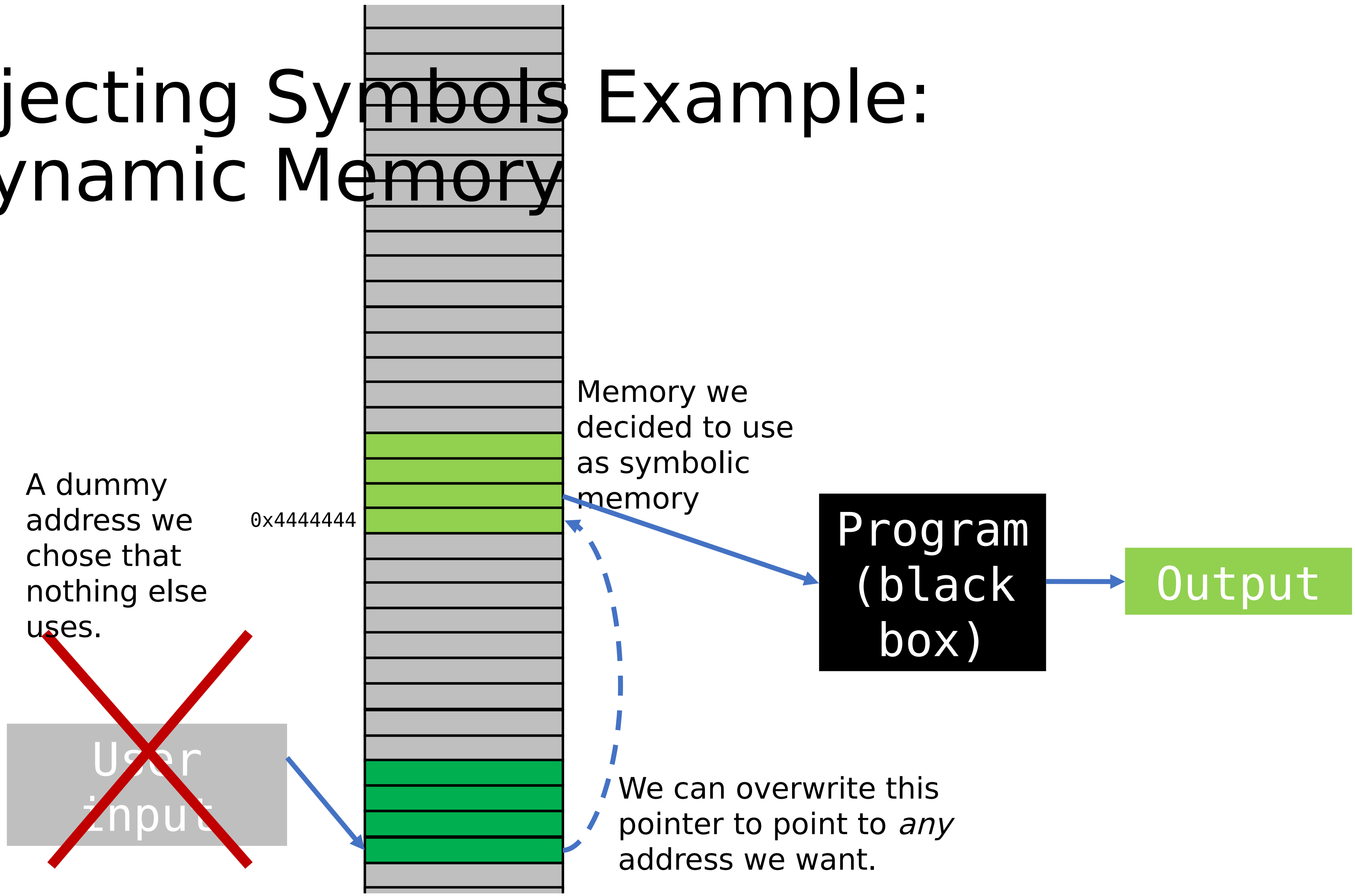
`state.regs.esp -= 4`

adds 4 bytes of padding

Injecting Symbols Example: Dynamic Memory



Injecting Symbols Example: Dynamic Memory



Injecting Symbols Example: Dynamic Memory

hat if you don’t know the memory location scanf to which scanf write

Scanf will write to the address stored in the pointer located at 0xaf84dd8

```
mov     0xaf84dd8,%edx
push    %edx
push    $0x8048843
call    8048460 <scanf@plt>
```

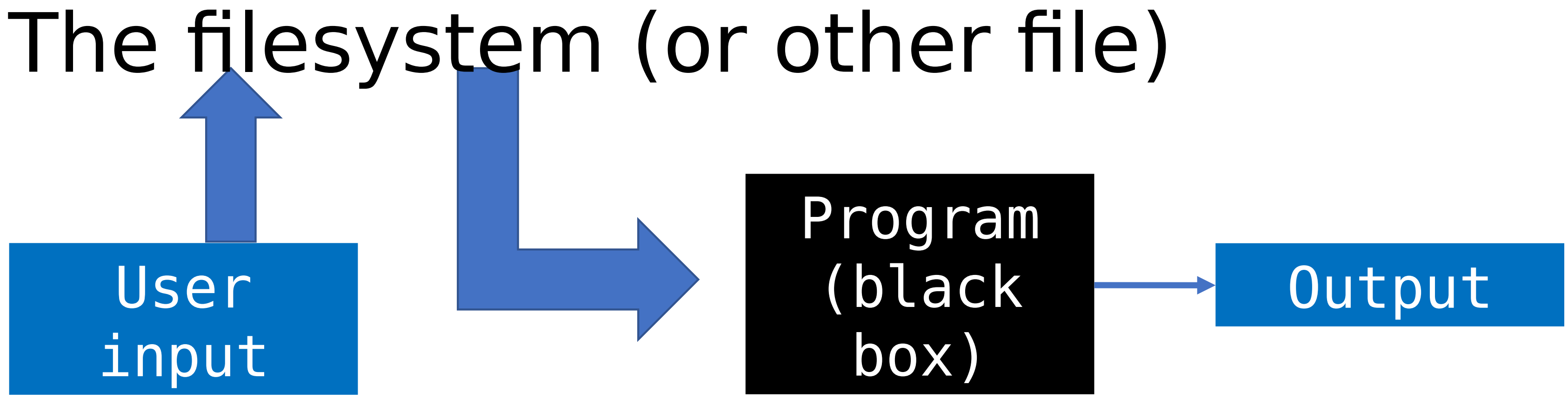
If you cannot determine the address to which scanf writes because it is stored in a pointer, you can overwrite the value of the pointer to point to an unused location of your choice (in this example, 0x4444444):

```
state.memory.store(0xaf84dd8, 0x4444444)
state.memory.store(0x4444444, my_bitvector)
```

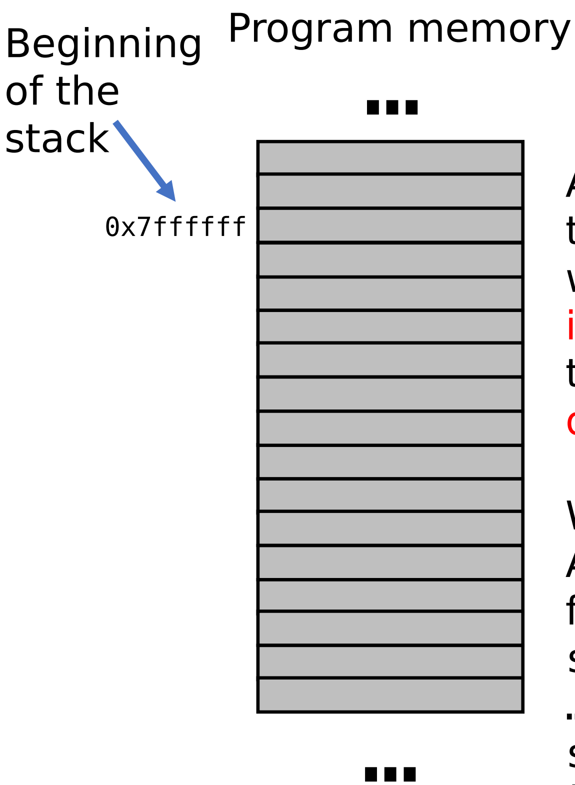
At this point, the pointer at 0xaf84dd8 will point to 0x4444444,

Injecting Symbols Example: The Filesystem

What if our user input function queries from the filesystem (or any other Linux file, including the network, the output of another program, /dev/urandom, etc)?



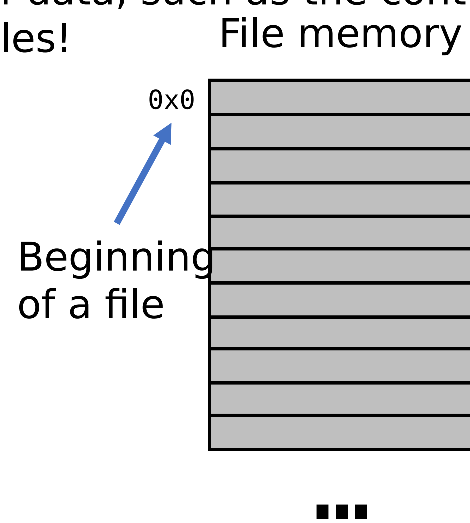
Representing a File as Memory



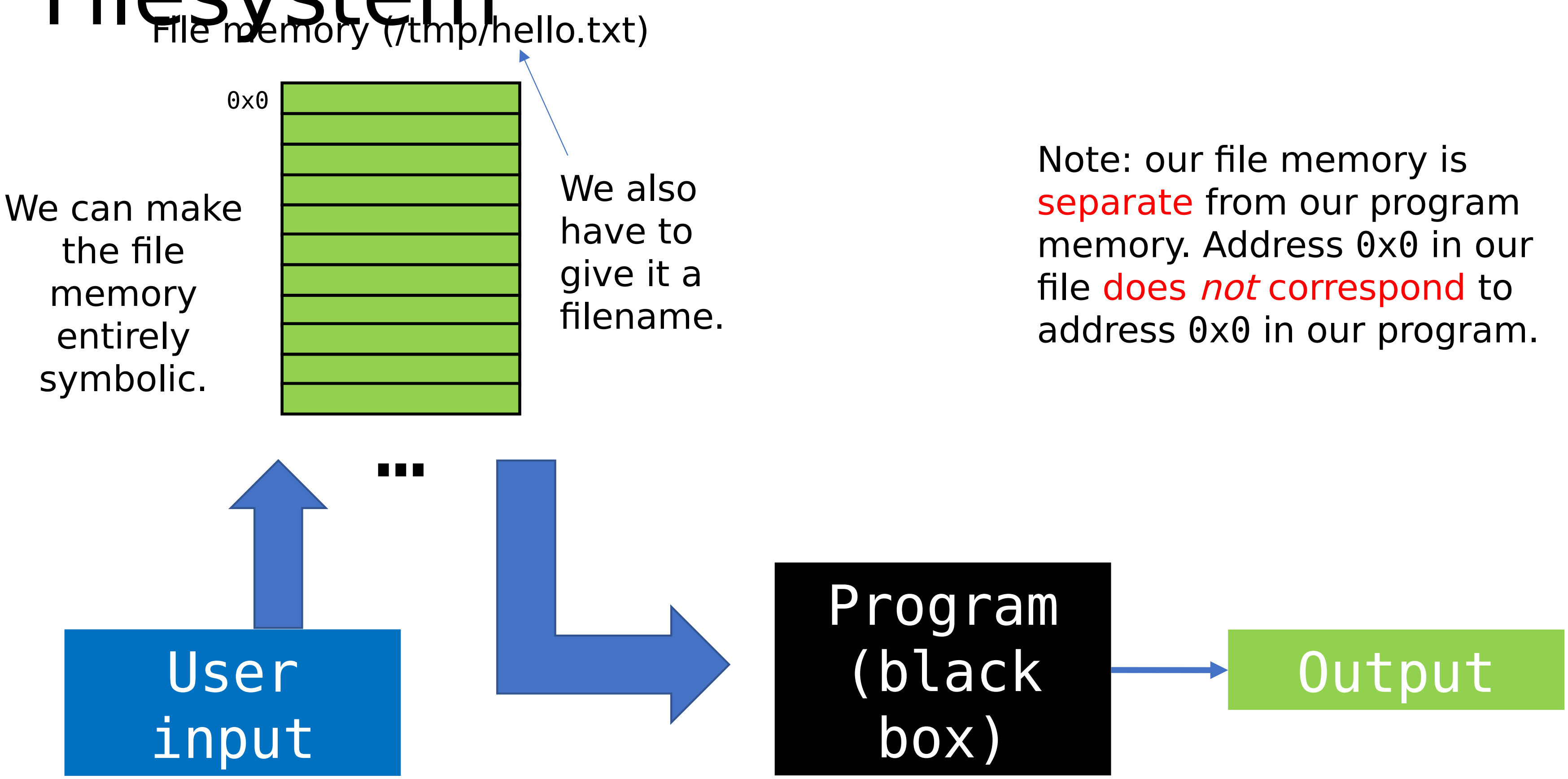
A program has access to an address space, which it uses to store instructions, the stack, the heap, and static data.

We have used it in Angr using the following functions:
`state.memory.store(…)`
`state.memory.load(…)`

We can use the same Python type as `state.memory` (which is `SimMemory`) to store other types of data, such as the contents of files!



Injecting Symbols Example: The Filesystem



Note: our file memory is separate from our program memory. Address `0x0` in our file does *not* correspond to address `0x0` in our program.

Injecting Symbols Example: The Filesystem

In short: Angr allows you to specify an alternate, symbolic filesystem of your own specification. More information on this is included in the CTF.

Angr Implementation of Previous Examples

The implementation details are included with the CTF, in scaffoldXX.py, for the challenges that involve injecting symbolic memory and constraining it.

Symbolic Execution CTF: Part 3

Handling Non-trivial Behavior

Motivation: A Simple Example

The program iterates through 16 elements, each time it branches.

By the end of the loop, there will be a total of 2^{16} or 65,536 branches.

Could be reduced to:

user_input == 'ZZZZZZZZZZZZZZZZ'.

One branch.

```
def check_all_Z(user_input):
  num_Z = 0
  for i in range(0, 16):
    if user_input[i] == 'Z':
      num_Z += 1
    else:
      pass
  return num_Z == 16
```

Solution

Of course, there are powerful algorithms to deduce the insight on the previous slide.

None work as well as human intuition for many cases (yet!).

For complex functions that can be easily simplified by a human, we can use Angr to replace the code with its *summary*, written in Python.

Hooks

We want to skip these instructions and instead run our own code.

```
...
8048774:  add    %edx,%eax
8048776:  sub    $0x4,%esp
804877c:  push   $0x804a420
8048781:  call   8048460 <check_all_Z>
8048786:  add    $0x10,%esp
8048789:  test   %eax,%eax
804878b:  jne    8048794 <main+0x19f>
...
```

You can do this using a hook. You specify an address to ‘hook’, the number of bytes of instructions you want to skip, and a Python function that will be run to replace the skipped instructions.

Note: the number of instructions you skip can be zero.

Hook Walkthrough

The parameter to check_all_Z

The instructions involved in calling check_all_Z

```
...
8048774:  add    %edx,%eax
8048776:  sub    $0x4,%esp
804877c:  push   $0x804a420
8048781:  call   8048460
<check_all_Z>
8048786:  add    $0x10,%esp
8048789:  test   %eax,%eax
804878b:  jne    8048794
<main+0x19f>
...
```

Let's imagine we want to replace the call to check_all_Z, with our own check function:

```
def replacement_check_all_Z():
  eax = (*0x804a420 == 'ZZZZZZZZZZZZZZZZZ')
```

Return values are stored in eax

The parameter to check_all_Z

Hook Walkthrough

```
...
8048774:  add    %edx,%eax
8048776:  sub    $0x4,%esp
804877c:  push   $0x804a420
8048781:  call   8048460
<check_all_Z>
8048786:  add    $0x10,%esp
8048789:  test   %eax,%eax
804878b:  jne    8048794
<main+0x19f>
...
```

```
def replacement_check_all_Z():
  eax = (*0x804a420 == 'ZZZZZZZZZZZZZZZZ')
```

Call: `binary.hook(0x8048776, length=16, replacement_check_all_Z)`

Address we want to hook

The instructions are represented with 16 bytes in memory. If we didn't want to skip any instructions (and run our Python code in addition to the instructions), we could let length=0

Function to replace run when we reach our hook

(Syntax altered for rhetorical purposes, see CTF for actual syntax)

Hook Walkthrough

Call: `binary.hook(0x8048776, length=16, replacement_check_all_Z)`

```
                 …

8048774:  add    %edx,%eax

8048776:  sub    $0x4,%esp
804877c:  push   $0x804a420
8048781:  call   8048460 <check_all_Z>
8048786:  add    $0x10,%esp

8048789:  test   %eax,%eax
804878b:  jne    8048794 <main+0x19f>

                 …
```

19 bytes

`eax = (*0x804a420 == 'ZZZZZZZZZZZZZZZZ')`

(Syntax altered for rhetorical purposes, see CTF for actual syntax)

Common Patterns

Hooks are useful for:

- Injecting symbolic values partway through the execution.
- Replacing complex functions.
- Replacing unsupported instructions (for example, most syscalls).

Complex Functions

Replacing complex functions with hooks is so common that Angr included sugar to make it easier.

A SimProcedure provides a simple way to replace a function with a summary in a Pythonic way.

Review of Functions

1. Push parameters to the stack
2. Push return address to the stack
3. Jump to function address
4. Handle parameters*
5. Execute function
6. Write return value to appropriate location
7. Pop return address and jump to it
8. Pop parameters

* The standard calling convention for programs compiled with gcc targeting IA-32 does not need to do anything with parameters once the function is called, since they are already on the stack, but you could imagine that a different calling convention might require the function to copy the parameter from, say, a register, onto the stack.

SimProcedure Algorithm

1. Push parameters to the stack
2. Push return address to the stack
3. Jump to function address

Hooks here, at the beginning of the function address

Allows user to replace this in a Pythonic way

4. Handle parameters
5. Execute function
6. Write return value to appropriate location

Done automatically

Skips all instructions until the function is about to return, and resumes execution here

7. Pop return address and jump to it
8. Pop parameters

SimProcedure Example

Ugly (hooks):

```
def replacement_check_all_Z():
  eax = (*0x804a420 == 'ZZZZZZZZZZZZZZZZZ')
```

Manually set return value

Handle parameters ourselves

Beautiful (sim procedures):

Uses Pythonic function arguments

```
def replacement_check_all_Z(input):
  return input == 'ZZZZZZZZZZZZZZZZZ'
```

Uses Python's return functionality

```
...
8048774:  add    %edx,%eax
8048776:  sub    $0x4,%esp
804877c:  push   $0x804a420
8048781:  call   8048460 <check_all_Z>
8048786:  add    $0x10,%esp
8048789:  test   %eax,%eax
804878b:  jne    8048794 <main+0x19f>
...
```

(Syntax altered for rhetorical purposes, see CTF for actual syntax)

SimProcedure in Practice

SimProcedures are used to replace anything you fully understand and don't want to test for bugs, or that is unsupported by Angr.

Because the problem complexity scales exponentially with the length of the program, any and every function that meets the above criteria should be replaced with a SimProcedure, to save time.

Currently, the reimplementation of a (quickly expanding) subset of libc is included with Angr.

If SimProcedures are impractical…

… for example, if you do not understand a function, need to test it for bugs, or do not want to invest time to reimplement it …

- Find a simpler version of the function(s)—glibc is complex, but an embedded version of libc might be simpler.
- Use an algorithm to automatically attempt to simplify the function

Veritesting and Why Human Intuition Always Wins

The Veritesting algorithm, developed at CMU, attempts to reduce state explosion by combining branches. It can automatically reduce:

```
def check_all_Z(user_input):
  num_Z = 0
  for i in range(0, 16):
    if user_input[i] == 'Z':
      num_Z += 1
    else:
      pass
  return num_Z == 16
```

```
user_input == 'ZZZZZZZZZZZZZZZZ'
```

The specifics of the algorithm are out of the scope of these notes.

Due to the difficult nature of reducing the algorithm, Veritesting relies on a heuristic to best determine how to merge states.

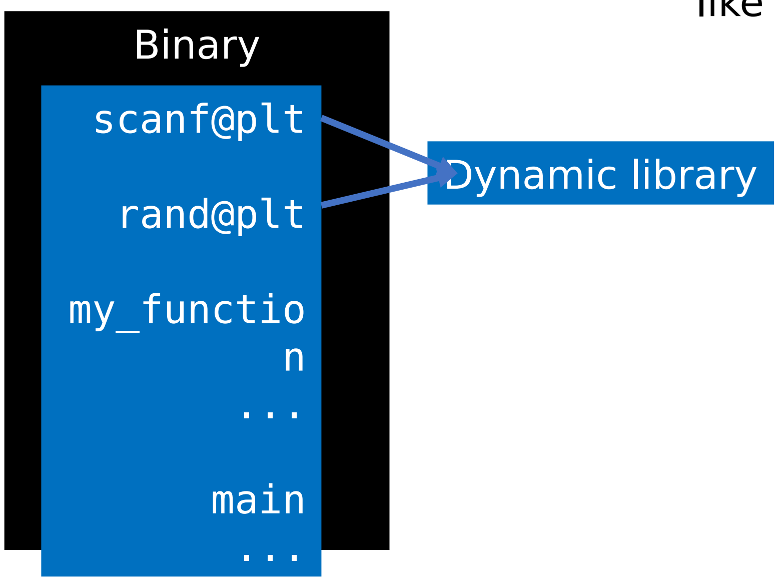
For more information on Veritesting…

T. Avgerinos, A. Rebert, S. K. Cha, and D. Brumley. Enhancing symbolic execution with veritesting. In *Proceedings of the International Conference on Software Engineering (ICSE)*, pages 1083–1094. ACM, 2014.

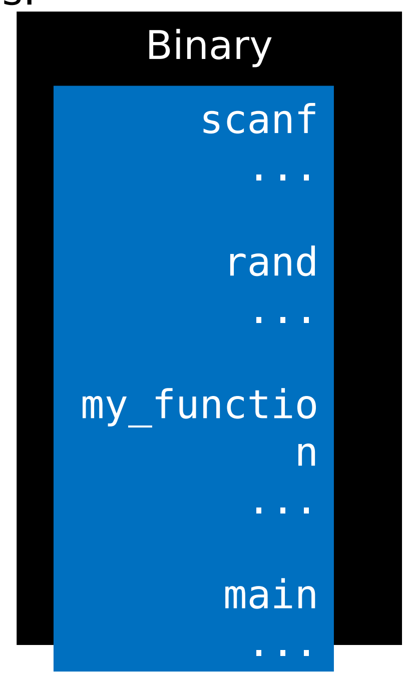
https://users.ece.cmu.edu/~aavgerin/papers/veritesting-icse-2014.pdf

Statically-Linked Binaries

Instead of...

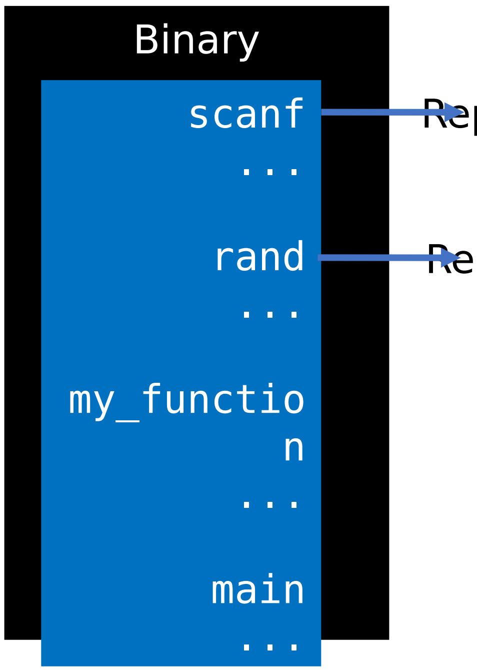


... Statically-linked binaries will look like this:



In order to replace libc functions with their corresponding already-implemented SimProcedures, Angr looks for the symbols 'scanf@plt' and 'rand@plt'. If the program is statically-linked, it does not know what to replace with a SimProcedure.

A Solution to Statically-Linked Binaries



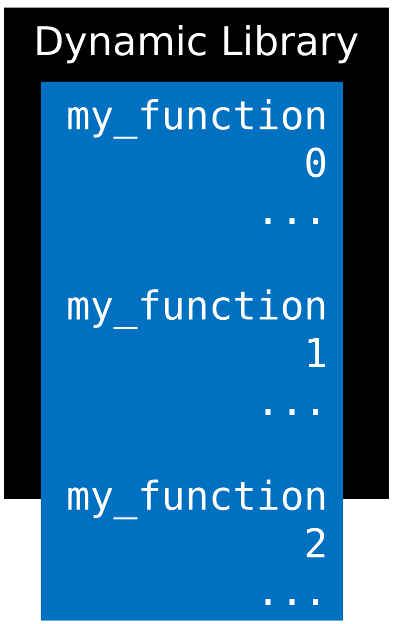
Replace with SimProcedure scanf

Replace with SimProcedure rand

Solution:
Manually hook them,
as you have done
already!

Implementation details are included with the CTF.

Analyzing Dynamic Libraries (and other binary formats)



We can begin wherever we want in the executable, in the same way as we have been doing in the CTF, using `blank_state`.

For position-independent code, we may need to specify a base address for the address space.

As always, implementation details are in the CTF.

Symbolic Execution CTF: Part 4

(An Intro to) Automatic Exploit Generation

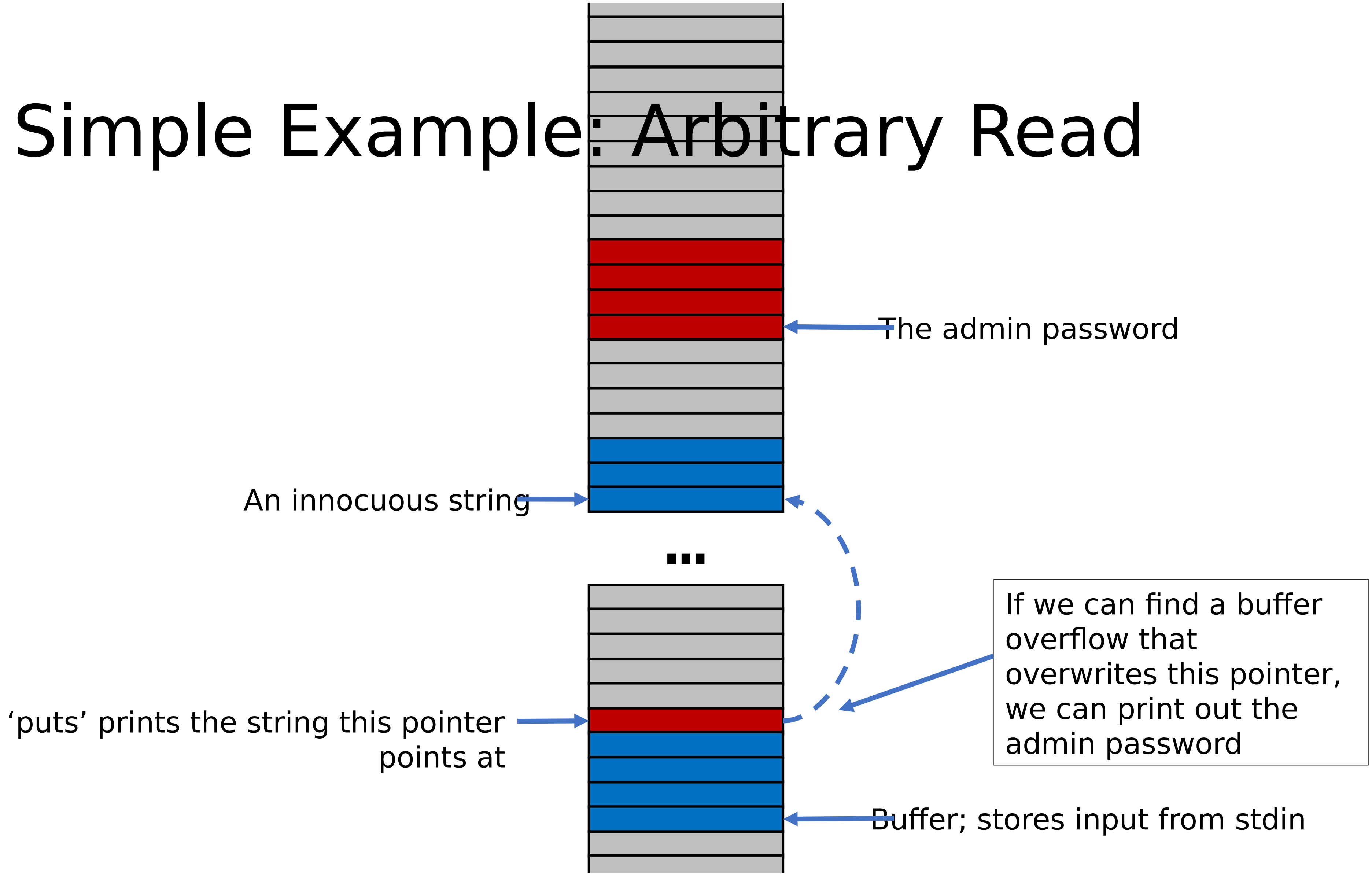
Really Really High-level Strategy

1. Determine the type of exploit you want to search for, for example:

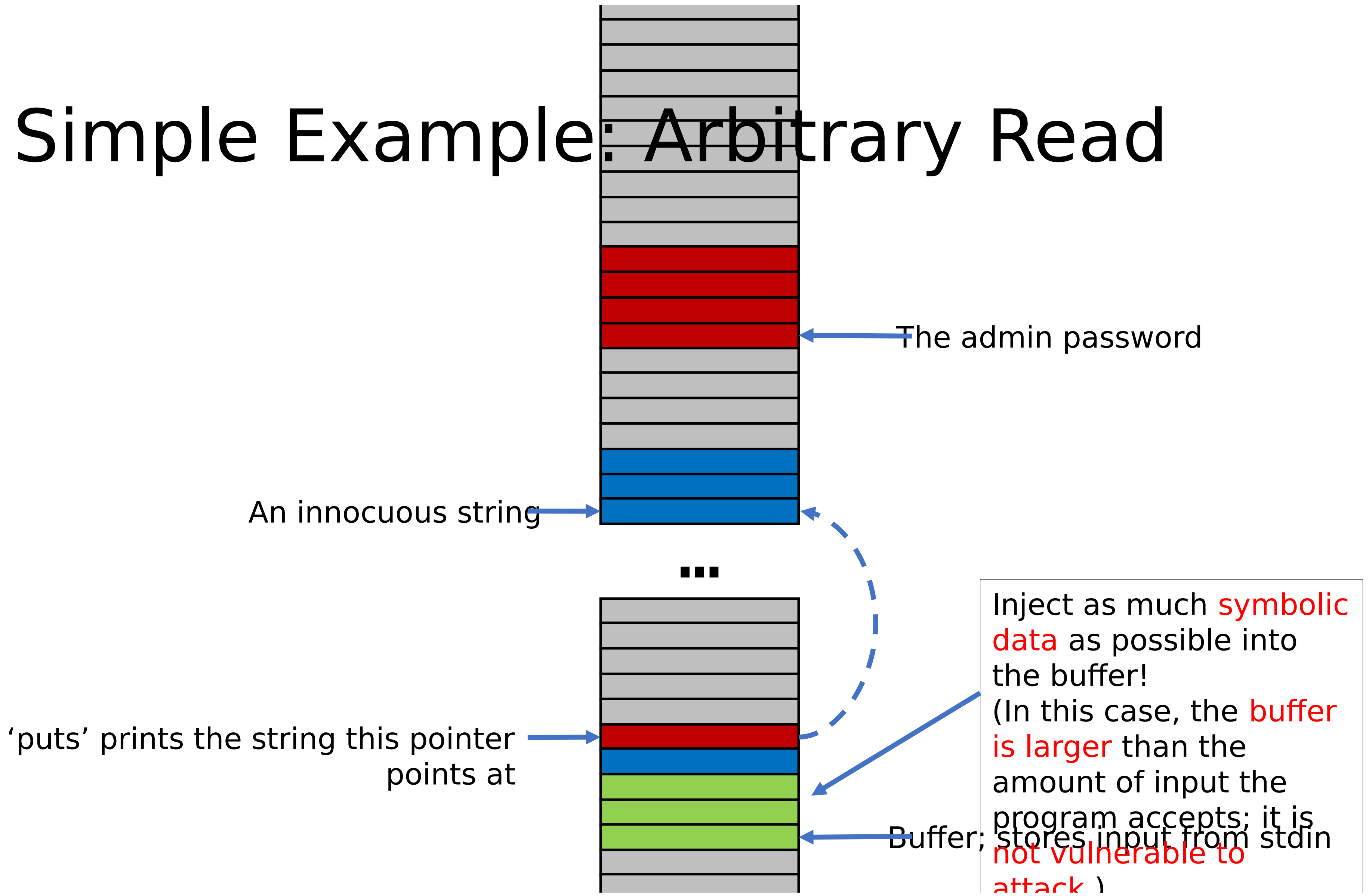
- Arbitrary read (crash the program, read a password, etc)
- Arbitrary write (inject shellcode, overwrite return address, etc)
- Arbitrary jump (jump to your shellcode, return oriented programming, etc)

2. Write a Python function using Angr to determine if we have reached the condition necessary for the exploit.
3. Constrain the system in a way that would set up the attack.

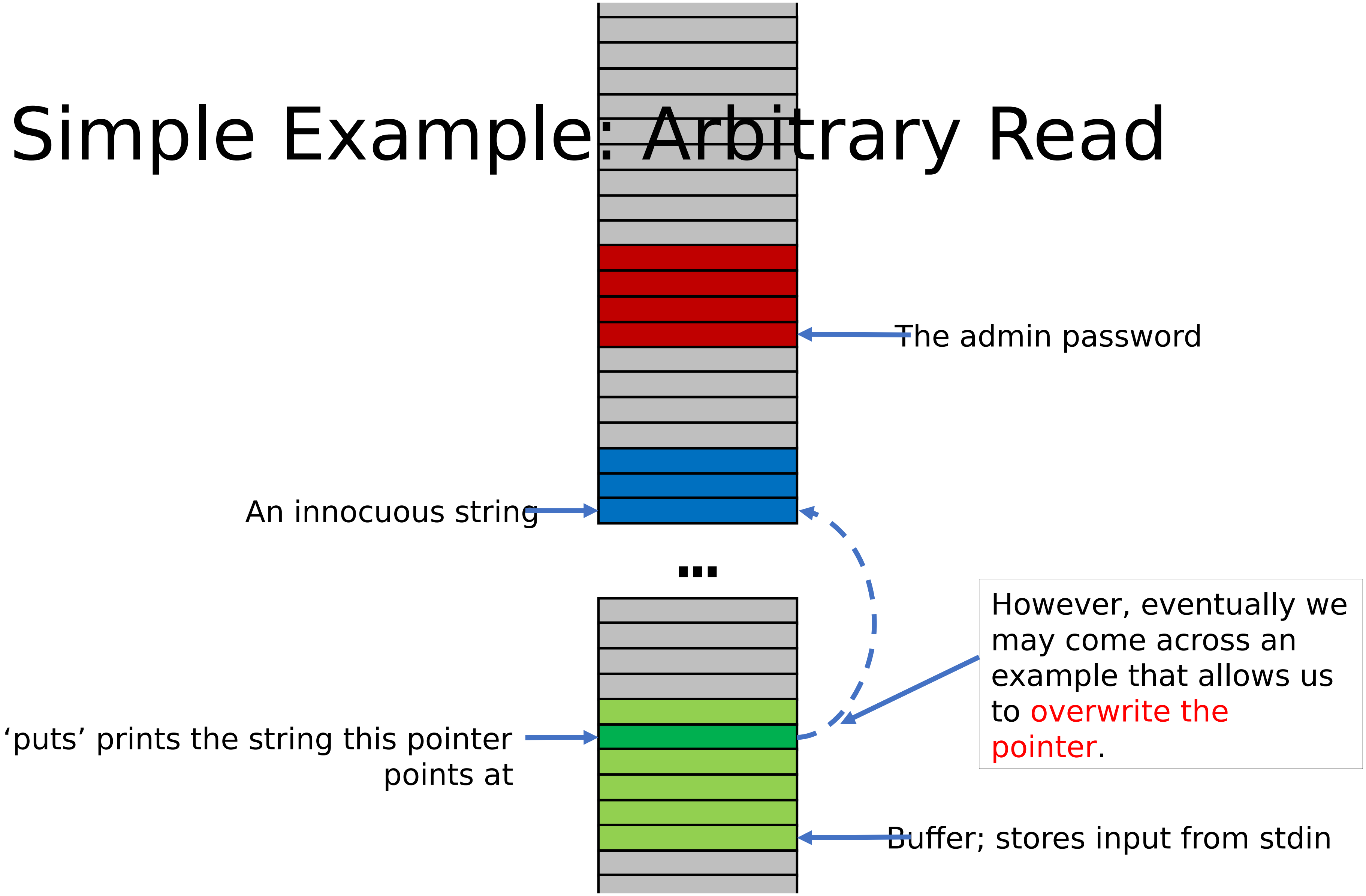
Simple Example: Arbitrary Read



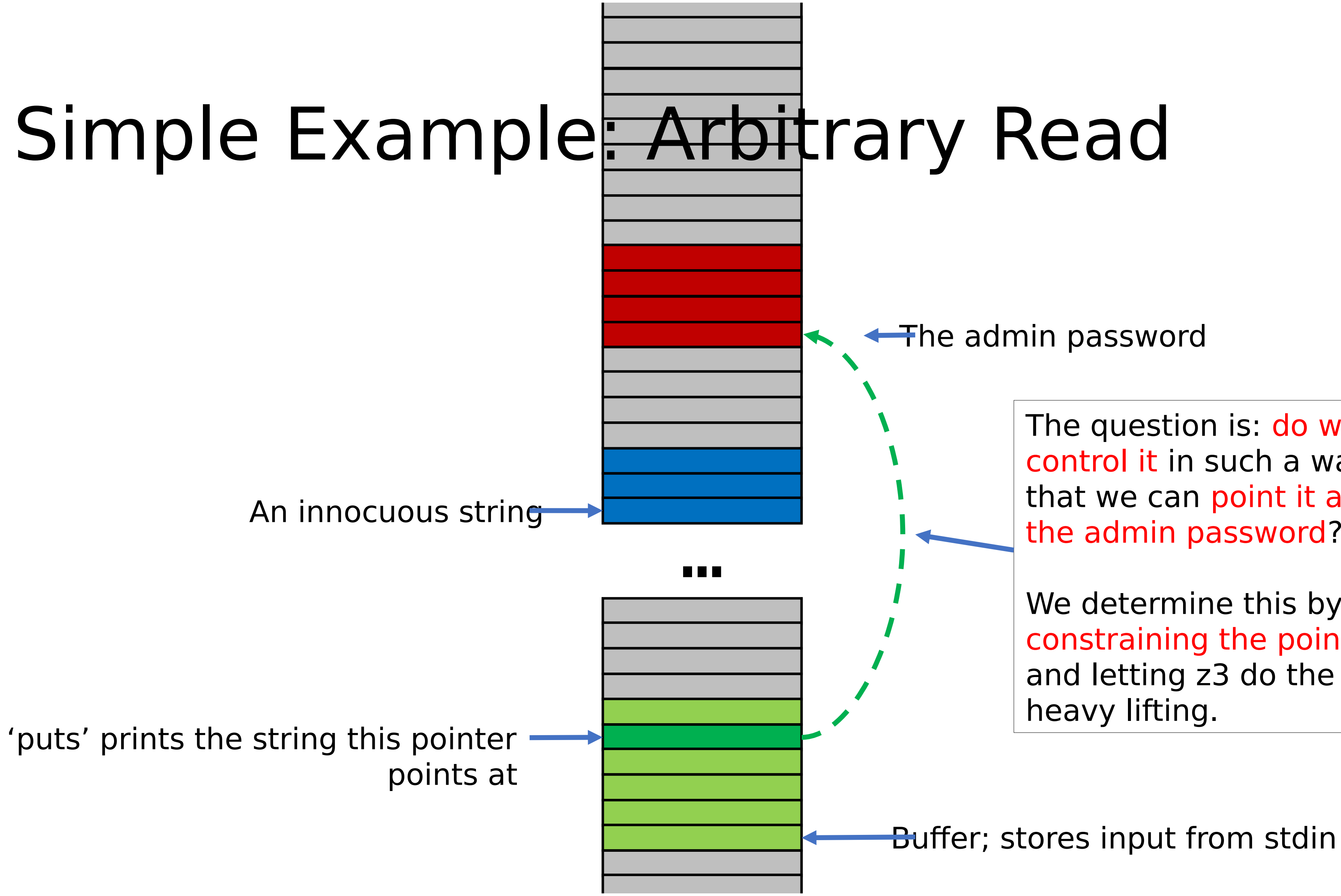
Simple Example: Arbitrary Read



Simple Example: Arbitrary Read



Simple Example: Arbitrary Read



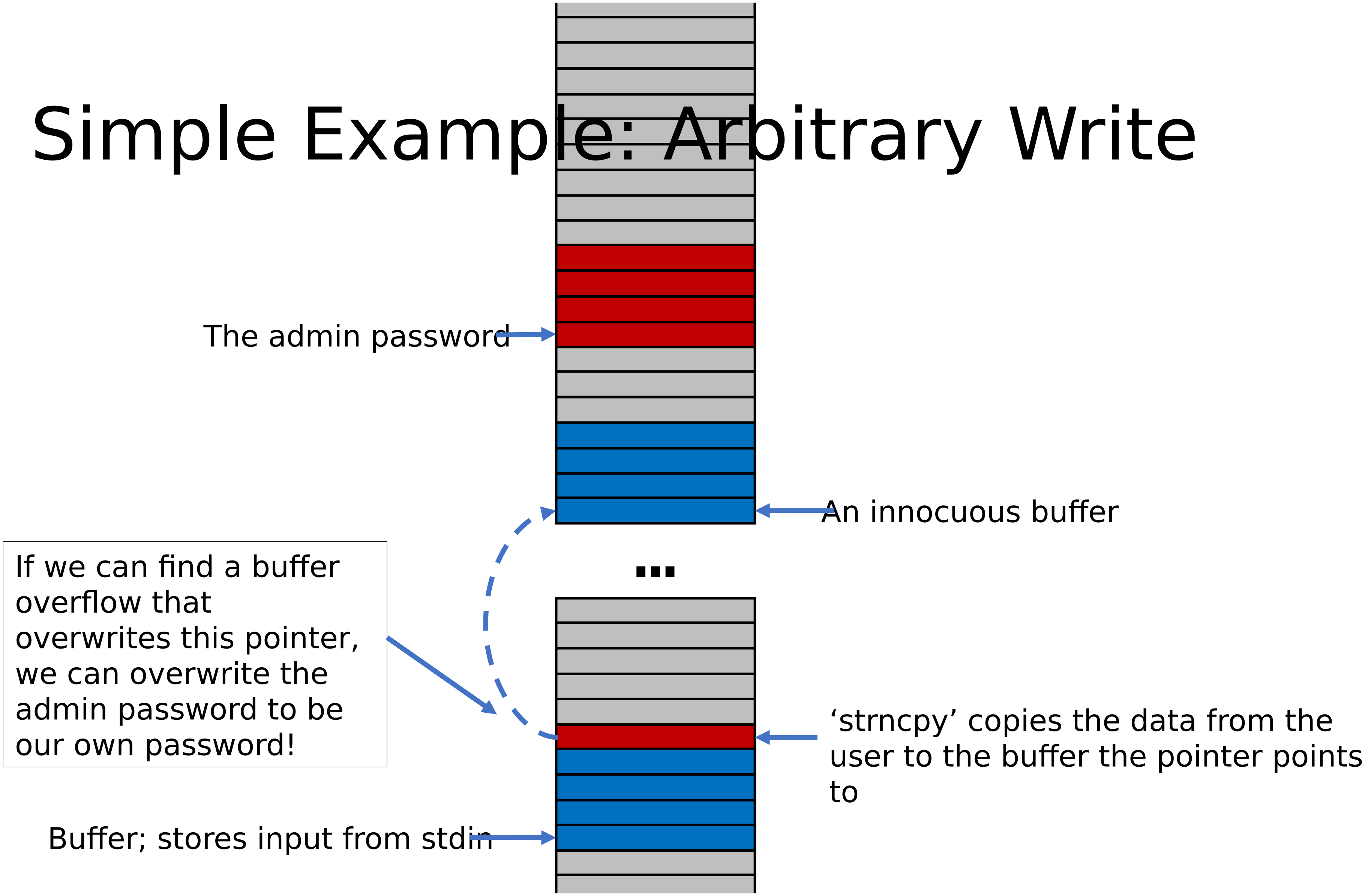
The question is: do we control it in such a way that we can point it at the admin password?

We determine this by constraining the pointer and letting z3 do the heavy lifting.

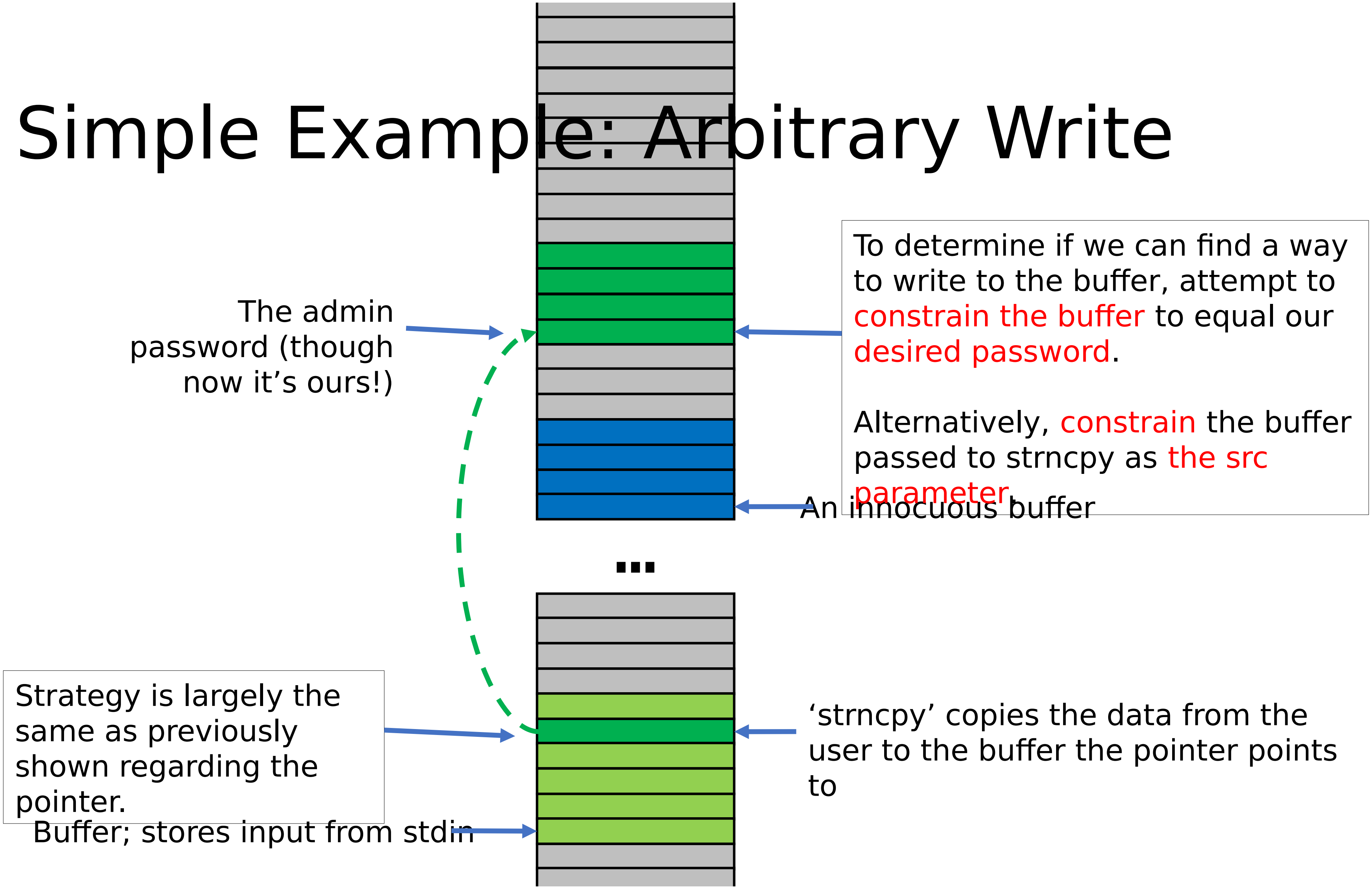
Simple Arbitrary Read Strategy

- Initialize state
- While we have not found a solution or exhaustively searched the binary:
  - For each active state:
    - If the program is calling puts (or printf, or send over the network, etc):
      - If the parameter (a pointer to a string to print) is symbolic and can be constrained to point to the memory address we want to read:
        - Constrain it as such
        - Solve for the user input
  - Step the active states

Simple Example: Arbitrary Write



Simple Example: Arbitrary Write

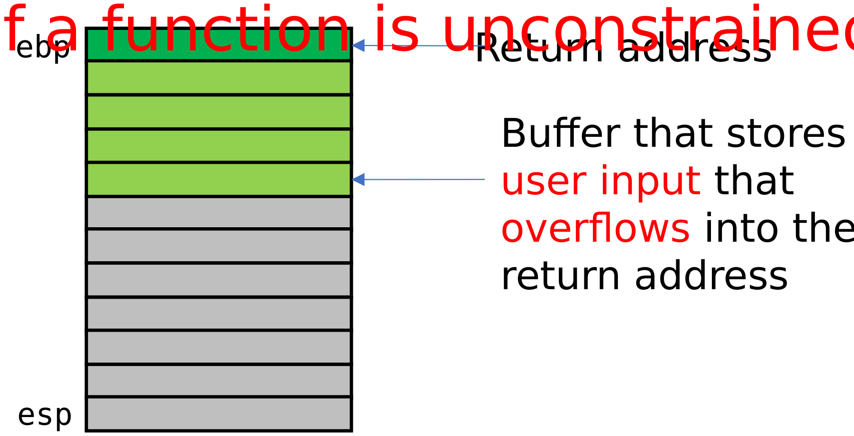


Simple Arbitrary Write Strategy

- Initialize state
- While we have not found a solution or exhaustively searched the binary:
  - For each active state:
    - If the program is calling strncpy (or memcpy, etc):
      - If the destination pointer and the source buffer are symbolic:
        - Constrain them to equal what we want
        - Solve for the user input
  - Step the active states

Simple Example: Arbitrary Jump

To determine if we can find a buffer overflow that would lead to an arbitrary jump, we could search for a situation where the return address of a function is unconstrained:



But there's an easier way…

Simple Example: Arbitrary Jump

Search for a situation where the instruction pointer (ip) is symbolic:

`eip`

One State, Many Possibilities

Typically, when the instruction pointer becomes symbolic, Angr branches:

```
# A simple guessing game.
user_input = raw_input('Enter the password: ')
if user_input == 'hunter2':
  print 'Success.'
else:
  print 'Try again.'
```

You could consider reaching both of these print statements as a single state, where the instruction pointer can take on multiple values: the address of “print ‘Success.’” or the address of “print ‘Try again.’”

Oh the Places You’ll Go!

However, when the instruction pointer is unconstrained, there are an infinite* number of possible branches. Execution cannot continue.

`eip`

Normally, Angr throws away unconstrained states and continues with other paths that have a logical continuation.

In our case, we want to save them and determine if we can constrain the instruction pointer to equal the address of our malicious code.

Simple Arbitrary Jump Strategy

- Initialize state; instruct Angr to save unconstrained states
- While we have not found a solution or exhaustively searched the binary:
  - For each unconstrained state (commonly will be none):
    - If we can constrain the instruction pointer to what we want:
      - Constrain the instruction pointer
      - Solve for input
  - Step every active state

Not-so Automatic Exploit Generation

A few questions may come to mind:

- How do we know what we want to read/write/jump to?
- How do we determine if the computer is making an arbitrary read/write for the general case (strncpy isn't used)?

Human intuition!

Researchers have only come up with mediocre algorithms for the general case (so far.)[citation needed]

If you find a better solution, publish it.

Complex Exploits

Real-world programs may not be exploitable by these simple approaches.

You may need to perform some combination of them, or take a different approach entirely.

To automatically do so is a very hard problem.

Conclusion

In some cases, symbolic execution can be a very powerful tool to automate vulnerability & bug discovery.

It is not a miracle algorithm that can autonomously discover any bug.

Nonetheless, understanding symbolic execution helps us understand the underlying concepts involved in exploit discovery, and gives us a powerful tool to use and research.