Lecture Note 6. File System Basic

April 21, 2021

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- Chap 35. A dialogue on Persistence
- Chap 36. I/O Devices
- Chap 37. Hard Disk Drives
- Chap 38. RAID
- Chap 39. Interlude: Files and Directories
  - ✓ APIs for file, directory and file system
- Chap 40. File System Implementation
  - ✓ Layout: superblock, bitmap, inode, data blocks, …
  - ✓ Access method: open, read, write, close, lseek, fsync, mount, …

Chap. 35 A Dialogue on Persistence

Professor: *And thus we reach the third of our four ... err... three pillars of operating systems:* ***persistence****.*

Student: *Did you say there were three pillars, or four? What is the fourth?*

Professor: *No. Just three, young student, just three. Trying to keep it simple here.*

Student: *OK, fine. But what is persistence, oh fine and noble professor?*

Professor: *Actually, you probably know what it means in the traditional sense, right? As the dictionary would say: "a firm or obstinate continuance in a course of action in spite of difficulty or opposition."*

Student: *It's kind of like taking your class: some obstinance required.*

Professor: *Ha! Yes. But persistence here means something else. Let me explain. Imagine you are outside, in a field, and you pick a —*

Student: *(interrupting) I know! A peach! From a peach tree!*

Professor: *I was going to say apple, from an apple tree. Oh well; we'll do it your way, I guess.*

Student: *(stares blankly)*

Professor: *Anyhow, you pick a peach; in fact, you pick many many peaches, but you want to make them last for a long time. Winter is hard and cruel in Wisconsin, after all. What do you do?*

Student: *Well, I think there are some different things you can do. You can pickle it! Or bake a pie. Or make a jam of some kind. Lots of fun!*

Professor: *Fun? Well, maybe. Certainly, you have to do a lot more work to make the peach* ***persist****. And so it is with information as well; making information persist, despite computer crashes, disk failures, or power outages is a tough and interesting challenge.*

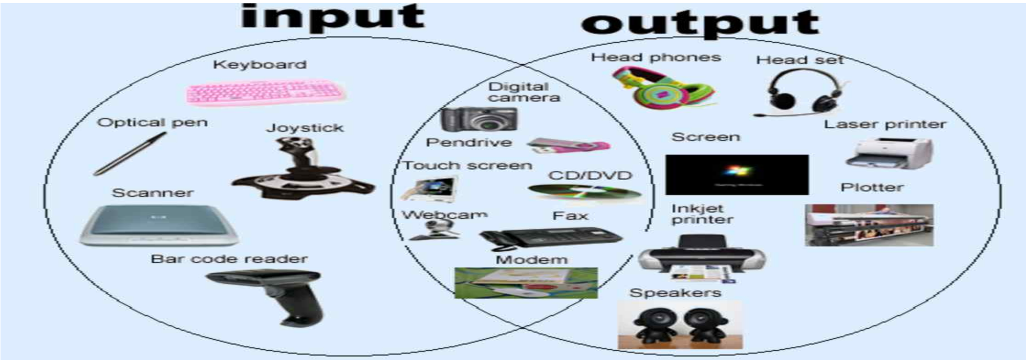
Student: *Nice segue; you're getting quite good at that.*

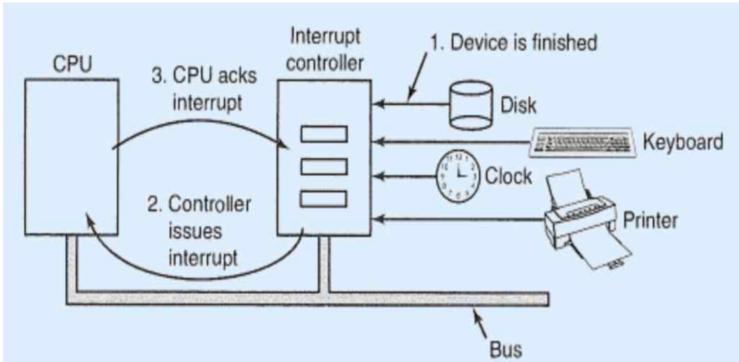
Professor: *Thanks! A professor can always use a few kind words, you know.*

☛ Persistence : Making information durable despite of computer crash, disk failures and so on

Chap. 36 I/O Devices

- 36.1 System Architecture
- 36.2 A Canonical Device
- 36.3 The Canonical Protocol
- 36.4 Lowering CPU overhead with Interrupt
- 36.5 More Efficient Data Movement with DMA
- 36.6 Methods of Device Interaction
- 36.7 Fitting into the OS: The Device Driver
- 36.8 Case Study: A simple IDE Disk Driver
- 36.9 Historical Notes





(Source: https://gcallah.github.io/OperatingSystems/IOHardware.html)

36.1 System Architecture

- Computer system focusing on Bus
  - ✓ Hierarchical structure
    - Memory bus (System bus): CPU and Memory
      - Fast, Expensive, Short
    - I/O bus: SCSI, SATA, USB (and/or separated bus for Graphic Cards)
      - Slow, Less expensive, long, pluggable
  - ✓ Modern system
    - Special interconnect: Memory interconnect (e.g. QPI, Hyperport), Graphic interconnect
    - Make use of specialized chipsets: I/O chips with different interfaces

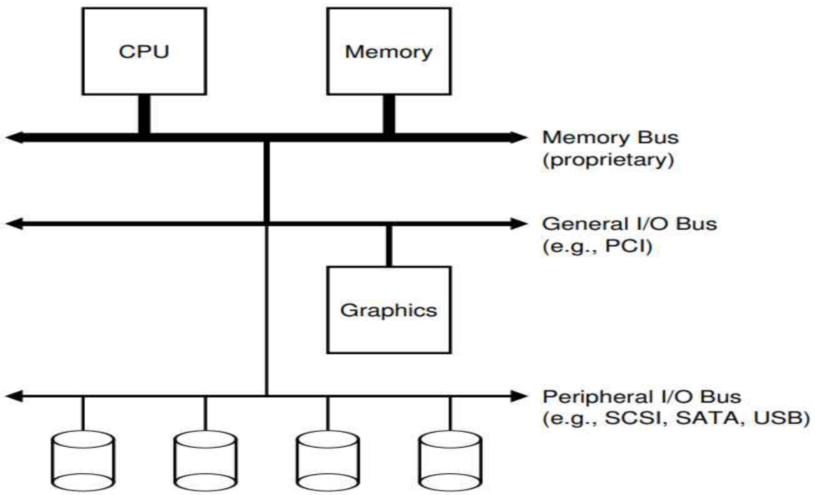


Figure 36.1: **Prototypical System Architecture**

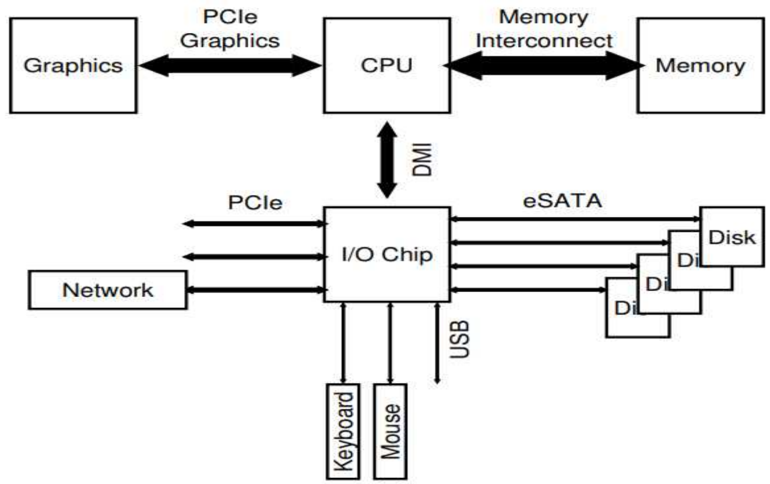


Figure 36.2: **Modern System Architecture**

36.2 A Canonical Device / 36.3 The Canonical Protocol

- Devices
  - ✓ Interface parts
    - Registers: command, status, data
  - ✓ Internals
    - Logic: controller and special chips (device specific) + SW (called firmware)
    - Memory: I/O Buffer (e.g. store receiving packet, delayed write, …)
- Protocol
  - ✓ How to interact with devices?
    - Example: Four steps 1) idle check, 2) data, 3) command, 4) finish check
  - ✓ 3 mechanisms: PIO(Programmed I/O), Interrupt, DMA
    - PIO: CPU performs all steps including idle/finish checking (polling)

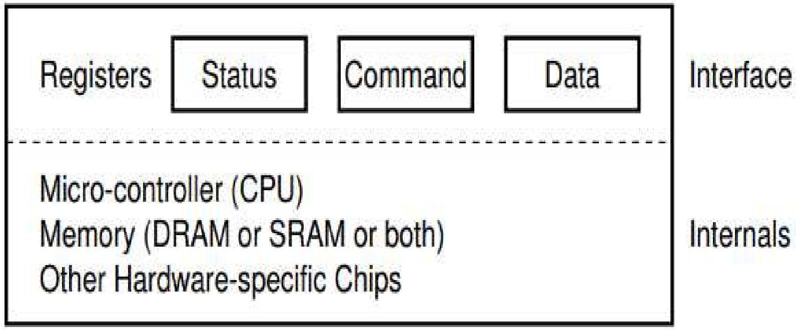
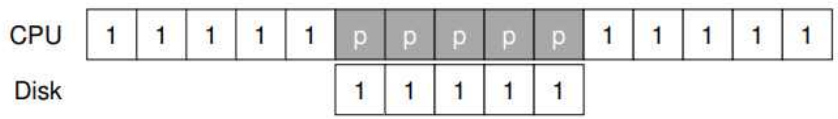


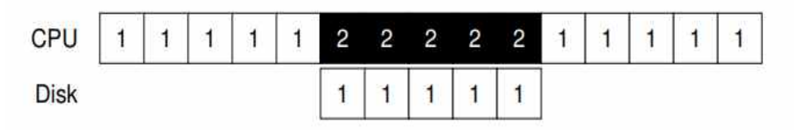
Figure 36.3: A Canonical Device

```
While (STATUS == BUSY)
    ; // wait until device is not busy
Write data to DATA register
Write command to COMMAND register
    (starts the device and executes the command)
While (STATUS == BUSY)
    ; // wait until device is done with your request
```

36.4 Lowering CPU overhead with Interrupt

- Interrupt vs Polling
  - ✓ Comparison
    - Polling: Checking status (busy or idle, like spin) ➔ thread state: running (still hold CPU while its usage is only checking device status)
    - Interrupt: Inform when device is idle (or work is done) ➔ thread state: sleeping (release CPU which can be utilized usefully by other threads
      - Note) Interrupt definition: a mechanism that informs an event to OS
  - ✓ Example
    - Thread 1 requests disk access (read or write)

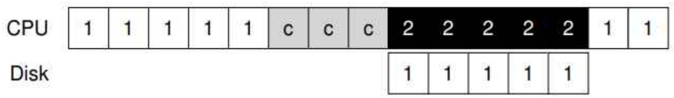


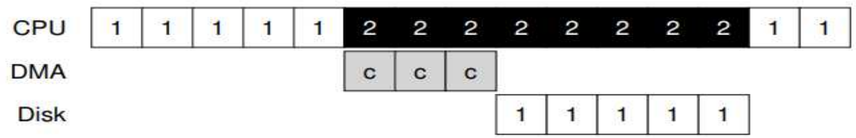


  - ✓ Tradeoffs
    - Benefit of Interrupt: overlapping
      - Interrupt: CPU can do other useful job (for thread 2) while doing I/Os (for thread 1)
      - Polling: CPU just polling (actually waiting) while doing I/Os
    - New requirement for Interrupt
      - Handling mechanism: call interrupt handler via interrupt table (page 28 in LN 2)
      - Sleep queue management (Context switch overhead)
    - Usage suggestion (depend on devices)
      - Slow device: Interrupt, Fast device: Polling (like spin and sleep lock)
      - Optimization: Hybrid, Interrupt coalescing

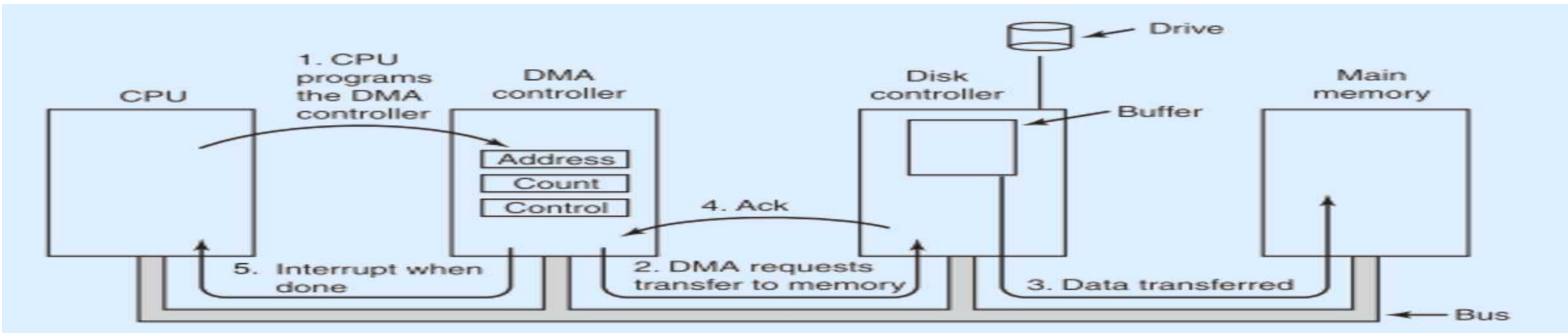
36.5 More Efficient Data Movement with DMA

- DMA (Direct Memory Access)
  - ✓ Comparison
    - PIO (Programmed I/O): CPU manages data copy between memory and devices
      - Concern: Devices are too slow for CPU (note CPU: ns, Disk: ms)
    - DMA controller performs data copy between memory and devices
      - CPU can do other useful job (better overlapping)
  - ✓ Example
    - Thread 1 requests disk write without/with DMA using Interrupt
    - Data copy (denoted as “c” in the figure is done by CPU vs. DMA)



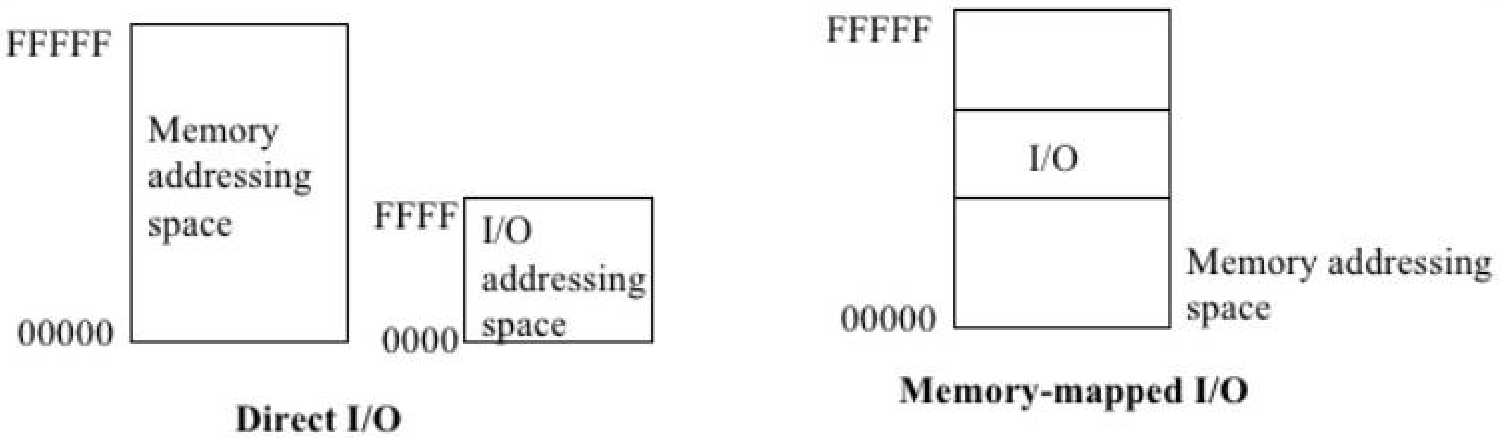


  - ✓ DMA mechanism



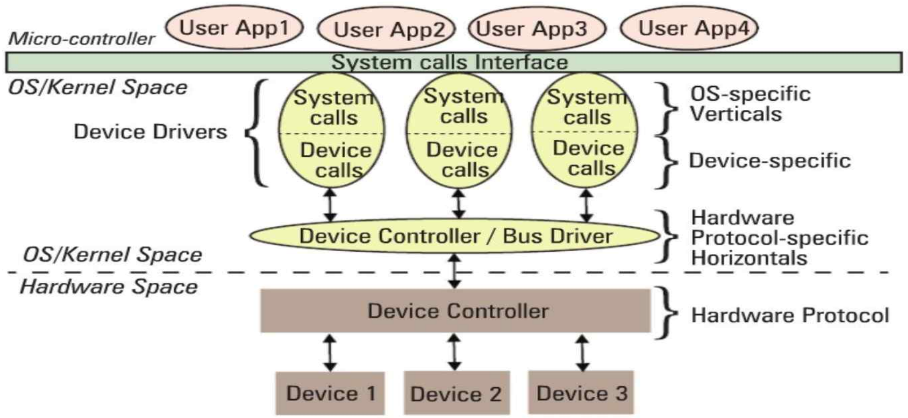
36.6. Methods of Device Interaction

- How to address registers in devices?
  - ✓ Two approaches
    - Direct I/O
      - Separated address space
      - Explicit I/O instruction (e.g. in/out + port)
    - Memory-mapped I/O
      - Single address space: DRAM + I/Os
      - Memory access instruction (e.g. load/store + I/O address space)
  - ✓ Privileged instruction
    - Kernel mode: okay vs User mode: protection fault
    - Usually accessed in a kernel component called device driver



36.7 Fitting into the OS: The Device Driver

- Device driver
  - ✓ A set of software in kernel that abstracts devices
  - ✓ Two layers
    - Manage 1) device registers (command, status, data), 2) interrupt and 3) DMA
    - Support generic interface such as open, read, write, close, … (like file)
  - ✓ 70% of codes in Linux is device drivers (mostly kernel module)
- Layered architecture
  - ✓ Character device (or raw mode): device accessed by user directly
    - System call ➔ Driver ➔ Devices
  - ✓ Block device: device accessed by user through file system (FS)
    - System call ➔ FS ➔ Block layer (buffer, scheduler) ➔ Driver ➔ Devices



(Device driver: general)

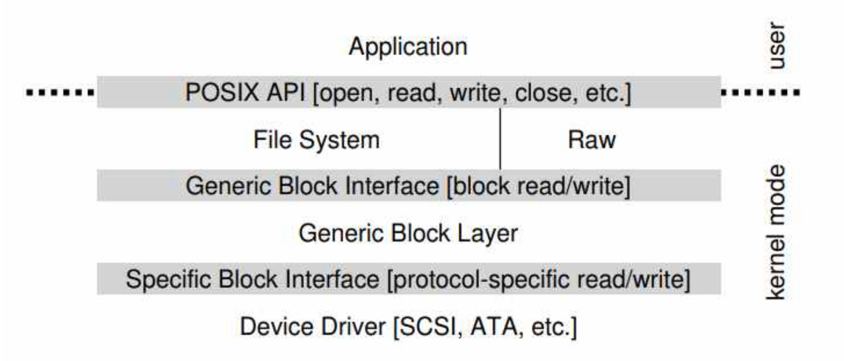


Figure 36.4: **The File System Stack**

(Device driver: block driver specific)

36.8 Case Study: A simple IDE Disk Driver (Optional)

- A simple IDE disk controller
  - ✓ Direct I/O (separated I/O address), I/O instruction: in/out
  - ✓ 4 Registers
    - Control (0x3f6), Command block (0x1f2~1f6), Command or Status (0x1f7), Data port (0x1f0), Error (0x1f1)
      - Note) 1) LBA: Logical Block Address, 2) Status: Busy/Ready, 3) Error: bad block,…
    - Example (low-level interface)
      - Wait for drive ready: read 0x1f7 until the READY bit is on
      - Write: Write sector count and LBA in 0x1f2~1f6 and Start I/O by writing WRITE command in 0x1f7
      - Data transfer: wait until READY and DRQ (Drive Request for Data), write data into the Data port

```
Control Register:
  Address 0x3F6 = 0x08 (0000 1RE0): R=reset,
                  E=0 means "enable interrupt"

Command Block Registers:
  Address 0x1F0 = Data Port
  Address 0x1F1 = Error
  Address 0x1F2 = Sector Count
  Address 0x1F3 = LBA low byte
  Address 0x1F4 = LBA mid byte
  Address 0x1F5 = LBA hi  byte
  Address 0x1F6 = 1B1D TOP4LBA: B=LBA, D=drive
  Address 0x1F7 = Command/status

Status Register (Address 0x1F7):
     7      6      5      4     3     2     1      0
   BUSY  READY  FAULT  SEEK  DRQ  CORR  IDDEX  ERROR

Error Register (Address 0x1F1): (check when ERROR==1)
     7      6      5      4     3     2     1      0
   BBK    UNC    MC   IDNF   MCR  ABRT  T0NF  AMNF

   BBK  = Bad Block
   UNC  = Uncorrectable data error
   MC   = Media Changed
   IDNF = ID mark Not Found
   MCR  = Media Change Requested
   ABRT = Command aborted
   T0NF = Track 0 Not Found
   AMNF = Address Mark Not Found
```

Figure 36.5: The IDE Interface

36.8 Case Study: A simple IDE Disk Driver (Optional)

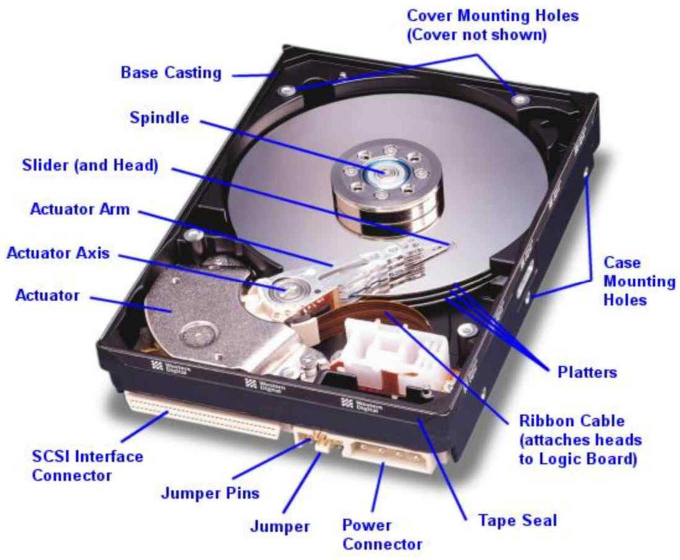
- Driver interface (OS-level interface)
  - ✓ Character driver: open, read, write, close, intr, …
  - ✓ Block driver: open, close, intr, rw (or request, strategy), …
    - Note: dynamic loadable kernel module interface for Linux (insmod, rmmod)
- IDE disk driver example: 4 main functions
  - ✓ ide_rw() ➔ ide_wait_ready() ➔ ide_start_request()
  - ✓ ide_intr()

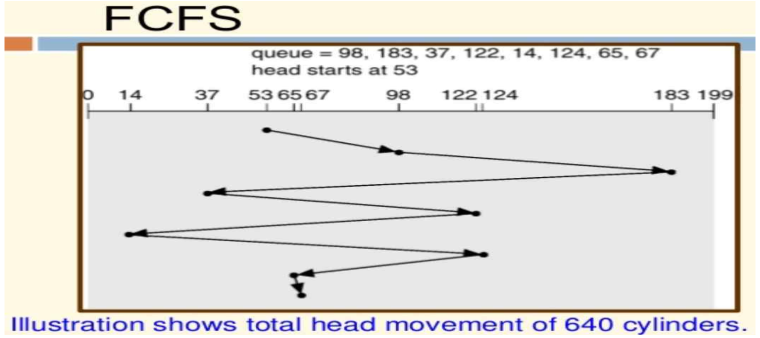
```
static int ide_wait_ready() {
  while (((int r = inb(0x1f7)) & IDE_BSY) || !(r & IDE_DRDY))
    ; // loop until drive isn't busy
}

static void ide_start_request(struct buf *b) {
  ide_wait_ready();
  outb(0x3f6, 0);                       // generate interrupt
  outb(0x1f2, 1);                       // how many sectors?
  outb(0x1f3, b->sector & 0xff);        // LBA goes here ...
  outb(0x1f4, (b->sector >> 8) & 0xff);     // ... and here
  outb(0x1f5, (b->sector >> 16) & 0xff);    // ... and here!
  outb(0x1f6, 0xe0 | ((b->dev&1)<<4) | ((b->sector>>24)&0x0f));
  if(b->flags & B_DIRTY){
    outb(0x1f7, IDE_CMD_WRITE);         // this is a WRITE
    outsl(0x1f0, b->data, 512/4);       // transfer data too!
  } else {
    outb(0x1f7, IDE_CMD_READ);          // this is a READ (no data)
  }
}

void ide_rw(struct buf *b) {
  acquire(&ide_lock);
  for (struct buf **pp = &ide_queue; *pp; pp=&(*pp)->qnext)
    ;                                   // walk queue
  *pp = b;                              // add request to end
  if (ide_queue == b)                   // if q is empty
    ide_start_request(b);               // send req to disk
  while ((b->flags & (B_VALID|B_DIRTY)) != B_VALID)
    sleep(b, &ide_lock);                // wait for completion
  release(&ide_lock);
}

void ide_intr() {
  struct buf *b;
  acquire(&ide_lock);
  if (!(b->flags & B_DIRTY) && ide_wait_ready() >= 0)
    insl(0x1f0, b->data, 512/4);        // if READ: get data
  b->flags |= B_VALID;
  b->flags &= ~B_DIRTY;
  wakeup(b);                            // wake waiting process
  if ((ide_queue = b->qnext) != 0)      // start next request
    ide_start_request(ide_queue);       // (if one exists)
  release(&ide_lock);
}
```

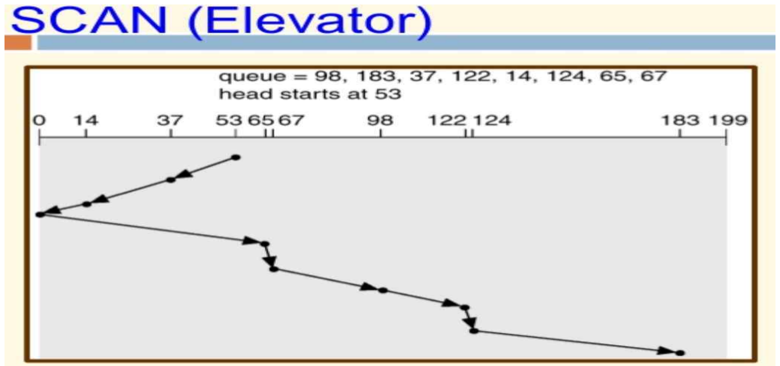
Figure 36.6: The xv6 IDE Disk Driver (Simplified)

37 Hard Disk Drives

- 37.1 The interface
- 37.2 Basic Geometry
- 37.3 A Simple Disk Drive
- 37.4 I/O Time: Doing the Math
- 37.5 Disk Scheduling



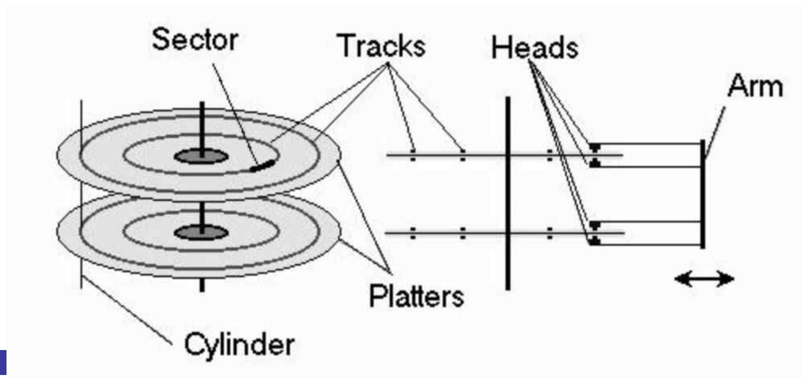


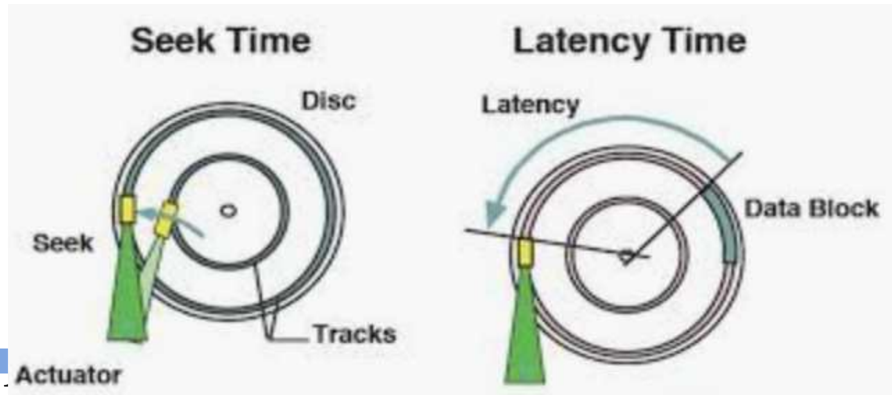


(Source: https://www.slideshare.net/PareshParmar6/disk-scheduling-algorithms-71247712)

37.1 The interface / 37.2 Basic Geometry

- Interface
  - ✓ Basic unit: sectors (512-byte)
    - Disk consists of a large number of sectors (0 ~ N-1 sectors or address space)
  - ✓ Addressing (LBA: logical block address for disk)
    - Sector addressing: 512B
    - Multi-sector addressing (usually called as a disk block): 4KB or 8KB ➔ Kernel developer's viewpoint: disk is a set of disk blocks whose size is 4KB
- Basic Geometry
  - ✓ Platter (two surface) ➔ Track (thousands tracks per surface) ➔ Sectors
  - ✓ Head: sensing data
    - Multiple heads (one per each surface), connected into an arm
  - ✓ Data access: seek time + rotation latency (time) + transfer time
    - Cylinder: a set of same tracks in each surface (no seek time required)





37.3 A simple Disk Drive

- In a same track access: Figure 37.2
  - ✓ Assume
    - 12 sectors in a track, original head position is 6, target is 10
    - 10,000 RPM (rotation per minute) ➔ 1/6 rotation per ms (millisecond) ➔ a rotation takes 6ms
    - Rotational latency ➔ 2ms in this case (3ms on average)
- Multiple tracks: Figure 37.3
  - ✓ Original head position is 30, target is 11
  - ✓ Need not only rotational latency but also seek time (ms)
    - Note that seek and rotational latency perform in parallel
- Track skew: Figure 37.4
  - ✓ To optimize sequential access (e.g. read sector 10, 11, 12, 13)
  - ✓ Other optimizations: multi-zones, disk cache (track buffer)

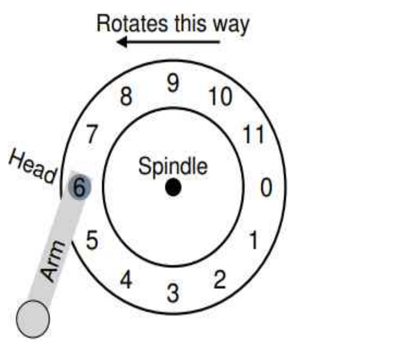


Figure 37.2: **A Single Track Plus A Head**

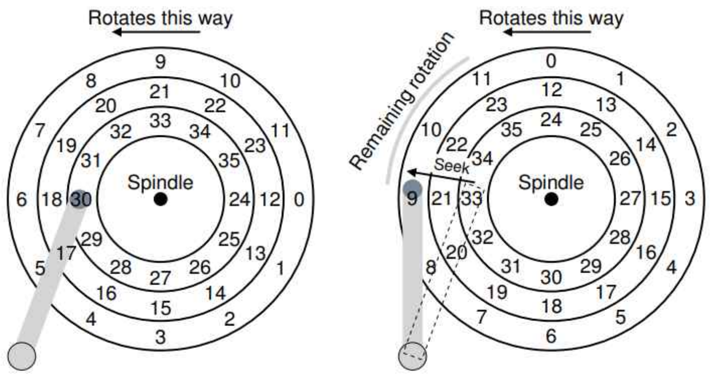


Figure 37.3: **Three Tracks Plus A Head (Right: With Seek)**

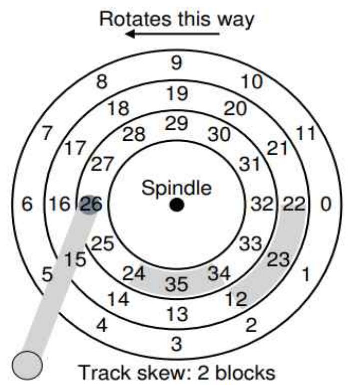
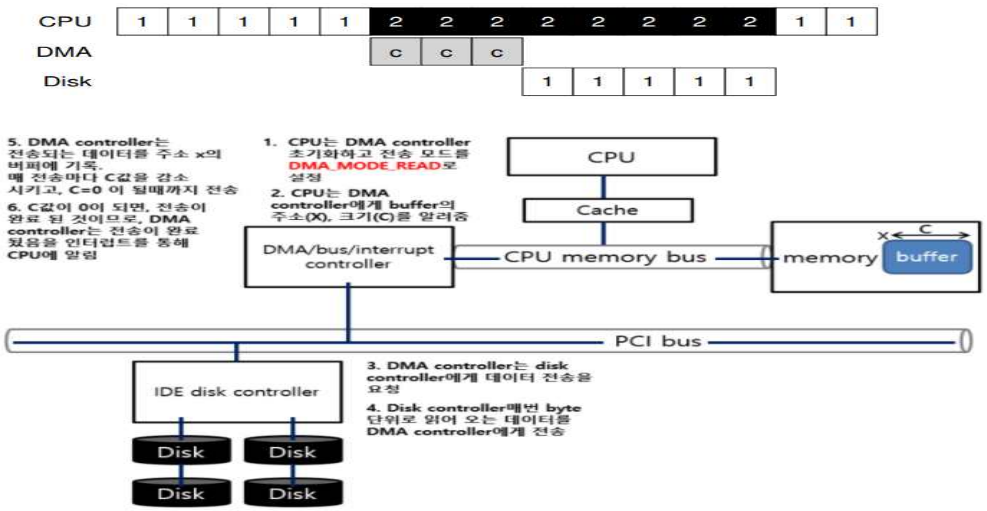


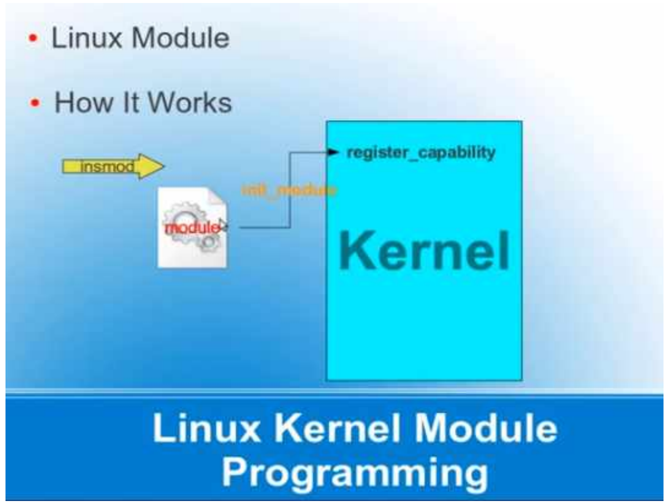
Figure 37.4: **Three Tracks: Track Skew Of 2**

Quiz for 9th-Week 1st-Lesson

- Quiz
  - ✓ 1. What is the benefit of DMA compared with the Interrupt-only? What is the benefit of the DMA compared with PIO?
  - ✓ 2. Discuss the differences between a character device driver and block device driver (at least two differences)
  - ✓ (Bonus) What is the command for loading a module (dynamic loadable module) in Linux?
  - ✓ Due: until 6 PM Friday of this week (30th, April)



(Source: https://m.blog.naver.com/PostView.nhn?blogId=bycho211&logNo=220975324334&proxyReferer=https:%2F%2Fwww.google.com%2F)



(Source: https://www.youtube.com/watch?v=o768iZKtzBA)

37.4 I/O Time: Doing the Math

- Metrics
  - ✓ I/O time (latency) $T_{I/O} = T_{seek} + T_{rotation} + T_{transfer}$
  - ✓ I/O rate (bandwidth, MB/s) $R_{I/O} = \frac{Size_{Transfer}}{T_{I/O}}$
- Workload
  - ✓ Random: issues small (e.g., 4KB) reads to random locations on disk
  - ✓ Sequential: reads a large number of sectors consecutively (100 MB)
- Disk considered: Figure 37.5
  - ✓ Cheetah: a high-performance SCSI drive
  - ✓ Barracuda: a drive built for capacity

	Cheetah 15K.5	Barracuda
Capacity	300 GB	1 TB
RPM	15,000	7,200
Average Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s
Platters	4	4
Cache	16 MB	16/32 MB
Connects via	SCSI	SATA

Figure 37.5: **Disk Drive Specs: SCSI Versus SATA**

37.4 I/O Time: Doing the Math

- Metrics
  - ✓ I/O time (latency) $T_{I/O} = T_{seek} + T_{rotation} + T_{transfer}$
  - ✓ I/O rate (bandwidth, MB/s) $R_{I/O} = \frac{Size_{Transfer}}{T_{I/O}}$
- Lessons
  - ✓ I/O rate calculation: 1) I/O component time, 2) I/O time, 3) I/O rate
  - ✓ Random: Seek + Rotation + Transfer per 4KB
    - I/O time: 4ms + 2ms (15000/60*1000 = ¼ rotation per second➔ 4ms ➔ 2ms on average) + 0.032ms (4KB / 125MB = 4KB * 1000 / 125 * 1000KB)
    - I/O rate: 4KB / 6ms = 0.66 MB/s
  - ✓ Sequential: One seek/rotation per large data (e.g. 100MB)
    - I/O time = 4ms + 2ms + 800ms(100MB/125MB/s), I/O rate = 100MB/0.8s
  - ✓ Implication
    - Sequential is much faster than random in disk
    - SW engineers need to make programs that access disks in sequential

	Cheetah 15K.5	Barracuda
Capacity	300 GB	1 TB
RPM	15,000	7,200
Average Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s
Platters	4	4
Cache	16 MB	16/32 MB
Connects via	SCSI	SATA

Figure 37.5: **Disk Drive Specs: SCSI Versus SATA**

	Cheetah	Barracuda
$R_{I/O}$ Random	0.66 MB/s	0.31 MB/s
$R_{I/O}$ Sequential	125 MB/s	105 MB/s

Figure 37.6: **Disk Drive Performance: SCSI Versus SATA**

37.5 Disk Scheduling

- Disk scheduler
  - ✓ Role: Examines I/O requests and decides which one to schedule next
- Examples
  - ✓ FCFS (First Come First Serve)
    - Pros) simple, Cons) may cause long seek distance
  - ✓ SSTF (Shortest Seek Time First)
    - Pros) reduce seek distance, Cons) unfair (especially boundary tracks)
  - ✓ SCAN (a.k.a. Elevator) and C-SCAN
    - Moves back and forth across all tracks
    - C-SCAN: handle requests from inner-to-outer, then go back inner tracks directly and handling requests again from inner-to-outer (or reverse)

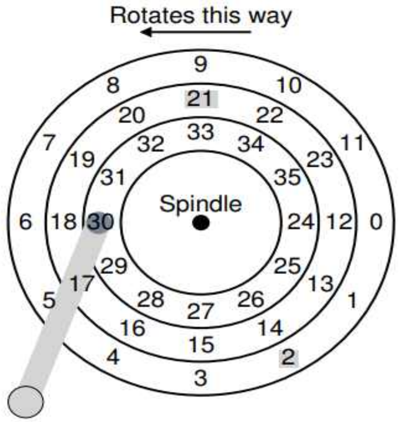
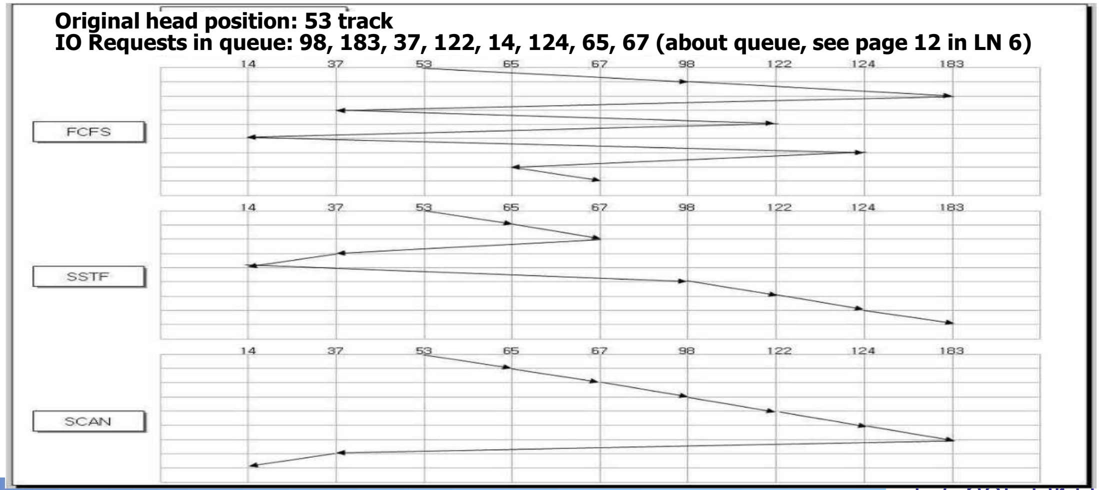


Figure 37.7: **SSTF: Scheduling Requests 21 And 2**



37.5 Disk Scheduling

- Examples (cont')
  - SPTF (Shortest Positioning Time First)
    - Consider seek and rotation latency
    - Why? Issues that consider seek only ➔ not optimal (Figure 37.8)
      - Head position: 30 (sector), Next requests: 16 and 8
      - SSTF: 16 and then 8 ➔ 1 seek + 5/6 rotation + 1 seek + 2/6 rotation
      - How about 8 and then 16 ➔ 1 seek (relatively further) + 1/6 rotation + 1 seek + 4/6 rotation
      - Performance depends on disk characteristics (seek vs. rotation)
    - SPTF select a request who has the smallest position time (seek + rotation time)
- Other scheduling issues
  - Merge: requests 33, 4, 34, …
  - Anticipatory disk scheduling

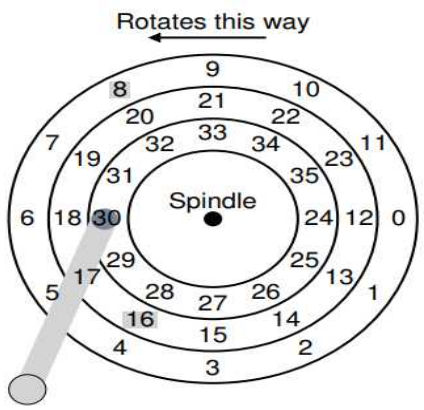
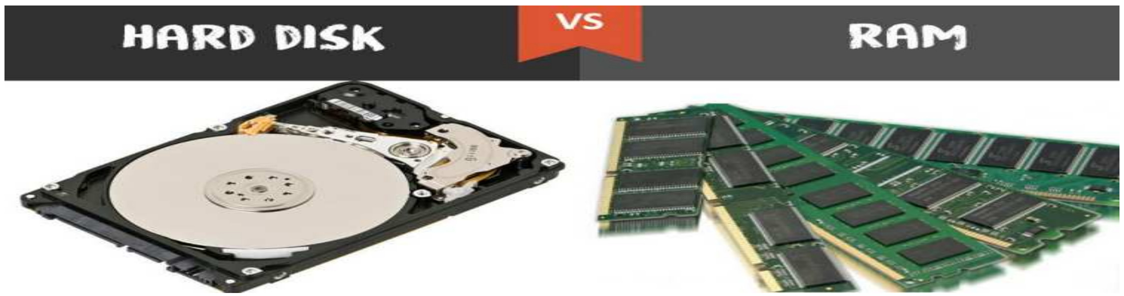


Figure 37.8: **SSTF: Sometimes Not Good Enough**

Chap. 39 Interlude: Files and Directories

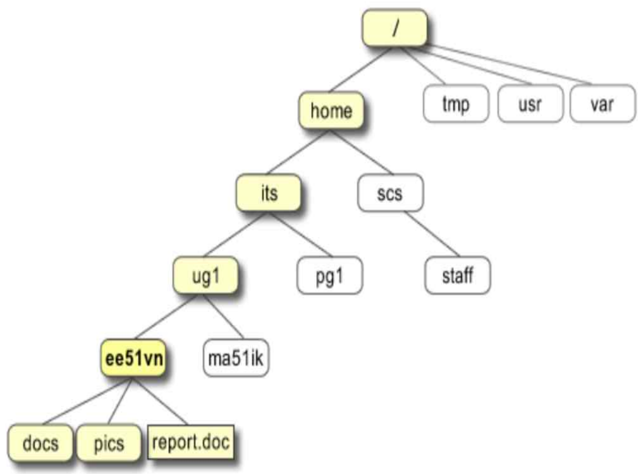
Chap. 39 Interlude: Files and Directories

- Computer system
  - ✓ Four key abstractions: process (thread), virtual memory, lock, and file
  - ✓ Files are in Storage (Hard disk, Solid State Drive)
    - Storage vs. Memory
    - Non-volatility
      - Advantages: Support persistence (store information permanently)
      - Issues: 1) Integrity, 2) Space-efficiency, 3) Consistency, 4) Crash consideration (fault-tolerance), 5) Access control, 6) Security, …
    - These issues are managed by a file system
  - ✓ How to analysis file system?
    - Interface: open, read, write, close, mkdir, link, mount, … (Chapter 39)
    - Layout: file, directory, inode, FAT, superblock, … (Chapter 40)



39.1 Files and Directories

- File
  - ✓ Definition: A linear array of characters (bytes), stored persistently
    - Each file has various data structure (text, c code, record, multimedia, …)
    - But, OS don't care its content, just treating it as a stream of bytes
  - ✓ Each file has its name (absolute path, relative path)
  - ✓ It also has some kind of low-level name in OS (e.g. inode)
    - Like each process has a unique PCB (like program and PCB)
- Directory
  - ✓ A special file that constructs a hierarchy (file hierarchy)
    - Root directory
    - Home directory
    - Working directory
  - ✓ Contain <file name, inode>
    - or low-level name or first disk block
- Others are also treated as a file
  - ✓ Device, pipe, socket, and even process



39.2 File System Interfaces

- APIs
  - ✓ System call: 1) open (return a file descriptor), 2) I/O, 3) attribute, 4) create, 5) name resolution (directory hierarchy traverse), 6) file system management, 7) directory management, …
  - ✓ Internals: 1) allocate/free block, 2) allocate/free inode, 3) namei (name-to-inode), 4) buffer related

Filesystem system calls

Filesystem system calls

Return a descriptor	Use namei		Allocate inode	Attributes	I/O	File System Structure Management	
open creat dup pipe close	open creat chdir chroot chown chmod	stat link unlink mknod mount umount	creat mknod link unlink	chown chmod stat	read write lseek	mount umount	chdir chroot

Filesystem low level functions

namei			alloc	free	ialloc	ifree
iget	iput	bmap				

buffer allocation algorithms

getblk	brelse	bread	breada	bwrite

(Source: http://slideplayer.com/slide/9118590/)

39.3 Creating Files / 39.4 Reading and Writing Files

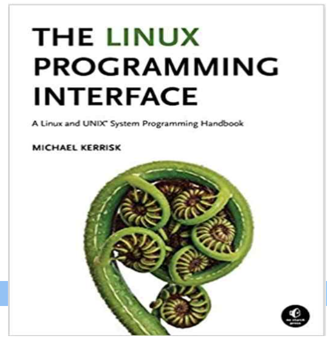
- Create API
  - ✓ open() with create flag (refer to LN1 or Figure 2.6 io.c in OSTEP)

```
int fd = open("foo", O_CREAT|O_WRONLY|O_TRUNC, S_IRUSR|S_IWUSR);
```

    - Arguments: 1) name, 2) flags, 3) permissions
    - Return: fd (file descriptor)
  - ✓ creat(): less used (but famous by Ken Thompson’s answer about redesigning UNIX)

```
int fd = creat("foo"); // option: add second flag to set permissions
```

- Read/Write API
  - ✓ read_size = read(fd, buf, request_size);
  - ✓ written_size = write(fd, buf, request_size);
    - Arguments: 1) fd, 2) buffer that points memory space for data, 3) request size
    - Return: read or written size



39.4 Reading and Writing Files

- Read and write example
  - ✓ Command line viewpoint

```
prompt> echo hello > foo
prompt> cat foo
hello
prompt>
```

  - ✓ System call viewpoint (using strace)

```
prompt> strace cat foo
...
open("foo", O_RDONLY|O_LARGEFILE)         = 3
read(3, "hello\n", 4096)                  = 6
write(1, "hello\n", 6)                    = 6
hello
read(3, "", 4096)                         = 0
close(3)                                  = 0
...
prompt>
```

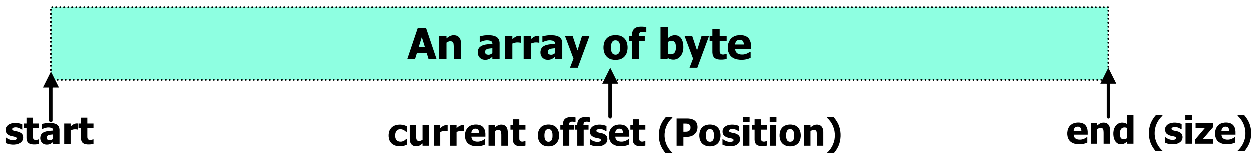
TIP: USE STRACE (AND SIMILAR TOOLS)

The `strace` tool provides an awesome way to see what programs are up to. By running it, you can trace which system calls a program makes, see the arguments and return codes, and generally get a very good idea of what is going on.

The tool also takes some arguments which can be quite useful. For example, `-f` follows any fork'd children too; `-t` reports the time of day at each call; `-e trace=open,close,read,write` only traces calls to those system calls and ignores all others. There are many more powerful flags — read the man pages and find out how to harness this wonderful tool.

39.5 Reading and Writing, But Not Sequentially

- Conventional accessing mechanism for a file
  - ✓ Sequential
  - ✓ From the begin, increasing the offset while reading or writing



- How to access random position? (not sequentially)
  - ✓ lseek()
    - Arguments: 1) fd, 2) relative offset from whence, 3) reference point

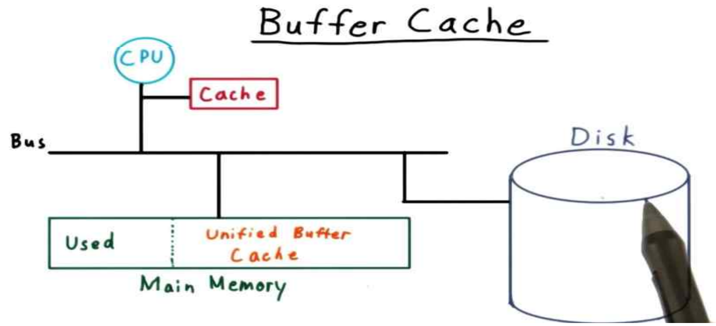
```
off_t lseek(int fildes, off_t offset, int whence);
```

      - Whence: SEEK_SET, SEEK CUR, SEEK_END
    - Explicit update the current offset (c.f. read/write: implicit update)
    - Do not confuse lseek() with disk seek :-)

☞ **Also do not confuse process and processor**

39.7 Writing Immediately with fsync()

- Performance consideration for write
  - ✓ Write to DRAM vs Disk: 100ns vs 10,000,000ns (10ms)
  - ✓ Delayed write
    - Write data into DRAM (called buffer or page cache) and set them dirty
    - Later write all dirty data into disk in a clustering fashion (5 or 30 seconds periodically)
    - Write grouping and write reordering indeed enhance performance
    - Synchronous vs. Asynchronous



- Concern of delayed write
  - ✓ Durability
    - User think his/her data is permanent but not in actuality
  - ✓ How to guarantee durability
    - fsync() system call

```
int fd = open("foo", O_CREAT|O_WRONLY|O_TRUNC, S_IRUSR|S_IWUSR);
assert(fd > -1);
int rc = write(fd, buffer, size);
assert(rc == size);
rc = fsync(fd);
assert(rc == 0);
```

Quiz for 9^{th}-Week 2^{nd}-Lesson

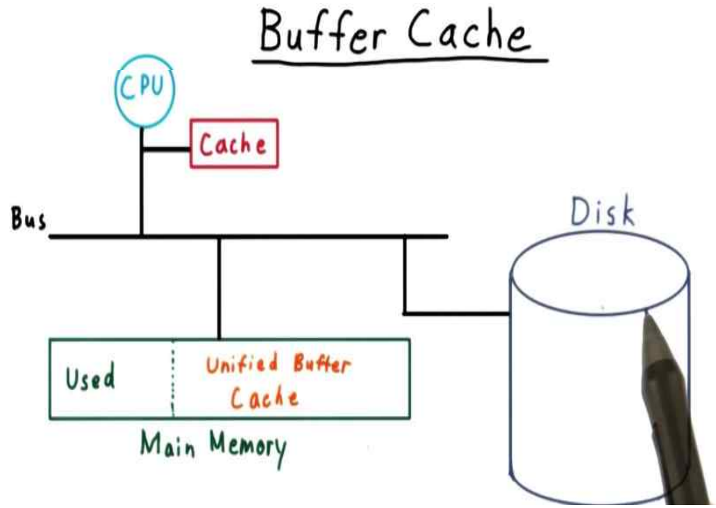
- Quiz
  - ✓ 1. Calculate the T_{seek}, $T_{rotation}$, $T_{transfer}$, $T_{I/O}$ and $R_{I/O}$ for the random and sequential workload using Barracuda (hint: refer to 7~8 pages of the chapter 37 in OSTEP).
  - ✓ 2. Discuss the similarity and differences between CPU cache and buffer cache (using delayed write).
  - ✓ Due: until 6 PM Friday of this week (30^{th}, April)

	Cheetah 15K.5	Barracuda
Capacity	300 GB	1 TB
RPM	15,000	7,200
Average Seek	4 ms	9 ms
Max Transfer	125 MB/s	105 MB/s
Platters	4	4
Cache	16 MB	16/32 MB
Connects via	SCSI	SATA

Figure 37.5: **Disk Drive Specs: SCSI Versus SATA**

	Cheetah	Barracuda
$R_{I/O}$ Random	0.66 MB/s	0.31 MB/s
$R_{I/O}$ Sequential	125 MB/s	105 MB/s

Figure 37.6: **Disk Drive Performance: SCSI Versus SATA**



39.8 Renaming Files / 39.10 Removing Files

- Change a file name
  - ✓ Command line viewpoint

```
prompt> mv foo bar
```

  - ✓ API (system call) viewpoint: editor example

```
int fd = open("foo.txt.tmp", O_WRONLY|O_CREAT|O_TRUNC,
              S_IRUSR|S_IWUSR);
write(fd, buffer, size); // write out new version of file
fsync(fd);
close(fd);
rename("foo.txt.tmp", "foo.txt");
```

    - rename(old name, new name)
    - conducted atomically
- Remove a file
  - ✓ API
    - unlink(file name)

```
prompt> strace rm foo
...
unlink("foo")                                    = 0
...
```

☞ **Why not remove() or delete() instead of unlink()? Then, what is link()?**

39.9 Getting Information about Files

- Contents in a file system
  - ✓ Two types of data in file system: User data vs. Metadata
    - User data (or just data): data written by users
    - Metadata: data written by a file system for managing files (in inode) and file system (in superblock)
  - ✓ API to see the metadata for a certain file
    - stat(file_name, struct stat)
    - fstat(fd, struct stat)

```
struct stat {
    dev_t     st_dev;     /* ID of device containing file */
    ino_t     st_ino;     /* inode number */
    mode_t    st_mode;    /* protection */
    nlink_t   st_nlink;   /* number of hard links */
    uid_t     st_uid;     /* user ID of owner */
    gid_t     st_gid;     /* group ID of owner */
    dev_t     st_rdev;    /* device ID (if special file) */
    off_t     st_size;    /* total size, in bytes */
    blksize_t st_blksize; /* blocksize for filesystem I/O */
    blkcnt_t  st_blocks;  /* number of blocks allocated */
    time_t    st_atime;   /* time of last access */
    time_t    st_mtime;   /* time of last modification */
    time_t    st_ctime;   /* time of last status change */
};
```

```
prompt> echo hello > file
prompt> stat file
  File: `file'
  Size: 6 Blocks: 8          IO Block: 4096   regular file
Device: 811h/2065d Inode: 67158084     Links: 1
Access: (0640/-rw-r-----) Uid: (30686/ remzi) Gid: (30686/ remzi)
Access: 2011-05-03 15:50:20.157594748 -0500
Modify: 2011-05-03 15:50:20.157594748 -0500
Change: 2011-05-03 15:50:20.157594748 -0500
```

39.11 Making Directories / 39.13 Deleting Directories

- API for making directory
  - ✓ mkdir(name, permission)

```
prompt> strace mkdir foo
...
mkdir("foo", 0777)                                  = 0
...
prompt>
```

  - ✓ After making
    - Two entries: parent directory and itself

```
prompt> ls -a
./  ../
prompt> ls -al
total 8
drwxr-x---  2 remzi remzi    6 Apr 30 16:17 ./
drwxr-x--- 26 remzi remzi 4096 Apr 30 16:17 ../
```

- API for deleting directory
  - ✓ rmdir(file_name)
  - ✓ We need to use it carefully

39.12 Reading Directories

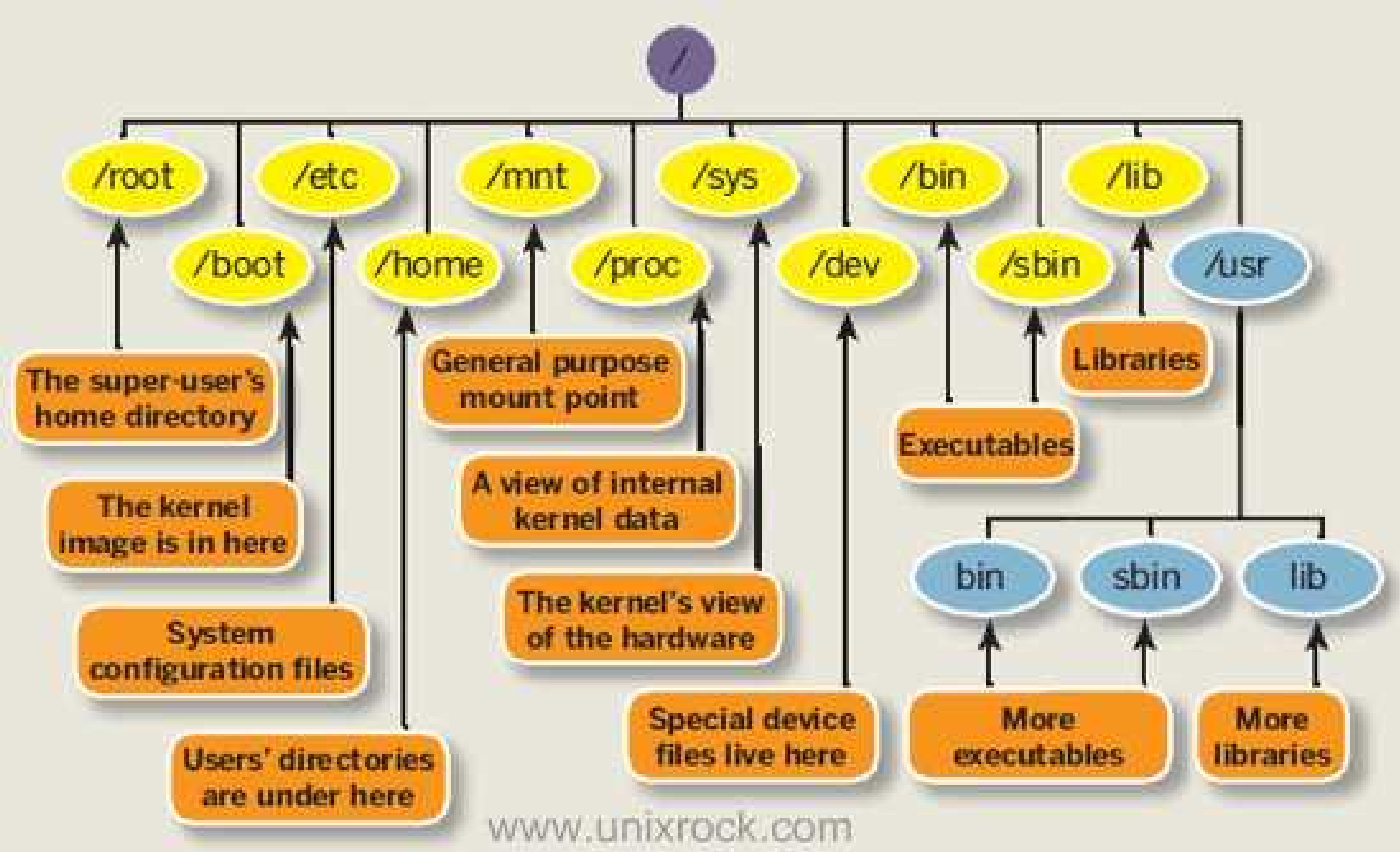
- APIs for reading directory
  - ✓ opendir(dp), readdir(dp), closedir(dp)
  - ✓ "ls": like the below example (c.f. "ls –l": readdir() + stat())

```
int main(int argc, char *argv[]) {
    DIR *dp = opendir(".");
    assert(dp != NULL);
    struct dirent *d;
    while ((d = readdir(dp)) != NULL) {
        printf("%d %s\n", (int) d->d_ino, d->d_name);
    }
    closedir(dp);
    return 0;
}

struct dirent {
    char            d_name[256]; /* filename */
    ino_t           d_ino;       /* inode number */
    off_t           d_off;       /* offset to the next dirent */
    unsigned short  d_reclen;    /* length of this record */
    unsigned char   d_type;      /* type of file */
};
```

☞ **Why there is no writedir()?**

39.12 Reading Directories

- Directory name convention



(Source: http://www.unixrock.com/2013/04/solaris-directory-hierarchy.html)

39.14 Hard Links

- Link
  - ✓ Make another file name to access an existing file
    - Connect a file name with an inode
  - ✓ Command line viewpoint
    - Either file or file2

```
prompt> echo hello > file
prompt> cat file
hello
prompt> ln file file2
prompt> cat file2
hello
```

```
prompt> ls -i file file2
67158084 file
67158084 file2
prompt>
```

  - ✓ API
    - link(old_name, new_name)
  - ✓ After remove one of them
    - Use unlink()
    - Still remain data

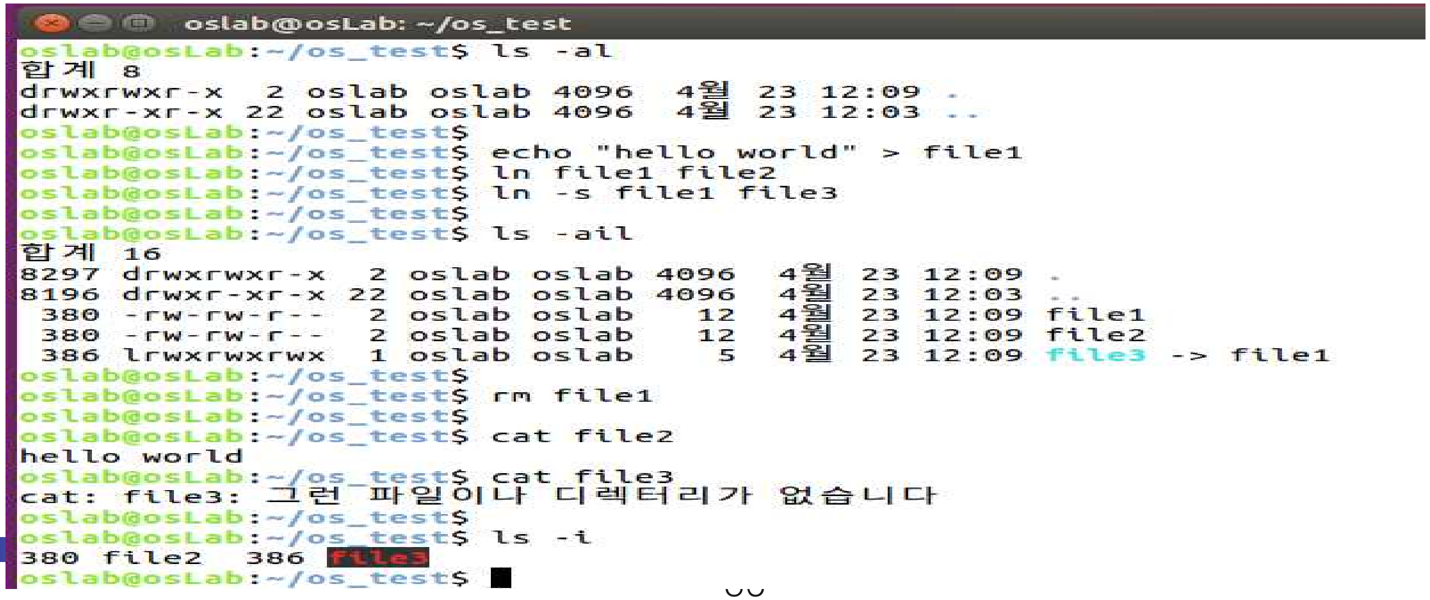
```
prompt> rm file
removed 'file'
prompt> cat file2
hello
```

  - ✓ Link count
    - Delete data when link count is 0

```
prompt> echo hello > file
prompt> stat file
... Inode: 67158084    Links: 1 ...
prompt> ln file file2
prompt> stat file
... Inode: 67158084    Links: 2 ...
prompt> stat file2
... Inode: 67158084    Links: 2 ...
prompt> ln file2 file3
prompt> stat file
... Inode: 67158084    Links: 3 ...
prompt> rm file
prompt> stat file2
... Inode: 67158084    Links: 2 ...
prompt> rm file2
prompt> stat file3
... Inode: 67158084    Links: 1 ...
prompt> rm file3
```

39.15 Symbolic Links

- Link
  - ✓ Hard link: share inode number
    - Create a new file name and share the existing inode
  - ✓ Symbolic link (Soft link): different inode number, but its data is the linked file name
    - Create not only a new file name but also a new inode (set it as a symbolic link)
    - Can link between different file systems, Can link to a directory
  - ✓ Dangling reference in symbolic link

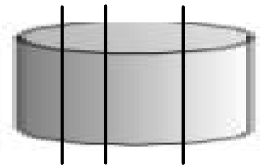


39.17 Making and Mounting a File System

- File system
  - ✓ Make a file system
    - Assemble directories and files
    - Related metadata: superblock, bitmap, … (main topic in chapter 40)
    - Command: mkfs
      - Make an empty file system (only root directory) in a disk partition

```
howtogeek@ubuntu: ~
howtogeek@ubuntu:~$ sudo mkfs
mkfs            mkfs.ext2       mkfs.ext4dev    mkfs.ntfs
mkfs.bfs        mkfs.ext3       mkfs.minix      mkfs.vfat
mkfs.cramfs     mkfs.ext4       mkfs.msdos
howtogeek@ubuntu:~$ sudo mkfs.ext4 /dev/sda5
```

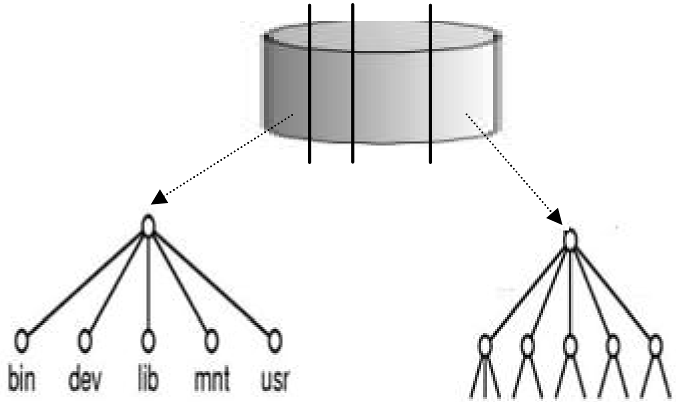
    - How to make partitions?: fdisk
  - ✓ Example
    - Partitioning and mkfs
    - Ext2/3/4, NFS, LFS, proc, sysfs, … per a partition



```
pritam@PPH:~$ sudo fdisk -l
[sudo] password for pritam:

Disk /dev/sda: 500.1 GB, 500107862016 bytes
255 heads, 63 sectors/track, 60801 cylinders, total 976773168 sectors
Units = sectors of 1 * 512 = 512 bytes
Sector size (logical/physical): 512 bytes / 512 bytes
I/O size (minimum/optimal): 512 bytes / 512 bytes
Disk identifier: 0x1707a8a5

   Device Boot      Start         End      Blocks   Id  System
/dev/sda1   *        2048    97656831    48827392    7  HPFS/NTFS/exFAT
/dev/sda2        97656832   293177343    97760256    7  HPFS/NTFS/exFAT
/dev/sda3       293177344   879116287   292969472    7  HPFS/NTFS/exFAT
/dev/sda4       879118334   976773119    48827393    5  Extended
/dev/sda5       879118336   888881151     4881408   82  Linux swap / Solaris
/dev/sda6       888883200   976773119    43944960   83  Linux
pritam@PPH:~$
```

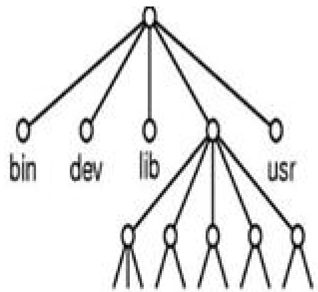
39.17 Making and Mounting a File System

- File system
  - ✓ Mount
    - Make a file system visible to users
    - Connect multiple file systems within the uniform directory tree
      - mount arguments: 1) FS type, 2) partition, 3) mount point



Before mount

$mount –t ext3 /dev/sda4 /mnt



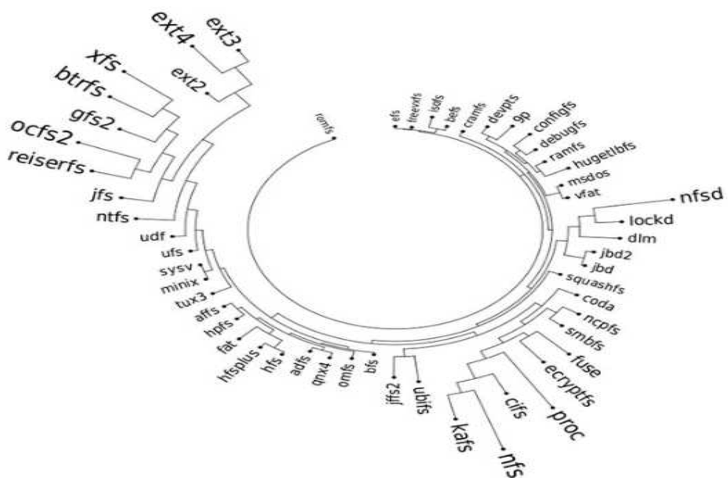
After mount

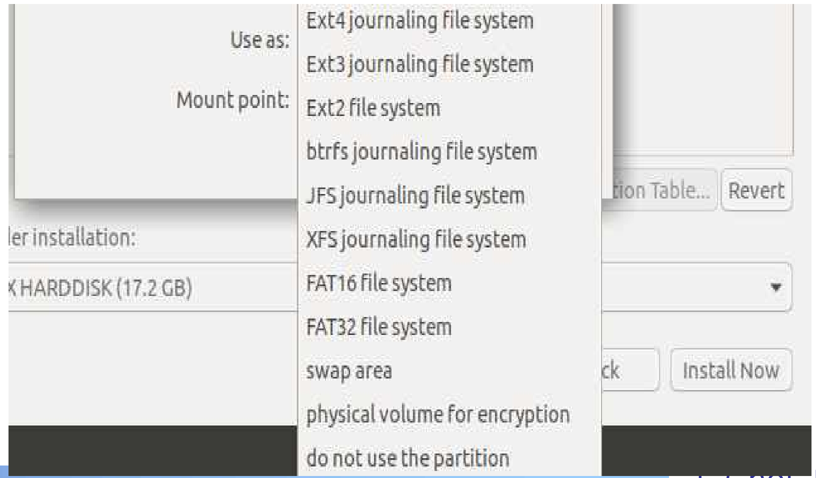
- mount point: mnt in the previous example ➔ point the root of the mounted FS

☞ **Why multiple partitions?**

Chap. 40 File System Implementation

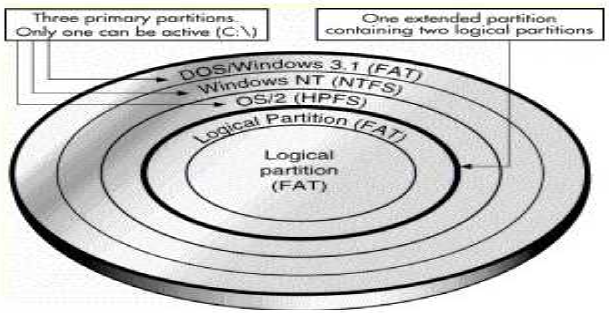
- Objective of this chapter
  - ✓ A variety of file systems
    - UFS, FFS, EXT2/3/4, JFS, LFS, NTFS, F2FS, FUSE, RAMFS, NFS, AFS, ZFS, GFS, FATFS, BtrFS, ….
  - ✓ Make a new file system: called VSFS(Very Simple File System)
    - Simplified version of UFS (Unix File System)
    - 1) On-disk structures: inode, bitmap, directory, …
    - 2) Access method: read, write, …
    - 3) Various policies: cache, delayed write, …
  - ✓ More complex file systems ➔ next chapters





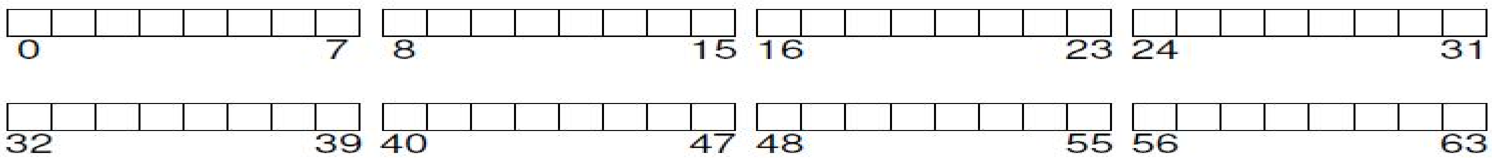
40.1 The Way to Think / 40.2 Overall Organization

- Disk
  - ✓ Consist of partitions
  - ✓ A file system is created in each partition




```
Disk /dev/sda: 320.1 GB, 320072933376 bytes
255 heads, 63 sectors/track, 38913 cylinders
Units = cylinders of 16065 * 512 = 8225280 bytes
Sector size (logical/physical): 512 bytes / 512 bytes
I/O size (minimum/optimal): 512 bytes / 512 bytes
Disk identifier: 0xaa692010

   Device Boot      Start         End      Blocks   Id  System
/dev/sda1   *           1        7681    61690880    7  HPFS/NTFS
/dev/sda2            7681       14182    52219904    7  HPFS/NTFS
/dev/sda3           14182       20556    51200000    7  HPFS/NTFS
/dev/sda4           20556       38913   147453953    f  W95 Ext'd (LBA)
/dev/sda5           20556       32030    92160000    7  HPFS/NTFS
/dev/sda6           34324       34770     3583999+  82  Linux swap / Solaris
/dev/sda7           34771       38913    33276928    7  HPFS/NTFS
/dev/sda8           32030       34323    18423808   83  Linux

Partition table entries are not in disk order
```

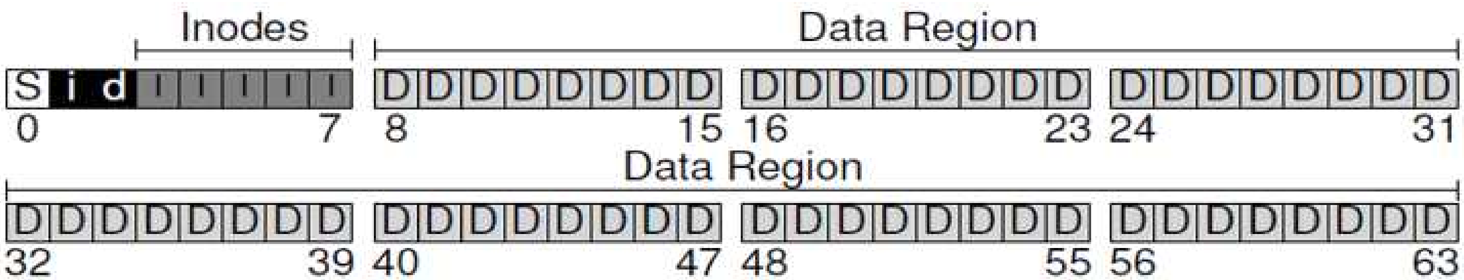
- Partition
  - ✓ Consist of disk blocks
  - ✓ User data is stored in a disk block (usually same size with the page)
  - ✓ Assume a partition having 64 disk blocks (or simply blocks)



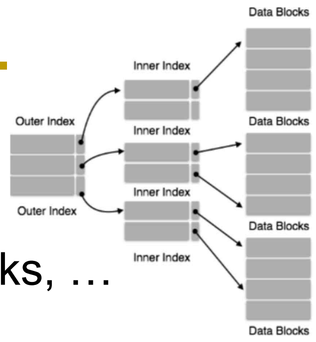
☞ **Now consider what data structures are required for making a FS?**

40.2 Overall Organization

- Layout of a file system (VSFS)
  - ✓ Superblock: 0 blocks
    - Metadata for managing a file system (one per a file system)
      - Information: how many data blocks, inodes, where they begin, …
    - Used during a mount function
  - ✓ Bitmap: 1~2 blocks
    - Metadata for managing free space (allocation structure)
    - Two bitmaps: one for data blocks and the other for inodes
  - ✓ Inode: 3~7 blocks
    - Metadata for managing files (one per a file)
    - Inode size = 256B ➔ 16 inodes per a block ➔ 5 blocks for inode ➔ total 80 files can be created
  - ✓ User data: 8 ~ 63 blocks (can be dynamically adjusted)
    - Data written by users



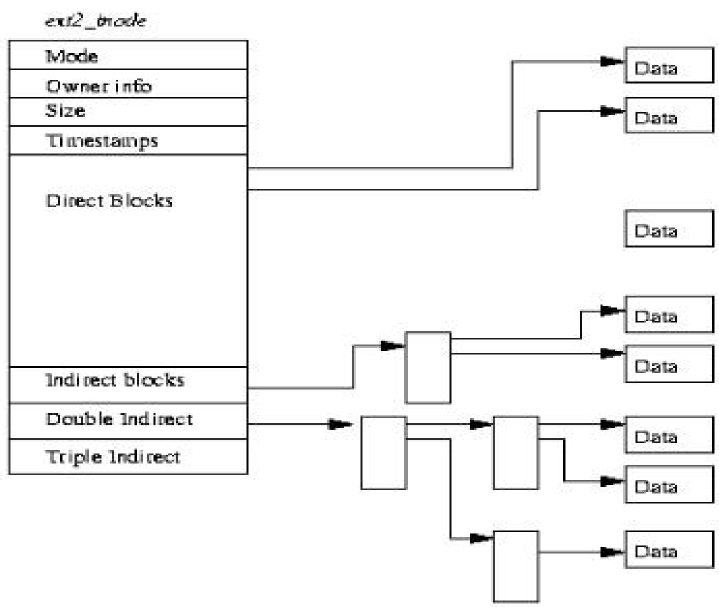
40.3 File Organization: The inode



- How to manage metadata for a file
  - ✓ inode (index node)
    - File information such as mode, uid, size, time, link count, blocks, …
      - Can be accessed using stat()
    - Locations of User data blocks ➔ Multi-Level index and Imbalanced tree
      - Direct block pointers (10 or 12 or 15), Single/Double/Triple indirect block pointers(1/1/1)
      - Benefit: Fast for a short file and Big size support for a large file
  - ✓ Other approach: FAT (linked based), Extent-based, Log-based, ..

Size	Name	What is this inode field for?
2	mode	can this file be read/written/executed?
2	uid	who owns this file?
4	size	how many bytes are in this file?
4	time	what time was this file last accessed?
4	ctime	what time was this file created?
4	mtime	what time was this file last modified?
4	dtime	what time was this inode deleted?
2	gid	which group does this file belong to?
2	links_count	how many hard links are there to this file?
4	blocks	how many blocks have been allocated to this file?
4	flags	how should ext2 use this inode?
4	osd1	an OS-dependent field
60	block	a set of disk pointers (15 total)
4	generation	file version (used by NFS)
4	file_acl	a new permissions model beyond mode bits
4	dir_acl	called access control lists

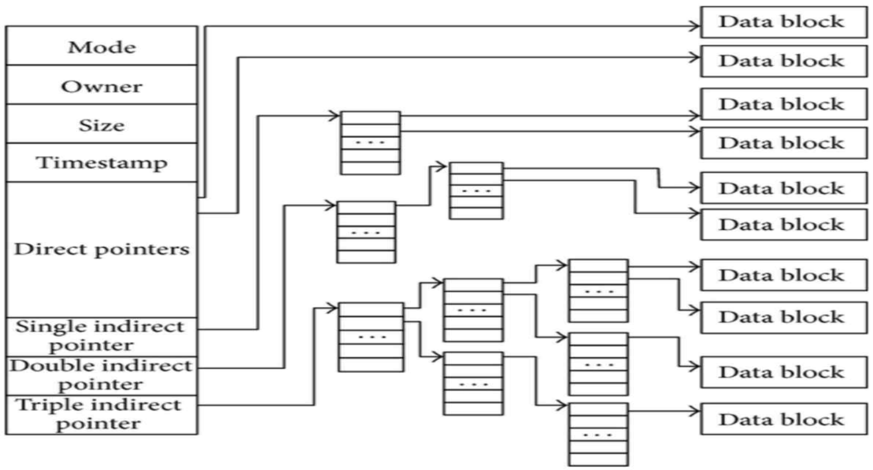
Figure 40.1: **Simplified Ext2 Inode**



☞ **How large size can be supported by direct block pointers? How about an indirect pointer?**

40.3 File Organization: The inode

- Maximum file size supported by an inode
  - ✓ Sum up: 48KB + 4MB + 4GB + 4TB
    - Direct block point: 12 x 4KB
    - Single indirect block pointers: 1 x 1024 x 4KB
      - Why 1024: 4KB / pointer size = 4KB/4B = 1024
    - Double indirect block pointers: 1 x 1024 x 1024 x 4KB
    - Triple indirect block pointers: 1 x 1024 x 1024 x 1024 x 4KB
  - ✓ Benefits of imbalance tree: both performance and large size
    - Small file: direct access via an inode
      - Indirect block ➔ require additional disk I/Os
    - Large file: support large size with the simple structure of inode



Most files are small	Roughly 2K is the most common size
Average file size is growing	Almost 200K is the average
Most bytes are stored in large files	A few big files use most of the space
File systems contains lots of files	Almost 100K on average
File systems are roughly half full	Even as disks grow, file systems remain ~50% full
Directories are typically small	Many have few entries; most have 20 or fewer

Figure 40.2: File System Measurement Summary

(Source: https://www.researchgate.net/figure/The-architecture-of-an-inode-in-EXT3-file-system_fig2_258396310)

Quiz for 10th-Week 1st-Lesson

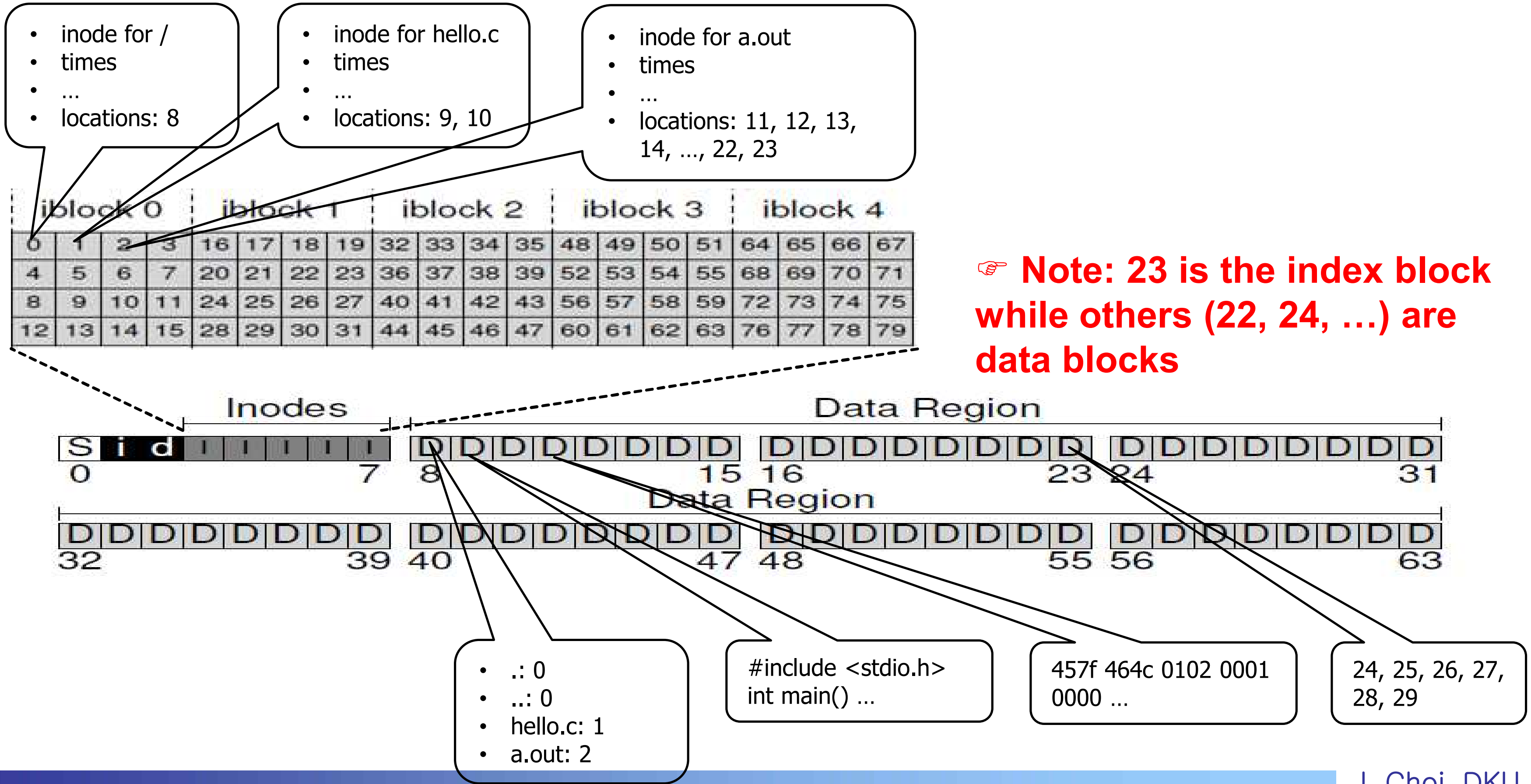
- Quiz
  - ✓ 1. What is the definition of metadata? List at least 5 examples of metadata that we can access using “stat()” API.
  - ✓ 2. Discuss the 4 components and their role when we create the VSFS using “mkfs” command.
  - ✓ (Bonus) The below figure is the snapshot that I perform the “ls –l” for “/dev/tty”, “/dev/sda”, “/dev/sda1” in our Lab. environment. What are the meaning of “b”, “c”, ”rw” “5”, “8”, “1” in the figure?
  - ✓ Due: until 6 PM Friday of this week (7th, May)

Create and mount filesystems in Linux

(Source: https://www.linuxsysadmins.com/create-and-mount-filesystems-in-linux/)

40.3 File Organization: The inode

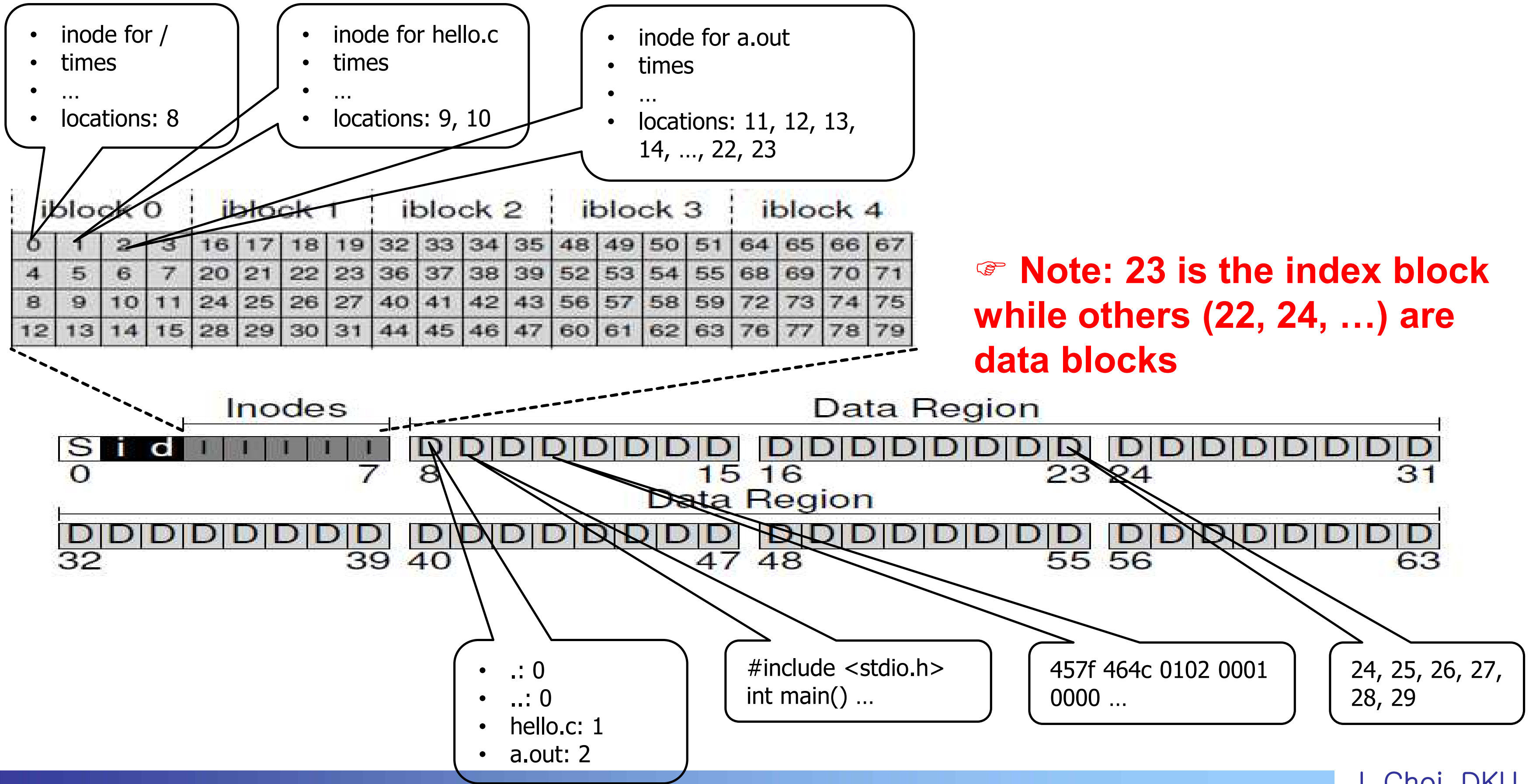
- inode manipulation example (assume 12 direct blocks)
  - ✓ When we create a new file (named hello.c whose size is 7KB) in a root directory?
  - ✓ Then, we compile it? (a.out whose size is 70KB)



☞ **Note: 23 is the index block while others (22, 24, …) are data blocks**

40.3 File Organization: The inode

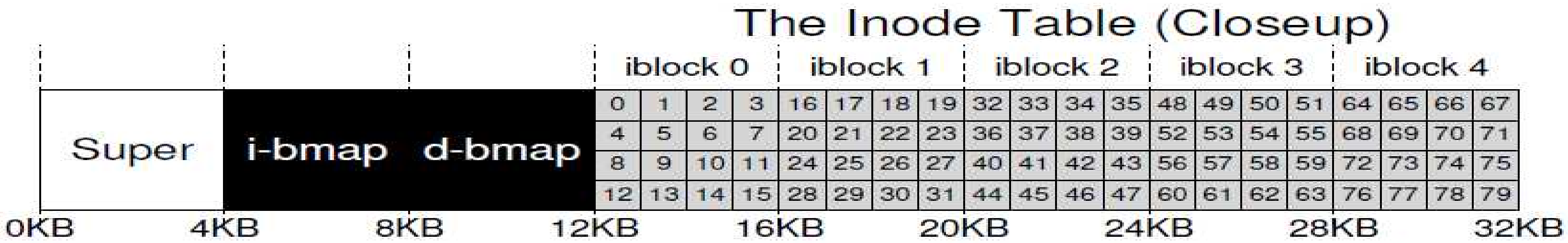
- inode manipulation example (assume 12 direct blocks)
  - ✓ How to read the a.out?
    - e.g. fd = open(“/a.out”, O_RDONLY);



☞ **Note: 23 is the index block while others (22, 24, …) are data blocks**

40.3 File Organization: The inode

- Find a location: inode and data in a real
  - ✓ How to find the location of an inode?
    - Directory entry: <file name, i_number>
    - i_number is used as the index in inode table (quotient and remainder)
      - e.g.) i_number = 33 ➔ 33 / (inodes per block) = 33/16 = 2 … 1 ➔ inode table start + 4KB x 2 = 12KB + 8KB = 20KB ➔ read a block starting 20KB ➔ go to the offset of inode_size x 1 = 256B



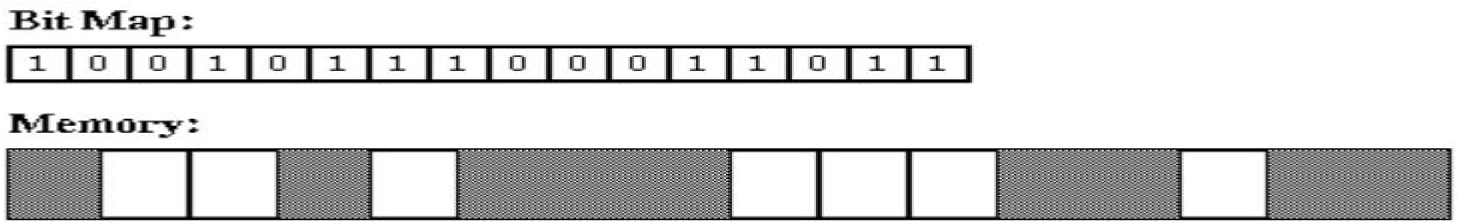
  - ✓ How to find the location of User data?
    - 1) Find inode, 2) file's current_offset / disk block size = quotient … remainder, 3) quotient is used to find a pointer in the inode (multi-level index), 4) remainder is used as the offset in the disk block
      - e.g.) file's current_offset=5000 ➔ 5000/(block size) = 5000/4096 = 1 … 904 ➔ index 1 in inode (e.g. block 12 in the previous slide when the file is a.out) ➔ read block 12 ➔ go to the 904 in the block

40.4 Directory Organization / 40.5 Free Space Mgmt.

- Directory
  - ✓ User viewpoint: containing files at a same location
  - ✓ System viewpoint: A list of pairs <file name, inode number>
  - ✓ For fast search, add the file name length and record length (total bytes including left over space)

inum	reclen	strlen	name
5	4	2	.
2	4	3	..
12	4	4	foo
13	4	4	bar
24	8	7	foobar

  - ✓ Can use more complex structure for directory (e.g. B-tree in XFS)
- Free space
  - ✓ Bitmap: one bit per block (or inode), indicating whether it is free or used
  - ✓ Alternative approach: free-list, tree, …
  - ✓ Pre-allocation: allocate free disk blocks in a batch manner ➔ less overhead, contiguous allocation, …



40.6 Access Paths: Reading and Writing

- Reading a file from disk
  - ✓ open a file “/foo/bar” whose size is 12KB, read data and close it
  - ✓ Timeline

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[2]
open(bar)			read							
						read				
				read						
							read			
					read					
read()					read					
								read		
					write					
read()					read					
									read	
					write					
read()					read					
										read
					write					

Figure 40.3: **File Read Timeline (Time Increasing Downward)**

- Open: directory tree traverse ➔ connect fd to inode
- Read: current_offset ➔ find disk block location using the inode and read it ➔ update the last access time in the inode
- Close: deallocate fd and related data structure in OS, No actions in disk
- Note: repeated reads for the bar’s inode ➔ How about caching it!

40.6 Access Paths: Reading and Writing

- Writing a file into disk
  - ✓ Create a file "/foo/bar", write data (also 12KB) and close it
  - ✓ Timeline

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[2]
create (/foo/bar)			read							
						read				
				read						
							read			
		read								
		write								
							write			
					read					
					write					
				write						
write()					read					
	read									
	write									
								write		
					write					
write()					read					
	read									
	write									
									write	
					write					
write()					read					
	read									
	write									
										write
					write					

Figure 40.4: **File Creation Timeline (Time Increasing Downward)**

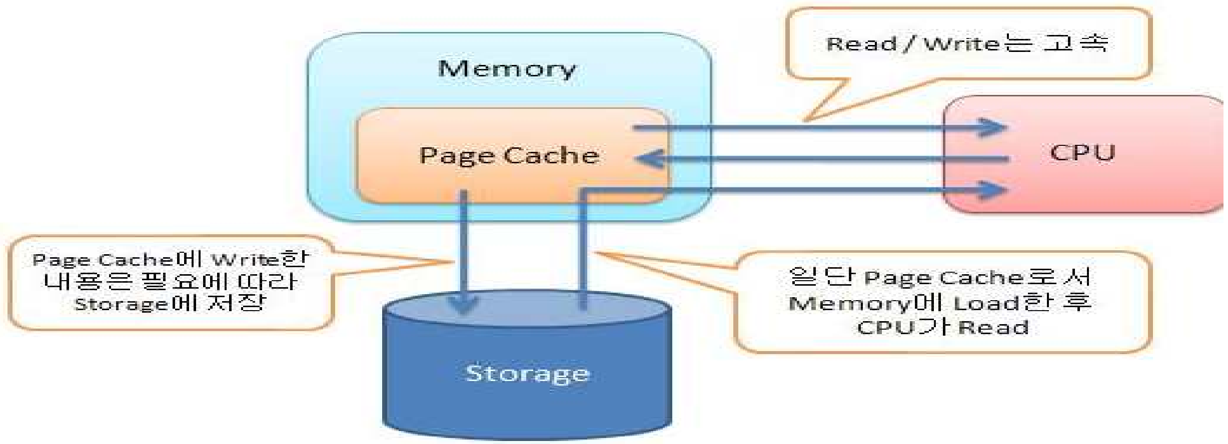
  - Open: 1) create a new inode for bar and update i-bitmap, 2) insert a new entry into foo's data block (10 I/Os for just creating a file)
  - Write: 5 I/Os per a write (d-bitmap read/update, inode read/update, actual user data write)

40.7 Caching and Buffering

- Issues
  - ✓ Disk is too slow.

> THE CRUX: HOW TO REDUCE FILE SYSTEM I/O COSTS
> Even the simplest of operations like opening, reading, or writing a file incurs a huge number of I/O operations, scattered over the disk. What can a file system do to reduce the high costs of doing so many I/Os?

- Solutions
  - ✓ 1. Caching
    - Caching directories (e.g. / inode, / data, current directory, …) in DRAM
    - Caching recently used file's inodes and data in DRAM
    - Management: LRU (Least Recently Used) replacement policy, dynamic cache size management



(Source: http://www.atmarkit.co.jp/ait/articles/0810/01/news134_2.html")

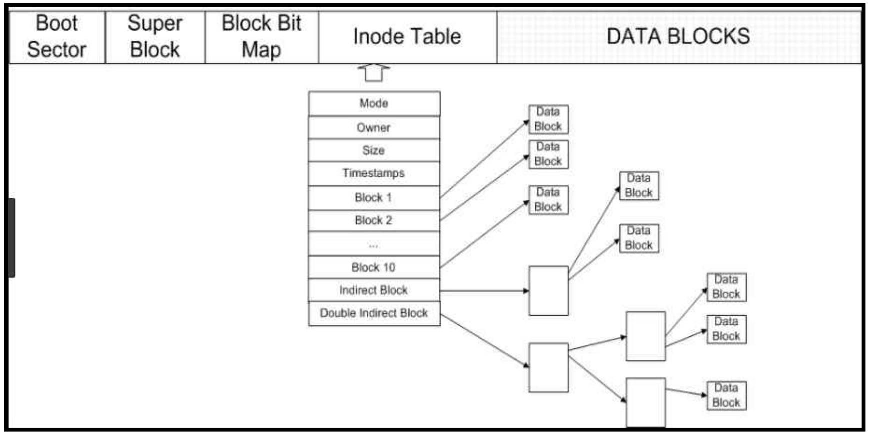
40.7 Caching and Buffering

- Solutions
  - ✓ 2. Write buffering (Delayed write)
    - Consolidate several writes into a single one: e.g.) d-bitmap
    - Schedule multiple writes so that they have less seek overhead: e.g.) bar data
    - Avoid writes: e.g.) temporary file (create and delete immediately)
    - Concern: Data loss due to power fault or crash ➔ fsync() or direct I/O

Figure 40.4: **File Creation Timeline (Time Increasing Downward)**

40.8 Summary

- Device and Driver
- Disk: I/O rate and Scheduling
- File system
  - ✓ Interface
    - open(), read(), write(), …
    - mkdir(), readdir(), …
    - mount(), mknod(), …
  - ✓ Layout
    - Data blocks
    - Inode, Bitmap, Superblock
    - Boot block



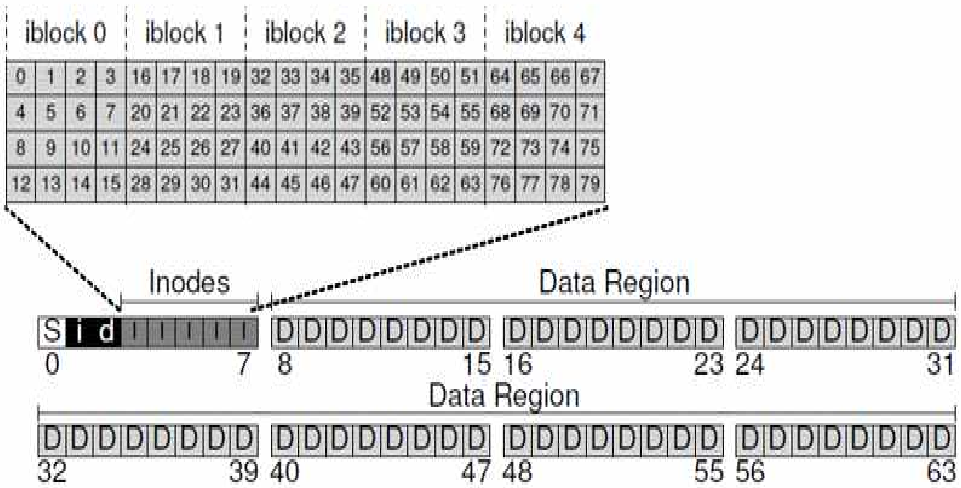
- Importance of mental model for OS study (also system study)

ASIDE: MENTAL MODELS OF FILE SYSTEMS

As we've discussed before, mental models are what you are really trying to develop when learning about systems. For file systems, your mental model should eventually include answers to questions like: what on-disk structures store the file system's data and metadata? What happens when a process opens a file? Which on-disk structures are accessed during a read or write? By working on and improving your mental model, you develop an abstract understanding of what is going on, instead of just trying to understand the specifics of some file-system code (though that is also useful, of course!).

Quiz for 10th-Week 2nd-Lesson

- Quiz
  - ✓ 1. How many disk blocks are allocated from the data region when we create a file “a.out” whose size is 70KB.
  - ✓ 2. When we read (or write) a file we need to access an inode and data alternately, which may cause a long seek distance. Propose your own idea for reducing this overhead.
  - ✓ Due: until 6 PM Friday of this week (7th, May)

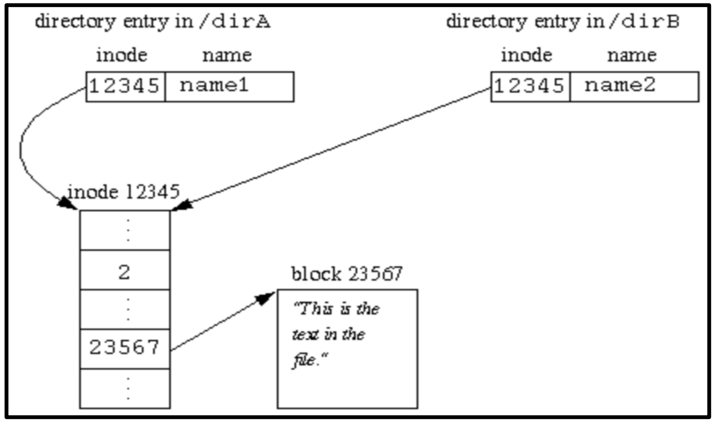


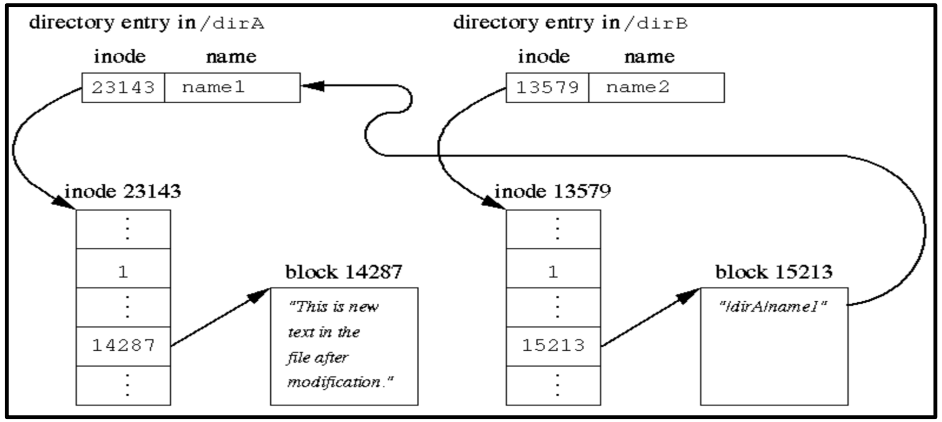
	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[2]
create (/foo/bar)			read							
						read				
				read						
							read			
		read write								
							write			
					read write					
				write						
write()					read					
	read write									
								write		
					write					
write()					read					
	read write									
									write	
					write					
write()					read					
	read write									
										write
					write					

Figure 40.4: **File Creation Timeline (Time Increasing Downward)**

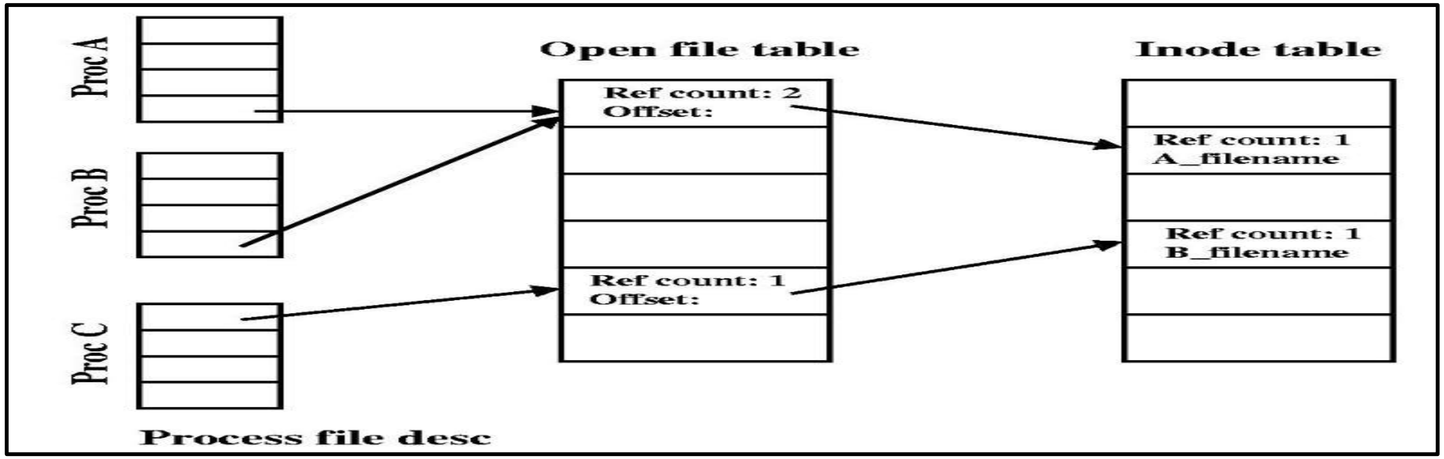
Appendix

- Hard link vs. Symbolic link(Soft link)





- fd (file descriptor), file table and inode



(Source: http://classque.cs.utsa.edu/classes/cs3733/notes/USP-05.html)