The Life Cycle of Binaries

How binary programs are built and run

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Outline

Introduction

We'll

- study the life cycle of (binary) programs
  - how they are built, loaded and run
- understand how to deduce properties and behavior of programs
- review how modern operating systems work
  - examine some aspects of prominent ones

Market share

According to various reports:

- 2013 — 2022, Windows is the dominant *desktop* OS, with 76% share
  - Apple remains a minor player
  - Linux has a small but stable share
- in 2017, according to the Linux Foundation, Linux
  - runs 90% of the public cloud workload
  - has 62% of the embedded market share
  - 99% of the supercomputer market share
  - runs 82% of smartphones

Microsoft ♡ Linux?

As declared by CEO Satya Nadella in 2015?

- 2016, joined The Linux Foundation (Platinum, $500,000 annually)
- 2016, introduced WSL with Windows 10 Anniversary Update,
- 2019, announced WSL 2
- 2020, developed an internal Linux distribution, CBL-Mariner
- 2021, released WSLg and a Windows Store version of WSL

Scott Hanselman jokes (e.g. see Developing for Linux on Windows) that this is *the year of the Linux desktop*

WSL magic

WSL2 transparently handles a VM, and you can access

- Linux files via `\\wsl$\`*`distro`*`\...`
- Windows disks via `/mnt/`*`drive-letter`*`/`*`path`*

Moreover,

- Listening sockets opened in WSL are reachable from Windows
- Your Windows `PATH` is appended to WSL path by default
- In WSL you can run Windows executables, they
  - retain the working directory (as UNC path; e.g. `\\wsl$\Ubuntu\home\...`; so `cmd.exe /c` doesn't work, but `powershell.exe /c` does)
  - run as the active Windows user, with permissions as the WSL process
- In Windows you can run Linux executables by prepending `wsl`
- I/O redirection works

Operating systems

We'll use:

- Windows 11
- Ubuntu/Ubuntu-derived Linux distros
  - Suggested: Ubuntu 22.04 (It's the one I'm currently using)

however, the same concepts apply to other versions

Warm-up

What are binaries?

Let's start with some examples to warm up

$\rightarrow$ `file0.exe`, ...

File formats

File extensions are immaterial

- For the OS, the content of a file is simply a sequence of bytes
- Different *parsers* can interpret the same sequence differently
  - ZIP/JAR parsers look for the "End of Central Directory" from the end of the file
  - BMP/PE/ELF/... parsers expects an header at *the beginning*
  - PDF header *should* be at the beginning, but most viewers are happy if it is in the first 1024 bytes of the file
  - ...

Polyglots

Files meeting the specifications of multiple file-formats are called polyglots

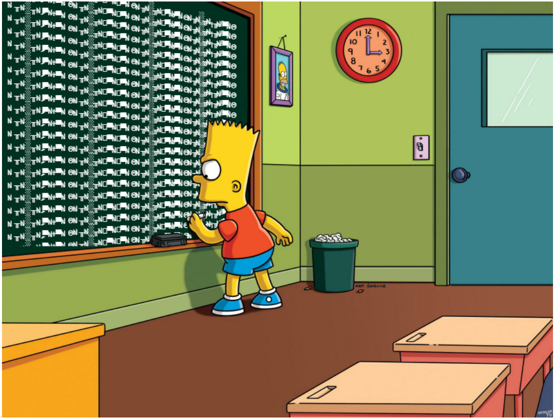
- e.g. Janus.com

  > *[...] a 512-byte file that is simultaneously an x86 bootloader, COM executable, ELF, ZIP, RAR, GNU Multiboot2 Image and Commodore 64 PRG executable [...]*

  https://xcellerator.github.io/posts/bggp21/
- *Ange Albertini* has done a lot of interesting work on file-formats and polyglots; e.g. *Funky File Formats*
  https://www.youtube.com/watch?v=hdCs6bPM4is
- See also: *Polyfile*
  https://github.com/trailofbits/polyfile

How can you “take a look” inside a binary file?

You can't really cat it...



https://twitter.com/Q3w3e3/status/1256293618991669249

Generic and structure-aware tools

Generic

- the (in)famous `strings`
- any hex-editor

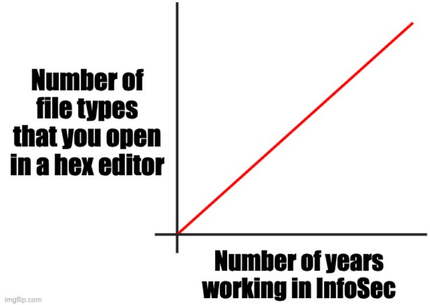
  Linux `bvi`, `ghex`, ...

  Windows HxD `https://mh-nexus.de/en/hxd/`, ...

Structure-aware

- Kaitai, a parser+viewer for binary structures
  `https://ide.kaitai.io/`
- similar, but can also edit: *010 Editor*; *non-free*, 30 day trial
  `https://www.sweetscape.com/010editor/`
- the open-source alternative, ImHex
  `https://github.com/WerWolv/ImHex`

The more you work in infosec...



https://twitter.com/cyb3rops/status/1493885187729547265

Joking aside, some tools offer specific features for executable formats...

Tools for executables

Even more specific tools:

ELF+PE `hte` can also *edit* — *note*: Ubuntu package name is `ht`
`http://hte.sourceforge.net/`
`https://github.com/sebastianbiallas/ht`

ELF
- `readelf` and `objdump`
  - `objdump` can also disassemble, and can parse PE too
- XELFViewer
  `https://github.com/horsicq/XELFViewer`
- ...

PE
- `dumpbin` more or less an `objdump` for PE files
- XPEViewer
  `https://github.com/horsicq/XPEViewer`
- PE Bear `https://hshrzd.wordpress.com/pe-bear/`
- PE Studio `https://www.winitor.com/`
- ...

Hello world

At last we have the “obligatory” C program:

```
#include <stdio.h>

int main()
{
        printf("Hello world!\n");
}
```

...can we run it?

→ `c_examples/hello_world/hello-world.c`

Long story short

1. CPUs do not “understand” C, they execute (their own) machine code
2. This is an ASCII text file, not a sequence of machine instructions
3. So, to run this “hello world” program, we first need to *compile* it

By doing so, we get an executable, that we can run

Binary Analysis

Can you be sure that the compiled program has the same semantics as the corresponding source? The unnerving answer is that you can't!

There might be surprises

As a matter of fact, it's extremely likely that running the compiled* version of the previous "Hello world" does *not* call the function `printf` (!)

(*) using gcc, unless `-fno-builtin` is specified

> *Binary analysis is the science and art of analyzing the properties of binary computer programs, called binaries, and the machine code and data they contain. ...the goal [...] is to figure out (and possibly modify) the true properties of binary programs: what they really do, as opposed to what we think they should do. [And18]*

Static vs Dynamic Analysis

Broadly speaking, the tools at our disposal are:

- Dynamic analysis: we run the binary and analyze it, or log its behavior, as it executes
  - often simpler, can observe runtime states
  - can be harmful; e.g., malware
  - not everything is necessarily apparent
  - for each run you observe *that* particular execution, and might miss *interesting* parts of the code; e.g.

    ```
    if (random()==0xcafebabe) { /* interesting stuff */ }
    ```

- Static analysis: we reason about the binary without running it
  - you can analyze the whole binary in one go
  - you don't need a CPU/system that can run such a binary
  - (obviously, almost) no knowledge of runtime states
  - can be difficult to pinpoint *interesting* parts

Challenges

- low-level languages
- often, no “symbols”; i.e. meaningful names
- (almost) no type information
- no class/module/namespace boundaries
- code and data can be mixed, and they usually do
- difficulty in adding/changing/removing instructions
- ...

Let’s take a step back: how are (binary) programs built?

Outline

Compilation pipeline

`gcc/g++`, `clang(++)`, `cl.exe` are *front-ends*, which run

1. C/C++ pre-processor, which handles macros/includes
2. C/C++ compiler, which translates into assembler code
3. assembler, which produces relocatable/object files:

$$\texttt{*.c + *.h} \xrightarrow{\texttt{(cpp)+cc1}} \texttt{*.s} \xrightarrow{\texttt{as}} \texttt{*.o}$$

$$\textit{sources in some language} \xrightarrow{\textit{compiler}} \texttt{*.s} \xrightarrow{\texttt{as}} \texttt{*.o}$$

4. (static) linker, which links relocatable files and libraries

to produce the executable/dynamic-library

With default dynamic-linking, the loader + dynamic-linker finish the job

Assembler files

A step towards machine code, however they contain

- assembler instructions, that will be translated into machine code
  - e.g., `push rbp` ⇒ 55
- pseudo-instructions, to emit arbitrary data/bytes
  - e.g., `.string "Hello world!"` ⇒ 48 65 6c 6c 6f...
- directives, to give the assembler information/commands
  - e.g., `.text` ⇒ following items belongs to the `.text` section

Moreover, they use symbols (=names) instead of addresses

- defined; e.g., `main:  push rbp ...`
- undefined; e.g., `call printf` gets translated into:
  1. `e8 ??  ??  ??  ??`; that is, machine code with "holes"
  2. and metadata: relocations that tell the linker how to "fill such holes"

→`c_examples/ex1/hello.c`, `hello.s` and `hello64.o`

Sections

Different data types are kept in different sections; e.g.

Common

- `.text` → code
- `.(r/ro)data` → initialized (read-only) data
- `.bss` → uninitialized data

ELF

- `.symtab/.dynsym` → symbol table/dynamic symbol table
- `.strtab/.dynstr` → symbol table's string tables
- `.rel[a](.dyn)`*section* → (dynamic) relocations for *section*
- `.shstrtab` → string table for section names
- ...

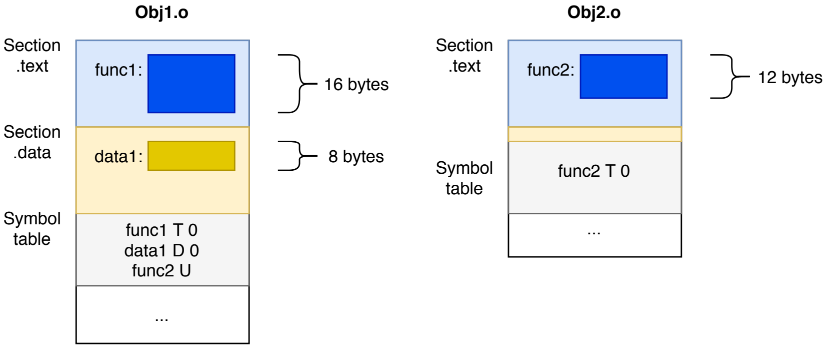
PE

- `.rsrc` → embedded resources
- `.reloc` → relocations
- ...

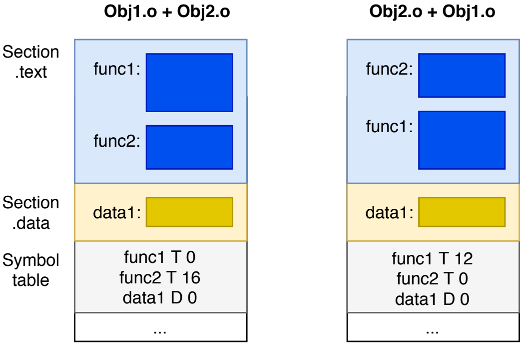
Section merging (1/2)

Object files are merged by the link editor, that

- concatenates all sections with the same name, applying relocations
- merges symbol tables, resolving undefined symbols and making sure that no symbols is multiple defined (there are exceptions)



Section merging (2/2)



Static vs Dynamic linking

The last phase is linking, where the linker combines object-files/libraries

Then, with

- Static linking executables are self-contained
- Dynamic linking executables/libraries contain
  1. *your* code and data
  2. metadata specifying what libraries/functions they need

  so

  - smaller programs, that *automatically* use the most recent libraries
  - less RAM needed (we'll see why later)

Dynamic linking

Dynamic linking can be:

- implicit, i.e. libraries are automatically loaded and linked when the program is run. Functions can be either
  - eagerly bound, at load-time
  - lazily bound, the first time they are called
- explicit; programs can
  - load (and link) dynamic libraries, by invoking special functions
  - lookup symbols in those

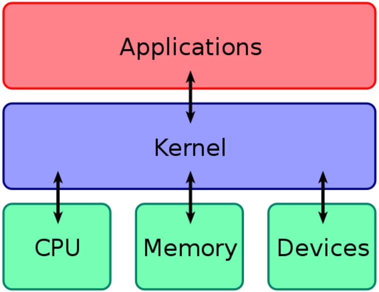
Who brings programs in memory and make them run?

Outline

The operating system layer

Unless you work on bare metal, programs are executed (in user-mode) on top of an Operating System (in supervisor/kernel-mode), which

- handles and virtualises hardware devices
- manages resources
- offers handy abstractions, e.g. a file system view of a block device
- ...



Source: Wikipedia

Processes

When you run a program, you create* a process, identified by a PID

To see the process list:

Linux `proc(5)`, `ps(1)`, `(h)top(1)`, ...

Windows `pslist`, Task manager, Process {Explorer,Hacker}, ...

Each process has its own

- threads, an abstraction of CPUs
  → `c-examples/proc-examples/cpu_example.c`
- address space, an abstraction of RAM
  → `c-examples/proc-examples/mem_example.c`
- security context
- handles/file-descriptors corresponding to “open” resources
- ...

(*) technically, this is a lie; details later

System calls

The OS offers its services by exposing system calls, often wrapped in *functions* that form the Application Programming Interface

- e.g. to open a file, `open` in POSIX or `CreateFile` in Win32
- For C/C++ programmers, "invoking a system call" means calling a *wrapper function*, which executes special instructions

  Linux `libc.so` exposes the syscall wrappers
  Windows `ntdll.dll` exposes the syscall wrappers
    - Which are, in turn, wrapped by API functions in `kernel32.dll`, `user32.dll`, ...
      E.g. `kernel32.CreateFile` relies on `ntdll.NtCreateFile`
- Languages may offer their own (more abstract) APIs; e.g. `fopen`

Compiled programs must be compliant to an Application *Binary* Interface...

ABI

An ABI is a set of specifications allowing the interface of programs, libraries and the operating system, detailing:

- executable and object file formats
- fundamental types (e.g. size and alignment for int, long, ...)
- how data types are laid out in memory
- (sys)calling conventions
- how programs are started up (initialization, dynamic linking, ...)

ABIs

Different architectures have different ABIs, and you can have even multiple ABIs on the same system. Examples of differences are:

- Machine instructions to invoke a system call:
  - 32-bits, x86: `INT` and, on some CPUs, `SYSENTER`
  - 64-bits, x64: `SYSCALL`
- System calls are identified by a number, which can change from version to version; e.g.
  - Linux: `open` is 5 for x86, 2 for x64, and `0x900005` for ARM
    - This is stable for *all* kernel versions (in "regular" PCs)
  - Windows: `NtCreateFile` is
    - x86: `0x163` on 8.0, `0x168` on 8.1, `0x016e` on 10.1507, `0x170` on 10.1511, `0x172` on 10.1607, . . .
    - x64: `0x53` on 8.0, `0x54` on 8.1, `0x55` on 10.1507 to 10.20H2

  See `https://syscalls.w3challs.com/`

Running code

The running code consists of

- user-mode machine instructions of the Instruction Set Architecture, e.g. x86/IA-32 (implemented by Intel 80486, Intel Pentium, AMD Athlon, ...) or ARMv7 (ARM Cortex A12, Apple A6, ...)
  - what if a process executes an instruction that is not in such a subset?
- system calls to the OS
  - you can think of system calls like a sort of “macro-instructions”

ISA+ABI implements an abstract machine for running programs

Emulators

ISA is typically implemented in HW, but *emulators* are (hardware or) software enabling one computer system to behave like another one

Some notable open-source projects are:

- QEMU [Bel05] a generic machine emulator and virtualizer
  `https://www.qemu.org/`
- MAME a multi-purpose emulation framework, with the purpose is to preserve decades of software history
  `https://www.mamedev.org/`
- DOSBox a DOS emulator to re-live the good old days
  `https://www.dosbox.com/`

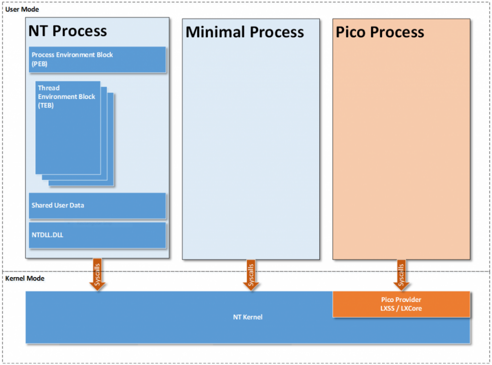
Translator layers

An ABI can be implemented on top of another; e.g.:

- Wine is a compatibility layer capable of running (many) Windows applications on Linux
  `https://www.winehq.org/`
- WSL 1 allows us to run (many) Linux programs on Windows
  `https://docs.microsoft.com/en-us/windows/wsl`
- WoW64 "... allows 32-bit Windows-based applications to run seamlessly on 64-bit Windows"
  `https://docs.microsoft.com/en-us/windows/win32/winprog64/running-32-bit-applications`

Windows-specific: Minimal and Pico processes

- Win8.1: minimal processes, empty address space, no handle-table
  - no official API, used for "secure system" and "memory compression"
- A Pico Process is a minimal process with a kernel Pico Provider
  - all system calls and exceptions forwarded to the provider to handle as it sees fit; e.g. WSL 1 (`wsl --set-version Ubuntu 1`)



https://docs.microsoft.com/en-us/archive/blogs/wsl/pico-process-overview

More resources

- Back to Basics: Compiling and Linking
  by Ben Saks @ CppCon2021
  https://youtu.be/cpkDQaYttR4
- The Bits Between the Bits: How We Get to main()
  by Matt Godbolt @ CppCon2018
  https://www.youtube.com/watch?v=dOfucXtyEsU
- The C++ ABI From the Ground Up
  by Louis Dionne @ CppCon2019
  https://youtu.be/DZ93lP1I7wU
- C and C++ Compiling, by Milan Stevanovic [Ste14]
- Useful video to understand user/kernel interface: "Linux User/Kernel ABI: the realities of how C and C++ programs really talk to the OS"
  by Greg Law @ ACCU 2018
  https://www.youtube.com/watch?v=4CdmGxc5BpU

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[Bel05] Fabrice Bellard.
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Apress, 2014.