OS Structures

Operating Systems
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Some slides are from OSC and Henri Casanova@Hawaii

OS Structures

- Operating System Services
- User and Operating System-Interface
- System Calls
- System Services
- Linkers and Loaders
- Why Applications are Operating System Specific
- Operating-System Design and Implementation
- Operating System Structure
- Building and Booting an Operating System
- Operating System Debugging

A View of Operating System Services

OS Services and Features

Helpful to users

Better efficiency/operation

OS Services and Features

- Load and run a program
- Allow a program to end in multiple ways
  - e.g., with error codes

OS Services and Features

- Allow programs access to I/O devices

OS Services and Features

- Provides file/directory abstractions
- Allow programs to create/delete/read/write
- Implements permissions

OS Services and Features

- Provides abstractions for processes to exchange information
  - Shared memory
  - Message passing

OS Services and Features

- The OS needs to be aware of all errors
  - CPU, memory, I/O, etc.
  - User programs
- The OS needs to take action

OS Services and Features

- Decides which process gets which resource when
  - CPUs, Memory, I/O, etc.

OS Services and Features

- Keeps track of how much is used by each user
  - Can impose limits
  - Useful for statistics

OS Services and Features

- Controls access to resources
- Enforces authentication of all users
- Allows users to protect their content

OS Services and Features

User Operating System Interface - CLI

CLI or **command interpreter** allows direct command entry

- Sometimes implemented in kernel, sometimes by systems program
- Sometimes multiple flavors implemented – **shells**
- Primarily fetches a command from user and executes it
- Sometimes commands built-in, sometimes just names of programs
  - If the latter, adding new features doesn't require shell modification

Bourne Shell Command Interpreter

```
wenbo@parallels: ~
wenbo@parallels: ~ 107x30
7ffc75a5f000-7ffc75a80000 rw-p 00000000 00:00 0                          [stack]
7ffc75aa7000-7ffc75aaa000 r--p 00000000 00:00 0                          [vvar]
7ffc75aaa000-7ffc75aac000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
wenbo@parallels:~$ which cat
/bin/cat
wenbo@parallels:~$ file /bin/cat
/bin/cat: ELF 64-bit LSB shared object, x86-64, version 1 (SYSV), dynamically linked, interpreter /lib64/l,
 for GNU/Linux 3.2.0, BuildID[sha1]=747e524bc20d33ce25ed4aea108e3025e5c3b78f, stripped
wenbo@parallels:~$ cat /proc/self/maps
55b793b79000-55b793b81000 r-xp 00000000 08:01 1048601                    /bin/cat
55b793d80000-55b793d81000 r--p 00007000 08:01 1048601                    /bin/cat
55b793d81000-55b793d82000 rw-p 00008000 08:01 1048601                    /bin/cat
55b794d33000-55b794d54000 rw-p 00000000 00:00 0                          [heap]
7f1974b90000-7f197555f000 r--p 00000000 08:01 662494                     /usr/lib/locale/locale-archive
7f197555f000-7f1975746000 r-xp 00000000 08:01 267596                     /lib/x86_64-linux-gnu/libc-2.27.so
7f1975746000-7f1975946000 ---p 001e7000 08:01 267596                     /lib/x86_64-linux-gnu/libc-2.27.so
7f1975946000-7f197594a000 r--p 001e7000 08:01 267596                     /lib/x86_64-linux-gnu/libc-2.27.so
7f197594a000-7f197594c000 rw-p 001eb000 08:01 267596                     /lib/x86_64-linux-gnu/libc-2.27.so
7f197594c000-7f1975950000 rw-p 00000000 00:00 0
7f1975950000-7f1975977000 r-xp 00000000 08:01 267568                     /lib/x86_64-linux-gnu/ld-2.27.so
7f1975b3c000-7f1975b60000 rw-p 00000000 00:00 0
7f1975b77000-7f1975b78000 r--p 00027000 08:01 267568                     /lib/x86_64-linux-gnu/ld-2.27.so
7f1975b78000-7f1975b79000 rw-p 00028000 08:01 267568                     /lib/x86_64-linux-gnu/ld-2.27.so
7f1975b79000-7f1975b7a000 rw-p 00000000 00:00 0
7ffc73010000-7ffc73031000 rw-p 00000000 00:00 0                          [stack]
7ffc73148000-7ffc7314b000 r--p 00000000 00:00 0                          [vvar]
7ffc7314b000-7ffc7314d000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
wenbo@parallels:~$
```

User Operating System Interface - GUI

- User-friendly **desktop** metaphor interface
  - Usually mouse, keyboard, and monitor
  - **Icons** represent files, programs, actions, etc
  - Various mouse buttons over objects in the interface cause various actions (provide information, options, execute function, open directory (known as a **folder**)
  - Invented at Xerox PARC
- Many systems now include both CLI and GUI interfaces
  - Microsoft Windows is GUI with CLI “command” shell
  - Apple Mac OS X is “Aqua” GUI interface with UNIX kernel underneath and shells available
  - Unix and Linux have CLI with optional GUI interfaces (CDE, KDE, GNOME)

The Mac OS X GUI

Touchscreen Interfaces

- Touchscreen devices require new interfaces
  - Mouse not possible or not desired
  - Actions and selection based on gestures
  - Virtual keyboard for text entry
- Voice commands

System Calls

- Programming interface to the services provided by the OS
- Typically written in a high-level language (C or C++)
- Mostly accessed by programs via a high-level **Application Programming Interface** (**API**) rather than direct system call use
- Three most common APIs:
  - Win32 API for Windows
  - POSIX API for POSIX-based systems (including virtually all versions of UNIX, Linux, and Mac OS X)
  - Java API for the Java virtual machine (JVM)

System Calls

```c
#include<stdio.h>

int main() {
    printf("hello world\n");
    return 0;
}
```

```c
#include <unistd.h>

int main () {
        write(1, "hello world!\n", 13);
        return 0;
}
```

- `printf` is a wrapper of the `write` system call
- C program invoking printf() library call, which calls write() system call
- `printf` explained
  - http://osteras.info/personal/2013/10/11/hello-world-analysis.html
  - https://code.woboq.org/userspace/glibc/sysdeps/unix/sysv/linux/not-cancel.h.html#__write_nocancel
  - https://code.woboq.org/userspace/glibc/sysdeps/unix/sysv/linux/write_nocancel.c.html#__write_nocancel

System Calls

- System call
  - x86_64, system call list in arch/x86/entry/syscalls/syscall_64.tbl

Syscall No.	Name	Entry point	Implementation
0	read	sys_read	fs/read_write.c
1	write	sys_write	fs/read_write.c
2	open	sys_open	fs/open.c
3	close	sys_close	fs/open.c
4	stat	sys_newstat	fs/stat.c
5	fstat	sys_newfstat	fs/stat.c

System Calls

- write() system call go through

```c
#include <unistd.h>

int main () {
        write(1, "hello world!\n", 13);
        return 0;
}
```

```
0000000000400c1d <main>:
  400c1d:       55                      push   %rbp
  400c1e:       48 89 e5                mov    %rsp,%rbp
  400c21:       48 83 ec 10             sub    $0x10,%rsp
  400c25:       89 7d fc                mov    %edi,-0x4(%rbp)
  400c28:       48 89 75 f0             mov    %rsi,-0x10(%rbp)
  400c2c:       ba 0c 00 00 00          mov    $0xc,%edx
  400c31:       48 8d 35 dc 13 09 00    lea    0x913dc(%rip),%rsi
  400c38:       bf 01 00 00 00          mov    $0x1,%edi
  400c3d:       e8 fe 87 04 00          callq  449440 <__libc_write>
```

System Calls

- write() system call go through
  - `syscall` instruction on x86_64
    - Same with `int $0x80` on 32-bit x86
    - Same with `svc` on arm64
  - Move syscall number `0x1` to `%eax`
  - `syscall` will transfer the control flow from user to kernel

```
0000000000449440 <__libc_write>:
  449440:       8b 05 0a 45 07 00       mov    0x7450a(%rip),%eax
  449446:       85 c0                   test   %eax,%eax
  449448:       75 16                   jne    449460 <__libc_write+0x20>
  44944a:       b8 01 00 00 00          mov    $0x1,%eax
  44944f:       0f 05                   syscall
  449451:       48 3d 00 f0 ff ff       cmp    $0xfffffffffffff000,%rax
  449457:       77 57                   ja     4494b0 <__libc_write+0x70>
  449459:       f3 c3                   repz retq
  44945b:       0f 1f 44 00 00          nopl   0x0(%rax,%rax,1)
```

System Calls

- write() system call go through
  - `syscall` instruction on x86_64
    - Same with `int $0x80` on 32-bit x86
    - Same with `svc` on arm64
  - Move syscall number `0x1` to `%eax`
  - `syscall` will transfer the control flow from user to kernel

Kernel

User

```
0000000000449440 <__libc_write>:
  449440:       8b 05 0a 45 07 00       mov    0x7450a(%rip),%eax
  449446:       85 c0                   test   %eax,%eax
  449448:       75 16                   jne    449460 <__libc_write+0x20>
  44944a:       b8 01 00 00 00          mov    $0x1,%eax
  44944f:       0f 05                   syscall
  449451:       48 3d 00 f0 ff ff       cmp    $0xfffffffffffff000,%rax
  449457:       77 57                   ja     4494b0 <__libc_write+0x70>
  449459:       f3 c3                   repz retq
  44945b:       0f 1f 44 00 00          nopl   0x0(%rax,%rax,1)
```

System Calls

- Kernel space
  - 1) `kernel_entry` code will be called
    - Saved all user space registers
  - 2) calls `write` syscall handler
    - Get from syscall_table, which is an array

```
SYSCALL_DEFINE3(write, unsigned int, fd, const char __user *, buf,
                size_t, count)
{
        return ksys_write(fd, buf, count);
}
```

  - After write finish, call `ret_to_user`
    - Restore all saved user space registers
    - Transfer control flow to user space

API – System Call – OS Relationship

System Call Implementation

- Typically, a number associated with each system call
  - **System-call interface** maintains a table indexed according to these numbers
- The system call interface invokes the intended system call in OS kernel and returns status of the system call and any return values
- The caller need know nothing about how the system call is implemented
  - Just needs to obey API and understand what OS will do as a result call
  - Most details of OS interface hidden from programmer by API
    - Managed by run-time support library (set of functions built into libraries included with compiler)

The Hidden Syscall Table

- Let's look a bit inside the Linux Kernel
- Linux kernel v6.0, ARM64
  - arch/arm64/kernel/sys.c

```
#undef __SYSCALL
#define __SYSCALL(nr, sym)      [nr] = (syscall_fn_t)__arm64_##sym,

const syscall_fn_t sys_call_table[__NR_syscalls] = {
        [0 ... __NR_syscalls - 1] = (syscall_fn_t)sys_ni_syscall,
#include <asm/unistd.h>
};
```

```
#define __NR_setxattr 5
__SYSCALL(__NR_setxattr, sys_setxattr)
#define __NR_lsetxattr 6
__SYSCALL(__NR_lsetxattr, sys_lsetxattr)
#define __NR_fsetxattr 7
__SYSCALL(__NR_fsetxattr, sys_fsetxattr)
#define __NR_getxattr 8
__SYSCALL(__NR_getxattr, sys_getxattr)
#define __NR_lgetxattr 9
__SYSCALL(__NR_lgetxattr, sys_lgetxattr)
#define __NR_fgetxattr 10
__SYSCALL(__NR_fgetxattr, sys_fgetxattr)
#define __NR_listxattr 11
__SYSCALL(__NR_listxattr, sys_listxattr)
```

The Hidden Syscall Table

- Let's look a bit inside the Linux Kernel
- Linux kernel v6.0, ARM64
  - make ARCH=arm64 CROSS_COMPILE=aarch64-linux-gnu- defconfig
  - make ARCH=arm64 CROSS_COMPILE=aarch64-linux-gnu-arch/arm64/kernel/sys.i

```
const syscall_fn_t sys_call_table[294] = {
[0] = (syscall_fn_t)__arm64_sys_io_setup,
[1] = (syscall_fn_t)__arm64_sys_io_destroy,
[2] = (syscall_fn_t)__arm64_sys_io_submit,
[3] = (syscall_fn_t)__arm64_sys_io_cancel,
[4] = (syscall_fn_t)__arm64_sys_io_getevents,
[5] = (syscall_fn_t)__arm64_sys_setxattr,
[6] = (syscall_fn_t)__arm64_sys_lsetxattr,
[7] = (syscall_fn_t)__arm64_sys_fsetxattr,
[8] = (syscall_fn_t)__arm64_sys_getxattr,
[9] = (syscall_fn_t)__arm64_sys_lgetxattr,
[10] = (syscall_fn_t)__arm64_sys_fgetxattr,
[11] = (syscall_fn_t)__arm64_sys_listxattr,
[12] = (syscall_fn_t)__arm64_sys_llistxattr,
[13] = (syscall_fn_t)__arm64_sys_flistxattr,
[14] = (syscall_fn_t)__arm64_sys_removexattr,
[15] = (syscall_fn_t)__arm64_sys_lremovexattr,
[16] = (syscall_fn_t)__arm64_sys_fremovexattr,
[17] = (syscall_fn_t)__arm64_sys_getcwd,
[18] = (syscall_fn_t)__arm64_sys_lookup_dcookie,
[19] = (syscall_fn_t)__arm64_sys_eventfd2,
```

The Hidden Syscall Table

- Let's look a bit inside the Linux Kernel
  - Linux kernel v6.0, ARM64
- In Lab 1, also find system call table for:
  - User latest kernel v6.0
  - ARM32
  - RISC-V(32 bit)
  - RISC-V(64 bit)
  - X86(32 bit)
  - X86_64

  - Details were added to Lab 1

Example of System Calls

- System call sequence to copy the contents of one file to another file

System Calls

- On Linux there is a “command” called strace that gives details about which system calls were placed by a program during execution
  - dtruss on Mac OSX is roughly equivalent
- Let’s look at what it shows us when I copy a large file with the cp command on my Linux server
  - strace -xf cp <some large file> bogus
  - Let’s count the number of system calls using the wc command
  - Let’s try with a tiny file and compare
  - Let’s look at the system calls and see if they make sense
  - Let’s try very simple commands and see...
- Conclusion: there are TONS of system calls
- strace can be “attached” to a running program!
  - to find out, e.g., why a program is stuck!

Example of Standard API

EXAMPLE OF STANDARD API

As an example of a standard API, consider the `read()` function that is available in UNIX and Linux systems. The API for this function is obtained from the `man` page by invoking the command

```
man read
```

on the command line. A description of this API appears below:

```
#include <unistd.h>

ssize_t     read(int fd, void *buf, size_t count)
```

return value — function name — parameters

A program that uses the `read()` function must include the `unistd.h` header file, as this file defines the `ssize_t` and `size_t` data types (among other things). The parameters passed to `read()` are as follows:

- `int fd`—the file descriptor to be read
- `void *buf`—a buffer into which the data will be read
- `size_t count`—the maximum number of bytes to be read into the buffer

On a successful read, the number of bytes read is returned. A return value of 0 indicates end of file. If an error occurs, `read()` returns −1.

Time Spent in System Calls?

- The time command is a simple way to time the execution of a program
  - Not great precision/resolution, but fine for getting a rough idea
- Time is used just like strace: place it in front of the command you want to time
- It reports three times:
  - “real” time: wall-clock time (also called elapsed time, execution time, run time, etc.)
  - “user” time: time spent in user code (user mode)
  - “system” time”: time spent in system calls (kernel mode)
- Let’s try it

System Call Parameter Passing

- Often, more information is required than simply identity of desired system call
  - Exact type and amount of information vary according to OS and call
- Three general methods used to pass parameters to the OS
  - Simplest: pass the parameters in registers
    - In some cases, may be more parameters than registers
  - Parameters stored in a block, or table, in memory, and address of block passed as a parameter in a register
    - This approach taken by Linux and Solaris
  - Parameters placed, or **pushed**, onto the **stack** by the program and **popped** off the stack by the operating system
  - Block and stack methods do not limit the number or length of parameters being passed

Parameter Passing via Table

Types of System Calls

- Process control
  - create process, terminate process
  - end, abort
  - load, execute
  - get process attributes, set process attributes
  - wait for time
  - wait event, signal event
  - allocate and free memory
  - Dump memory if error
  - **Debugger** for determining **bugs, single step** execution
  - **Locks** for managing access to shared data between processes

Types of System Calls (cont.)

- File management
  - create file, delete file
  - open, close file
  - read, write, reposition
  - get and set file attributes
- Device management
  - request device, release device
  - read, write, reposition
  - get device attributes, set device attributes
  - logically attach or detach devices

Types of System Calls (Cont.)

- Information maintenance
  - get time or date, set time or date
  - get system data, set system data
  - get and set process, file, or device attributes
- Communications
  - create, delete communication connection
  - send, receive messages if **message passing model** to **host name** or **process name**
    - From **client** to **server**
  - **Shared-memory model** create and gain access to memory regions
  - transfer status information
  - attach and detach remote devices

Types of System Calls (Cont.)

- Protection
  - Control access to resources
  - Get and set permissions
  - Allow and deny user access

Examples of Windows and Unix System Calls

EXAMPLES OF WINDOWS AND UNIX SYSTEM CALLS

The following illustrates various equivalent system calls for Windows and UNIX operating systems.

	Windows	Unix
Process control	`CreateProcess()`	`fork()`
	`ExitProcess()`	`exit()`
	`WaitForSingleObject()`	`wait()`
File management	`CreateFile()`	`open()`
	`ReadFile()`	`read()`
	`WriteFile()`	`write()`
	`CloseHandle()`	`close()`
Device management	`SetConsoleMode()`	`ioctl()`
	`ReadConsole()`	`read()`
	`WriteConsole()`	`write()`
Information maintenance	`GetCurrentProcessID()`	`getpid()`
	`SetTimer()`	`alarm()`
	`Sleep()`	`sleep()`
Communications	`CreatePipe()`	`pipe()`
	`CreateFileMapping()`	`shm_open()`
	`MapViewOfFile()`	`mmap()`
Protection	`SetFileSecurity()`	`chmod()`
	`InitlializeSecurityDescriptor()`	`umask()`
	`SetSecurityDescriptorGroup()`	`chown()`

System Services

- System programs provide a convenient environment for program development and execution. They can be divided into:
  - File manipulation
  - Status information sometimes stored in a file
  - Programming language support
  - Program loading and execution
  - Communications
  - Background services
  - Application programs
- Most users' view of the operation system is defined by system programs, not the actual system calls

System Services (cont.)

- Provide a convenient environment for program development and execution
  - Some of them are simply user interfaces to system calls; others are considerably more complex
- **File management** - Create, delete, copy, rename, print, dump, list, and generally manipulate files and directories
- **Status information**
  - Some ask the system for info - date, time, amount of available memory, disk space, number of users
  - Others provide detailed performance, logging, and debugging information
  - Typically, these programs format and print the output to the terminal or other output devices
  - Some systems implement a **registry** - used to store and retrieve configuration information

System Services (Cont.)

- **File modification**
  - Text editors to create and modify files
  - Special commands to search contents of files or perform transformations of the text
- **Programming-language support** - Compilers, assemblers, debuggers and interpreters sometimes provided
- **Program loading and execution**- Absolute loaders, relocatable loaders, linkage editors, and overlay-loaders, debugging systems for higher-level and machine language
- **Communications** - Provide the mechanism for creating virtual connections among processes, users, and computer systems
  - Allow users to send messages to one another's screens, browse web pages, send electronic-mail messages, log in remotely, transfer files from one machine to another

System Services (Cont.)

- **Background Services**
  - Launch at boot time
    - Some for system startup, then terminate
    - Some from system boot to shutdown
  - Provide facilities like disk checking, process scheduling, error logging, printing
  - Run in user context not kernel context
  - Known as **services**, **subsystems**, **daemons**
- **Application programs**
  - Don't pertain to system
  - Run by users
  - Not typically considered part of OS
  - Launched by command line, mouse click, finger poke

Linkers and Loaders

- Source code compiled into object files designed to be loaded into any physical memory location – **relocatable object file**
- **Linker** combines these into single binary **executable** file
  - Also brings in libraries
- Program resides on secondary storage as binary executable
- Must be brought into memory by **loader** to be executed
  - **Relocation** assigns final addresses to program parts and adjusts code and data in program to match those addresses
- Modern general purpose systems don't link libraries into executables
  - Rather, **dynamically linked libraries** (in Windows, **DLLs**) are loaded as needed, shared by all that use the same version of that same library (loaded once)
- Object, executable files have standard formats, so operating system knows how to load and start them

The Role of the Linker and Loader

ELF binary basics

- What's main（a.out）
  - Executable and Linkable Format - ELF
  - Program header table and section header table
    - For Linker and Loader
  - .text: code
  - .rodata: initialized read-only data
  - .data: initialized data
  - .bss: uninitialized data
- Quiz
  - Where does static variable go?
  - Static const?

ELF binary basics

- Dump all sections
  - *readelf -S a.out*

```
Wenbos-MacBook-Pro:c-hello wenbo$ readelf -S a.out
There are 31 section headers, starting at offset 0x1708:

Section Headers:
  [Nr] Name              Type             Address           Offset
       Size              EntSize          Flags  Link  Info  Align
  [ 0]                   NULL             0000000000000000  00000000
       0000000000000000  0000000000000000           0     0     0
  [ 1] .interp           PROGBITS         0000000000000238  00000238
       000000000000001c  0000000000000000   A       0     0     1
  [ 2] .note.ABI-tag     NOTE             0000000000000254  00000254
       0000000000000020  0000000000000000   A       0     0     4

  [13] .text             PROGBITS         0000000000000550  00000550
       00000000000001a2  0000000000000000  AX       0     0     16
  [14] .fini             PROGBITS         00000000000006f4  000006f4
       0000000000000009  0000000000000000  AX       0     0     4
  [15] .rodata           PROGBITS         0000000000000700  00000700
       0000000000000010  0000000000000000   A       0     0     4

  [23] .data             PROGBITS         0000000000002000  00001000
       0000000000000010  0000000000000000  WA       0     0     8
  [24] .tm_clone_table   PROGBITS         0000000000002010  00001010
       0000000000000000  0000000000000000  WA       0     0     8
  [25] .bss              NOBITS           0000000000002010  00001010
       0000000000000001  0000000000000000  WA       0     0     1
```

Linking

- Static linking
  - All needed code is packed in single binary, leading to large binary
- Dynamic linking
  - Reuse libraries to reduce ELF file size
  - How to resolve library calls?

Linking

- Statically-linked ELF has no .interp section
- Dynamically-linked ELF has .interp section

```
wenbo@parallels:~/os-course$ readelf -S a.dynamic
There are 29 section headers, starting at offset 0x1928:

Section Headers:
  [Nr] Name              Type             Address           Offset
       Size              EntSize          Flags  Link  Info  Align
  [ 0]                   NULL             0000000000000000  00000000
       0000000000000000  0000000000000000           0     0     0
  [ 1] .interp           PROGBITS         0000000000000238  00000238
       000000000000001c  0000000000000000   A       0     0     1
```

```
wenbo@parallels:~/os-course$ readelf -p .interp a.dynamic

String dump of section '.interp':
  [     0]  /lib64/ld-linux-x86-64.so.2
```

Linking

- Static linking
  - All needed code is packed in single binary, leading to large binary
- Dynamic linking
  - Reuse libraries to reduce ELF file size
  - How to resolve library calls?
    - It is the loader who resolves lib calls.

Running a binary

- Who setups ELF file mapping?
- Who setups stack and heap?
- Who setups libraries?

https://manybutfinite.com/post/anatomy-of-a-program-in-memory/

Running a binary

- ELF to memory layout

```
Wenbos-MacBook-Pro:android_common.git wenbo$ readelf -S vmlinux
There are 38 section headers, starting at offset 0xbf4a700:

Section Headers:
  [Nr] Name              Type             Address           Offset
       Size              EntSize          Flags  Link  Info  Align
  [ 0]                   NULL             0000000000000000  00000000
       0000000000000000  0000000000000000           0     0     0
  [ 1] .head.text        PROGBITS         ffffff8008080000  00010000
       0000000000001000  0000000000000000  AX       0     0     4096
  [ 2] .text             PROGBITS         ffffff8008081000  00011000
       0000000000a459c0  0000000000000008  AX       0     0     2048
  [ 3] .rodata           PROGBITS         ffffff8008ad0000  00a60000
       00000000003ffbd0  0000000000000000  WA       0     0     4096
```

Running a binary

- Run a program

pid

```
wenbo@wenbo-ThinkPad:~$ cat /proc/self/maps
559a61b8d000-559a61b95000 r-xp 00000000 08:05 3145753                    /bin/cat
559a61d94000-559a61d95000 r--p 00007000 08:05 3145753                    /bin/cat
559a61d95000-559a61d96000 rw-p 00008000 08:05 3145753                    /bin/cat
559a63860000-559a63881000 rw-p 00000000 00:00 0                          [heap]
7f8fc2690000-7f8fc305f000 r--p 00000000 08:05 4725339                    /usr/lib/locale/locale-archive
7f8fc305f000-7f8fc3246000 r-xp 00000000 08:05 2626368                    /lib/x86_64-linux-gnu/libc-2.27.so
7f8fc3246000-7f8fc3446000 ---p 001e7000 08:05 2626368                    /lib/x86_64-linux-gnu/libc-2.27.so
7f8fc3446000-7f8fc344a000 r--p 001e7000 08:05 2626368                    /lib/x86_64-linux-gnu/libc-2.27.so
7f8fc344a000-7f8fc344c000 rw-p 001eb000 08:05 2626368                    /lib/x86_64-linux-gnu/libc-2.27.so
7f8fc344c000-7f8fc3450000 rw-p 00000000 00:00 0
7f8fc3450000-7f8fc3477000 r-xp 00000000 08:05 2626340                    /lib/x86_64-linux-gnu/ld-2.27.so
7f8fc3635000-7f8fc3659000 rw-p 00000000 00:00 0
7f8fc3677000-7f8fc3678000 r--p 00027000 08:05 2626340                    /lib/x86_64-linux-gnu/ld-2.27.so
7f8fc3678000-7f8fc3679000 rw-p 00028000 08:05 2626340                    /lib/x86_64-linux-gnu/ld-2.27.so
7f8fc3679000-7f8fc367a000 rw-p 00000000 00:00 0
7ffd416e0000-7ffd41701000 rw-p 00000000 00:00 0                          [stack]
7ffd4178b000-7ffd4178e000 r--p 00000000 00:00 0                          [vvar]
7ffd4178e000-7ffd41790000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
```

Running a binary (Statically-linked)

- Behind ./a.out
  - *strace ./a.out*
  - Call a serial of system calls: execve, brk, write
- Revisit system call

```
wenbo@parallels:~/os-course$ strace ./a.static
execve("./a.static", ["./a.static"], 0x7ffc89bb12f0 /* 68 vars */) = 0
brk(NULL)                               = 0xc17000
brk(0xc181c0)                           = 0xc181c0
arch_prctl(ARCH_SET_FS, 0xc17880)       = 0
uname({sysname="Linux", nodename="parallels", ...}) = 0
readlink("/proc/self/exe", "/home/wenbo/os-course/a.static", 4096) = 30
brk(0xc391c0)                           = 0xc391c0
brk(0xc3a000)                           = 0xc3a000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(136, 2), ...}) = 0
write(1, "hello world!\n", 13hello world!
)           = 13
exit_group(0)                           = ?
+++ exited with 0 +++
```

Running a binary

- Behind ./a.out
  - Entry point address
  - In kernel v3.18, syscall SyS_execve -> do_execve -> do_execve_common -> exec_binprm -> search_binary_handler -> load_elf_binary -> start_thread
  - start_thread will use entry point address as user space program start address
  - Linux kernel cross reference: https://elixir.bootlin.com/linux/v5.1-rc4/source

```
static int load_elf_binary(struct linux_binprm *bprm)
{
        ......
        if (elf_interpreter) {
        ......
        } else {
                elf_entry = loc->elf_ex.e_entry;
                if (BAD_ADDR(elf_entry)) {
                        retval = -EINVAL;
                        goto out_free_dentry;
                }
        }
        ......
        start_thread(regs, elf_entry, bprm->p);
}

static inline void start_thread_common(struct pt_regs *regs, unsigned long pc)
{
        memset(regs, 0, sizeof(*regs));
        regs->syscallno = ~0UL;
        regs->pc = pc;
}
```

Running a binary

- Who setups ELF file mapping
  - Kernel
  - exec syscall
- Who setups stack and heap?
  - Kernel
  - exec syscall
- Who setups libraries?
  - Loader
  - ld-xxx

https://manybutfinite.com/post/anatomy-of-a-program-in-memory/

Clarify

- Stack and Heap in OS
- Stack and Heap in Data Structure

Running a binary (Statically-linked)

- Where to start?
- Static link
  - All needed code is packed in single binary, leading to large binary
  - Does not require dynamic loader
  - **_start is executed after evecve system call**

- R

```
wenbo@parallels:~/os-course$ gcc -static main.c -o a.static
wenbo@parallels:~/os-course$ readelf -h a.static
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 03 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - GNU
  ABI Version:                       0
  Type:                              EXEC (Executable file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
  Entry point address:               0x400a50
```

ELF binary (Statically-linked)

- Dump code
  - objdump -d a.out

crtn.o compiler linked with main.o

```
0000000000400a50 <_start>:
  400a50:       31 ed                   xor    %ebp,%ebp
  400a52:       49 89 d1                mov    %rdx,%r9
  400a55:       5e                      pop    %rsi
  400a56:       48 89 e2                mov    %rsp,%rdx
  400a59:       48 83 e4 f0             and    $0xfffffffffffffff0,%rsp
  400a5d:       50                      push   %rax
  400a5e:       54                      push   %rsp
  400a5f:       49 c7 c0 10 19 40 00    mov    $0x401910,%r8
  400a66:       48 c7 c1 70 18 40 00    mov    $0x401870,%rcx
  400a6d:       48 c7 c7 6d 0b 40 00    mov    $0x400b6d,%rdi
  400a74:       67 e8 86 03 00 00       addr32 callq 400e00 <__libc_start_main>
  400a7a:       f4                      hlt
```

```
0000000000400b6d <main>:
  400b6d:       55                      push   %rbp
  400b6e:       48 89 e5                mov    %rsp,%rbp
  400b71:       48 8d 3d 2c 14 09 00    lea    0x9142c(%rip),%rdi
  400b78:       e8 a3 f6 00 00          callq  410220 <_IO_puts>
  400b7d:       b8 00 00 00 00          mov    $0x0,%eax
  400b82:       5d                      pop    %rbp
  400b83:       c3                      retq
  400b84:       66 2e 0f 1f 84 00 00    nopw   %cs:0x0(%rax,%rax,1)
  400b8b:       00 00 00
  400b8e:       66 90                   xchg   %ax,%ax
```

ELF binary basics

- __libc_start_main
  - glibc/csu/libc-start.c
  - Setup environment and stack, then call main

```
93  # define LIBC_START_MAIN __libc_start_main
```

```
129 LIBC_START_MAIN (int (*main) (int, char **, char ** MAIN_AUXVEC_DECL),
130                  int argc, char **argv,
131 #ifdef LIBC_START_MAIN_AUXVEC_ARG
132                  ElfW(auxv_t) *auxvec,
133 #endif
134                  __typeof (main) init,
135                  void (*fini) (void),
136                  void (*rtld_fini) (void), void *stack_end)
137 {
138   /* Result of the 'main' function.  */
139   int result;
140
141   __libc_multiple_libcs = &_dl_starting_up && !_dl_starting_up;
```

```
338   /* Nothing fancy, just call the function.  */
339   result = main (argc, argv, __environ MAIN_AUXVEC_PARAM);
```

Running a binary

- Behind ./a.out
  - Entry point address
  - In kernel v3.18, syscall SyS_execve -> do_execve -> do_execve_common -> exec_binprm -> search_binary_handler -> load_elf_binary -> start_thread
  - start_thread will use entry point address as user space program start address
  - Linux kernel cross reference: https://elixir.bootlin.com/linux/v5.1-rc4/source

```
static int load_elf_binary(struct linux_binprm *bprm)
{
        ......
        if (elf_interpreter) {
        ......
        } else {
                elf_entry = loc->elf_ex.e_entry;
                if (BAD_ADDR(elf_entry)) {
                        retval = -EINVAL;
                        goto out_free_dentry;
                }
        }
        ......
        start_thread(regs, elf_entry, bprm->p);
}

static inline void start_thread_common(struct pt_regs *regs, unsigned long pc)
{
        memset(regs, 0, sizeof(*regs));
        regs->syscallno = ~0UL;
        regs->pc = pc;
}
```

Running statically-linked ELF

From 长亭科技

Static link vs dynamic link

- Running statically-linked ELF
  - All code are packed in single binary, leading to large binary
  - Does not require dynamic loader
  - _start is executed after evecve system call
- Running dynamically-linked ELF
  - Reuse libraries to reduce ELF file size
  - Where to start? 0x530?
- Read header: *readelf -h a.out*

```
wenbo@parallels:~/os-course$ gcc main.c -o a.dynamic
wenbo@parallels:~/os-course$ readelf -h a.dynamic
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              DYN (Shared object file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
  Entry point address:               0x530
```

ELF binary (Dynamically-linked)

- Dump code
  - objdump -d a.out

```
0000000000000530 <_start>:
 530:   31 ed                   xor    %ebp,%ebp
 532:   49 89 d1                mov    %rdx,%r9
 535:   5e                      pop    %rsi
 536:   48 89 e2                mov    %rsp,%rdx
 539:   48 83 e4 f0             and    $0xfffffffffffffff0,%rsp
 53d:   50                      push   %rax
 53e:   54                      push   %rsp
 53f:   4c 8d 05 8a 01 00 00    lea    0x18a(%rip),%r8        # 6d0 <__libc_csu_fini>
 546:   48 8d 0d 13 01 00 00    lea    0x113(%rip),%rcx        # 660 <__libc_csu_init>
 54d:   48 8d 3d e6 00 00 00    lea    0xe6(%rip),%rdi        # 63a <main>
 554:   ff 15 86 0a 20 00       callq  *0x200a86(%rip)        # 200fe0 <__libc_start_main@GLIBC_2.2.5>
 55a:   f4                      hlt
```

```
000000000000063a <main>:
 63a:   55                      push   %rbp
 63b:   48 89 e5                mov    %rsp,%rbp
 63e:   48 8d 3d 9f 00 00 00    lea    0x9f(%rip),%rdi
 645:   e8 c6 fe ff ff          callq  510 <puts@plt>
 64a:   b8 00 00 00 00          mov    $0x0,%eax
 64f:   5d                      pop    %rbp
 650:   c3                      retq
```

When is puts resolved?

Running a binary (Dynamically-linked)

- Behind ./a.out
  - *strace ./a.out*
  - Call more system calls
- Details in https://unix.stackexchange.com/questions/160578/strace-hello-world-program

```
wenbo@parallels:~/os-course$ strace ./a.dynamic
execve("./a.dynamic", ["./a.dynamic"], 0x7fff3a6f0fb0 /* 68 v
brk(NULL)                                   = 0x5557aa1b4000
access("/etc/ld.so.nohwcap", F_OK)          = -1 ENOENT (No such
access("/etc/ld.so.preload", R_OK)          = -1 ENOENT (No such
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=108112, ...}) = 0
mmap(NULL, 108112, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7f08914a
close(3)                                    = 0
access("/etc/ld.so.nohwcap", F_OK)          = -1 ENOENT (No such
openat(AT_FDCWD, "/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0\20\35
fstat(3, {st_mode=S_IFREG|0755, st_size=2030928, ...}) = 0
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYM
mmap(NULL, 4131552, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENY
mprotect(0x7f089108e000, 2097152, PROT_NONE) = 0
mmap(0x7f089128e000, 24576, PROT_READ|PROT_WRITE, MAP_PRIVATE
mmap(0x7f0891294000, 15072, PROT_READ|PROT_WRITE, MAP_PRIVATE
close(3)                                    = 0
arch_prctl(ARCH_SET_FS, 0x7f08914a54c0) = 0
mprotect(0x7f089128e000, 16384, PROT_READ) = 0
mprotect(0x5557a8550000, 4096, PROT_READ) = 0
mprotect(0x7f08914c1000, 4096, PROT_READ) = 0
munmap(0x7f08914a6000, 108112)              = 0
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(136, 2), ...}
brk(NULL)                                   = 0x5557aa1b4000
brk(0x5557aa1d5000)                         = 0x5557aa1d5000
write(1, "hello world!\n", 13hello world!
)           = 13
exit_group(0)                               = ?
+++ exited with 0 +++
```

Dynamic loader

Running a binary

- In function load_elf_binary
- https://elixir.bootlin.com/linux/v5.15-rc3/source/fs/binfmt_elf.c#L1214

```
if (elf_interpreter) {
        unsigned long interp_map_addr = 0;

        elf_entry = load_elf_interp(&loc->interp_elf_ex,
                                    interpreter,
                                    &interp_map_addr,
                                    load_bias);
        if (!IS_ERR((void *)elf_entry)) {
                /*
                 * load_elf_interp() returns relocation
                 * adjustment
                 */
                interp_load_addr = elf_entry;
                elf_entry += loc->interp_elf_ex.e_entry;
        }
        if (BAD_ADDR(elf_entry)) {
                retval = IS_ERR((void *)elf_entry) ?
                                (int)elf_entry : -EINVAL;
                goto out_free_dentry;
        }
        reloc_func_desc = interp_load_addr;

        allow_write_access(interpreter);
        fput(interpreter);
        kfree(elf_interpreter);
} else {
        elf_entry = loc->elf_ex.e_entry;
        if (BAD_ADDR(elf_entry)) {
                retval = -EINVAL;
                goto out_free_dentry;
        }
}
```

Running a binary

- In function load_elf_binary
- https://elixir.bootlin.com/linux/v5.15-rc3/source/fs/binfmt_elf.c#L1214

Dynamically-linked ELF, entry points to loader

Statically-linked ELF, entry points to _start

```
if (elf_interpreter) {
        unsigned long interp_map_addr = 0;

        elf_entry = load_elf_interp(&loc->interp_elf_ex,
                                    interpreter,
                                    &interp_map_addr,
                                    load_bias);
        if (!IS_ERR((void *)elf_entry)) {
                /*
                 * load_elf_interp() returns relocation
                 * adjustment
                 */
                interp_load_addr = elf_entry;
                elf_entry += loc->interp_elf_ex.e_entry;
        }
        if (BAD_ADDR(elf_entry)) {
                retval = IS_ERR((void *)elf_entry) ?
                                (int)elf_entry : -EINVAL;
                goto out_free_dentry;
        }
        reloc_func_desc = interp_load_addr;

        allow_write_access(interpreter);
        fput(interpreter);
        kfree(elf_interpreter);
} else {
        elf_entry = loc->elf_ex.e_entry;
        if (BAD_ADDR(elf_entry)) {
                retval = -EINVAL;
                goto out_free_dentry;
        }
}
```

Running statically-linked ELF

From 长亭科技

Running dynamically-linked ELF

From 长亭科技

Running a binary

- Run a dynamically-linked program

```
wenbo@wenbo-ThinkPad:~$ cat /proc/self/maps
559a61b8d000-559a61b95000 r-xp 00000000 08:05 3145753                    /bin/cat
559a61d94000-559a61d95000 r--p 00007000 08:05 3145753                    /bin/cat
559a61d95000-559a61d96000 rw-p 00008000 08:05 3145753                    /bin/cat
559a63860000-559a63881000 rw-p 00000000 00:00 0                          [heap]
7f8fc2690000-7f8fc305f000 r--p 00000000 08:05 4725339                    /usr/lib/locale/locale-archive
7f8fc305f000-7f8fc3246000 r-xp 00000000 08:05 2626368                    /lib/x86_64-linux-gnu/libc-2.27.so
7f8fc3246000-7f8fc3446000 ---p 001e7000 08:05 2626368                    /lib/x86_64-linux-gnu/libc-2.27.so
7f8fc3446000-7f8fc344a000 r--p 001e7000 08:05 2626368                    /lib/x86_64-linux-gnu/libc-2.27.so
7f8fc344a000-7f8fc344c000 rw-p 001eb000 08:05 2626368                    /lib/x86_64-linux-gnu/libc-2.27.so
7f8fc344c000-7f8fc3450000 rw-p 00000000 00:00 0
7f8fc3450000-7f8fc3477000 r-xp 00000000 08:05 2626340                    /lib/x86_64-linux-gnu/ld-2.27.so
7f8fc3635000-7f8fc3659000 rw-p 00000000 00:00 0
7f8fc3677000-7f8fc3678000 r--p 00027000 08:05 2626340                    /lib/x86_64-linux-gnu/ld-2.27.so
7f8fc3678000-7f8fc3679000 rw-p 00028000 08:05 2626340                    /lib/x86_64-linux-gnu/ld-2.27.so
7f8fc3679000-7f8fc367a000 rw-p 00000000 00:00 0
7ffd416e0000-7ffd41701000 rw-p 00000000 00:00 0                          [stack]
7ffd4178b000-7ffd4178e000 r--p 00000000 00:00 0                          [vvar]
7ffd4178e000-7ffd41790000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
```

How about statically-linked ELF?

Recommendation

Why Applications are Operating System Specific

- Apps compiled on one system usually not executable on other operating systems
- Each operating system provides its own unique system calls
  - Own file formats, etc
- Apps can be multi-operating system
  - Written in interpreted language like Python, Ruby, and interpreter available on multiple operating systems
  - App written in language that includes a VM containing the running app (like Java)
  - Use standard language (like C), compile separately on each operating system to run on each
- **Application Binary Interface** (**ABI**) is architecture equivalent of API, defines how different components of binary code can interface for a given operating system on a given architecture, CPU, etc

Operating System Design and Implementation

- Design and Implementation of OS not “solvable”, but some approaches have proven successful
- Internal structure of different Operating Systems can vary widely
- Affected by choice of hardware, type of system
- Start the design by defining goals and specifications
- **User** goals and **System** goals
  - User goals – operating system should be convenient to use, easy to learn, reliable, safe, and fast
  - System goals – operating system should be easy to design, implement, and maintain, as well as flexible, reliable, error-free, and efficient

Operating System Design and Implementation (Cont.)

- Important principle to separate

  Policy: ***What*** will be done?
  Mechanism: ***How*** to do it?

- Mechanisms determine how to do something, policies decide what will be done
- The separation of policy from mechanism
  - A very important principle
  - Allows policy changes without changed implemented mechanism
- Door Example
  - Entrance policy with regular door lock (mechanism) BAD
  - Smart door lock (mechanism) GOOD
- Scheduling
  - Scheduling policy and how to pick the next (mechanism)

Implementation

- Much variation
  - Early OSes in assembly language
  - Then system programming languages like Algol, PL/1
  - Now C, C++
- Actually usually a mix of languages
  - Lowest levels in assembly
  - Main body in C
  - Systems programs in C, C++, scripting languages like PERL, Python, shell scripts
- More high-level language easier to **port** to other hardware
  - But slower
- **Emulation** can allow an OS to run on non-native hardware

Operating System Structure

- General-purpose OS is very large program
- Various ways to structure ones
  - Simple structure – MS-DOS
  - Monolithic – Unix, Linux
  - Layered – an abstraction
  - Microkernel – Mach

Monolithic Structure – Original UNIX

UNIX – limited by hardware functionality, the original UNIX operating system had limited structuring. The UNIX OS consists of two separable parts

- Systems programs
- The kernel
  - Consists of everything below the system-call interface and above the physical hardware
  - Provides the file system, CPU scheduling, memory management, and other operating-system functions; a large number of functions for one level

Traditional UNIX System Structure

Beyond simple but not fully layered

Linux System Structure

Monolithic supports loadable kernel module

Linux kernel map

© 2007–2010 Constantine Shulyupin www.MakeLinux.net/kernel-map

Layered Approach

- The operating system is divided into a number of layers (levels), each built on top of lower layers. The bottom layer (layer 0), is the hardware; the highest (layer N) is the user interface.
- With modularity, layers are selected such that each uses functions (operations) and services of only lower-level layers

Microkernels

- Moves as much from the kernel into user space
- **Mach** example of **microkernel**
  - Mac OS X kernel (**Darwin**) partly based on Mach
- Communication takes place between user modules using **message passing**
- Benefits:
  - Easier to extend a microkernel
  - Easier to port the operating system to new architectures
  - More reliable (less code is running in kernel mode)
  - More secure
- Detriments:
  - Performance overhead of user space to kernel space communication

Microkernel System Structure

Modules

- Many modern operating systems implement **loadable kernel modules** (**LKMs**)
  - Uses object-oriented approach
  - Each core component is separate
  - Each talks to the others over known interfaces
  - Each is loadable as needed within the kernel
- Overall, similar to layers but with more flexible
  - Linux, Solaris, etc

Hybrid Systems

- Most modern operating systems are actually not one pure model
  - Hybrid combines multiple approaches to address performance, security, usability needs
  - Linux and Solaris kernels in kernel address space, so monolithic, plus modular for dynamic loading of functionality
  - Windows mostly monolithic, plus microkernel for different subsystem ***personalities***
- Apple Mac OS X hybrid, layered, **Aqua** UI plus **Cocoa** programming environment
  - Below is kernel consisting of Mach microkernel and BSD Unix parts, plus I/O kit and dynamically loadable modules (called **kernel extensions**)

macOS and iOS Structure

Android

- Developed by Open Handset Alliance (mostly Google)
  - Open Source
- Similar stack to iOS
- Based on Linux kernel but modified
  - Provides process, memory, device-driver management
  - Adds power management
- Runtime environment includes core set of libraries and Dalvik virtual machine
  - Apps developed in Java plus Android API
    - Java class files compiled to Java bytecode then translated to executable than runs in Dalvik VM
- Libraries include frameworks for web browser (webkit), database (SQLite), multimedia, smaller libc

Android Architecture

openEuler

- EulerOS is a Linux-based OS for server
  - The primary maintainer is Huawei
- EulerOS is open-sourced in 2019, named as openEuler
- Details are in separated slides

https://openeuler.org/

https://gitee.com/openeuler/

Building and Booting an Operating System

- Operating systems generally designed to run on a class of systems with variety of perpherals
- Commonly, operating system already installed on purchased computer
  - But can build and install some other operating systems
  - If generating an operating system from scratch
    - Write the operating system source code
    - Configure the operating system for the system on which it will run
    - Compile the operating system
    - Install the operating system
    - Boot the computer and its new operating system

Building and Booting Linux

- Download Linux source code (http://www.kernel.org)
- Configure kernel via "`make menuconfig`"
- Compile the kernel using "`make`"
  - Produces `vmlinuz`, the kernel image
  - Compile kernel modules via "`make modules`"
  - Install kernel modules into `vmlinuz` via "`make modules_install`"
  - Install new kernel on the system via "`make install`"

System Boot

- When power initialized on system, execution starts at a fixed memory location
- Operating system must be made available to hardware so hardware can start it
  - Small piece of code – **bootstrap loader**, **BIOS**, stored in **ROM** or **EEPROM** locates the kernel, loads it into memory, and starts it
  - Sometimes two-step process where **boot block** at fixed location loaded by ROM code, which loads bootstrap loader from disk
  - Modern systems replace BIOS with **Unified Extensible Firmware Interface** (**UEFI**)
- Common bootstrap loader, **GRUB**, allows selection of kernel from multiple disks, versions, kernel options
- Kernel loads and system is then **running**
- Boot loaders frequently allow various boot states, such as single user mode

Operating-System Debugging

Kernighan's Law: "Debugging is twice as hard as writing the code in the first place. Therefore, if you write the code as cleverly as possible, you are, by definition, not smart enough to debug it."

- OS generate **log files** containing error information
- Failure of an application can generate **core dump** file capturing memory of the process
- Operating system failure can generate **crash dump** file containing kernel memory
- Beyond crashes, performance tuning can optimize system performance
  - Sometimes using ***trace listings*** of activities, recorded for analysis
  - **Profiling** is periodic sampling of instruction pointer to look for statistical trends

Performance Tuning

- Improve performance by removing bottlenecks
- OS must provide means of computing and displaying measures of system behavior
- For example, “top” program or Windows Task Manager

Tracing

- Collects data for a specific event, such as steps involved in a system call invocation
- Tools include
  - strace – trace system calls invoked by a process
  - gdb – source-level debugger
  - perf – collection of Linux performance tools
  - tcpdump – collects network packets

Linux bcc/BPF Tracing Tools

Takeaway

- System calls
  - Kernel interfaces provided to user space
  - Syscall table
  - strace
- OS Structures
  - Monolithic vs microkernel
- Linkers and Loaders
  - Research more by yourself
  - Static linking vs dynamic linking
  - Loaders
- Separation of policy from mechanism