# Lecture 10: elf

## (From ELF to EXE and Hacking)

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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

# Read Your helloworld

```
$ file helloworld
$ cat helloworld
$ cat helloworld | hexdump | less
$ objdump -d helloworld | less
```

First 4 bytes should be: 0x 457f 464c
That is 16-bit little-endian grouping of ”0x7F E L F”

# What is an Executable File?

**Before Learning OS:**

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


**After Learning OS:**

- 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.

# 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.

# In-Class Quiz

# 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 3 

  - 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.

# Binutils - Binary Utilities

**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:**

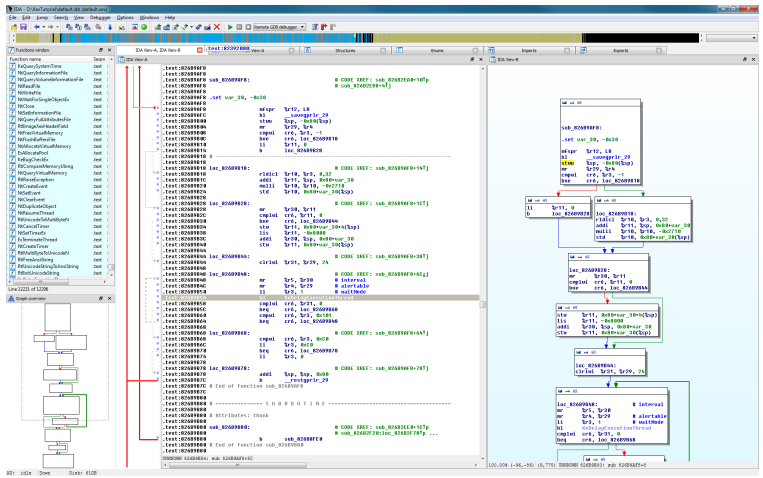
- The DWARF Debugging Standard (dwarfstd.org) defines an instruction set, `DW_OP_XXX`, that is Turing Complete.
- This instruction set can perform "arbitrary computations" to map the current machine state back to the C language state.

**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

# Reverse Engineering

- 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:**

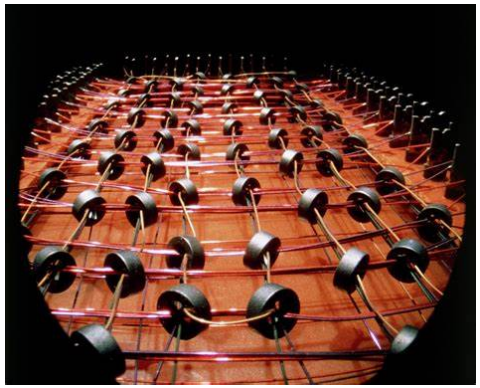
- ELF is not a human-friendly "state machine data structure."
- For the sake of performance, it sacrifices readability, violating the principle of "information locality."

**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.

# But It Wasn't Always Like This

## 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**
  - **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.

# Implementation of FLE Binutils

**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

# Generating Executable Files (2): Compilation

**Assembly Code (.s) → 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[](unsi
```

- (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 0000000000000004 R_X86_64_GOTPCREL x
000000000000020 0000000000000006 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.

# Understanding Executable Files and Buffer Overflow

- 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.