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Programs and their Analysis

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Prerequisites

- Lecture:
  - *SS_1.1 – Secure programming*

Outline

- From code to Programs
- Executable and Linkable Format (ELF)
- From Programs to code
  - Decompilation
  - Disassembly
- Tools for static analysis
  - Extracting data from binaries
  - Code obfuscation
- Debugging and Tracing
  - Tools for dynamic analysis (an overview)
  - Memory leaks
  - Anti-debug protection techniques

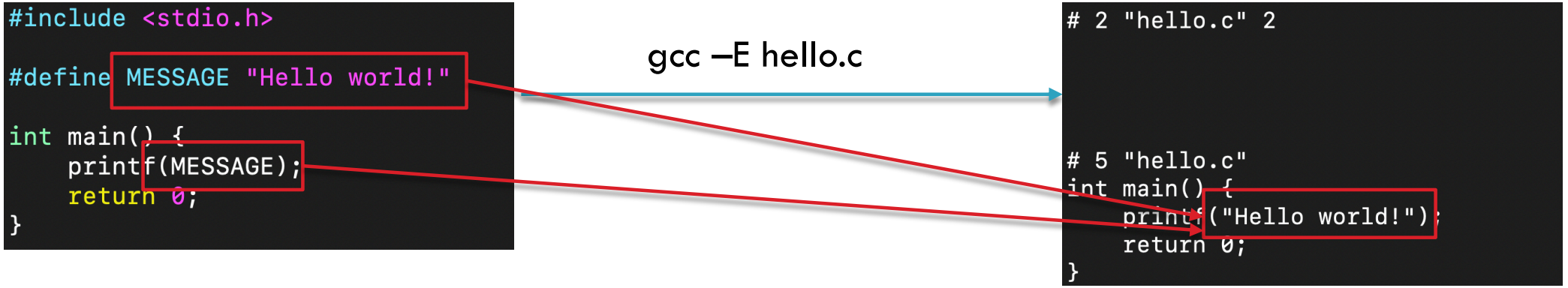
From code to programs

Compiling a C program is a multi-stage process composed by four steps:

- preprocessing
- compilation
- assembly
- linking

From code to programs: preprocessing

In the first phase *preprocessor commands (in C they start with '#') are interpreted:*



From code to programs: compilation

In the second phase, preprocessed code is translated in *assembly instructions*:

From code to programs: assembly

In the *assembly* phase assembly instructions are translated in *machine* or *object code*:

From code to programs: linking

- In the last phase (multiple) *object code* are combined in a single executable.
- In the generated file references (links) to the used library are added.

Static vs Dynamic Linking

Two approaches can be used in the linking phase:

- Static Link
  - Binaries are *self-contained* and do not depend on any external libraries.
- Dynamic Link
  - Binaries rely on system libraries that are loaded when needed;
  - Mechanisms are needed to *dynamically* relocate code.

Executable and Linkable Format

The Executable and Linkable Format (ELF) is a common file format for object files.

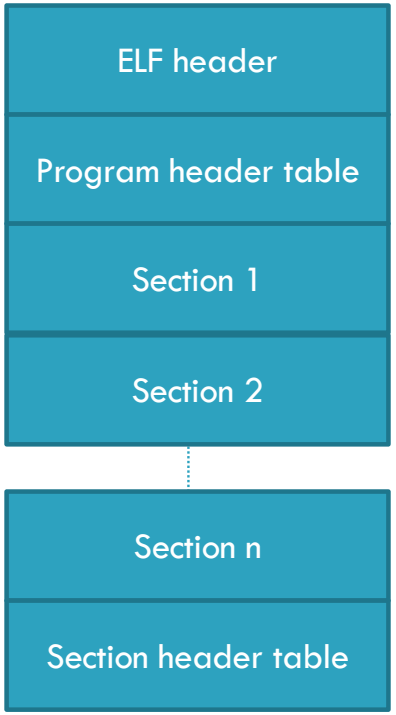
There are three types of object files:

- Relocatable file containing code and data that can be linked with other object files to create an executable or shared object file;
- Executable files holding a program suitable for execution;
- Shared object files that can be:
  - linked with other relocatable and shared object files to obtain another object file;
  - used by a dynamic linker together with other executable files and object files to create a process image.

Executable and Linkable Format

Any ELF file is structured as:

- an ELF header describing the file content
- a Program header table providing info about how to create a process image
- a sequence of Sections containing what is needed for linking (instructions, data, symbol table, relocation information,…)
- a Section header table with a description of previous sections.



ELF: Relevant sections

- .text: contains the executable instructions of a program;
- .bss: contains uninitialised data that contribute to the program's memory image;
- .data, .data1: contain initialized data that contribute to the program's memory image;
- .rodata, .rodata1: are similar to .data and .data1, but refer to read only data;
- .symtab: contains the program's symbol table;
- .dynamic: provides linking information.

Gathering info from binary files

- Several tools are available to extract information from an ELF file, such as:
  - objdump
  - readelf
- These tools can be used to gather information from binaries that can be used to discover vulnerabilities.
- This is static analysis
  - A program is not analyzed while it is running, but by only inspecting the static structure of its binary file.

Gathering info from binary files

Given a binary file we can…

- check if the file is executable or not;
- discover the architecture for which the binary has been compiled;
- collect symbols and strings used in the program;
- check if there is a running process associated with the binary;
- read the SHA of a file and check if it is associated with some malicious software;
- identify function names and used libraries.

Disassembly

- Given a binary file we can use a disassembler to extract from a binary file info about the executed code.
- This can be done by using objdump:

objdump –d <file>

Disassembly in action


```c
#include <stdio.h>

#define MESSAGE "Hello world!"

int main() {
    printf(MESSAGE);
    return 0;
}
```

gcc –s hello.c

```
main:
.LFB0:
        .cfi_startproc
        pushq   %rbp
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        movq    %rsp, %rbp
        .cfi_def_cfa_register 6
        movl    $.LC0, %edi
        movl    $0, %eax
        call    printf
        movl    $0, %eax
        popq    %rbp
        .cfi_def_cfa 7, 8
        ret
```

gcc –o hello hello.c

hello.o

objdump -d hello

```
0000000000400526 <main>:
  400526:       55                      push   %rbp
  400527:       48 89 e5                mov    %rsp,%rbp
  40052a:       bf c4 05 40 00          mov    $0x4005c4,%edi
  40052f:       b8 00 00 00 00          mov    $0x0,%eax
  400534:       e8 c7 fe ff ff          callq  400400 <printf@plt>
  400539:       b8 00 00 00 00          mov    $0x0,%eax
  40053e:       5d                      pop    %rbp
  40053f:       c3                      retq
```


Decompilation

- A decompiler is a tool that, given a binary file, tries to reconstruct a high-level source file;
- The output of a decompiler is typically concise and the program logic is clear;
- Decompilation is quite easy in languages like Java, while it is complex for general binary files;
- Obfuscator can be used to make decompilation harder.

Identifying vulnerabilities

Information collected from binaries can be used to discover program vulnerabilities:

- where a program takes an input and if this is validated;
- if memory is safely managed;
- if up-to-date libraries or third-party frameworks are used;
- how the application is compiled;
- if (static) strings are used to record sensitive data.

Example

Let us assume we have a program named guessmyname. When executed this program just ask the user to guess a name:

```
CC> ./guessmyname
Guess my name: Paulo
I am sorry, this is not my name!
Please, try again!
CC>
```

We can use readelf to check if the name to guess is *hardcoded* in the file.

Example

We can read the content of .rodata section:

```
CC> readelf -x .rodata guessmyname

Hex dump of section '.rodata':
  0x00400760 01000200 00000000 43616c65 66004775 ........Calef.Gu
  0x00400770 65737320 6d79206e 616d653a 20002531 ess my name: .%1
  0x00400780 30730000 00000000 57656c6c 20646f6e 0s......Well don
  0x00400790 65212059 6f752067 75657373 6564206d e! You guessed m
  0x004007a0 79206e61 6d652100 4920616d 20736f72 y name!.I am sor
  0x004007b0 72792c20 74686973 20697320 6e6f7420 ry, this is not
  0x004007c0 6d79206e 616d6521 0a506c65 6173652c my name!.Please,
  0x004007d0 20747279 20616761 696e2100           try again!.
```


Example

We can now use the string we have discovered in our program:

```
CC> ./guessmyname
Guess my name: Calef
Well done! You guessed my name!
CC>
```

WARNING: To avoid information leakage, never hardcode secrets in your program!

Example

We can also use the tool strings to extract all the constant strings used in the code:

```
CC> strings guessmyname
/lib64/ld-linux-x86-64.so.2
libc.so.6
__isoc99_scanf
puts
printf
malloc
strcmp
__libc_start_main
__gmon_start__
GLIBC_2.7
GLIBC_2.2.5
UH-X
AWAVA
AUATL
[]A\A]A^A_
Calef
Guess my name:
%10s
Well done! You guessed my name!
I am sorry, this is not my name!
Please, try again!
```


Example

Looking at the code, we can observe that the name is in fact *hardcoded*:

```
int main() {
    char* name = "Calef";
    char* input = malloc(10);

    printf("Guess my name: ");
    scanf("%10s",input);
    if (strcmp(name,input)==0) {
        printf("Well done! You guessed my name!\n");
    } else {
        printf("I am sorry, this is not my name!\nPlease, try again!\n");
    }
    return 0;

}
```


From static to dynamic analysis

- We have seen how information can be collected from a binary file.
- We learnt that, to avoid information leakage, private data should not be hardcoded.
- This is not enough!
- Program data can be inspected at runtime!

Dynamic analysis

- Dynamic analysis is a program analysis technique performed either on virtual or on real processor.
- This kind of analysis is performed using tools that are able to observe program execution:
  - *dynamic memory analysis*
  - *dynamic disassembly*

Debugging

- One approach to perform dynamic analysis is via a debugger
- A debugger is a software tool that allows to:
  - run the target program under controlled conditions
  - track program operations in progress
  - monitor changes in computer resources
  - display the contents of memory
  - modify memory or register contents

Debugging

- Compilers can be instrumented to emit extra (optional) data that debugger can use for a more informative input
- In the case of *gcc* compiler the parameter *–g* can be used
- Debugging information is stored in specific sections of ELF file:
  - .debug, containing info for symbolic debugging;
  - .line, containing line number information.

Example


```
CC> gcc -o hello -g hello.c
CC> readelf --debug-dump hello
Contents of the .debug_aranges section:

  Length:                   44
  Version:                  2
  Offset into .debug_info:  0x0
  Pointer Size:             8
  Segment Size:             0

    Address           Length
    0000000000400526 000000000000001a
    0000000000000000 0000000000000000

Contents of the .debug_info section:

  Compilation Unit @ offset 0x0:
   Length:        0x8d (32-bit)
   Version:       4
   Abbrev Offset: 0x0
```


GDB: The GNU Project Debugger

- GDB, the GNU Project debugger, is a debugger that:
  - Starts your program, specifying anything that might affect its behavior (parameters, value of registries,…).
  - Makes your program stop on specified conditions.
  - Examines what has happened, when your program has stopped.
  - Changes things in your program, to enable you to experiment with correcting the effects of one bug and to go on to learn about others.

GDB: The GNU Project Debugger

- Main gdb commands
  - file <filename>: loads a file
  - break <function>: sets a breakpoint at a given function
  - layout asm: displays disassembly and command info
  - layout regs: displays registers info
  - run: starts debugged program
  - stepi: execute next instruction

GDB in action

A new version of our *game* has been released where developers say they have fixed the previously identified vulnerabilities:

```
CC> ./guessmyname2
Guess my name: Calef
I am sorry, this is not my name!
Please, try again!
```

They also changed the name…

Example

We read the content of .rodata section:

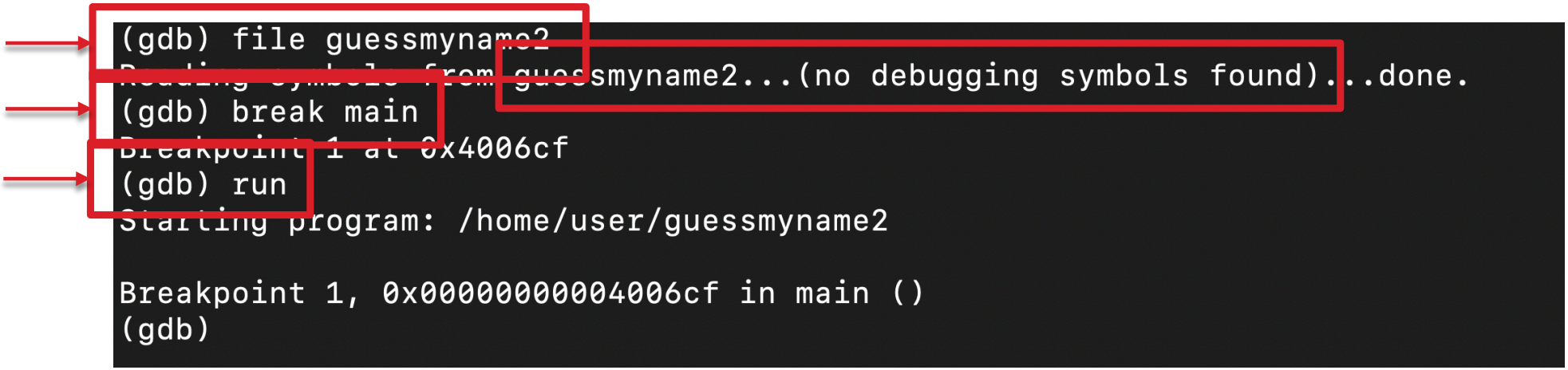
```
CC> readelf -x .rodata guessmyname2

Hex dump of section '.rodata':
  0x004007d0 01000200 00000000 47756573 73206d79 ........Guess my
  0x004007e0 206e616d 653a2000 25313073 00000000  name: .%10s....
  0x004007f0 57656c6c 20646f6e 65212059 6f752067 Well done! You g
  0x00400800 75657373 6564206d 79206e61 6d652100 uessed my name!.
  0x00400810 4920616d 20736f72 72792c20 74686973 I am sorry, this
  0x00400820 20697320 6e6f7420 6d79206e 616d6521  is not my name!
  0x00400830 0a506c65 6173652c 20747279 20616761 .Please, try aga
  0x00400840 696e2100                           in!.
```

- The lesson has been learnt… no name is evident in the program.
- We can use gdb to perform dynamic analylis of our code.

Example

We start gdb, load the binary, and set a breakpoint at function main:



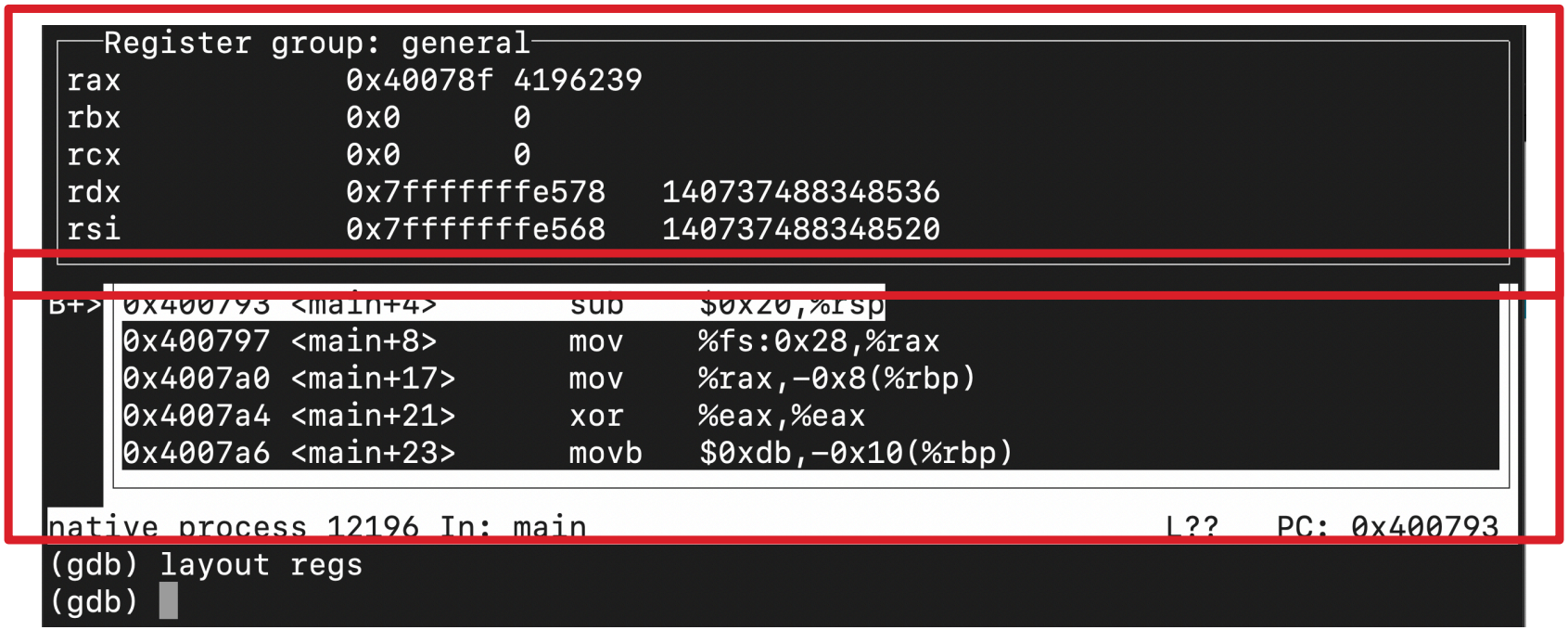
```
(gdb) file guessmyname2
Reading symbols from guessmyname2...(no debugging symbols found)...done.
(gdb) break main
Breakpoint 1 at 0x4006cf
(gdb) run
Starting program: /home/user/guessmyname2

Breakpoint 1, 0x00000000004006cf in main ()
(gdb)
```

Note that we have not debug data in the object files.

Example

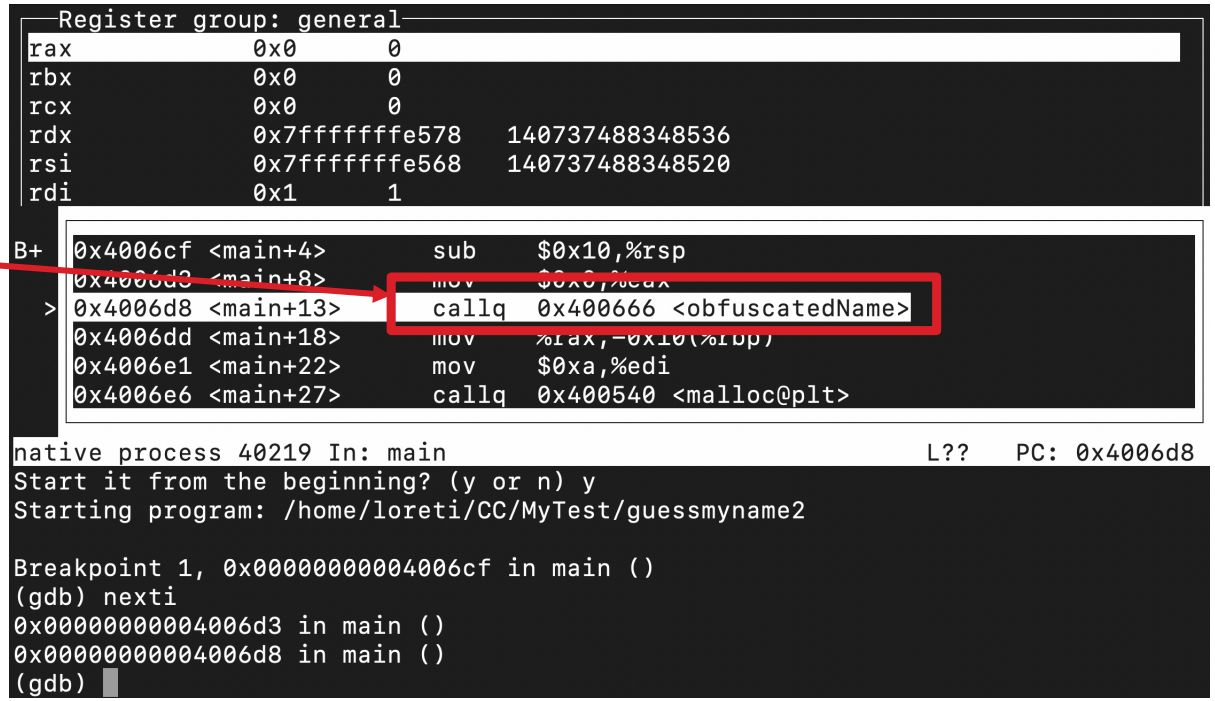
We setup the layout to see both registry and assembly:



Example

By using comman nexti we can interactively execute the program:

Function ‘obfuscated Name’ is called!



Example

In the next step, the result of invocation is copied from one registry ($rax) to a memory address:

```
B+  0x4006cf <main+4>       sub    $0x10,%rsp
    0x4006d3 <main+8>       mov    $0x0,%eax
>   0x4006d8 <main+13>      callq  0x400666 <obfuscatedName>
  > 0x4006dd <main+18>      mov    %rax,-0x10(%rbp)
    0x4006e1 <main+22>      mov    $0xa,%edi
    0x4006e6 <main+27>      callq  0x400540 <malloc@plt>
native process 40219 In: main                                  L??   PC: 0x4006dd
```


Example

We can inspect the content of registy $rax to read the value:

```
(gdb) x/s $rax
0x602010:       "Ulisse"
(gdb)
```

This is the name that we have to guess!

```
CC> ./guessmyname2
Guess my name: Ulisse
Well done! You guessed my name!
CC>
```


Example

If we examine the code we can observe that in this case the password is obfuscated, however it is revealed when saved in a variable:

```
int main() {
    char* name = obfuscatedName();
    char* input = malloc(10);

    printf("Guess my name: ");
    scanf("%10s",input);
    if (strcmp(name,input)==0) {
        printf("Well done! You guessed my name!\n");
    } else {
        printf("I am sorry, this is not my name!\nPlease, try again!\n");
    }
    return 0;

}
```


Example

The same information can be extraced by using the tool ltrace that allows to trace calls to libraries:

```
CC> ltrace ./guessmyname2
__libc_start_main(0x4006cb, 1, 0x7ffc04c1b0f8, 0x400750 <unfinished ...>
malloc(7)                                                = 0x25a9010
malloc(10)                                               = 0x25a9030
printf("Guess my name: ")                                = 15
__isoc99_scanf(0x4007e8, 0x25a9030, 0x7f3b635e9780, 15Guess my name: Harry
) = 1
strcmp("Ulisse", "Harry")                                = 13
puts("I am sorry, this is not my name!"...I am sorry, this is not my name!
Please, try again!
)      = 52
+++ exited (status 0) +++
CC>
```


How can we patch this program?


```
int main() {
    char* name = readEncryptedName();
    char* input = malloc(10);

    printf("Guess my name: ");
    scanf("%10s",input);
    if (strcmp(name,encrypt(input))==0) {
        printf("Well done! You guessed my name!\n");
    } else {
        printf("I am sorry, this is not my name!\nPlease, try again!\n");
    }
    return 0;

}
```


How can we patch this program?


```
int main() {
    char* name = readEncryptedName();
    char* input = malloc(10);

    printf("Guess my name: ");
    scanf("%10s",input);
    if (strcmp(name,encrypt(input))==0) {
        printf("Well done! You guessed my name!\n");
    } else {
        printf("I am sorry, this is not my name!\nPlease, try again!\n");
    }
    return 0;

}
```

Read encrypted name from a file.

How can we patch this program?


```
int main() {
    char* name = readEncryptedName();
    char* input = malloc(10);

    printf("Guess my name: ");
    scanf("%10s",input);
    if (strcmp(name,encrypt(input))==0) {
        printf("Well done! You guessed my name!\n");
    } else {
        printf("I am sorry, this is not my name!\nPlease, try again!\n");
    }
    return 0;

}
```

Encrypt the name read from input and compare it with the one we have!

How can we patch this program?


```
int main() {
    char* name = readEncryptedName();
    char* input = malloc(10);

    printf("Guess my name: ");
    scanf("%10s",input);
    if (strcmp(name,encrypt(input))==0) {
        printf("Well done! You guessed my name!\n");
    } else {
        printf("I am sorry, this is not my name!\nPlease, try again!\n");
    }
    return 0;

}
```

The implementation of ‘readEncryptedName’ and ‘encrypt’ is left as an exercise!

Programs and their Analysis

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