CMSC 611: Advanced Computer Architecture

Memory & Storage
Main Memory Background

• Performance of Main Memory:
  – Latency: affects cache miss penalty
    • Access Time: time between request and word arrives
    • Cycle Time: time between requests
  – Bandwidth: primary concern for I/O & large block

• Main Memory is DRAM: Dynamic RAM
  – Dynamic since needs to be refreshed periodically
  – Addresses divided into 2 halves (Row/Column)

• Cache uses SRAM: Static RAM
  – No refresh
    • 6 transistors/bit vs. 1 transistor/bit, 10X area
  – Address not divided: Full address
4 Mbit DRAM: square root of bits per RAS/CAS

- Refreshing prevents access to the DRAM (typically 1-5% of the time)
- Reading one byte refreshes the entire row
- Read is destructive and thus data need to be re-written after reading
  - Cycle time is significantly larger than access time
**Problem:**
Improvements in access time are not enough to catch up

**Solution:**
Increase the bandwidth of main memory (improve throughput)
a. One-word-wide memory organization

b. Wide memory organization

- **Simple**: CPU, Cache, Bus, Memory same width (32 bits)
- **Wide**: CPU/Mux 1 word; Mux/Cache, Bus, Memory N words
- **Interleaved**: CPU, Cache, Bus 1 word: Memory N Modules (4 Modules); example is *word interleaved*

c. Interleaved memory organization

Memory organization would have significant effect on bandwidth
Memory Interleaving

- Access Pattern without Interleaving:

- Access Pattern with 4-way Interleaving:

We can Access Bank 0 again
**Input/Output**

- **I/O Interface**
  - Device drivers
  - Device controller
  - Service queues
  - Interrupt handling

- **Design Issues**
  - Performance
  - Expandability
  - Standardization
  - Resilience to failure

- **Impact on Tasks**
  - Blocking conditions
  - Priority inversion
  - Access ordering
Impact of I/O on System Performance

Suppose we have a benchmark that executes in 100 seconds of elapsed time, where 90 seconds is CPU time and the rest is I/O time. If the CPU time improves by 50% per year for the next five years but I/O time does not improve, how much faster will our program run at the end of the five years?

**Answer:**

Elapsed Time = CPU time + I/O time

<table>
<thead>
<tr>
<th>After n years</th>
<th>CPU time</th>
<th>I/O time</th>
<th>Elapsed time</th>
<th>% I/O time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>90 Seconds</td>
<td>10 Seconds</td>
<td>100 Seconds</td>
<td>10%</td>
</tr>
<tr>
<td>1</td>
<td>(\frac{90}{1.5} = 60) Seconds</td>
<td>10 Seconds</td>
<td>70 Seconds</td>
<td>14%</td>
</tr>
<tr>
<td>2</td>
<td>(\frac{60}{1.5} = 40) Seconds</td>
<td>10 Seconds</td>
<td>50 Seconds</td>
<td>20%</td>
</tr>
<tr>
<td>3</td>
<td>(\frac{40}{1.5} = 27) Seconds</td>
<td>10 Seconds</td>
<td>37 Seconds</td>
<td>27%</td>
</tr>
<tr>
<td>4</td>
<td>(\frac{27}{1.5} = 18) Seconds</td>
<td>10 Seconds</td>
<td>28 Seconds</td>
<td>36%</td>
</tr>
<tr>
<td>5</td>
<td>(\frac{18}{1.5} = 12) Seconds</td>
<td>10 Seconds</td>
<td>22 Seconds</td>
<td>45%</td>
</tr>
</tbody>
</table>

*Over five years:*

CPU improvement = \(\frac{90}{12} = 7\).  **BUT**  System improvement = \(\frac{100}{22} = 4.5\)
The connection between the I/O devices, processor, and memory are usually called (local or internal) bus.

Communication among the devices and the processor use both protocols on the bus and interrupts.
## I/O Device Examples

<table>
<thead>
<tr>
<th>Device</th>
<th>Behavior</th>
<th>Partner</th>
<th>Data Rate (KB/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keyboard</td>
<td>Input</td>
<td>Human</td>
<td>0.01</td>
</tr>
<tr>
<td>Mouse</td>
<td>Input</td>
<td>Human</td>
<td>0.02</td>
</tr>
<tr>
<td>Line Printer</td>
<td>Output</td>
<td>Human</td>
<td>1.00</td>
</tr>
<tr>
<td>Floppy disk</td>
<td>Storage</td>
<td>Machine</td>
<td>50.00</td>
</tr>
<tr>
<td>Laser Printer</td>
<td>Output</td>
<td>Human</td>
<td>100.00</td>
</tr>
<tr>
<td>Optical Disk</td>
<td>Storage</td>
<td>Machine</td>
<td>500.00</td>
</tr>
<tr>
<td>Magnetic Disk</td>
<td>Storage</td>
<td>Machine</td>
<td>5,000.00</td>
</tr>
<tr>
<td>Network-LAN</td>
<td>Input or Output</td>
<td>Machine</td>
<td>20 – 1,000.00</td>
</tr>
<tr>
<td>Graphics Display</td>
<td>Output</td>
<td>Human</td>
<td>30,000.00</td>
</tr>
</tbody>
</table>
Disk History

Data density in Mbit/square inch

Capacity of Unit Shown in Megabytes

• Typical numbers (depending on the disk size):
  – 500 to 2,000 tracks per surface
  – 32 to 128 sectors per track
    • A sector is the smallest unit that can be read or written to
• Traditionally all tracks have the same number of sectors:
  – Constant bit density: record more sectors on the outer tracks
  – Recently relaxed: constant bit size, speed varies with track location
Magnetic Disk Operation

- **Cylinder**: all the tracks under the head at a given point on all surface
- **Read/write is a three-stage process:**
  - Seek time
    - position the arm over proper track
  - Rotational latency
    - wait for the sector to rotate under the read/write head
  - Transfer time
    - transfer a block of bits (sector) under the read-write head
- **Average seek time**
  - $(\sum \text{ time for all possible seeks}) / (\# \text{ seeks})$
  - Typically in the range of 8 ms to 12 ms
  - Due to locality of disk reference, actual average seek time may only be 25% to 33% of the advertised number
Magnetic Disk Characteristic

• Rotational Latency:
  – Most disks rotate at 3,600 to 7,200 RPM
  – Approximately 16 ms to 8 ms per revolution, respectively
  – An average latency to the desired information is halfway around the disk:
    • 8 ms at 3600 RPM, 4 ms at 7200 RPM

• Transfer Time is a function of:
  – Transfer size (usually a sector): 1 KB / sector
  – Rotation speed: 3600 RPM to 7200 RPM
  – Recording density: bits per inch on a track
  – Diameter: typical diameter ranges from 2.5 to 5.25”
  – Typical values: 2 to 12 MB per second
Calculate the access time for a disk with 512 byte/sector and 12 ms advertised seek time. The disk rotates at 5400 RPM and transfers data at a rate of 4MB/sec. The controller overhead is 1 ms. Assume that the queue is idle (so no service time)

**Answer:**

Disk Access Time  =  Seek time  +  Rotational Latency  + Transfer time  
+ Controller Time  +  Queuing Delay

=  12 ms + 0.5 / 5400 RPM + 0.5 KB / 4 MB/s + 1 ms + 0

=  12 ms + 0.5 / 90 RPS + 0.125 / 1024 s + 1 ms + 0

=  12 ms + 5.5 ms + 0.1 ms + 1 ms + 0 ms

=  18.6 ms

If real seeks are 1/3 the advertised seeks, disk access time would be 10.6 ms, with rotation delay contributing 50% of the access time!