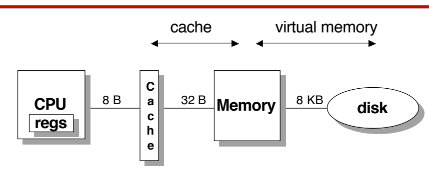
EE108B
Lecture 16
I/O

Kunle Olukotun
Stanford University
http://eeclass.stanford.edu/ee108b

Announcements

- PA2 (part 2) is due today
- HW5 is out today, due on 12/5
- Lab4 is due on 12/11
- Final exam
  - Thursday 12/7
  - 11am - 1pm

Review: Levels in Memory Hierarchy



	Register	Cache	Memory	Disk Memory
size:	128 B	<4MB	< 16 GB	> 100 GB
Speed(cycles):	0.5-1	1-20	80-100	5-10 M
$/Mbyte:		$30/MB	$0.128/MB	$0.001/MB
line size:	8 B	32 B	>8 KB	

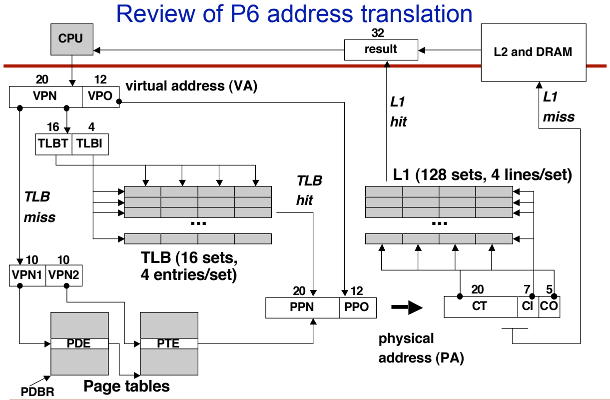
larger, slower, cheaper →

Review: Memory Hierarchy Framework

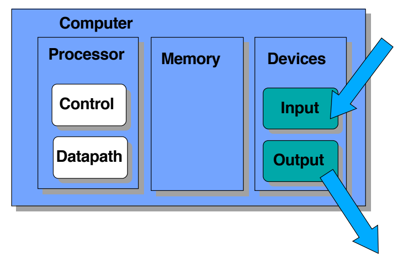
- Placing a Block
  - Direct mapped – Element hashed to a single location
  - Set Associative – Element can go in one of N locations
  - Fully Associative – Element can go anywhere
- Finding a Block
  - Index with partial map (cache) or full map (page table)
  - Index and search (set associative)
  - Search (fully associative)
- Replacing a Block
  - Random – Pick one of the elements to replace
  - Least Recently Used (LRU) – Use bits to track usage
- Writing
  - Write back – Data is written only on eviction
  - Write through – Each write is passed through to lower level

Locality makes this work

Review of P6 address translation



Five Components



- Datapath
- Control
- Memory
- Input
- Output

Outline

- I/O Systems and Performance
  - Types and characteristics of I/O devices
  - Magnetic disks
- Buses
  - Bus types and bus operation
  - Bus arbitration
- Interfacing the OS and I/O devices
  - Operating System’s role in handling I/O devices
  - Delegating I/O responsibility by the CPU
- I/O workloads and performance

Today’s Lecture

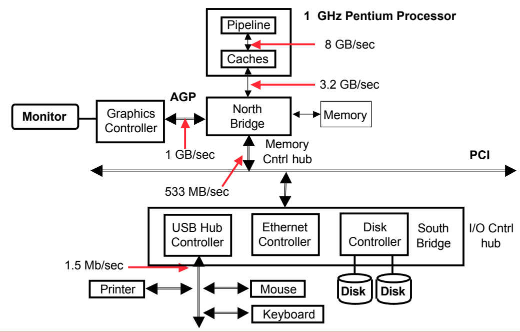
- I/O overview
- I/O performance metrics
- High performance I/O devices
  - Disk

Diversity of Devices

Device	Behavior	Partner	Data Rate (KB/sec)
Keyboard	Input	Human	0.01
Mouse	Input	Human	0.02
Line Printer	Output	Human	1.00
Laser Printer	Output	Human	100.00
Graphics	Output	Human	100,000.00
Network-LAN	Communication	Machine	10,000.00
Floppy disk	Storage	Machine	50.00
Optical Disk	Storage	Machine	10, 000.00
Magnetic Disk	Storage	Machine	30,000.00

- Behavior refers to what I/O device does
- Since I/O connects two things, partner refers to the object on the other end of the connection

Speeds and Feeds of a PC System



Throughput vs. Response time

- Throughput
  - Aggregate measure of amount of data moved per unit time, averaged over a window
  - Sometimes referred to as bandwidth
    - Example: Memory bandwidth
    - Example: Disk bandwidth
- Response time
  - Response time to do a single I/O operation
    - Example: Write a block of bytes to disk
    - Example: Send a data packet over the network

I/O System Design Issues

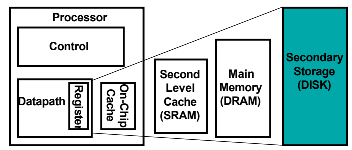
- Performance
  - Is throughput or response time more critical?
  - Huge diversity of devices means wide performance spectrum
  - I/O device performance tends to be technology driven
  - I/O system performance also depends on OS, software, bus performance, etc
- Expandability
- Resilience in the face of failure
- Computer classes
  - Desktop: response time and diversity of devices
  - Server: throughput, expandability, failure resilience
  - Embedded: cost and response time

I/O Devices

- I/O devices leverage various implementation techniques
  - Magnetic disks

Magnetic Hard Disks

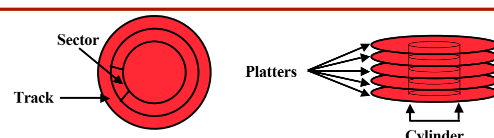
- Characteristics
  - Long term, nonvolatile storage
  - Large, inexpensive, but slow
- Usage
  - Virtual memory (swap area)
  - File system



Hard Disk

- Basic operation
  - Rotating platter coated with magnetic surface
  - Moving read/write head used to access the disk
- Features of hard disks
  - Platters are rigid (ceramic or metal)
  - High density since head can be controlled more precisely
  - High data rate with higher rotational speed
  - Can include multiple platters
- Incredible improvements
  - Example of I/O device performance being technology driven
  - Capacity: 2x every year
  - Transfer rate: 1.4x every year
  - Price approaching 1$/GB = 10^9 bytes

Hard Disk Organization



- Important definitions
  - Each drive uses one or more magnetic platters to store data
  - A head is used to read/write data on each size of each platter
  - Each platter is divided into a series of concentric rings called tracks
  - Each track is in turn divided into a series of sectors which is the basic unit of transfer for disks (“block size”)
    - One method is to have a constant number of sectors per track
    - Alternative is constant bit density which places more sectors on outer track
  - A common track across multiple platters is referred to as a cylinder

Measuring Disk Access Time

- Each read or write has three major components
  - *Seek time* is the time to position the arm over the proper track
  - *Rotational latency* is the wait for the desired sector to rotate under the read/write head
  - *Transfer time* is the time required to transfer a block of bits (sector) under the read/write head
- Note that these represent only the “raw performance” of the disk drive
  - Also neglects to account for the I/O bus, controller, other caches, interleaving, etc.

Seek Time

- Seek time is the time to position the arm over the proper track
- Average seek time is the time it takes to move the read/write head from its current position to a track on the disk
- Industry definition is that seek time is the time for all possible seeks divided by the number of possible seeks
- In practice, locality reduces this to 25-33% of this number
- Note that some manufacturers report minimum seek times rather than average seek times

Rotational Latency

- Rotational latency is the time spent waiting for the desired sector to rotate under the read/write head
- Based upon the rotational speed, usually measured in revolutions per minute (RPM)
- Average rotational latency
  - Average rotational latency = 0.5 rotation / RPM
- Example: 7200 RPM

$$Average\ rotational\ latency = \frac{0.5\ rotation}{7200\ RPM} = \frac{0.5\ rotation}{7200\ RPM / (60\ \mathrm{sec/min})} = 4.2ms$$

Transfer Time

- Transfer time is the time required to transfer a block of bits
- A factor of the transfer size, rotational speed, and recording density
  - Transfer size is usually a sector
- Most drives today use caches to help buffer the effects of seek time and rotational latency

Typical Hard Drive

- Typical hard disk drive
  - Rotation speed: 3600, 5200, 7200, or 10000 RPM
  - Tracks per surface: 500-2,000 tracks
  - Sectors per track: 32-128 sectors
  - Sectors size: 512 B-1024 KB
  - Minimum seek time is often approximately 0.1 ms
  - Average seek time is often approximately 5-10 ms
  - Access time is often approximately 9-10 ms
  - Transfer rate is often 2-4 MB/s

Average Access Example

- Consider the Seagate 36.4 GB Ultra2 SCSI
  - Rotation speed: 10,000 RPM
  - Sector size: 512 B
  - Average seek time: 5.7 ms
  - Transfer rate: 24.5 MB/s
  - Controller overhead of 1 ms
- What is the average read time?

$$Average\ rotational\ latency = \frac{0.5\ rotation}{10000\ RPM} = \frac{0.5\ rotation}{10000\ RPM/(60\ \sec/\min)} = 3ms$$

$$Average\ transfer\ time = \frac{0.5\ KB}{24.5\ MB/s} = 0.02\ ms$$

$$Average\ access\ time = seek + rotational + transfer + overhead$$
$$= 5.7\ ms + 3\ ms + 0.02\ ms + 1\ ms = 9.72\ ms$$

Important Footnote

- If the actual seek time is only 25% of the average seek time as a result of locality, we get a very different number

$$Expected\ seek\ time = 0.25 \times 5.7\ ms = 1.43\ ms$$
$$Expected\ access\ time = seek + rotational + transfer + overhead$$
$$= 1.43\ ms + 3\ ms + 0.02\ ms + 1\ ms = 5.45\ ms$$

- Note that the effects of the rotational delay are even more pronounced

Reliability vs. Availability

- *Reliability* refers to the likelihood an individual component has failed whereas *availability* refers to whether the collection of components is available to the user
  - These two terms are frequently misused
- Improving Availability
  - Adding hardware, such as ECC memory (does not improve reliability since the memory is still broken, but corrects for the problem so that the data is still available)
- Improving Reliability
  - Better environmental conditions
  - Building with more reliable components
  - Using fewer components
- Note that improved availability may come at the cost of lower reliability

Disk Arrays

- Disk drives are arranged in an array
  - Combine multiple physical drives into single virtual drive
  - Small independent disks are usually cheaper than a single large drive
- Benefits
  - Increased availability since lost information can be reconstructed from redundant information (note that reliability is actually worse)
    - Mean Time To Failure (MTTF) is often 3-5 years
    - Mean Time To Repair (MTTR) is usually several hours
  - Increased throughput using many disk drives
    - Data is spread over multiple disks
    - Multiple access are made to several disks in parallel
- Known as a redundant array of inexpensive/independent drives (RAID)

I/O System Example : Transaction Processing

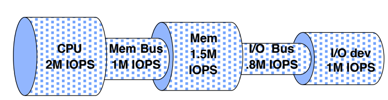
- Examples: Airline reservation, bank ATM, inventory system, e-business
- Workload
  - Many small changes to shared data space
    - Each transaction takes 2-10 disk I/Os
    - Approximately 2M-5M CPU instructions per disk I/O
  - Demands placed on system by many different users
- Important Considerations
  - Terrible locality
  - Requires graceful handling of failures (fault tolerance) by way of built-in redundancy and multiple-phase operations
  - Both throughput and response times are important
    - High throughput needed to keep cost low
    - Measure I/O rate as the number of accesses per second
    - Low response time is also very important for the users

I/O Performance Factors

- Overall performance is dependent upon a great many implementation factors
  - CPU
    - How fast can bits be moved in and out?
    - How fast can the processor operate on the data?
  - Memory system bandwidth and latency
    - Internal and external caches
    - Main memory
  - System interconnection
    - I/O and memory buses
    - I/O controller
    - I/O device
  - Software efficiency
    - I/O device handler instruction path length

Designing an I/O System

- General approach
  - Find the weakest link in the I/O system (consider things such as the CPU, memory system, buses, I/O controllers, and I/O devices)
  - Configure this component to sustain the required throughput
  - Determine the requirements for the rest of the system and configure them to support this throughput



Typical Storage Design Problem

- Analyze a multiprocessor to be used for transaction processing, using a TPC-A like benchmark, with the following characteristics:
  - each transaction = two 128-byte disk accesses + 3.2 M instructions, on a single disk whose account file size must be TPS x 10^9 bytes
  - the base hardware (no CPUs) costs $4,000
  - each processor is a 40 MIPS CPU and costs $3000
  - each processor can have any number of disks
  - disk controller delay = 2 msec
  - can choose between two disk types, but can't mix them

Disk size	Cost	Capacity	Avg seek time	Rotation speed	Transfer rate
3.5 inch	$200	50 GB	8 msec	5400 RPM	4 MB/s
2.4 inch	$120	25 GB	12 msec	7200 RPM	2 MB/s

- What is the highest TPS you can process for $40,000, and with what configuration?

Solution
Part 1: pick a disk

- First calculate how many TPS each disk can sustain
- access time = seek time + rotational delay + transfer + controller
  - 3.5" disk time = 8 + 1/2(1/5400 RPM) + 128B / 4MB/s + 2 = 15.6 msec
  - 2.4" disk time = 12 + 1/2(1/7200 RPM) + 128B / 2MB/s + 2 = 18.2 msec
- Need 2 accesses per transaction, so TPS = 1/(2*time)
  - 3.5" TPS = 1/(2*15.6 msec) = 32.0 TPS
  - 2.4" TPS = 1/(2*18.2 msec) = 27.4 TPS
- But the account file size on each disk = TPS x 10^9 bytes
  - 3.5" size = 32 GB = max 32 TPS (fits!) (I/O limited)
  - 2.4" size = 25 GB = max 25 TPS (doesn't fit!) (capacity limited) Must reduce TPS to 25 so that file fits
- Which has better cost/performance?
  - $/TPS for 3.5" = $200/32TPS = 6.25 $/TPS
  - $/TPS for 2.4" = $120/25TPS = 4.8 $/TPS
- Pick the 2.4" disk

Solution
Part 2: pick a CPU configuration

- TPS limit for each CPU =
  400 MIPS / (3.2 M instructions/transaction) = 125 TPS
- To fully utilize the CPU TPS, the number of disks that each can accommodate is
  #disks/CPU = (125 TPS/CPU) / (25 TPS/disk) = 5
- So a system with *n* CPUs and 5*n* disks costing $40,000 means
  $4000 + $3000*n* + $120*5*n* = $40000
  or *n* = 10
- The system has 10 CPUs, 50 2.4" disks, a total account file size of (50 x 250MB) = 12.5 GB, and can process (50 x 25) = 1250 TPS.

I/O Device Summary

- I/O Performance depends on many factors
  - Device performance (typically technology driven)
  - CPU and OS performance
  - Software efficiency
- I/O System must exploit good aspects and hide bad aspects of the I/O
  - Disk caching and prefetching
  - Color maps for frame buffers
- Some measurements are only meaningful with respect to a particular workload
  - Transactional Processing
- High performance I/O devices
  - Disks
  - Graphics