ECEN 449 – Microprocessor System Design

Introduction to Linux

Objectives of this Lecture Unit

- Learn basics of Linux O/S

Objectives

- The Operating System environment and services
- How are services accessed in Linux?

Motivation

- Applications need an execution environment:
  - Portability, standard interfaces
  - File and device controlled access
  - Preemptive multitasking
  - Virtual memory (protected memory, paging)
  - Shared libraries
  - Shared copy-on-write executables
  - TCP/IP networking
  - SMP support
- Hardware developers need to integrate new devices
  - Standard framework to write device drivers
  - Layered architecture dependent and independent code
  - Extensibility, dynamic kernel modules

Linux O/S Architecture

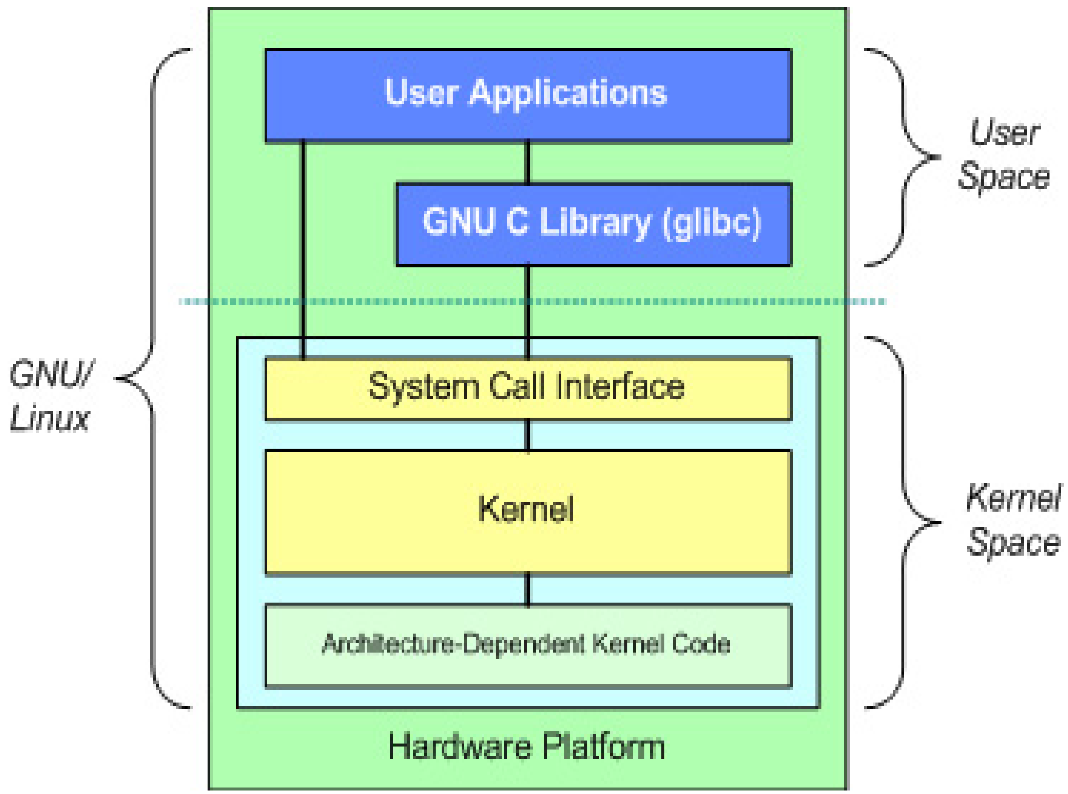


Fig. Source: IBM, Anatomy of Linux Kernel

General view of O/S

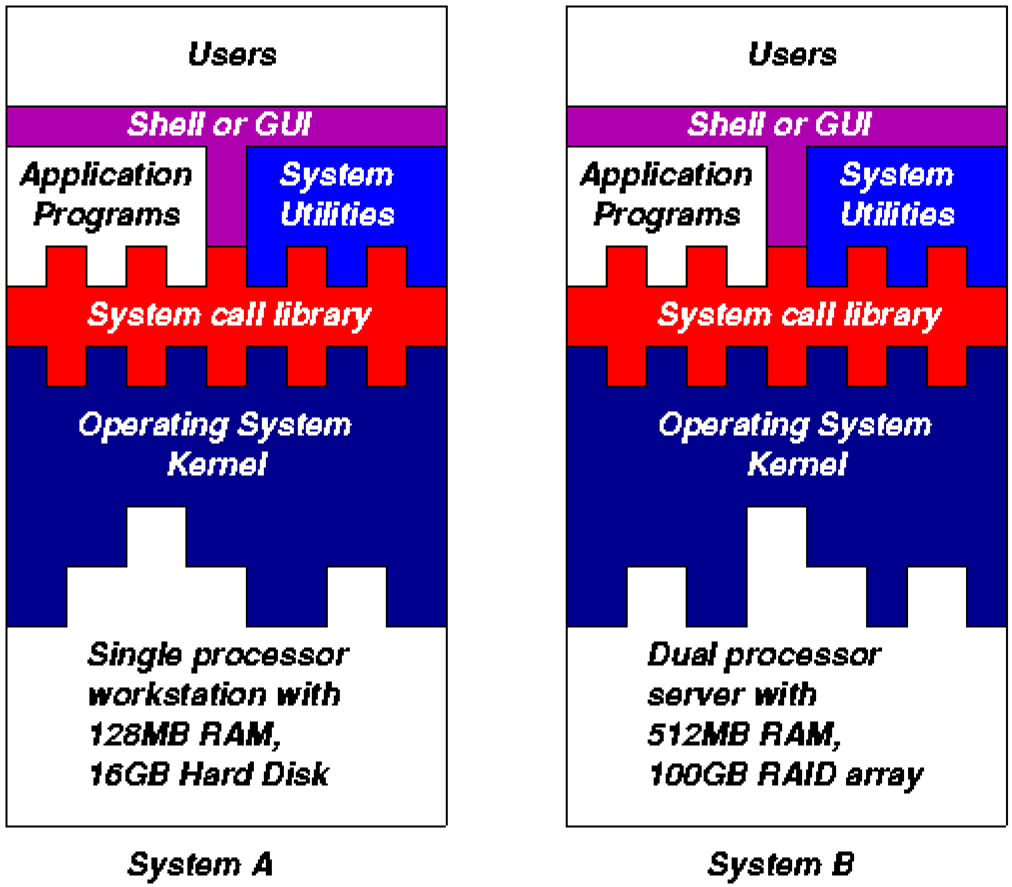


Fig. Source: W. Knottenbelt, UK

Linux Kernel

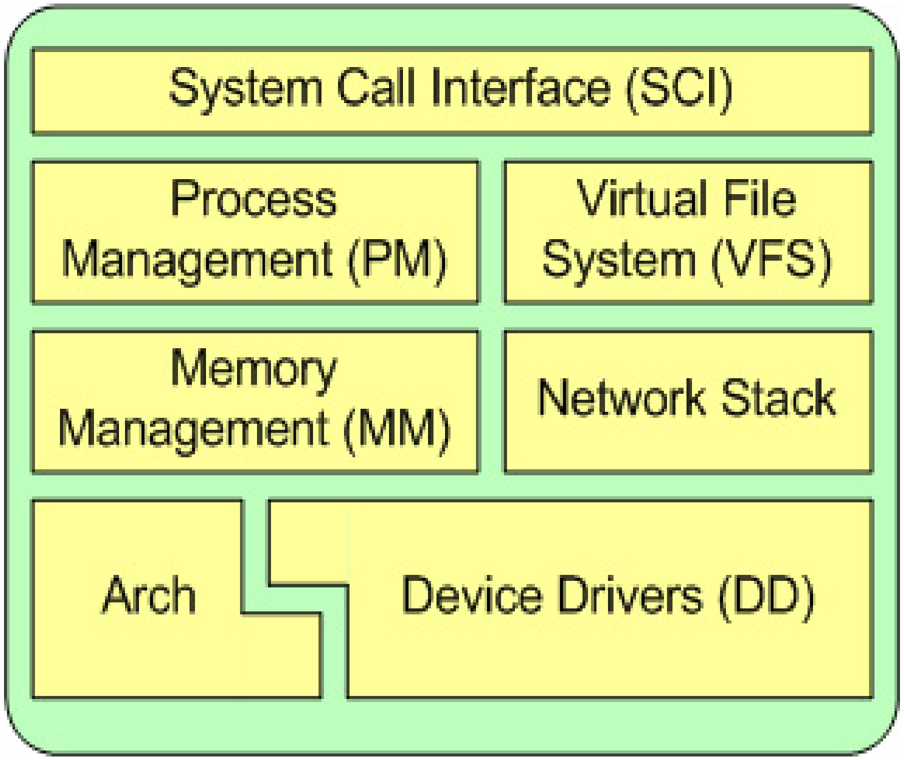
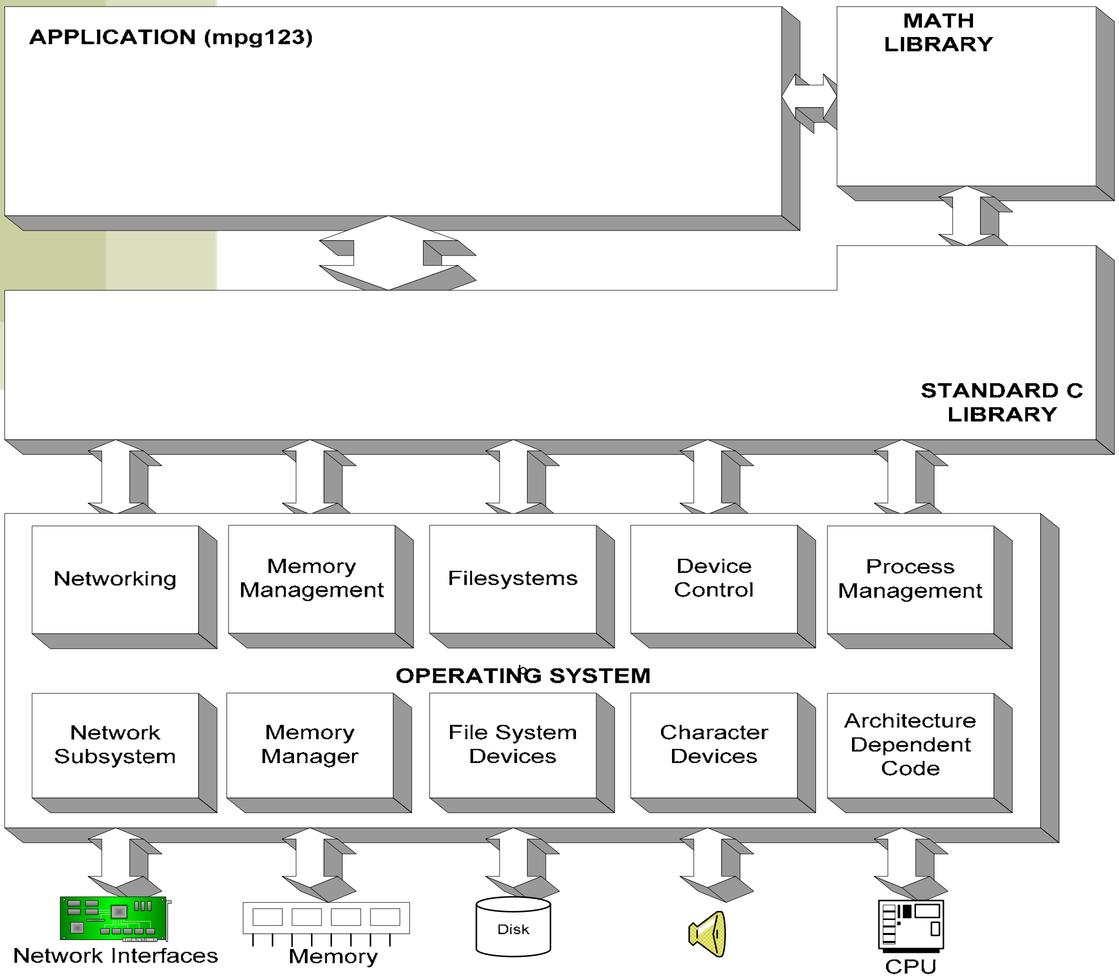


Fig. Source: IBM, Anatomy of Linux Kernel

The Operating System Kernel

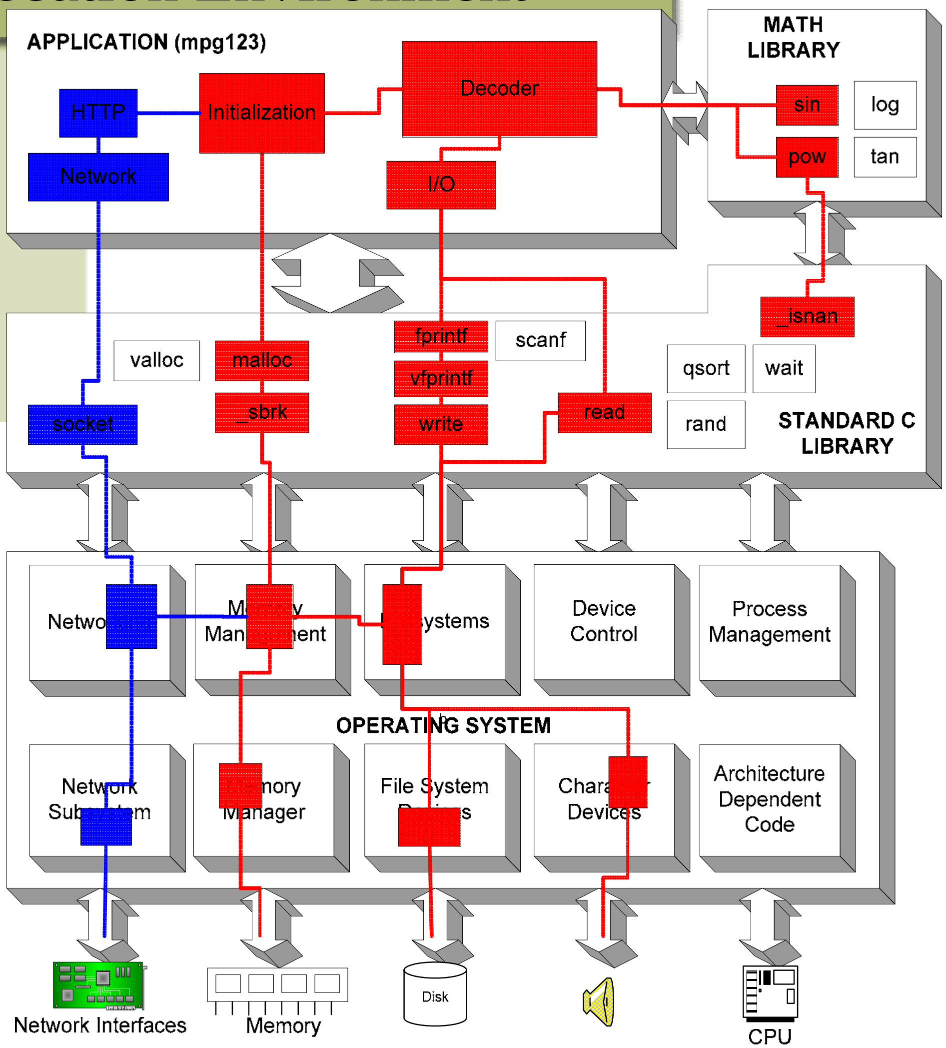
- Resident in memory, privileged mode
- System calls offer general purpose services
- Controls and mediates access to hardware
- Implements and supports fundamental abstractions:
  - Process, file (file system, devices, interprocess communication)
- Schedules / allocates system resources:
  - CPU, memory, disk, devices, etc.
- Enforces security and protection
- Event driven:
  - Responds to user requests for service (system calls)
  - Attends interrupts and exceptions
  - Context switch at quantum time expiration

Linux Execution Environment



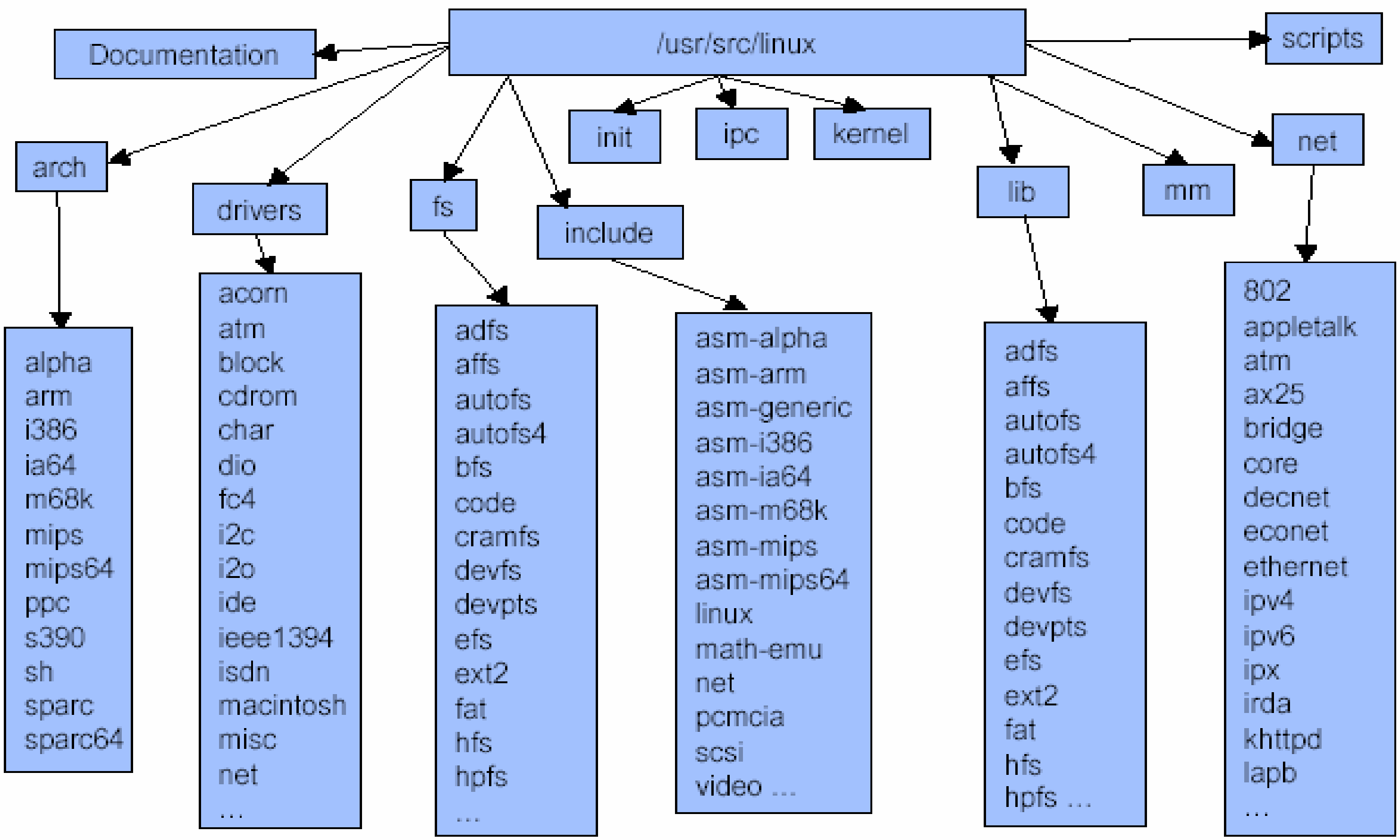
- Program
- Libraries
- Kernel subsystems

Linux Execution Environment



- Execution paths

Linux Source Layout



Linux Code Layout

- **Linux/arch**
  - Architecture dependent code.
  - Highly-optimized common utility routines such as memcpy
- **Linux/drivers**
  - Largest amount of code
  - Device, bus, platform and general directories
  - Character and block devices , network, video
  - Buses – pci, agp, usb, pcmcia, scsi, etc
- **Linux/fs**
  - Virtual file system (VFS) framework.
  - Actual file systems:
    - Disk format: ext2, ext3, fat, RAID, journaling, etc
    - But also in-memory file systems: RAM, Flash, ROM

Linux Code Layout

- **Linux/include**
  - Architecture-dependent include subdirectories.
  - Need to be included to compile your driver code:
    - gcc … -I/<kernel-source-tree>/include …
  - Kernel-only portions are guarded by #ifdefs

```
#ifdef __KERNEL__
  /* kernel stuff */
#endif
```

  - Specific directories: asm, math-emu, net, pcmcia, scsi, video.

VFS and File Systems

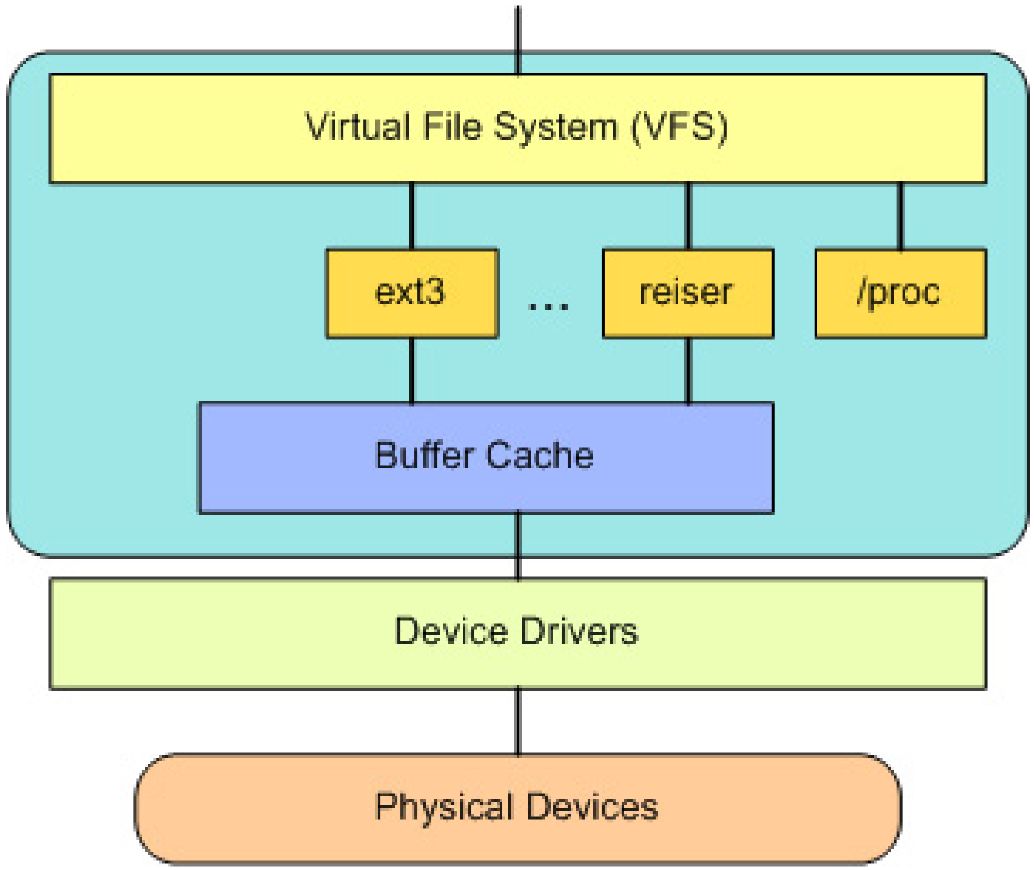


Fig. Source: Anatomy of Linux Kernel, IBM

Linux commands

- ls : list directory contents
- ls –l : long or verbose option to ls

drwxr-xr-x 2 reddy faculty 4096 May 17 2005 bin/

d for directory, r for read, w for write x for executable

r-x : faculty can read and execute, but can’t write

r-x: others can read and execute, but can’t write

reddy is the owner, belongs to group “faculty”

size is 4096 bytes, created on May 17 2005, name of the directory bin

* -rw------- 1 reddy faculty 43231 Jun 20 2007 temp.txt

- mkdir: create a directory
- rm: remove a file
- rm –r : remove recursively
- rm –i: ask before removing or confirm
- vi or emacs : editors to open and edit files
- cp : copy one file to another cp file1 file2: copies file1 to file2
- cat file1 : list the contents of file1
- more file1: list one screen of file1
- grep string file1 : list all the lines in file1 that contain string
- mv file1 file2 : move file1 to file2 i.e., rename file1 to file2, remove earlier file if file2 exists.

Linux commands

- diff file1 file2 : find the differences between file1 and file2
- grep string file1 | wc
  - Look for string in file1 and do “word count” on those lines of the file
- Command1 | command2
  - Run command1 and “pipe” the result into command2
- grep string file1 > file2
  - Store the result of grep into file2 instead of displaying them on the terminal
- grep string file1 &
  - Run the command in the background
  - Can run other commands in the foreground
  - Or use the terminal for other things

Reentrant code

- A function or code that can be reentered safely
  - It can be executed safely concurrently
- Int i;

  Function f()

    {

      i = i+2;

      return(i);

    }
- Returned value i can change if two threads enter f concurrently
  - --Not reentrant

Reentrant code

- function f(int i)
  ```
  {
    int temp = i;
    return (temp+2);
  }
  ```
- f() return value is only based on how it is called f(1), f(2) …
  - Not on the order in which it is called or how many threads are executing f()

Process and System Calls

- Process: program in execution. Unique “pid”. Hierarchy.
- User address space vs. kernel address space
- Application requests OS services through TRAP mechanism
  - x86: syscall number in eax register, exception (int $0x80)
  - result = read (file descriptor, user buffer, amount in bytes)
  - Read returns real amount of bytes transferred or error code (<0)
- Kernel has access to kernel address space (code, data, and device ports and memory), and to user address space, but only to the process that is currently running
- “Current” process descriptor. “current→pid” points to current pid
- Two stacks per process: user stack and kernel stack
- Special instructions to copy parameters / results between user and kernel space

Exceptions and Interrupts

- Hardware switch to kernel mode. Uses "interrupt stack".
- Synchronous exceptions: page fault, illegal instruction, etc
  - Triggered in the context of the current process
  - Can access user space; have a default kernel recovery action
  - Can be managed by the process itself (signal handling)
    - Signal (signum, handler) [signal(SIGSEGV,invalid_mem_handler)]
  - Can also be initiated by the kernel or other (related) process
    - Kill (pid, signum) [kill(1234, SIGSTOP)]
- Asynchronous interrupts: devices, clock, etc
  - Not in the context of the related process → no access to user memory, must buffer data in kernel space
  - Can signal a process (will be handled when scheduled to run)
- Traps, exceptions, interrupts can trigger process scheduling

Scheduling and Exception Delivering

- Kernel is non **preemptible** (changed in Linux 2.6), but is multithreaded and multiprocessor: concurrency and parallelism
- Kernel state needs to be coherent before exit to user mode:
  - Process pending signals are checked and handlers are called
  - Context switch if current process is no longer at highest priority
  - Zombie (dead) process final dispositions, deallocation of resources and notification to related living ones
  - If no process to run, switch to kernel idle thread

Kernel Modules

- Kernel modules are inserted and unloaded dynamically
  - Kernel code extensibility at run time
  - insmod / lsmod/ rmmod commands. Look at /proc/modules
  - Kernel and servers can detect and install them automatically, for example, cardmgr (pc card services manager)
- Modules execute in kernel space
  - Access to kernel resources (memory, I/O ports) and global variables (look at /proc/ksyms)
  - Export their own visible variables, register_symtab ();
  - Can implement new kernel services (new system calls, policies) or low level drivers (new devices, mechanisms)
  - Use internal kernel basic interface and can interact with other modules (pcmcia memory_cs uses generic card services module)
  - Need to implement init_module and cleanup_module entry points, and specific subsystem functions (open, read, write, close, ioctl …)

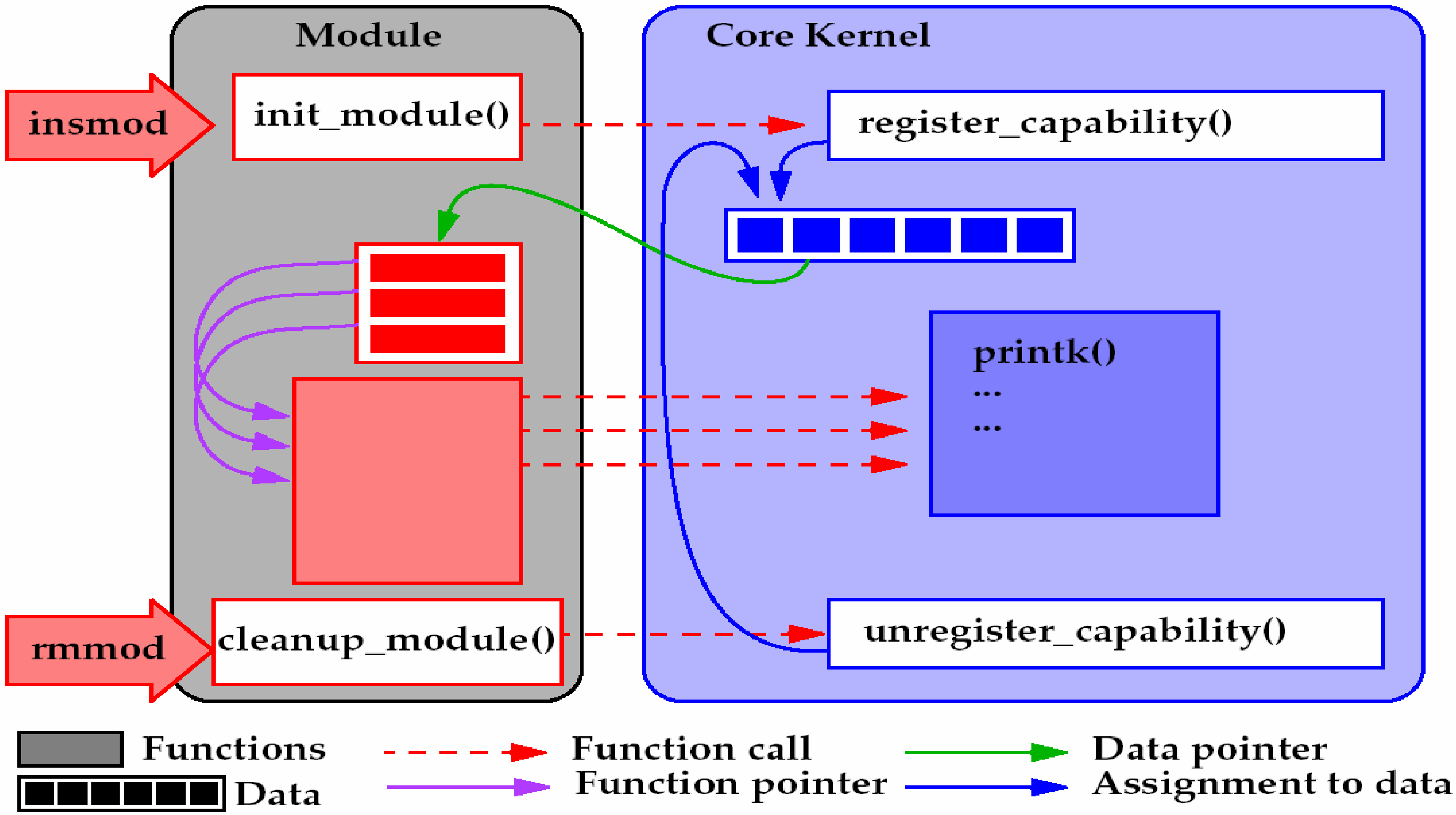
Hello World

- hello_world_module.c:

```
#define MODULE
#include <linux/module.h>
static int __init init_module(void)
{
  printk("<1>Hello, world\n"); /* <1> is message priority. */
  return 0;
}
static int __exit cleanup_module(void)
{
  printk("<1>Goodbye cruel world\n");
}
```

- Printk (basic kernel service) outputs messages to console and/or to /var/log/messages
- Use "insmod hello_world_module.o" to load it into the kernel space

Linking a module to the kernel (from Rubini's book)



Module programming

- Be careful: a kernel fault is fatal to the current process and sometimes the whole system
- Modules should support *concurrency* (support calls by different processes). Distinct data structures for each process (since the same code is executed) to ensure data is not corrupted.
- Driver code must be *reentrant:* keep status in local (stack allocated) variables or dynamic memory allocation: kmalloc / kfree
- This allows the process executing to suspend (e.g., wait for pcmcia card interrupt) and other processes to execute the same code.
- It is not a good idea to assume your code won't be interrupted.
- Sleep_on(wait_queue) or interruptible_sleep_on(wait_queue) to yield the cpu to another process
- */proc/ioports* contains information about registered ports. */proc/iomem* contains info about I/O memory

Modules and Device Drivers

- Device Driver is a loadable module that manages data transfers between device and O/S.
- Modules can be loaded and unloaded at boot time
- A device driver can be used by other modules
- Device driver must use standard entry points
- Standard entry points are listed in struct file_operations
- Standard entry points struct file_operations custom_fops = {

```
        llseek:   NULL,
        read:     custom_read,
        write:    custom_write,
        ioctl:    NULL,
        open:     custom_open,
        release:  custom_release,
•       mmap:     NULL
    };
```

Different Operations

- Open: Opens and initializes the device internal structures
- my_open(struct inode *inode, struct file *filp);
  - Register the device driver
  - Do initial setting up of driver structues
- my_release(struct inode *inode, struct file *filp);
  - Release any resources
  - Unregister the device driver

Different Operations

- ssize_t read(struct file *filep, char *buf, size_t count, loff_t * offp);
- ssize_t write(struct file *filep, char *buf, size_t count, loff_t * offp)
- buf is a buffer in user space
- When you want to transfer data from kernel to user space, use copy_to_user (buf, kbuf, size), copy data in kernel buffer kbuf to user buffer buf of size bytes
- Similarly, use copy_from_user(buf, kbuf, size) when you want to transfer data from user space to kernel space

Device Drivers

- Character Drivers: deal with reading and writing one character at a time
  - Keyboard, line printer etc.
  - Not limited to “character” at a time
  - More flexible (see below)
- Block Drivers: deal with reading and writing blocks of data at a time
  - File systems, disk drives
  - All I/O done through buffer cache in kernel
- Network device drivers: deal with interacting with network interfaces

Device Drivers

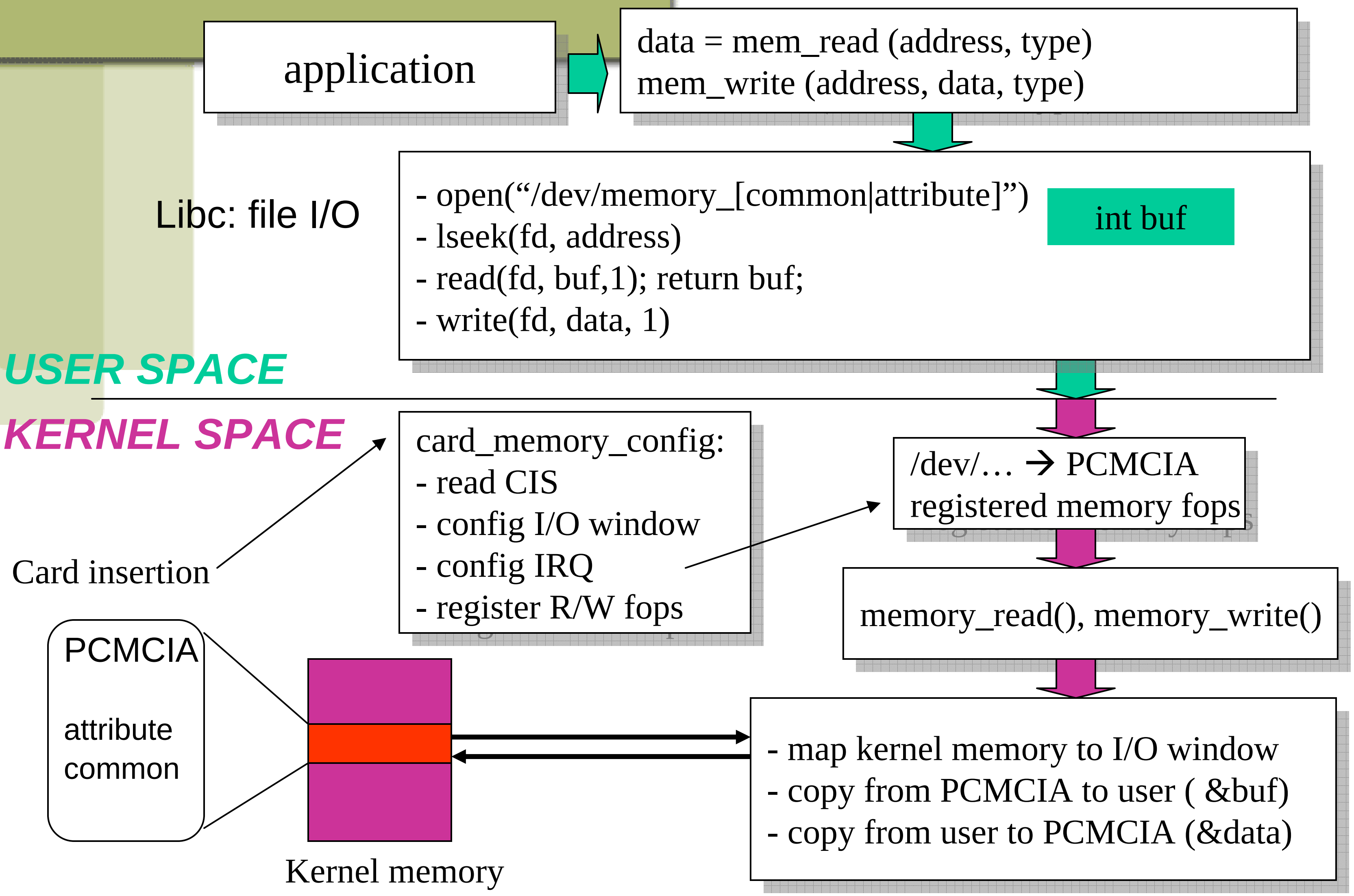
- Have Major number and Minor numbers
  - Major number could identify a type of device
  - Could be serviced by a single device driver
  - Minor number identifies a number of such devices
  - Together they identify a specific device

  - crw-rw-rw- 1 root root **1, 3** Feb 23 1999 null
  - crw------- 1 root root 10, 1 Feb 23 1999 psaux
  - crw------- 1 rubini tty 4, 1 Aug 16 22:22 tty1
  - crw-rw-rw- 1 root dialout 4, 64 Jun 30 11:19 ttyS0
  - crw-rw-rw- 1 root dialout 4, 65 Aug 16 00:00 ttyS1
  - crw------- 1 root sys 7, 1 Feb 23 1999 vcs1
  - crw------- 1 root sys 7, 129 Feb 23 1999 vcsa1
  - crw-rw-rw- 1 root root **1, 5** Feb 23 1999 zero

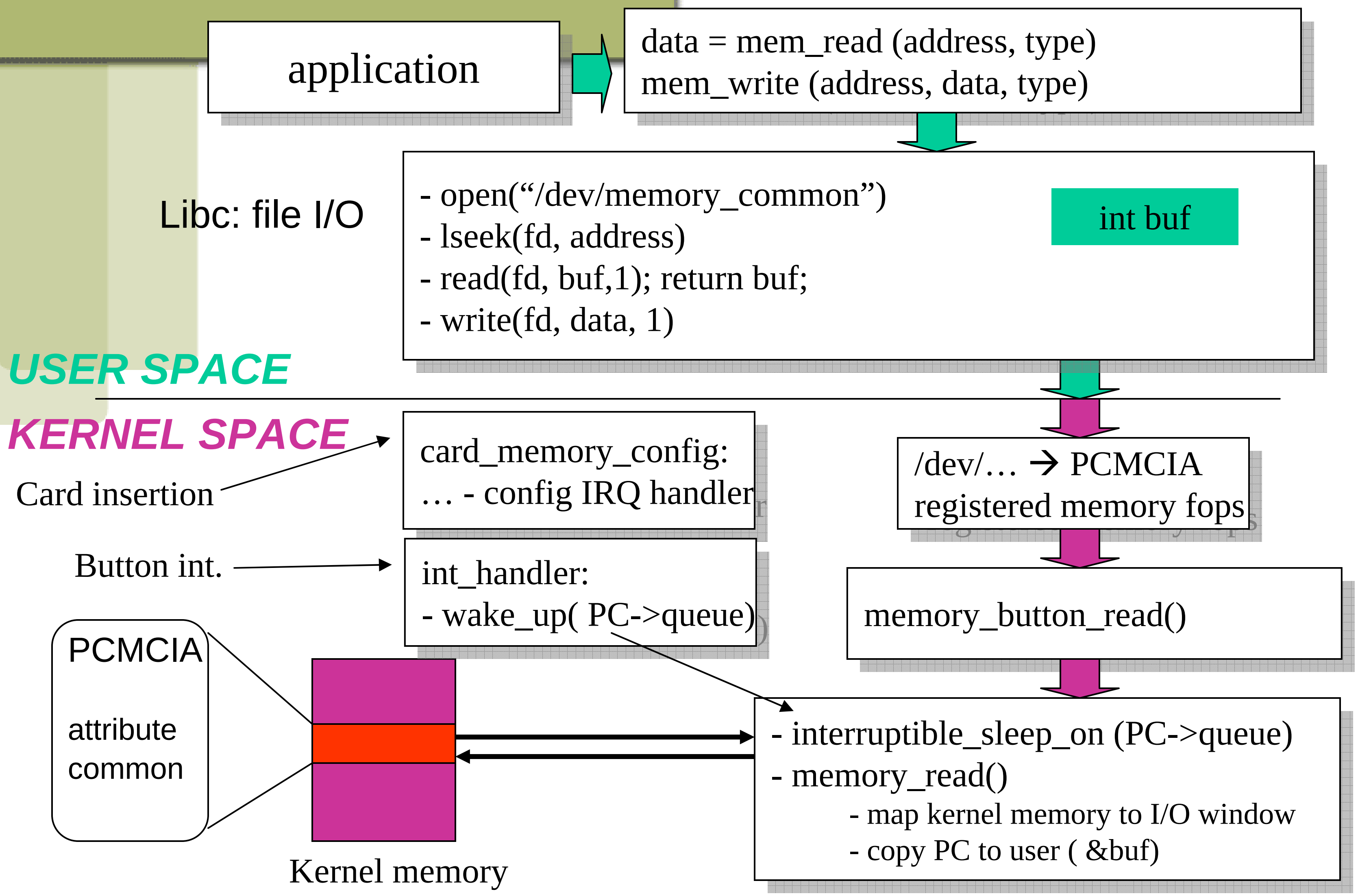
Register Capability

- You can register a new device driver with the kernel:
  - int register_chrdev(unsigned int major, const char *name, struct file_operations *fops);
  - A negative return value indicates an error, 0 or positive indicates success.
  - *major*: the major number being requested (a number < 128 or 256).
  - *name*: the name of the device (which appears in */proc/devices*).
  - *fops*: a pointer to a global jump table used to invoke driver functions.
- Then give to the programs a name by which they can request the driver through a device node in */dev*
  - To create a char device node with major 254 and minor 0, use:
    - mknod /dev/memory_common c 254 0
  - Minor numbers should be in the range of 0 to 255.

PCMCIA Read/Write Common/Attribute Memory



PCMCIA “Button Read” Interrupt handling



Links for Driver Developers

- “Linux Device Drivers”, Alessandro Rubini & Jonathan Corbet, O’Reilly, 2nd Edition
  - On-line version: http://www.xml.com/ldd/chapter/book
  - Book examples: http://examples.oreilly.com/linuxdrive
- PCMCIA programming:
  - http://pcmcia-cs.sourceforge.net/ftp/doc/PCMCIA-HOWTO.html
  - http://pcmcia-cs.sourceforge.net/ftp/doc/PCMCIA-PROG.html
- Linux :
  - Kernel archives: http://www.kernel.org
  - Linux for PDA: http://handhelds.org
  - Cross-Referencing: http://lxr.linux.no/source

Design Pitfalls

- Making things too complex
  - I’ve said it before, I’ll probably say it again. This is really critical

- Not using one clock signal everywhere
  - This is really important.
    - Multiple clocks can create Heisenbugs that only appear some of the time
    - Worse yet, can create bugs that only appear in hardware vs. being testable in simulation

Common Logic Problems

- INOUT Ports
  - If you have a port of type INOUT in a module, you need to explicitly drive it to high impedance “z” when the module is not driving the port.
    - Simply failing to specify an output value for the port isn’t good enough, you can get flaky signal or even fire hazard
- Gated clocks
  - Your design should have one clock. It should go to all clock pins on all modules.
  - Never, ever, put any logic between the clock and the clock pin of a module
  - Never, ever, connect anything but the global clock to the clock pin of a module.