Operating Systems
Lecture 13

IO devices and disk

Prof. Mengwei Xu

Goals for Today

- I/O Devices
- Storage Devices

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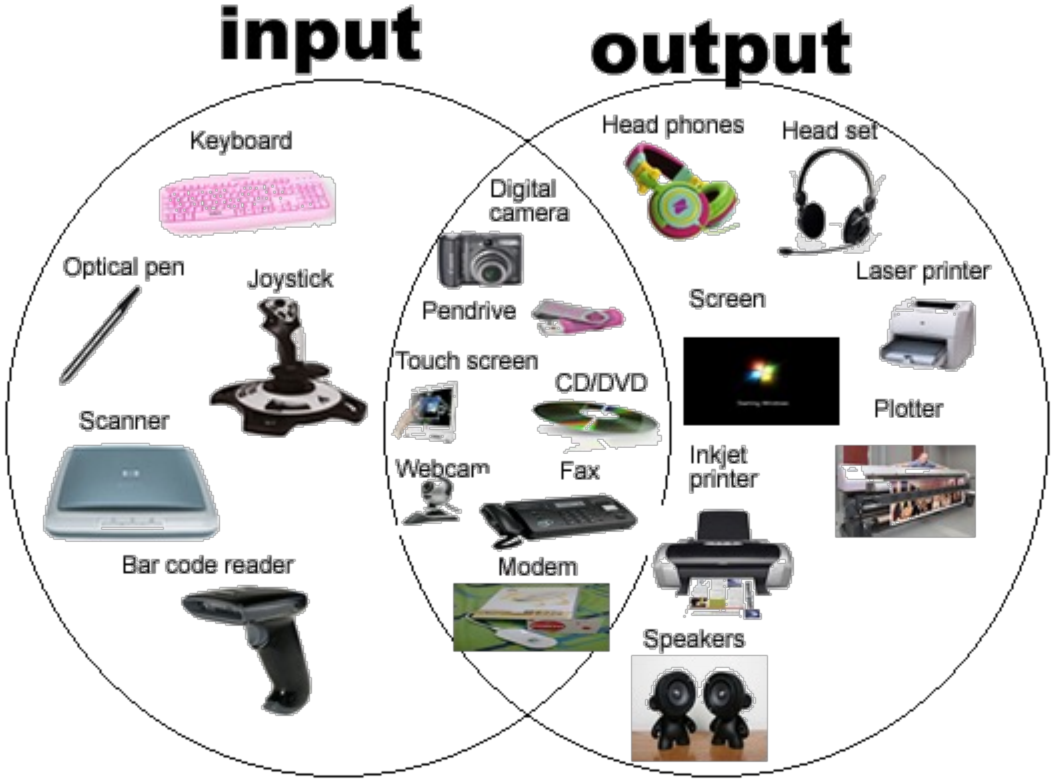
- I/O Devices
- Storage Devices

I/O Devices

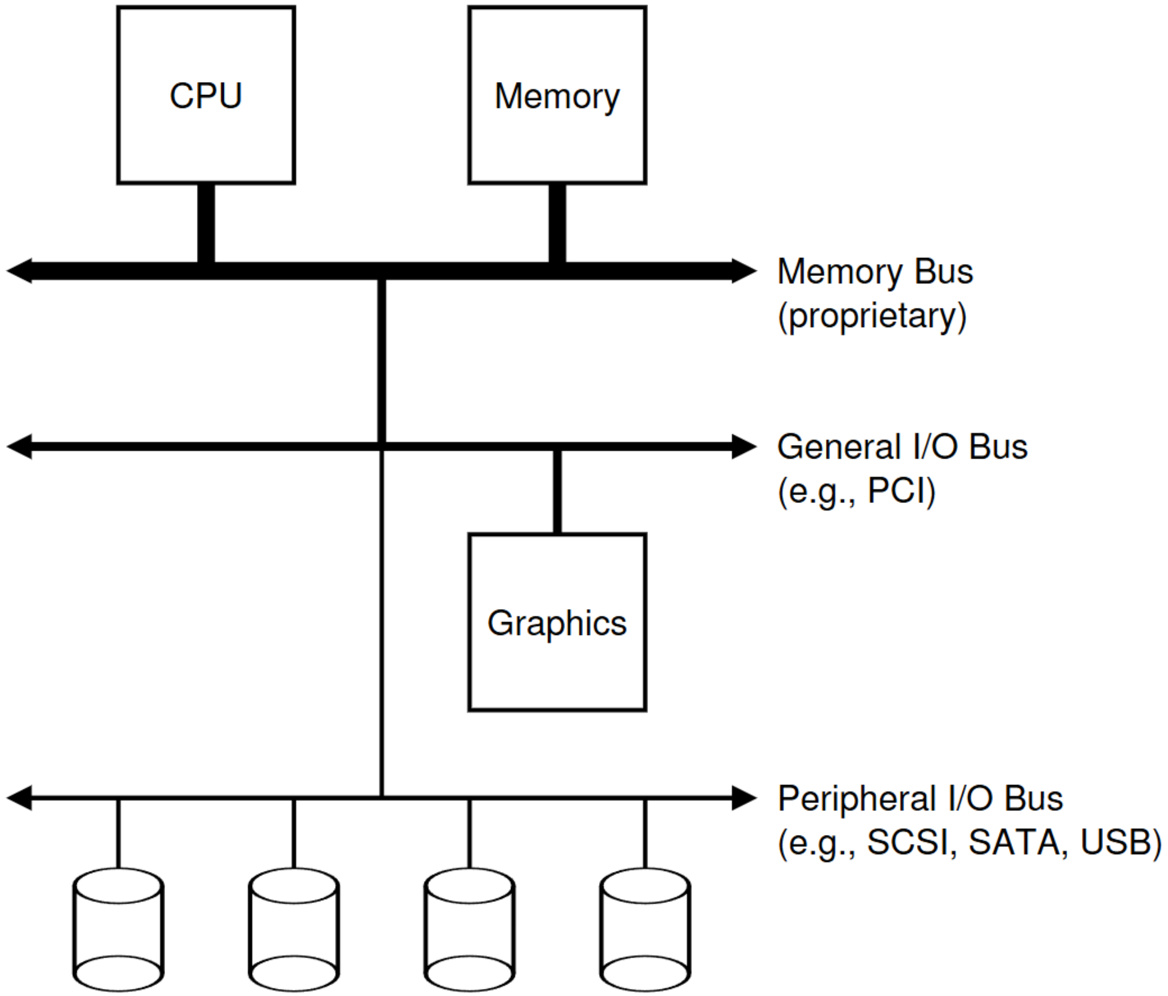
- I/O Devices (输入输出设备) are important to today's computers



- Without input devices, the machine only repeat computations and generate the same output
- Without output devices.. What's the purpose of it?

System Architecture

- The old architecture of computer IO



System Architecture

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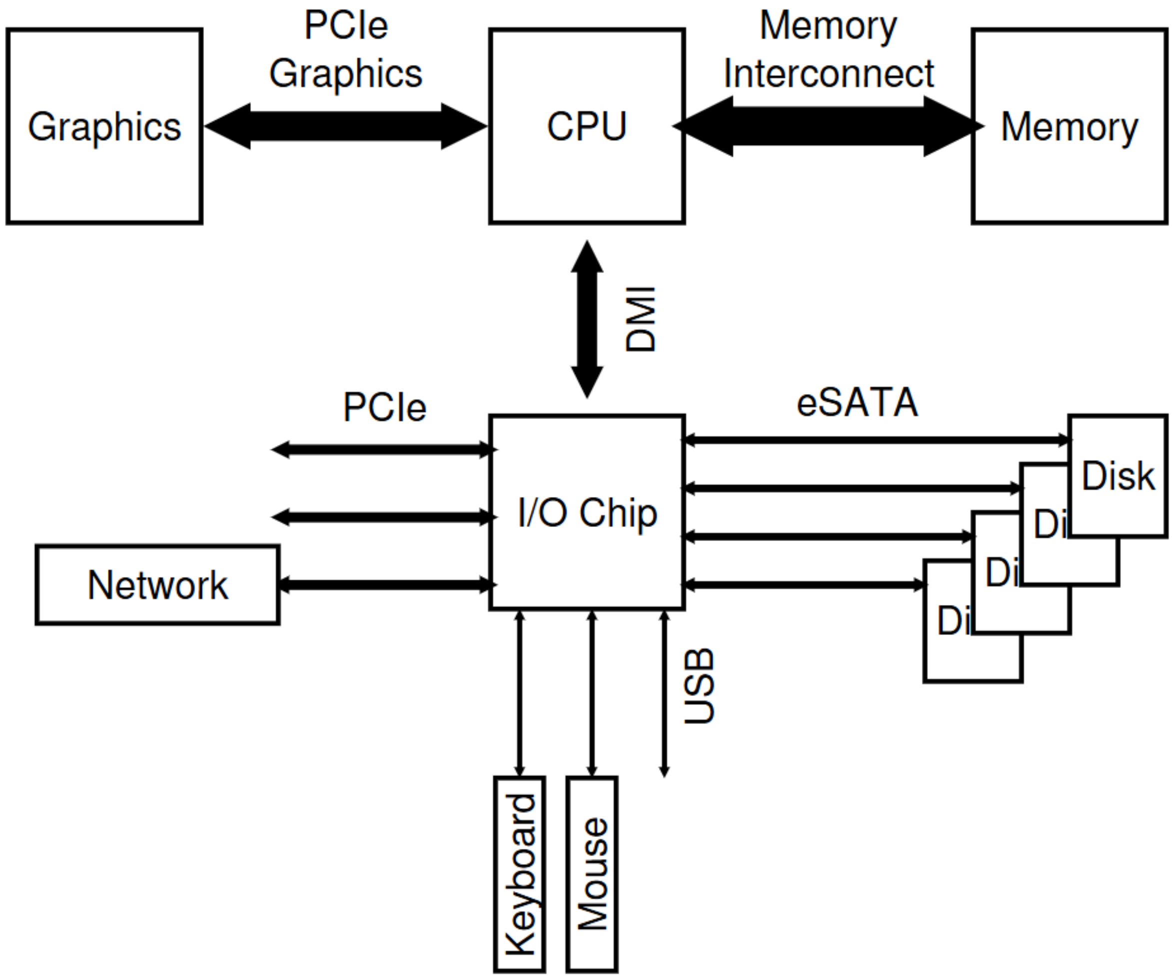
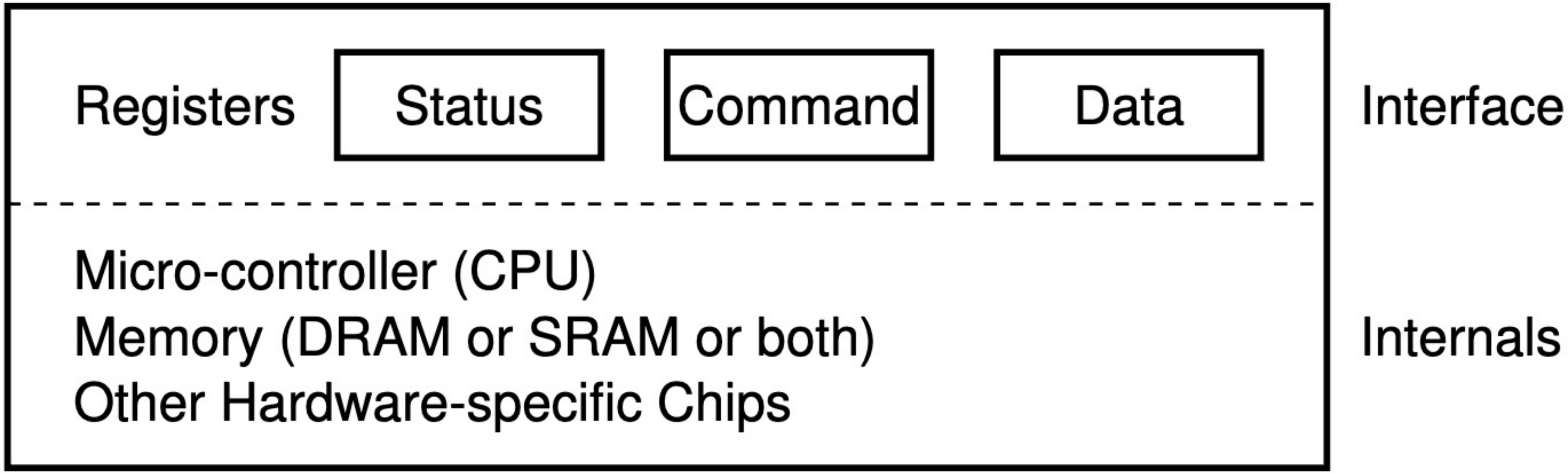


A Simple IO Device

- Part#1: interface
- Part#2: internal structure
  - Implementation specific and is responsible for implementing the abstraction the device presents to the system.
  - Complex devices could have their own CPU and memory as well.



A Simple IO Device

- a status register, which can be read to see the current status of the device;
- a command register, to tell the device to perform a certain task;
- a data register to pass data to the device, or get data from the 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
```

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Polling is inefficient!

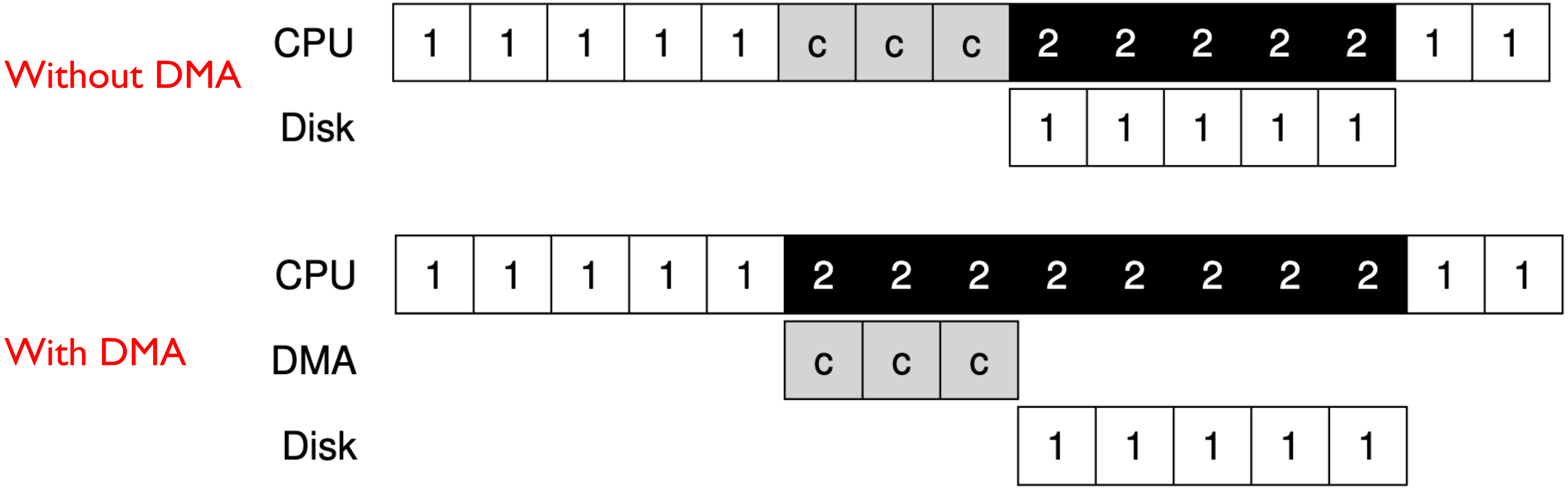
A Simple IO Device

- a status register, which can be read to see the current status of the device;
- a command register, to tell the device to perform a certain task;
- a data register to pass data to the device, or get data from the device.

- Using interrupts instead of polling

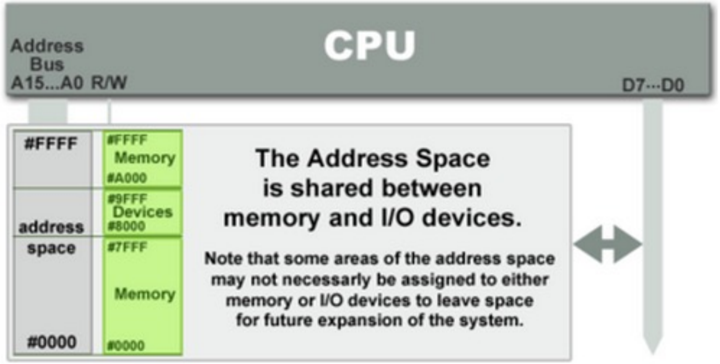
Direct Memory Access

- A DMA engine is a very specific device that can orchestrate transfers between devices and main memory without much CPU intervention.
  - To transfer data to the device, for example, the OS would program the DMA engine by telling it where the data lives in memory, how much data to copy, and which device to send it to. At that point, the OS is done with the transfer and can proceed with other work. When the DMA is complete, the DMA controller raises an interrupt, and the OS thus knows the transfer is complete.

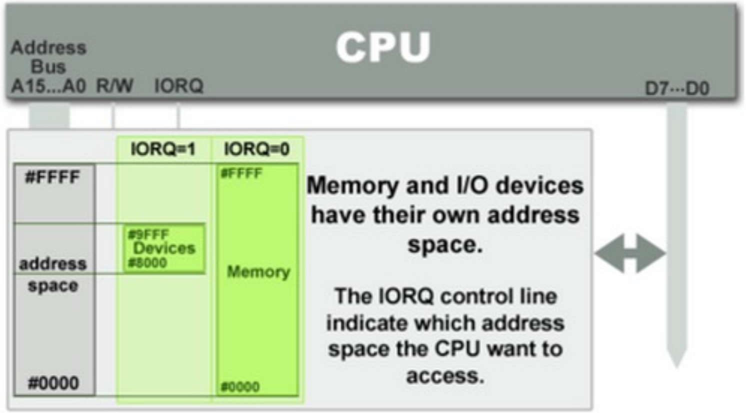


Memory-mapped I/O vs. Port-mapped I/O

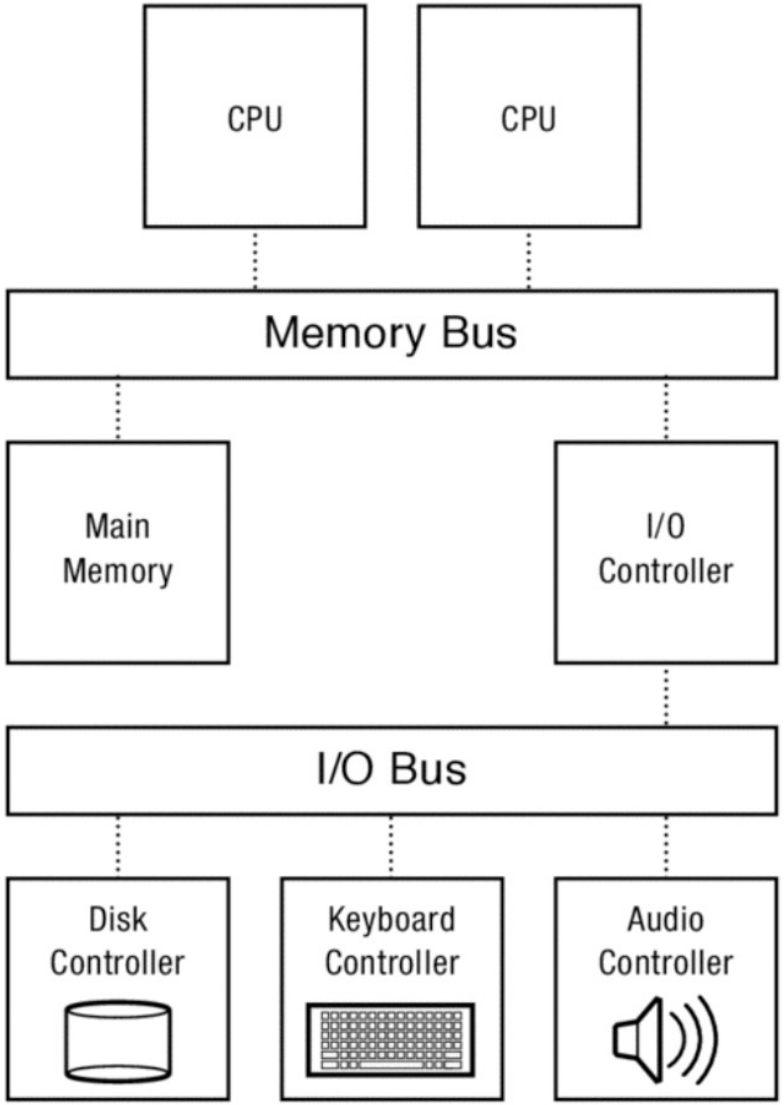
- Two complementary ways for CPU to access I/O devices
  - I/O devices have their own registers (or memory)
- Memory-mapped I/O (MMIO): let memory and devices share the physical address space.
  - Most widely adopted
  - Shared address bus

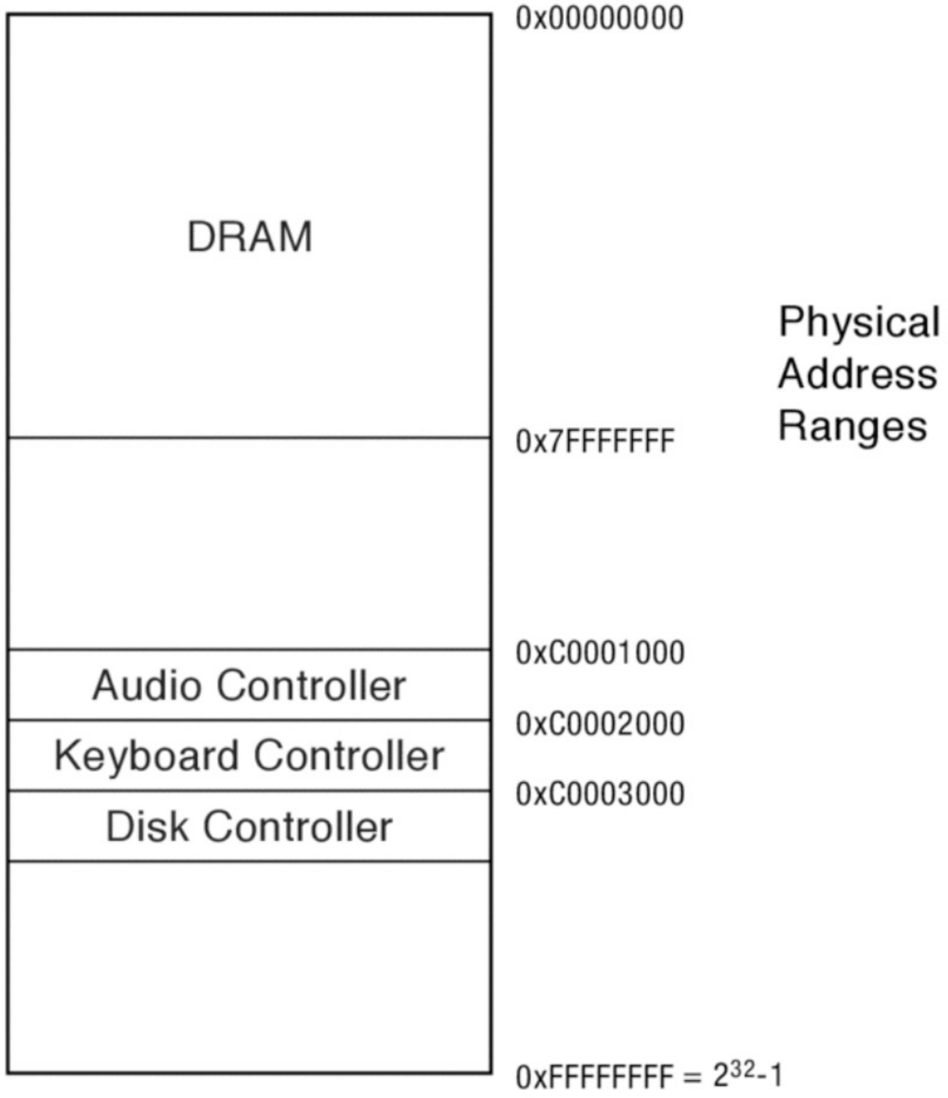


- Port-mapped I/O (PMIO), or isolated I/O: use specialized instructions to R/W I/O devices
  - In Intel: outb, outw, etc.



Storage Stack





A Simple IDE Disk Driver

```
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
```

```
static int ide_wait_ready() {
  while (((int r = inb(0x1f7)) & IDE_BSY) || !(r & IDE_DRDY))
    ;  // loop until drive isn't busy
  // return -1 on error, or 0 otherwise
}

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)
  }
}
```

Polling or Interrupt?

Memory-mapped IO or port-mapped IO?

Code from xv6

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  outb(0x1f2, 1);                  // how many sectors?
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  outb(0x1f4, (b->sector >> 8) & 0xff);   // ... and here
```

```
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);
}

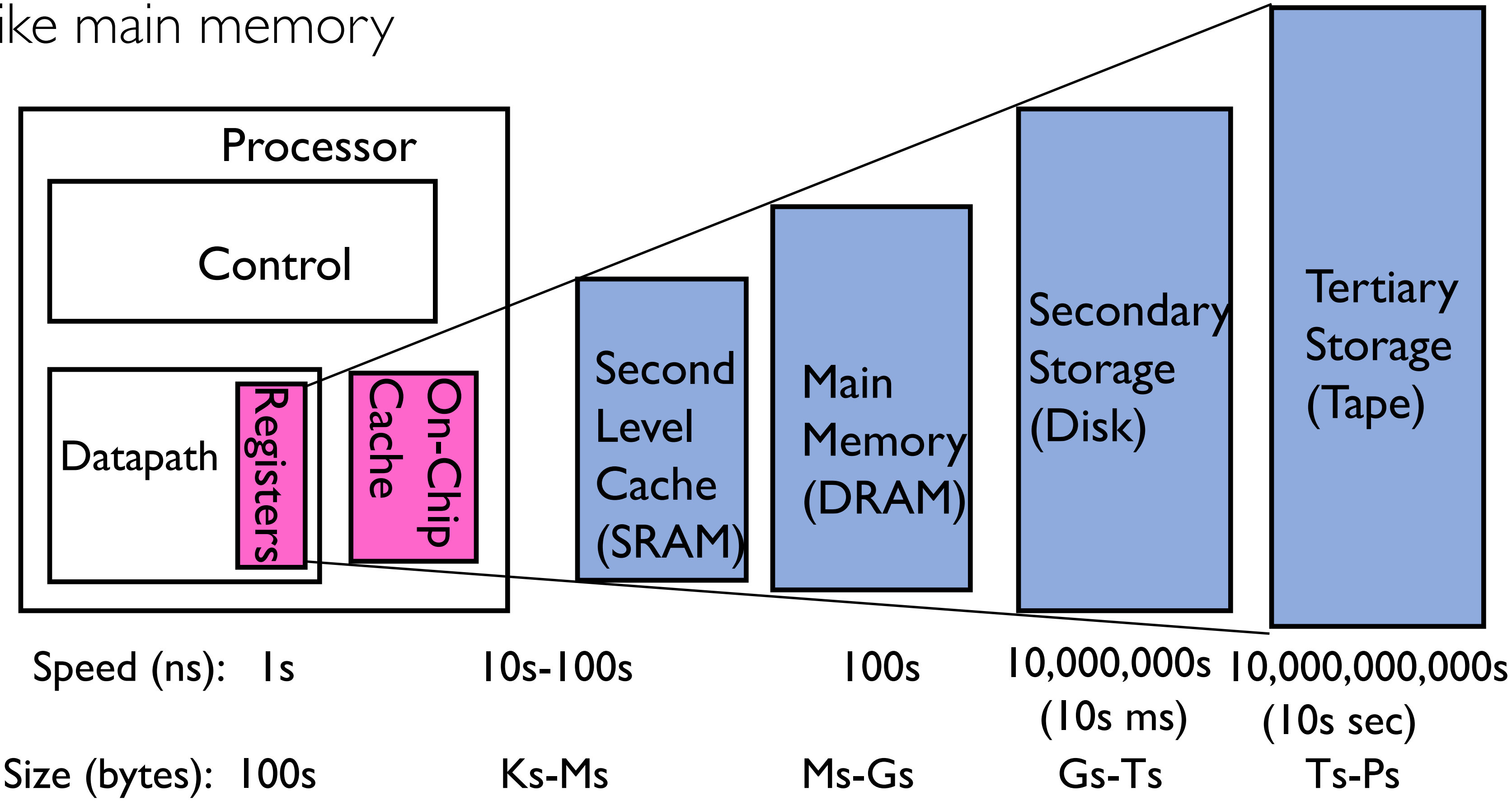
void ide_intr() {
  struct buf *b;
  acquire(&ide_lock);
  if (!(b->flags & B_DIRTY) && ide_wait_ready() >= 0)
    insl(0x1f0, b->data, 512/4);     // if READ: get data
  b->flags |= B_VALID;
  b->flags &= ˜B_DIRTY;
  wakeup(b);                           // wake waiting process
  if ((ide_queue = b->qnext)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

Goals for Today

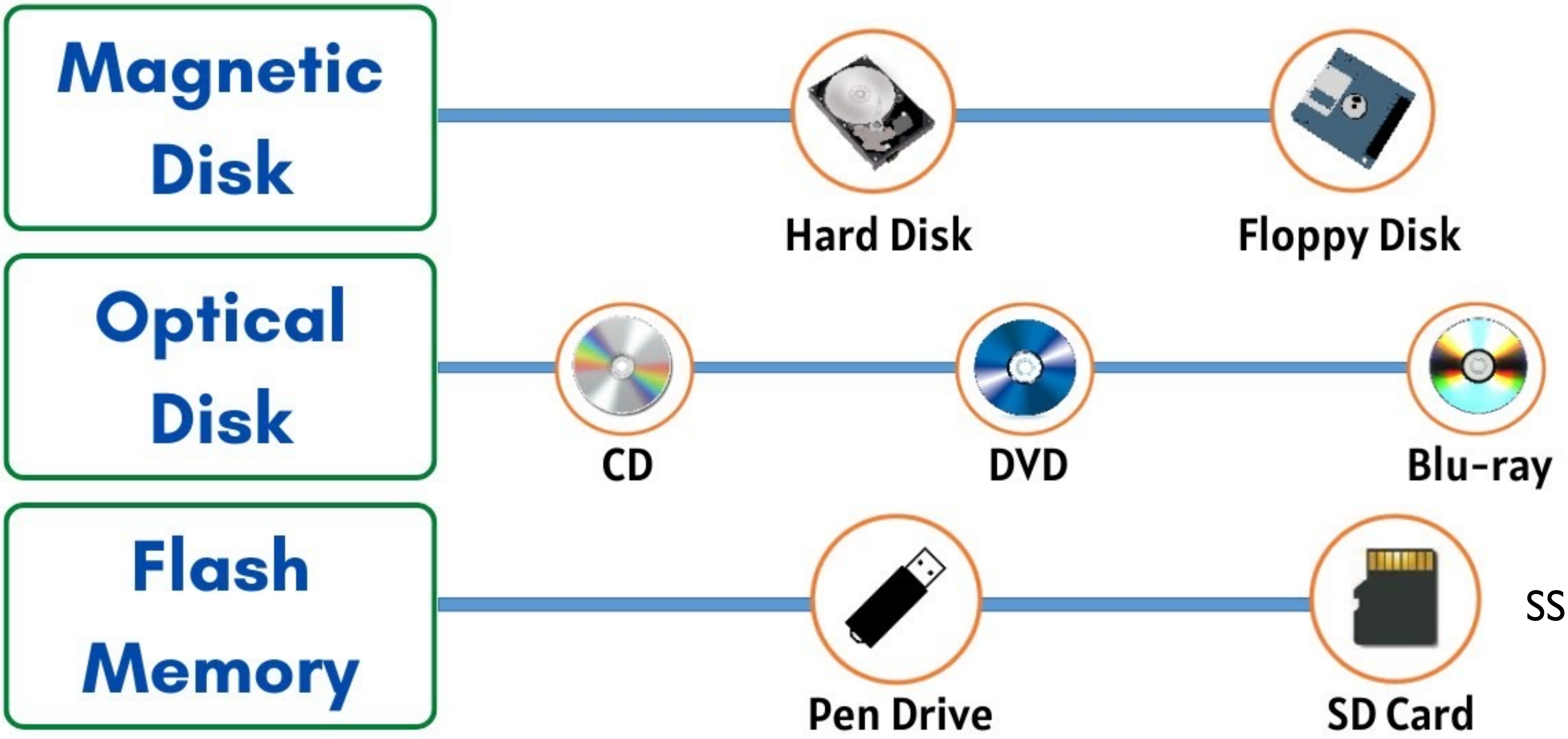
- I/O Devices
- Storage Devices

Storage Devices

- Why we learn the hardware characteristics? Because they help us build better OSes and applications!
- As secondary storage to computers, storage devices are persistent.
  - Unlike main memory



Secondary Storage

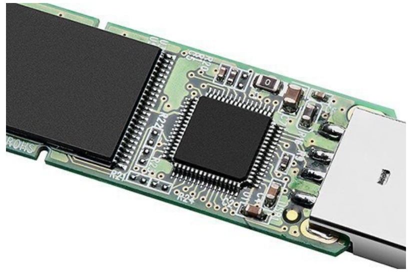


SSDs

Storage Devices

1. Magnetic disks (磁盘)
   - Storage that rarely becomes corrupted
   - Large capacity at low cost
   - Block level random access
   - Slow performance for random access
   - Better performance for sequential access
2. Flash memory (闪存)
   - Storage that rarely becomes corrupted
   - Capacity at intermediate cost (5-20x disk)
   - Block level random access
   - Good performance for reads; worse for random writes
   - Erasure requirement in large blocks
   - Wear patterns issue

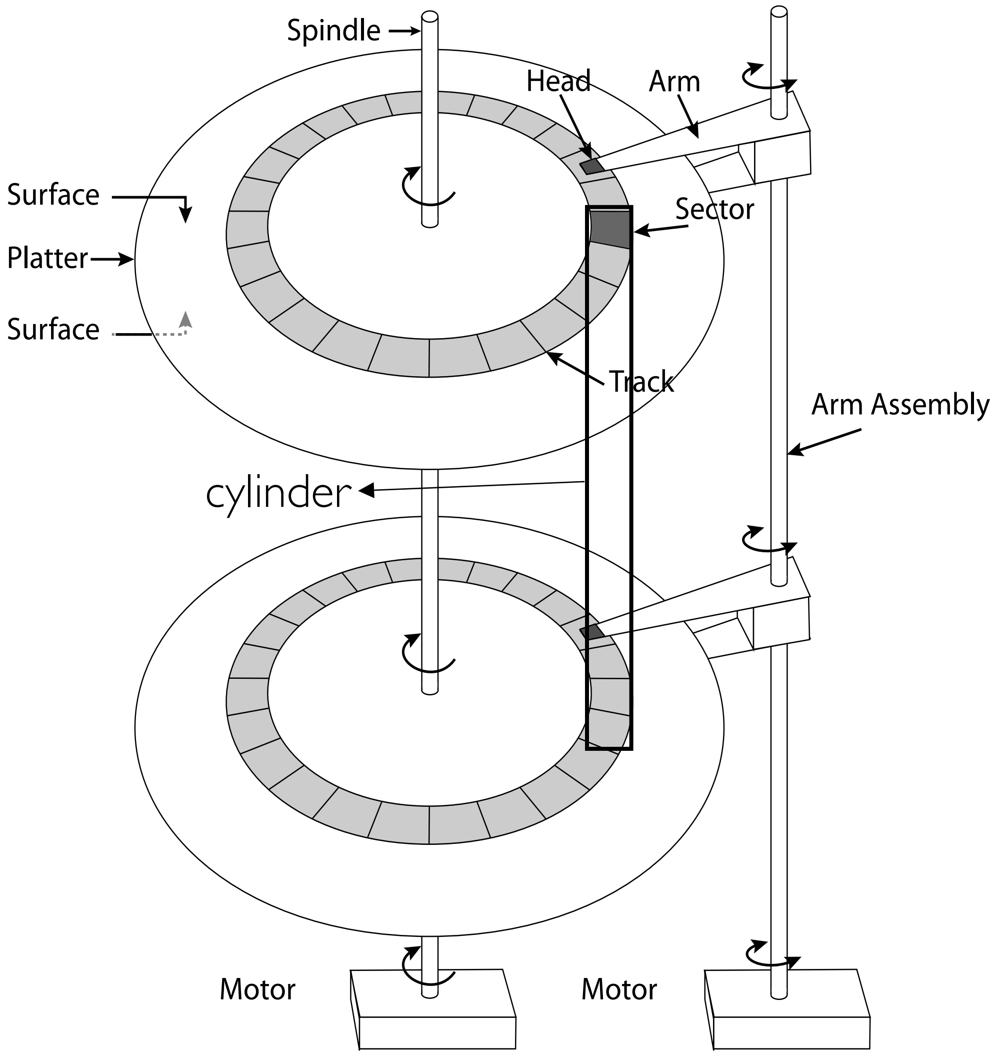
Servers, workstations, and labtops



Smartphones and tablets

The Magnetic Disk

- Sector (扇区): the unit of transfer
- Track (磁道): ring of sectors
  - ~ 1um (10^{-6}m) wide
    - ❑ Resolution of human eye: 50um
    - ❑ Wavelength of light is ~0.5um
- Cylinder (柱面): stacked tracks
- Head (磁头): attached to movable arms to read data
  - 2 per each platter (磁片) for each surfaces



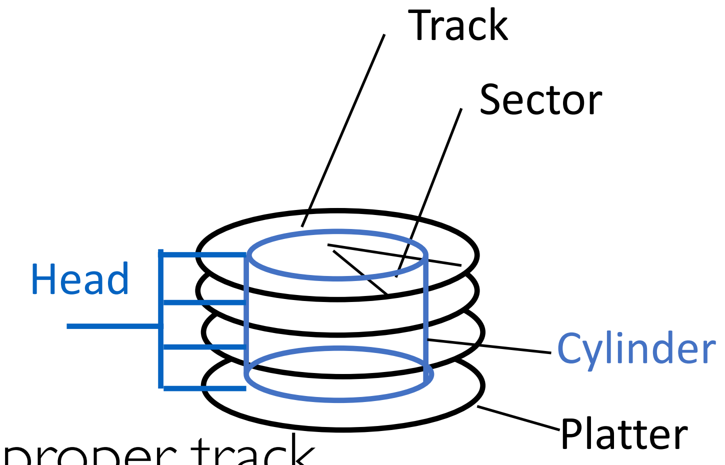
- Storage capacity =

(head #) * (cylinder #) * (sector #) * (sector size)

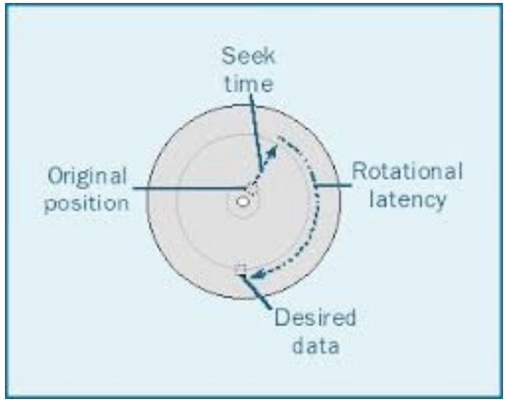
Often 512 bytes

The Magnetic Disk

- Cylinders: all the tracks under the head at a given point on all surface



- Read/write data is a three-stage process:
  - Seek time (寻道时间): position the head/arm over the proper track
  - Rotational latency (延迟时间): wait for desired sector to rotate under r/w head
  - Transfer time (传输时间): transfer a block of bits (sector) under r/w head



Seek time = 4-8ms
One rotation = 1-2ms
(3600-7200 RPM)

The Magnetic Disk

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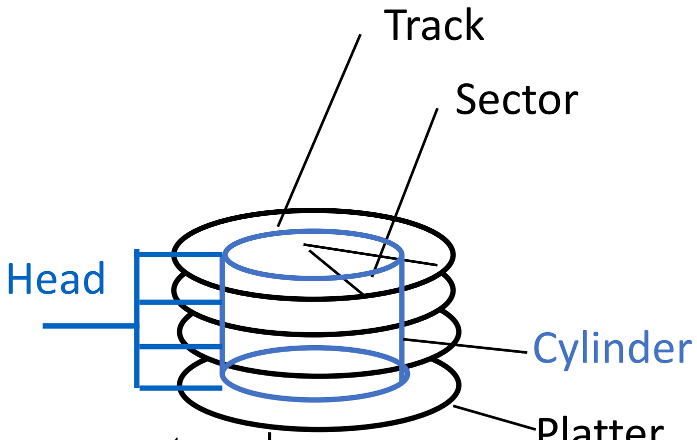

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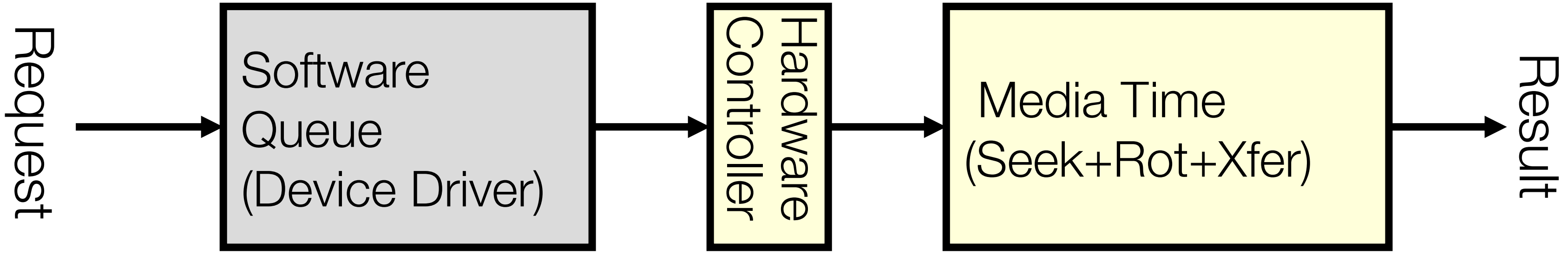
Disk Latency = Queuing Time + Controller time +
Seek Time + Rotation Time + Transfer Time



Disk Performance Example

- Assumptions:
  - Ignoring queuing and controller times for now
  - Avg seek time of 5ms,
  - 7200RPM ⇒ Time for rotation: 60000 (ms/minute) / 7200(rev/min) ~= 8ms
  - Transfer rate of 4MByte/s, sector size of 1 Kbyte ⇒ 1024 bytes/4×10^{6} (bytes/s) = 256×10^{-6} sec ≅ .26 ms
- Read sector from random place on disk:

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- Read sector from random place on disk:
  - Seek (5ms) + Rot. Delay (4ms) + Transfer (0.26ms) = 9.26ms
  - *Approx* 10ms to fetch/put data: **100 KByte/sec**
- Read sector from random place in same cylinder:

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- Read sector from random place in same cylinder:
  - Rot. Delay (4ms) + Transfer (0.26ms) = 4.26ms
  - *Approx* 5ms to fetch/put data: **200 KByte/sec**
- Read next sector on same track:

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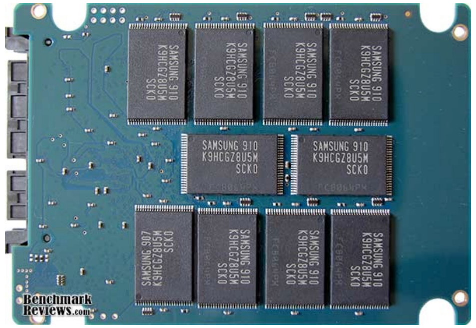
- Read sector from random place in same cylinder:
  - Rot. Delay (4ms) + Transfer (0.26ms) = 4.26ms
  - *Approx* 5ms to fetch/put data: **200 KByte/sec**
- Read next sector on same track:
  - Transfer (0.26ms): **4 MByte/sec**

Key to using disk effectively (especially for file systems) is to *minimize seek and rotational delays*

(Lots of) Intelligence in the Controller

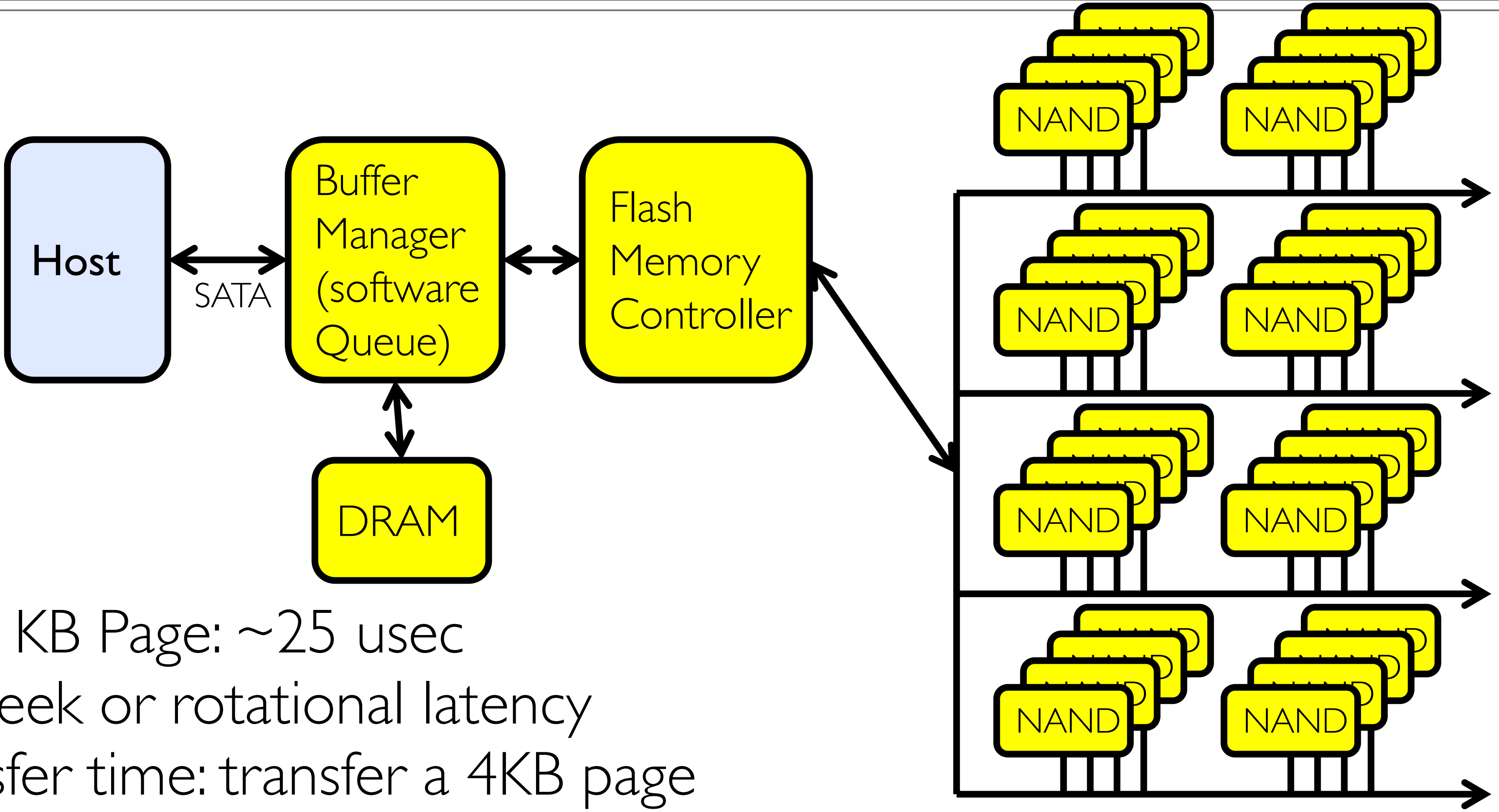
- Sectors contain sophisticated error correcting codes
  - Disk head magnet has a field wider than track
  - Hide corruptions due to neighboring track writes
- Sector sparing
  - Remap bad sectors transparently to spare sectors on the same surface
- Slip sparing
  - Remap all sectors (when there is a bad sector) to preserve sequential behavior
- Track skewing
  - Sector numbers offset from one track to the next, to allow for disk head movement for sequential ops
- …

Solid State Disks (SSDs)



- 1995 – Replace magnetic media with non-volatile memory (battery backed DRAM)
- 2009 – Use NAND Multi-Level Cell (2 or 3-bit/cell) flash memory
  - Sector (4 KB page) addressable, but stores 4-64 "pages" per memory block
  - Trapped electrons distinguish between 1 and 0
- No moving parts (no rotate/seek motors)
  - Eliminates seek and rotational delay (0.1-0.2ms access time)
  - Very low power and lightweight
  - Limited "write cycles"
- Rapid advances in capacity and cost ever since!
- A 5-min video on SSD: https://www.bilibili.com/video/BV1644y157mB

SSD Architecture – Reads

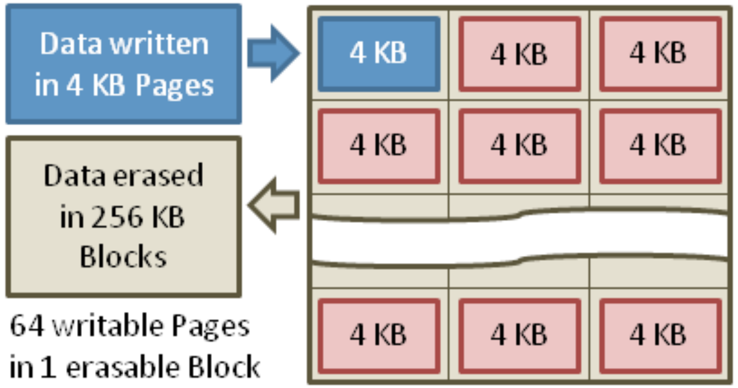


Read 4 KB Page: ~25 usec

- No seek or rotational latency
- Transfer time: transfer a 4KB page
  - SATA: 300-600MB/s => ~4 x10^3 b / 400 x 10^6 bps => 10 us
- Latency = Queuing Time + Controller Time + Xfer Time
- Highest Bandwidth: Sequential OR Random reads

SSD Architecture – Writes

- Writing data is complex! (~200µs – 1.7ms)
  - Can only write empty pages in a block
  - Erasing a block takes ~1.5ms
  - Controller maintains pool of empty blocks by coalescing used pages (read, erase, write), also reserves some % of capacity
- Rule of thumb: writes 10x reads, erasure 10x writes



Typical NAND Flash Pages and Blocks

https://en.wikipedia.org/wiki/Solid-state_drive

Amusing calculation: is a full Kindle heavier than an empty one?

- Actually, "Yes", but not by much
- Flash works by trapping electrons:
  - So, erased state lower energy than written state
- Assuming that:
  - Kindle has 4GB flash
  - ½ of all bits in full Kindle are in high-energy state
  - High-energy state about 10^{-15} joules higher
  - Then: Full Kindle is 1 attogram (10^{-18}gram) heavier (Using $E = mc^2$)
- Of course, this is less than most sensitive scale can measure (it can measure 10^{-9} grams)
- Of course, this weight difference overwhelmed by battery discharge, weight from getting warm, ….
- According to John Kubiatowicz (New York Times, Oct 24, 2011)

SSD Summary

- Pros (vs. hard disk drives):
  - Low latency, high throughput (eliminate seek/rotational delay)
  - No moving parts:
    - ❑ Very light weight, low power, silent, very shock insensitive
  - Read at memory speeds (limited by controller and I/O bus)
- Cons
  - Small storage (0.1-0.5x disk), expensive (3-20x disk)
    - ❑ Hybrid alternative: combine small SSD with large HDD

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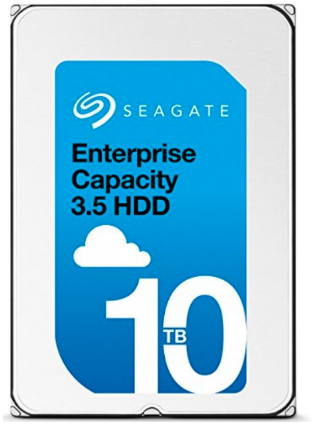
  - ~~Small storage (0.1-0.5x disk)~~, expensive (3-20x disk)
    - ❑ Hybrid alternative: combine small SSD with large HDD
  - Asymmetric block write performance: read pg/erase/write pg
    - ❑ Controller garbage collection (GC) algorithms have major effect on performance
  - Limited drive lifetime
    - ❑ 1-10K writes/page for MLC NAND
    - ❑ Avg failure rate is 6 years, life expectancy is 9–11 years
- These are changing rapidly!

No longer true!

Enterprise

10TB (2016)

- 7 platters, 14 heads
- 7200 RPMs
- 6 Gbps SATA /12Gbps SAS interface
- 220MB/s transfer rate, cache size: 256MB
- Helium filled: reduce friction and power usage
- Price: $500 ($0.05/GB)



IBM Personal Computer/AT (1986)

- 30 MB hard disk
- 30-40ms seek time
- 0.7-1 MB/s (est.)
- Price: $500 ($17K/GB, 340,000x more expensive !!)

Largest SSDs

- 60TB (2016)
- Dual port: 16Gbs
- Seq reads: 1.5GB/s
- Seq writes: 1GB/s
- Random Read Ops (IOPS): 150K
- Price: ~ $20K ($0.33/GB)

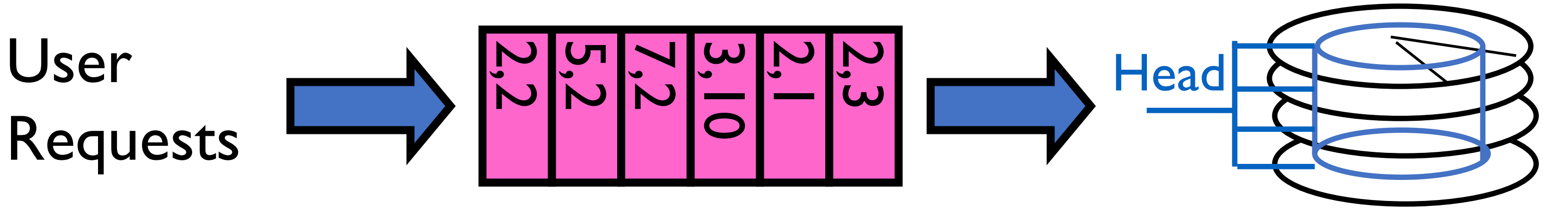
USB Drive

1GB~8GB, 2010

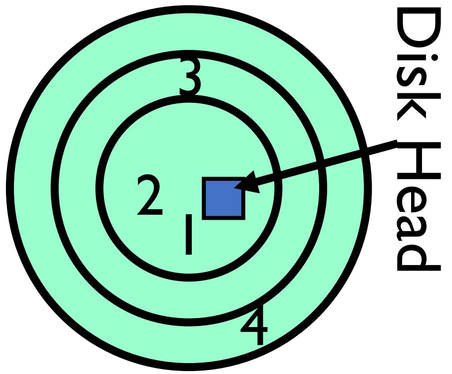
Up to 1TB, 2023

Disk Scheduling

- Disk can do only one request at a time; What order do you choose to do queued requests?
  - The scheduling can be done in OS, firmware, or both.



- FIFO Order
  - Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks



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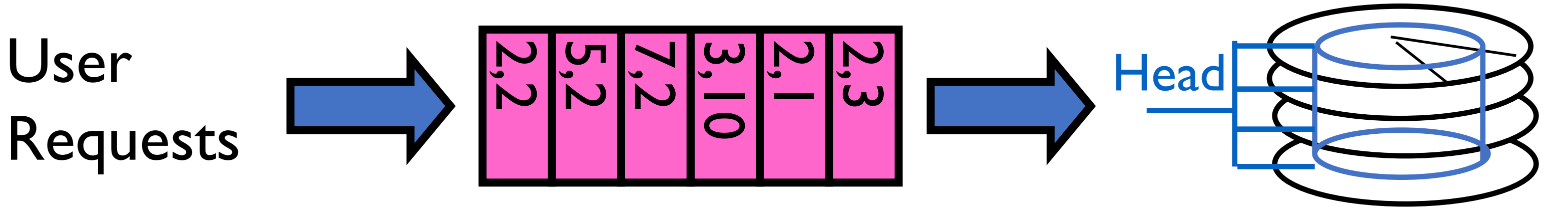
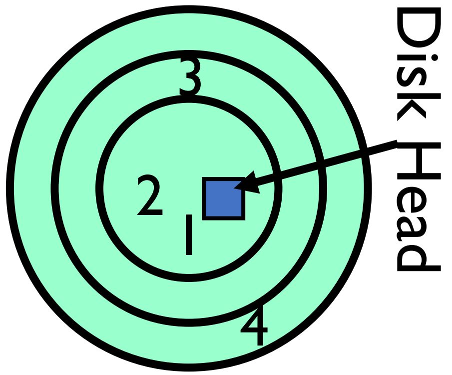
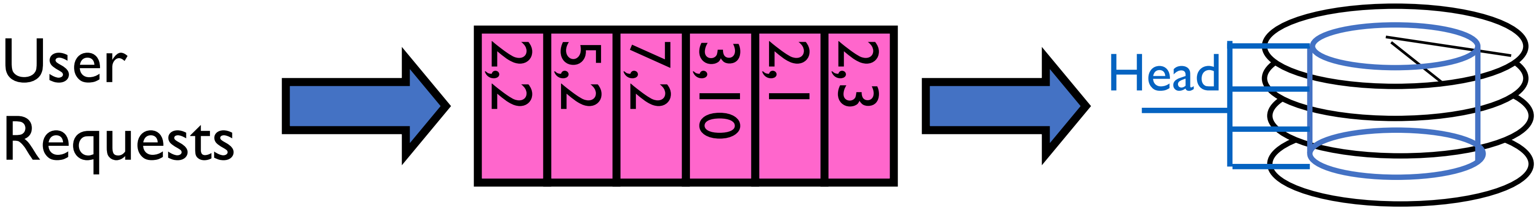


- SSTF: Shortest seek time first
  - Pick the request that's closest on the disk
  - Although called SSTF, today must include rotational delay in calculation, since rotation can be as long as seek
  - Con: SSTF good at reducing seeks, but may lead to starvation

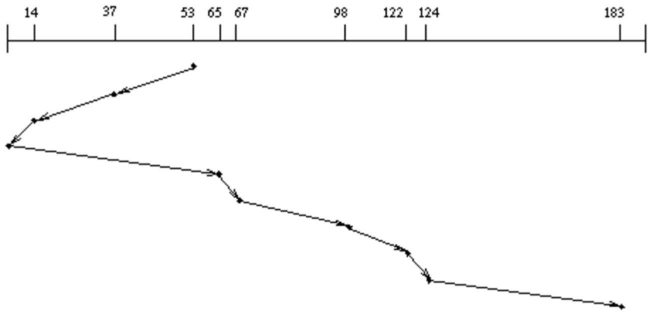


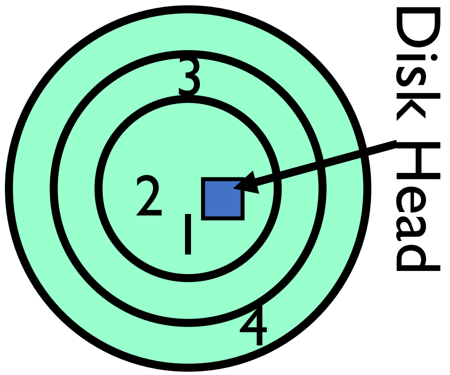
Disk Scheduling

- Disk can do only one request at a time; What order do you choose to do queued requests?
  - The scheduling can be done in OS, firmware, or both.



- SCAN: Implements an Elevator Algorithm (电梯算法): take the closest request in a fixed direction of travel (reversed at the end)
  - No starvation, but retains flavor of SSTF





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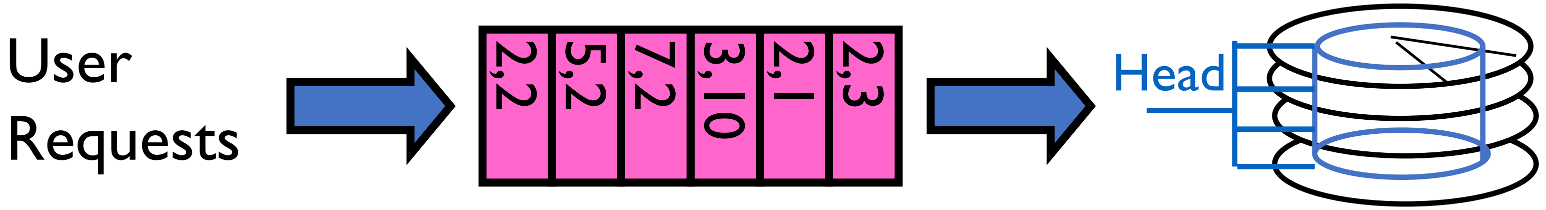
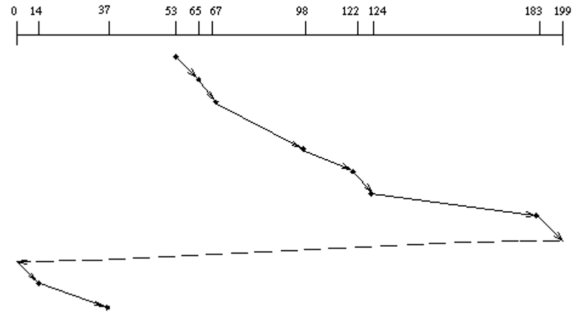
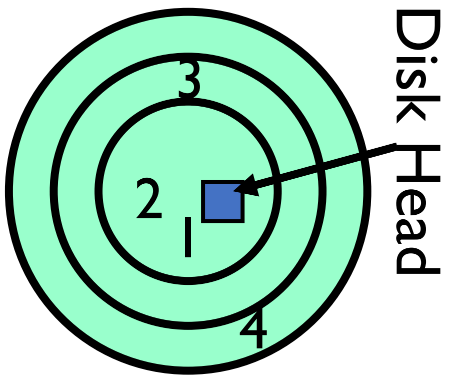


- C-SCAN: Circular-Scan: only goes in one direction
  - Skips any requests on the way back
  - Fairer than SCAN, not biased towards pages in middle





A Simple Read() Lifecycle

- A process issues a syscall read()
- OS moves the calling thread to a wait queue (state=WAITING)
- OS uses memory-mapped I/O to tell the disk to read the requested data and set up DMA so the disk can place the data in kernel's memory
- Disk reads the data and DMAs it into main memory
- Disk triggers an interrupt
- OS's interrupt handler copies the data from the kernel's buffer into the process's address space
- OS moves the thread to the ready list
- The thread is scheduled on CPU, and returns from the read()

Goals for Today

- Storage Devices
- File System Abstraction

I/O & Storage Layers

Operations, Entities and Interface

Application / Service

High Level I/O — *streams*

Low Level I/O — *handles*

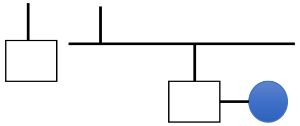
Syscall — *registers*

`file_open, file_read, … on struct file * & void *`

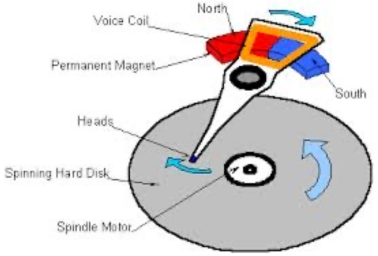
File System ← *descriptors*

we are here …

I/O Driver — *Commands and Data Transfers*



Disks, Flash, Controllers, DMA



Layered abstractions of I/O and storage

- Application
- Library
- File System
- Block Cache
- Device Driver
- Memory-Mapped I/O, DMA, Interrupts
- Physical Devices

stdio: fopen(), fclose(), fread(), fwrite()

syscall: open(), close(), read(), write()

How files and directories are organized in memory and disk

Data block ops between storage and memory

Caching blocks in memory; write buffering, synchronization

Block device interface: a standard interface for different I/O devices to R/W in fixed-sized blocks (e.g., 512 bytes).

Translate I/O abstractionsinto device-specific I/O operations

Memory-mapped I/O: maps each device's control registers to a range of physical addresses on the memory bus. For example, the OS knows last key pressed by keyboard in a physical address.

Direct Memory Access: copy a block of data between storage and memory.

Interrupts are needed so OS knows when I/O device completes its request (otherwise use polling).

Recall: C Low level I/O

- File Descriptors – as OS object representing the state of a file
  - User has a "handle" on the descriptor

```
#include <fcntl.h>
#include <unistd.h>
#include <sys/types.h>

int open (const char *filename, int flags [, mode_t mode])
int create (const char *filename, mode_t mode)
int close (int filedes)
```

Bit vector of:
- Access modes (Rd, Wr, …)
- Open Flags (Create, …)
- Operating modes (Appends, …)

Bit vector of Permission Bits:
- User|Group|Other X R|W|X

http://www.gnu.org/software/libc/manual/html_node/Opening-and-Closing-Files.html

Recall: C Low level I/O

- File Descriptors – as OS object representing the state of a file
  - User has a "handle" on the descriptor

```
ssize_t read (int filedes, void *buffer, size_t maxsize)
 - returns bytes read, 0 => EOF, -1 => error
ssize_t write (int filedes, const void *buffer, size_t size)
 - returns bytes written
off_t lseek (int filedes, off_t offset, int whence)
 - set the file offset
   * if whence == SEEK_SET: set file offset to "offset"
   * if whence == SEEK_CRT: set file offset to crt location + "offset"
   * if whence == SEEK_END: set file offset to file size + "offset"
int fsync (int fildes)
 – wait for i/o of filedes to finish and commit to disk
void sync (void) – wait for ALL to finish and commit to disk
```

- When write returns, data is on its way to disk and can be read, but it may not actually be permanent!

Building a File System

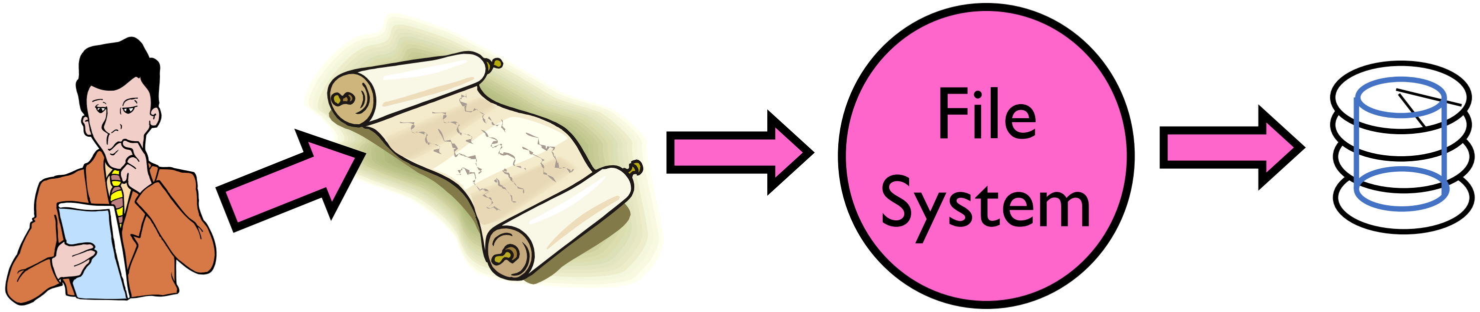
- **File System:** Layer of OS that transforms block interface of disks (or other block devices) into Files, Directories, etc.

- File System Components
  - **Naming**: Interface to find files by name, not by blocks
  - **Disk Management**: collecting disk blocks into files
  - **Protection**: Layers to keep data secure
  - **Reliability/Durability**: Keeping of files durable despite crashes, media failures, attacks, etc.

User vs. System View of a File

- User's view:
  - Durable Data Structures
- System's view (system call interface):
  - Collection of Bytes (UNIX)
  - Doesn't matter to system what kind of data structures you want to store on disk!
- System's view (inside OS):
  - Collection of blocks (a block is a logical transfer unit, while a sector is the physical transfer unit)
  - Block size ≥ sector size; in UNIX, block size is 4KB

Translating from User to System View



- What happens if user says: give me bytes 2—12?
  - Fetch block corresponding to those bytes
  - Return just the correct portion of the block
- What about: write bytes 2—12?
  - Fetch block
  - Modify portion
  - Write out Block
- Everything inside File System is in whole size blocks
  - For example, `getc()`, `putc()` ⇒ buffers something like 4096 bytes, even if interface is one byte at a time
- From now on, file is a collection of blocks

Disk Management Policies (1/2)

- Basic entities on a disk:
  - File: user-visible group of blocks arranged sequentially in logical space
  - Directory: user-visible index mapping names to files

- Access disk as linear array of sectors. Two Options:
  - Identify sectors as vectors [cylinder, surface, sector], sort in cylinder-major order
    - ❑ Used in BIOS, but not in OSes anymore
  - Logical Block Addressing (LBA, 逻辑块寻址): Every sector has integer address from zero up to max number of sectors
  - Controller translates from address ⇒ physical position
    - ❑ First case: OS/BIOS must deal with bad sectors
    - ❑ Second case: hardware shields OS from structure of disk

Disk Management Policies (2/2)

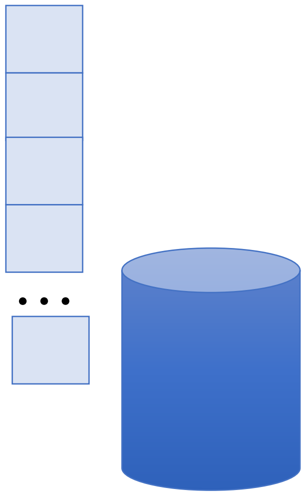
- Need way to track free disk blocks
  - Link free blocks together $\Rightarrow$ too slow today
  - Use bitmap to represent free space on disk
- Need way to structure files: File Header
  - Track which blocks belong at which offsets within the logical file structure
  - Optimize placement of files' disk blocks to match access and usage patterns

File

- Named permanent storage

- Contains
  - Data
    - ❑Blocks on disk somewhere
  - Metadata (Attributes)
    - ❑Owner, size, last opened, …
    - ❑Access rights
      - R, W, X
      - Owner, Group, Other (in Unix systems)
      - Access control list in Windows system

Data blocks



File handle

File descriptor

Fileobject (inode)

Position

Directory

- Basically a hierarchical structure

- Each directory entry is a collection of
  - Files
  - Directories
    - ❑A link to another entries

- Each has a name and attributes
  - Files have data

- Links (hard links) make it a DAG, not just a tree
  - Softlinks (aliases) are another name for an entry

Directory

- Conventions of directory
  - Root directory (根目录): "/"
  - Home directory (主目录): "~/cur_dir/file.txt"
  - Absolute path (绝对路径): "/home/mwx/cur_dir/file.txt"
  - Relative path (相对路径): "file.txt"
- Volume (卷): a collection of physical storage resources that form a logical storage device. Could be a part of or many physical devices.
- Mount (挂载): an operation that creates a mapping from some path in the existing file system to the root directory of the mounted volume's file system

mount –t *type* *device* *dir*

Directory

```
mwx@Dragon21:~$ findmnt -t ext4
TARGET            SOURCE                   FSTYPE   OPTIONS
    /             /dev/sda6                ext4     rw,relatime,errors=remount-ro
├─/data2          /dev/sdc                 ext4     rw,relatime
├─/data           /dev/sdb1                ext4     rw,relatime
├─/var/lib/snapd  /dev/sdc[/zl/snap/snapd] ext4     rw,relatime
└─/boot           /dev/sda1                ext4     rw,relatime
```

Designing a File System …

- What factors are critical to the design choices?
- Durable data store => it's all on disk
- (Hard) Disks Performance !!!
  - Maximize sequential access, minimize seeks
- Open before Read/Write
  - Can perform protection checks and look up where the actual file resource are, in advance
- Size is determined as they are used !!!
  - Can write (or read zeros) to expand the file
  - Start small and grow, need to make room
- Organized into directories
  - What data structure (on disk) for that?
- Need to allocate / free blocks
  - Such that access remains efficient

Reminder

- Easy_lab 3 is available
- Don't forget the first homework (LLM-powered command line helper)