Lecture 6: Hacking the Execution Flow

(From ELF to EXE and Beyond)

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Outline

Today's Key Question:

- **Buffer Overflow Is Not Enough!**
- **How can we understand and exploit program execution?**

Main Topics for Today:

- **Executable and Linkable Format (ELF):**
  - Structure, Creation, and How ELF Is Executed
  - Create Your Own ELF
- **Memory Execution Process:**
  - From Source Code to Execution
  - Create Your Own `execve`
- **Security Implications:**
  - Identifying and Addressing Vulnerabilities
  - Techniques for Secure Programming

Excutable Linkable File (ELF)

Making the Program Recognizable to the Machine

Example: Minimum HelloWorld

```
$ ls -l
$ file helloworld
$ cat helloworld
$ cat helloworld | hexdump | less
```

Magic Number: 0x 457f 464c

What is an Executable File?

Before Learning Computer Security:

- "That thing you double-click to open a window"

After Learning Computer Security:

- An object in the operating system (a file)
- A sequence of bytes (we can edit it as characters)
- A **data structure** that describes the initial state of a state machine (Better understand attacks like buffer overflows, format string vulnerabilities, heap overflows, integer overflows, and other related attacks).

ELF is A Data Structure

The computer is a machine.
Everything in the computer is a state machine.
Executable files describes the initial state of a process.

- Each line of assembly code represents a state transition.
- When using the system call `execve`, the initial state of the program, as defined in the ELF, is fixed.
- There is a document that explicitly defines what the initial state of the program should be.

RTFM: Read The "Fine" Manual

Key Manuals for This Lesson:

- **System V ABI:** Defines the System V Application Binary Interface for the AMD64 architecture, providing essential specifications for binary compatibility.
- The answer of in-class quiz 2 

  - System V ABI (AMD64 Architecture Processor Supplement)
  - Section 3.4 Process Initialization
    - Figure 3.9 Initial Process Stack
    - Specifies certain parts of registers and memory.
    - Other states (mainly in memory) are determined by the executable file.
- **Refspecs:** Additional reference specifications to deepen understanding of Linux-based systems.
  - Linux Refspecs

What Exactly is the State of a Process?

The State of a Process:

- The process state is composed of:
  - **Memory**: Describes the program's address space and its contents.
  - **Registers**: Includes general-purpose registers and program-specific configurations.

However,

- Figure 3.9 (System V ABI) shows the **initial process stack**, but this is not part of the executable file itself.
- It is the responsibility of the operating system to construct the initial stack based on the ABI specification.

What Does the ELF Actually Define?

ELF and Memory Data Structures:

- The ELF defines **how data is structured in memory**, including both fixed and dynamic components.
- These structures are binary and can be complex to interpret directly.
- Specialized tools like `readelf` and `objdump` are essential for reading and understanding these memory structures.

GNU Binutils: Essential Tools for Executable Files

- **Creating Executable Files:**
  - `ld` (Linker): Combines object files into a single executable.
  - `as` (Assembler): Translates assembly code into machine code.
  - `ar` and `ranlib`: Manage static libraries.
- **Analyzing Executable Files:**
  - `objcopy`, `objdump`, `readelf`: Inspect and modify executables, often used in computer systems basics.
  - `addr2line`: Maps addresses to line numbers for debugging.
  - `size`, `nm`: Display size information and symbol tables.

Learn More: GNU Binutils Official Page

So, I can use the command `size` to determine the smallest 'Hello World' program from each student's HW2 and give extra credit to the one with the smallest. 

Why Can We See All This Information?

Debugging Information Added During Compilation:

- When we compile with debug flags, the compiler includes extra information in the binary.
- This information allows tools like `objdump` and `addr2line` to map assembly code back to the original source code.

Example Command:

- Using `gcc -g -S hello.c` generates assembly code with debugging information.
- This enables us to see additional sections in the assembly output, including variable names, line numbers, and other metadata.

Standard of Debugging Information

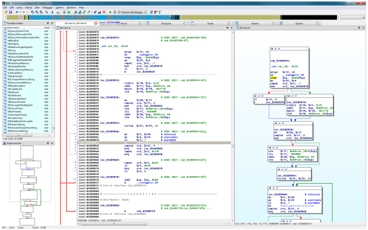
Mapping Machine State to "C World" State:

- The DWARF Debugging Standard (dwarfstd.org) defines an instruction set, `DW_OP_XXX`, that is Turing Complete.
- This instruction set can perform "arbitrary computations" to map the current machine state back to the C language state.

Challenges and Limitations:

- **Limited Support for Modern Languages:** Advanced features (e.g., C++ templates) are not fully supported.
- **Complexity of Programming Languages:** As languages evolve, it becomes increasingly challenging to accurately map machine states to source code.
- **Compiler Limitations:** Compilers may not always produce perfect debug information, leading to issues like:
  - Frustrating instances of variables being `<optimized out>`
  - Incorrect or incomplete debugging information

- Provides insights into commercial software without access to the original source code.
- Challenges:
  - No Debug Information
  - Stripped Symbols
  - Opaque Instruction Sequences
- Techniques:
  - Analysts use specialized tools (e.g., `objdump`, `IDA Pro`, `Ghidra`) to disassemble and analyze the instruction sequences.
  - Techniques like pattern recognition, control flow analysis, and heuristic methods help infer program functionality.



Funny Little Executable

Let's create our own ELF file from scratch.

Why is learning ELF so challenging?

No difference for you!

```
$ readelf -a helloworld
$ cat helloworld
```

Reflection:

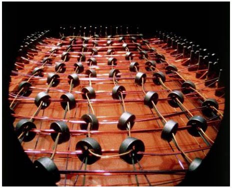
- ELF is not a human-friendly ”state machine data structure.”
- For the sake of performance, it sacrifices readability, violating the principle of ”information locality.”

Almost Like Reading a Core Dump:

- ”Hell’s joke: Today’s core dump is an ELF file.”

Magnetic Core Memory

- The origin of ”Segmentation fault (core dumped)”
- Non-volatile memory!



Magnetic core memory, storing data by the magnetization direction of tiny ferrite cores. Each core represents a single bit, retaining data even when powered off.

UNIX a.out "assembler output"

- A relatively simple data structure
- Describes the initial state (structure) of the address space
- Once the data is loaded into the process and the pointer is set to the entry point, the program can start running.

```
struct exec {
   uint32_t a_midmag; // Machine ID & Magic
   uint32_t a_text; // Text segment size
   uint32_t a_data; // Data segment size
   uint32_t a_bss; // BSS segment size
   uint32_t a_syms; // Symbol table size
   uint32_t a_entry; // Entry point
   uint32_t a_trsize; // Text reloc table size
   uint32_t a_drsize; // Data reloc table size
};
```

Why Was It Replaced?

- Limited functionality:
  - No support for dynamic linking, debugging information (why `gdb` works), thread-local storage, etc.
- Naturally phased out due to increasing demands.

In Other Words...

The More Features Supported, the Less Human-Friendly:

- Hearing terms like ”program header,” ”section header” feels overwhelming for the human brain.
- Contains cryptic values like `R_X86_64_32`, `R_X86_64_PLT32`.
- A massive amount of ”pointers” (essentially unreadable to humans).
  - LLM can help us read them, but it’s still far from easy!

A More Human-Friendly Approach:

- Simpler and flatter design is easier to understand.
- All necessary information is immediately visible.

A Chance to Redesign

Design Your Own FLE:

- **FLE**:
  - **Funny (Fluffy) Linkable Executable**
  - **Project 1**: **Friendly Learning Executable** (my favorite!)

Core Design Principles:

- Make everything human-readable (all information should be at the top).
- Revisit the core concepts of linking and loading: code, symbols, relocations.
- How would you design it?

Let's use emojis!

Code 🔢, **Symbols** 📤, and **Relocations** ❓
By combining these three elements, we can create an executable file!

🔢: ff ff ff ff ff ff ff ff
🔢: ff ff ff ff ff ff ff ff
📤: _start
🔢: 48 c7 c0 2a 00 00 00
🔢: 48 c7 c7 2a 00 00 00
🔢: 0f 05 ff ff ff ff ff ff
🔢: ff ff ff ff ff ff ff ff
❓ : i32(unresolved_symbol - 0x4 - 📍)

- You can use text to hack the excutable file.
- You can also get the debugging information.

Implemented Tools:

- `exec` (loader)
- `objdump`/`readfle`/`nm` (display)
- `cc`/`as` (compiler/assembler)
- `ld` (linker)

Most Components Reuse GNU Binutils:

- `elf_to_fle`

Step 1: Preprocessing and Compilation

Source Code (.c) $\rightarrow$ **Intermediate Code (.i):**

- Ctrl-C & Ctrl-V (`#include`)
  - GCC first performs a preprocessing step without macros

    ```
    gcc -E foo.c | less
    ```

  -
- String substitution
- Today: We use macros

Intermediate Code (.i) $\rightarrow$ **Assembly Code (.s):**

- Translation from "high-level state machine" to "low-level state machine"
- Final output: annotated instruction sequences

Assembly Code (.s) $\rightarrow$ Object File (.o):

- File = sections (`.text`, `.data`, `.rodata.str1.1`, ...)
  - For ELF, each section has its own permissions and stores corresponding information.
- Three key elements in a section:
  - **Code:** Sequence of instructions.
  - **Symbols:** Marks the location of "current."
  - **Relocations:** Values that cannot be determined yet (resolved during linking).

Quick Quiz: What is the difference between global and local symbols in ELF? Are there other types of symbols?

Generating Executable Files (3): (Static) Linking

Multiple Object Files (.o) $\rightarrow$ Executable File (a.out):

- Combine all sections:
  - Merge code from `.text`, `.data`, `.bss`, etc.
  - Flatten sections into a linear sequence.
  - Determine the locations of all symbols.
  - Resolve all relocations.
- Produce a single **executable file**:
  - A description of the program's initial memory state.

FLE Program: Loading

Load the "byte sequence" into memory:

- That's all there is to do.
- Then set the correct PC (program counter) and start running.

```
mem = mmap.mmap(
   fileno=-1, length=len(bs),
   prot=mmap.PROT_READ | mmap.PROT_WRITE | mmap.PROT_EXEC
         ,
   flags=mmap.MAP_PRIVATE | mmap.MAP_ANONYMOUS,
)
mem.write(bs)
mem.flush()
call_pointer(mem, fle['symbols']['_start'])
```

Shebang

#! - Shebang

Easter Egg:

- Our FLE files can be executed directly:

```
#!/./exec
```

The "magic" of #! in UNIX:

- Example: `file.bin`

```
#!A B C
```

- The operating system executes:

```
execve(A, ["A", "B C", "file.bin"], envp)
```

Example: Executable Files on an Operating System

Requirements for an Executable File:

- Must have execution ('x') permission.
- Must be in a format that the loader can recognize as executable.

Example Commands and Output:

```
$ ./a.c
bash: ./a.c: Permission denied

$ ./a.c
bash: ./a.c: Permission denied

$ chmod -x a.out && ./a.out
bash: The file './a.out' is not executable by this user

$ chmod +x a.c && ./a.c
Failed to execute process './a.c'. Reason:
exec: Exec format error
The file './a.c' is marked as an executable but could not
      be run by the operating system.
```

Who Decides If a File is Executable?

The Operating System (OS Code - `execve`) Determines Executability:

- The OS, through `execve`, decides whether a file can be executed.

Try It Out:

- Use `strace` to trace `execve` calls and observe execution failures.
  - `strace ./a.c`
    - Without execute permission on `a.c`: `execve` returns `-1, EACCES`
    - With execute permission but incorrect format on `a.c`: `execve` returns `-1, ENOEXEC`

She-bang (#!/path/to/interpreter):

- The She-bang (`#!`) allows specifying an interpreter for a script or executable.
- She-bang effectively performs a "parameter swap" in `execve`, launching the specified interpreter to execute the file.

Example: Running Python Code in a C File

- Save the Following Code as `helloworld.c`:

```
#! /usr/bin/python3
print("Hello␣World!")
```

- Give the file execute permission:

```
$ chmod +x helloworld.c
```

- Now, you can directly run the `helloworld.c` file to execute the Python code:

```
$ ./helloworld.c
Hello World!
```

Static Linking and Loading

Why ELF When We Have FLE?

If you want to build Chrome (2017):

- 2 GiB binary (with debug info)
- 17,000 files
- 1,800,000 sections
- 6,300,000 symbols
- 13,000,000 relocations

C++ Name Mangling:

- Example: `_ZNK8KxVectorI6DlTypejEixEj` is:

  `KxVector<DlType, unsigned int>::operator[](uns`

- (It seems impossible to skip pointers.)

ELF Linking

Built upon FLE: `readelf -a` provides detailed insights!
Sections: More sections; more flags

```
[Nr] Name          Type          Address               Offset
     Size          EntSize       Flags   Link   Info   Align
 [ 5] .tdata       PROGBITS      0000000000000000     0000000c
      00000004     00000000      WAT     0      0      4
```

Relocations: Similar but more powerful

```
Offset            Info              Type                Name + A
000000000000016   000000000000004   R_X86_64_GOTPCREL   x
000000000000020   000000000000006   R_X86_64_TPOFF32    y -
```

```
extern __thread int x;
extern __thread int y;
```

Loading: ELF vs. FLE

FLE Loader: Does Only One Thing

- Copies a single byte sequence into the address space:
  - Grants read, write, and execute permissions.
- Then jumps to `_start` for execution.

ELF: Not Much More

- Copies multiple segments into the address space:
  - Separately grants read, write, and execute permissions.
- Then jumps to the specified entry point (default: `_start`) for execution.

Loading: ELF vs. FLE (cont'd)

They Are Both Data Structures

- Example: ELF is a "binary data structure."
- `readelf -l` describes how it is loaded:
  - **Offset:** Segment's offset in the file.
  - **VirtAddr:** Virtual address where the segment is loaded in memory.
  - **PhysAddr:** Physical address (rarely used).
  - **FileSize:** Number of bytes in the segment in the file.
  - **MemSize:** Number of bytes in the segment in memory (may exceed file size).
  - **Flags:** Permissions, such as RWE (Read, Write, Execute).
  - **Align:** Alignment of the segment's virtual address.

- What is an Executable File?
  - An executable file is a data structure (a sequence of bytes) that describes the initial state of a state machine.
  - The loader transfers this ”initial state” into the operating system.
  - It is difficult to read because it was never designed for human readability.
- It helps us understanding the buffer overflow:
  - Why can we use `gdb` to compute stack offsets that helps analyze function call stack structures?
  - Observing local variables, return addresses, and how an overflow can overwrite the return address.
  - Redirecting execution to malicious code (e.g., shellcode) reveals how control flow is hijacked.
  - This process provides insight into program execution, stack management, and security vulnerabilities.