Lecture 17: Introduction to Linux Kernel

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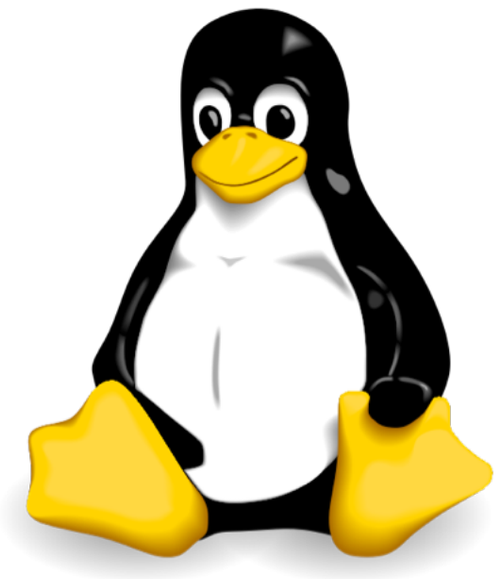
Slides based upon Linux Device Drivers, 3rd Edition
http://lwn.net/Kernel/LDD3/

Topics

- Linux-specific Filesystems
- Linux Kernel Source Tree Layout
- Writing Kernel Modules

Linux Kernel

- Initially created in 1991 by Linus Torvalds, as a hobby during college
- Supported by numerous companies, often for embedded and specialized systems
- Now used by billions of people, via Android
- Over 25 million lines of code spread across over 62,000+ files



Linux Distributions

- Although there is just one official Linux kernel, various people/groups package the kernel with system libraries, system utilities, and common applications to form entire distributions

- Thousands of distributions:
  - Red Hat: Fedora, Red Hat Enterprise Linux (RHEL), CentOS
  - Debian: Debian, Ubuntu, Mint
  - Gentoo: Gentoo, Chrome OS
  - SUSE: openSuse, SUSE Linux Enterprise
  - Google: Android

Filesystem Hierarchy Standard (FHS)

- Most distributors have agreed upon general layout of a running Linux system
  - /bin, /lib: essential binaries and libraries
  - /etc: host-specific system configuration
  - /media, /mnt: mount point for removable media or temporary filesystems
  - /opt: add-on application software
  - /tmp: temporary files

Pseudo-filesystems

- Linux represents almost everything as a file within the filesystem
    - Not everything actually stored on hard disk
- Memory-backed files: “files” stored entirely in RAM
    - /dev (via devfs), /tmp (via tmpfs), shared memory (via shmfs), other ramfs
- Virtual files: “files” dynamically generated by kernel during file operations
    - /proc (via procfs), /sys (via sysfs), /sys/debug (via debugfs)

/dev

- Traditional location for permanently attached devices (as compared to hotplug devices)

- Accessing a file within invokes matching kernel driver
  - /dev/mem, /dev/null, /dev/zero: calls into kernel's `memory` driver
  - /dev/random, /dev/urandom: calls into kernel's `random` driver
- Most devices implement file reading and/or writing
  - "Reading" /dev/random returns random numbers from kernel's PRNG pool

Device Classes

- Character (char) device: expressed as a stream of bytes, volatile storage
  - Examples: /dev/console, /dev/random, /dev/ttyS0
- Block device: I/O must be transferred in one or more whole blocks, often in increments of 512 bytes, non-volatile storage
  - Examples: /dev/loop0, /dev/sda, /dev/sr0
- Network device: network I/O via kernel's networking system
  - No matching entry within /dev

/proc

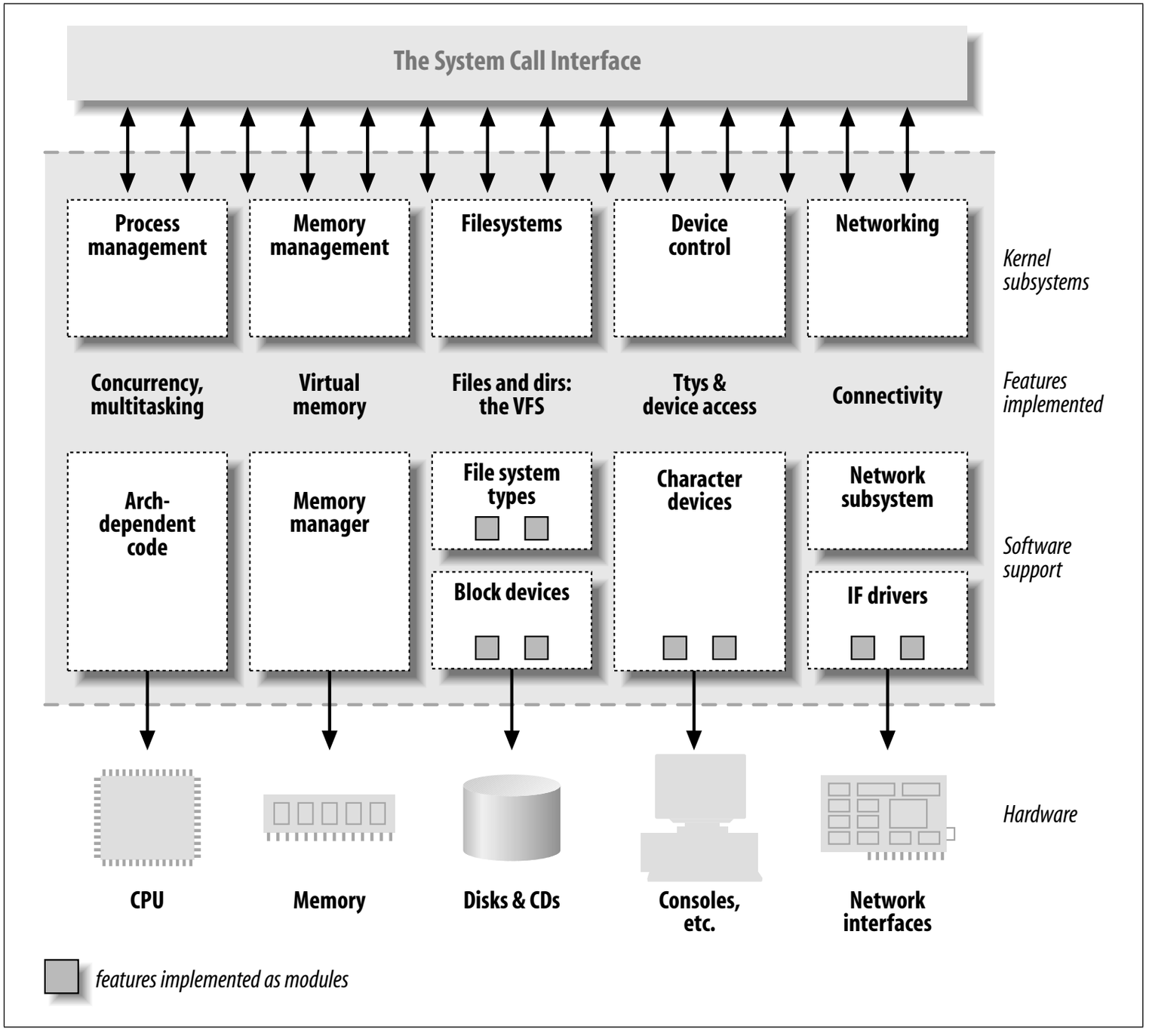
- Holds process information and other control information
- Most of these virtual files implement reading, some also implement writing
  - /proc/*PID*/status: returns status of process *PID*
  - /proc/self: symbolic link to current process's *PID* directory
  - /proc/interrupts: returns all installed interrupt handlers and number of interrupts that have been serviced
  - /proc/slabinfo: returns state of kernel's slab pools

/sys

- Holds state of kernel subsystems and device drivers
- Like /proc, reading virtual files in /sys within returns current state, while writing changes state
- Modern location to hold driver states
  - Older kernels used to cram everything in /proc
  - Hotplug devices represented in /sys

Kernel Subsystems

- Process management
- Memory management
- Filesystems
- Device control
- Networking



Kernel Source

- Linux kernel source code now controlled via git revision control system
  - Stable branches are named *linux-4.9.y*, *linux-4.14.y*, etc
  - Next release of kernel is on *master* branch
- Linus Torvalds normally controls what gets pushed onto the *master* branch
  - Other major developers maintain stable branches (e.g., Greg Kroah-Hartman)
- **Linux kernel written entirely in C** (not C++, Java, Lua, Python, Ruby, …)

Kernel Source Code Layout

- /Documentation: lots of information about kernel development, coding style, notes about specific hardware
- /arch: architecture-dependent code
- /drivers: device drivers
- /include: header files
  - /include/linux: internal kernel header files
  - /include/UAPI/linux: user space API, which are headers exported to user programs

Kernel Source Code Layout

- /kernel: core kernel code (scheduler, thread synchronization)
- /lib: common kernel data structures and other code (linked list, trees)
- /net: networking code (TCP, UDP, IPv6)
- /scripts: kernel build system

Kernel Module (kmod)

- Chunk of code that may be added to kernel at runtime to extend functionality
- All kernel code written in **C89**, which means:
  - Comments must be of form `/* ... */` (slash-star)
    - `//` (slash-slash) style **is not permitted**
- Variables **must be declared at top of functions**, not intermixed with code
- **No** variable-length arrays
- **No** floating-point arithmetic

Kernel Module Example

```c
#include <linux/init.h>
#include <linux/module.h>
MODULE_LICENSE("GPL");

static int hello_init(void)
{
    printk(KERN_ALERT "Hello, world\n");
    return 0;
}

static void hello_exit(void)
{
    printk(KERN_ALERT "Goodbye, cruel world\n");
}

module_init(hello_init);
module_exit(hello_exit);
```

Writing Kernel Modules

- Similar to C user software, in that there is a single entry point and exit point
    - **Module is responsible for cleaning up after itself during exit**
    - **No standard library**; only header files in kernel source tree's /include may be used
- Typically designed as event-driven application:
    - During initialization, module registers callbacks into core kernel code
    - When event occurs, core kernel invokes callback
    - `goto`s used for error handling

Concurrency

- Linux kernel internally is multithreaded (via kthreads)
- Modules can be preempted, or can also be invoked concurrently
    - Example: Multiple user space processes can read from /dev/random simultaneously
- Callbacks must use synchronization to avoid race conditions
    - mutex, semaphore, and/or condition variable
    - futex, rcu_lock, spinlock

Compiling Kernel Modules

- Module could be compiled as part of Linux kernel (an in-tree module) or in separate directory (an out-of-tree module)

- Either way requires kernel build system (Kbuild) support

- Typically, Kbuild will compile a file named *foo.c* into the kernel module *foo.ko*

- Load a module via insmod: `insmod foo.ko`

- Remove a module via rmmod: `rmmod foo`

Module Initialization

```
static int __init hello_init(void)
{
    printk(KERN_ALERT "Hello, world\n");
    return 0;
}

module_init(hello_init);
```

- Entry point into module, called by core kernel when module is inserted

- Nearly always declared as `static` and has `__init` token

  - Hint to kernel that function is only used at initialization, and can be purged from memory afterwards

- Use `module_init()` macro to declare which function is for initialization

Module Initialization

```
static int __init hello_init(void)
{
    printk(KERN_ALERT "Hello, world\n");
    return 0;
}

module_init(hello_init);
```

- Function returns 0 on successful initialization, or negative on error
- Return the negative of an errno value:
  - `-ENOMEM`: out of memory
  - `-EPERM`: operation not permitted

Displaying Messages

```c
static int __init hello_init(void)
{
    printk(KERN_ALERT "Hello, world\n");
    return 0;
}

module_init(hello_init);
```

- Classically, use `printk()` to generate messages
  - Superseded in newer kernels by `pr_*()` and `dev_*()` functions
- Messages sent to kernel log
- Use `dmesg` command to view contents of kernel log

Module Shutdown

```
static void hello_exit(void)
{
    printk(KERN_ALERT "Goodbye, cruel world\n");
}

module_exit(hello_exit);
```

- Invoked by core kernel when module is unloaded
- Responsible for releasing memory, unlocking locks, etc.
  - **You are responsible for cleaning up after yourself**
- Normally declared as both `static` and with `__exit` token
- Use `module_exit()` macro to declare which function is for cleanup