Lecture 2: Hello, OS World!

Viewing Operating Systems from Multiple Angles

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COP 4610 Operating Systems
https://xinliulab.github.io/FSU-COP4610-Operating-Systems/

Programs Running on the Operating System

What is an Operating System?

Operating System: A body of software, in fact, that is responsible for <u>making it easy to run programs</u> (even allowing you to seemingly run many at the same time), allowing programs to share memory, enabling programs to interact with devices, and other fun stuff like that. (Operating Systems: Three Easy Pieces)

To understand an "Operating System", you must understand what a "program" is

- This course explains OS from an application-driven perspective

Hello, World!

```c
#include <stdio.h>
int main()
{
    printf("Hello, World!");
    return 0;
}
```

From this point on,
you began your journey as a

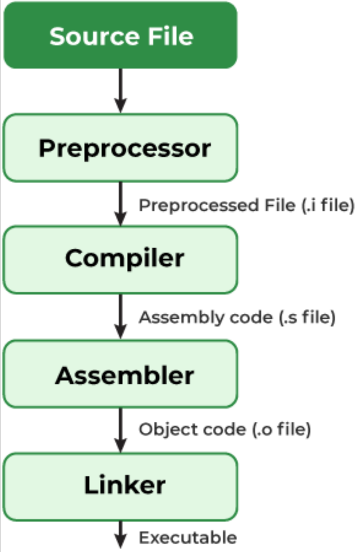
PROGRAMMER.

- Try It: hello.c
- How to make your code readable?
  - Ctrl+Shift+P
  - Search `"Format Document"`.

Each Step of Compilation

What it does and what you get

1. Preprocessor: Expands macros and includes headers.
   `gcc -E hello.c -o hello.i`
   Output: `hello.i`
2. Compiler: Translates C into assembly.
   `gcc -S -O0 hello.c -o hello.s`
   Output: `hello.s`
3. Assembler: Converts assembly to an object file.
   `gcc -c hello.s -o hello.o`
   Output: `hello.o`
4. Linker: Links object files and libraries into an executable.
   `gcc hello.o -o hello`
   Output: `hello`



Computer Programs

```c
#include <stdio.h>

int main() {
    int a = 1;
    int b = 1;
    int c = a + b;

    printf("%d + %d = %d\n", a, b, c);
}
```

- Try It: abc.c

Computer: A machine that executes instructions without emotion

- The machine is always ”correct”
- If the compiler does not optimize, blue“it executes exactly what we write”

Compiler Optimization

If the compiler does not optimize, "it executes exactly what we write"

- What might a compiler optimize in this code?
- Try It Again: abc.c

Bonus Time: 0.5 Extra-Credit Points

How many compilers are there in our computers?

Understanding "Computer Programs"

Everything is a state machine.

- Every program runs on a computer
- The computer is a state machine
- Program execution is state transition

State Machine Model in C

- **PicoC**: a very small C interpreter for scripting; supports step-by-step execution

```
while (1) {
    stmt = next_statement();
    execute(stmt);
}
```

Can we really turn those imaginative ideas into reality?

- In the AI era: If you can imagine it, you can build it
- GDB debugging used to be tedious
- But now, tedious tasks no longer require human labor
  - Even in the future, almost nothing may need humans

Given a Python script that executes GDB step by step and generates a `plot.md`, embedding the state transition of `main()` execution (tracked by local variables only), where each `step` denotes a transition. Executed statements are visualized line by line with highlighted blocks.

Rewrite Any Program Into Non-Recursive Form

Any C Code Can Be Rewritten as Equivalent “SimpleC”

- Each statement does one operation (A function call also counts as one operation)
- Conditional statements contain no operations.
- There is a real tool for this(C Intermediate Language) and an interpreter.

Everything (a C Program) Is a State Machine

- State = variable values + stack
- Initial state = the first statement of `main`
- State transition = execute a small step of one statement

Program = State Machine

A "state machine" is a mathematically rigorous object. This means you can **formally define** it and **reason about it rigorously**.

State:

- A list of stack frames [StackFrame, StackFrame, . . .] plus global variables

Initial State:

- Only one stack frame: `main(argc, argv, PC=0)`
- All global variables are initialized

State Transition:

- Execute the simple statement at `frames[-1].PC`

This Is All of C (Formal Semantics)

With this semantics, we can implement any pure computation:

- From simple to complex: `strlen`, `strstr`, `memcpy`, `sprintf`, ...

But some things *cannot* be implemented:

- Some behaviors of the standard library go beyond "pure computation"
- Examples: `putchar`, `exit`
  - Observation: Pure computation only changes internal program state
  - But these APIs involve "external state" beyond the program
  - **This is the topic of the Operating Systems course.**

The Smallest Program on an Operating System

Let’s try: What Exactly Changes a Program’s State from the Outside?

What Is a Program? (After Compilation)

A Minimal CPU State (i.e., your a.out):

```
struct CPUState {
  uint32_t regs[32], csrs[CSR_COUNT];
  uint8_t *mem;
  uint32_t mem_offset, mem_size;
};
```

Processor: A cold, instruction-executing state machine

- Fetch an instruction from $M[PC]$
- Execute it
- Repeat

Can We Gain Control of the Program from the Start?

Building the "Smallest" Program

- Gain control from the very beginning of the program
- According to *Computer Systems: A Programmer's Perspective*, a program starts executing from `_start`
- Try It: smallest.c

```
void _start() {
  // ...
}
```

Let AI Help You Seize Control

- I defined `_start`, how do I compile and run the program directly from `_start`?
  - `gcc -nostartfiles -static -nostdlib smallest.c`

Building the “Smallest” Program

```
void _start() {
  // ...
}
```

- But this program causes a Segmentation Fault — why?
- Again, please ask our AI teacher.

```
void _start() {
    __asm__("mov $60, %eax\n"  // syscall: exit
            "xor %edi, %edi\n" // status: 0
            "syscall");
}
```

(Binary) Program = State Machine

State

- Your C code compiles to assembly that executes on a machine state.
- A program state is the combination of memory and registers.
- In `gdb`, you can inspect this state (memory and registers).

Initial State

- Defined by the ABI (e.g., a valid `%rsp`)
- What else is defined by ABI (Application Binary Interface)?

State Transitions

- Executing an instruction
- All instructions change only the program's internal state (memory and registers), except the instruction `syscall`.
  - `gdb` can observe the execution of the state machine step by step
- `syscall` instruction: hands over the state machine to the operating system.

Read the Man Pages

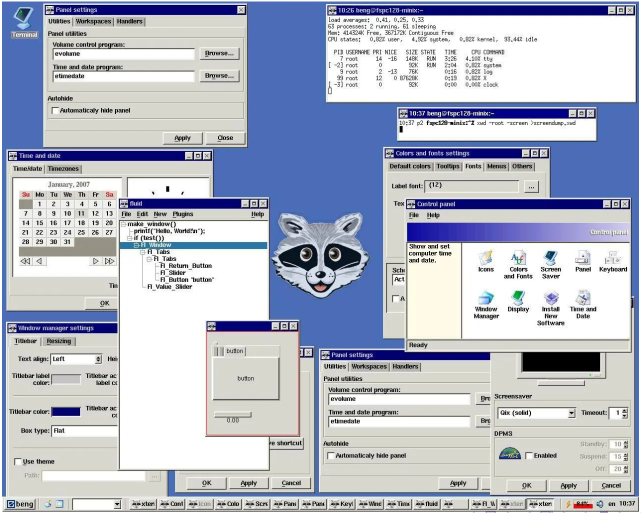
- `man 2 syscalls`: lists all system calls. Online: man7: `syscalls(2)`.
- `man 2 syscall`: describes the generic `syscall()` interface. Online: man7: `syscall(2)`.
  - You will see `x86-64 syscall rax ....` This means that on x86/64 the system call number must be placed in `RAX` (64-bit OS) or `EAX` (32-bit OS).
- You can also use Linux syscall table to see that 60 corresponds to `exit`.
- That is why `"mov $60, %eax\n"`

```
void _start() {
    __asm__("mov $60, %eax\n"  // syscall: exit
            "xor %edi, %edi\n" // status: 0
            "syscall");
}
```

Applications Running on Top of the Operating System

What We Perceive as the “Operating System”

- As users, **we do not perceive the operating system itself**.
- We only interact with **programs running on top of the OS** (processes).



Visible Programs: Applications

Development

- Integrated Development Environments: VSCode, Cursor, ...
- Programming Tools: gcc, clang, nodejs, gdb, ...
- Terminal Tools: tmux, vim, htop, ...

Daily Use

- Office: LibreOffice, GIMP, ...
- Browsers: Chrome, Firefox, ...
- Media: OBS, VLC, ...

Visible (Background) Programs: Utilities

Core Utilities (coreutils)

- *Standard* programs for text and file manipulation
- The default installation is GNU Coreutils
- Lightweight alternatives: busybox, toybox

System Utilities: Essential and Powerful

- Shell, binutils, ...
- Package management: apt, dpkg, ...
- Networking: ip, ssh, curl, ...
- Multimedia: ffmpeg, gstreamer, ...

Invisible Programs: Background Processes

Daemon Processes

- The omnipresent `systemd`
  - `systemd-network`, `systemd-logind`, `systemd-udevd`, ...
- System management: `cron`, `udisksd`, `unattended-upgrade` (loathed), ...
- Services: `httpd`, `sshd`, ...
- Security modules: `auditd`, `firewalld`, ...
- User services: `pulseaudio`, `dbus-daemon`, ...

Graphics and Media

- Wayland compositor: `xfce4`, `lxde`, ...
- `Pulseaudio`, `pipewire`, `video4linux`, ...

Therefore, all these programs...

Any difference from `4_smallest.c`?

- Short answer: No
- Any program = `4_smallest.c` = state machine

Executable files are OS objects

- Essentially no difference from the binary file `a.out`
- Let's examine the "programs" mentioned above in the command line
  - Don't worry even if it's your first time touching the command line...
  - Ask like a ChatGPT: I have an `a.out` file, how can I explore what's inside?

Takeaways: Everything Is a State Machine

- Both high-level code and machine code can be viewed as state machines.
- A compiler acts as a translator between two types of state machines.
- Without an operating system, state machines can only perform pure computation.
- They can't even communicate results to the outside world.
- The only bridge between a program and the OS is through **system calls**.
- On `x86-64`, this bridge is built on the `syscall` instruction.
- Because system calls are so important, the OS provides tools to observe them.
  - For example, `strace` can track a program's system call sequence during execution.
  - We'll dive into this in the next lecture.