Lecture 25: I/O Introduction

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Computer Science 252
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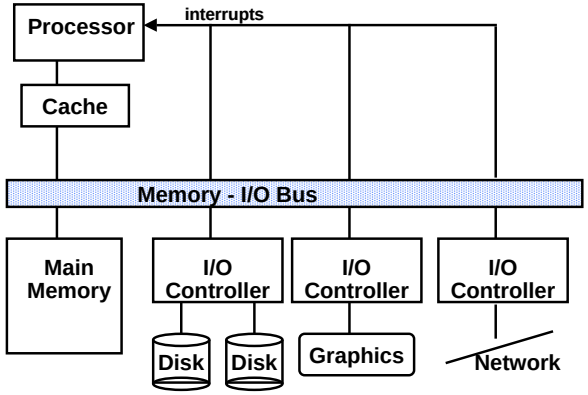
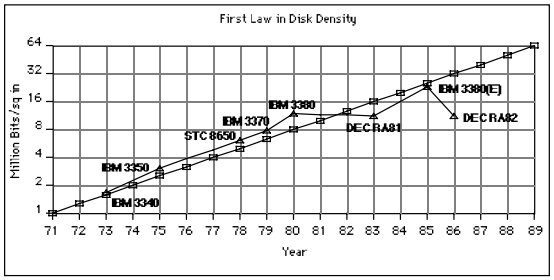
Motivation: Who Cares About I/O?

- CPU Performance: 60% per year
- I/O system performance limited by *mechanical* delays (disk I/O)
  - < 10% per year (IO per sec or MB per sec)
- Amdahl's Law: system speed-up limited by the slowest part!
  - 10% IO & 10x CPU => 5x Performance (lose 50%)
  - 10% IO & 100x CPU => 10x Performance (lose 90%)
- I/O bottleneck:
  - Diminishing fraction of time in CPU
  - Diminishing value of faster CPUs

I/O Systems



Technology Trends



Disk Capacity now doubles every 18 months; before 1990 every 36 motnhs

- Today: Processing Power Doubles Every 18 months
- Today: Memory Size Doubles Every 18 months(4X/3yr)
- Today: Disk Capacity Doubles Every 18 months
- *Disk Positioning Rate (Seek + Rotate) Doubles Every Ten Years!*

The I/O GAP

Storage Technology Drivers

- Driven by the prevailing computing paradigm
  - 1950s: migration from batch to on-line processing
  - 1990s: migration to ubiquitous computing
    - » computers in phones, books, cars, video cameras, …
    - » nationwide fiber optical network with wireless tails
- Effects on storage industry:
  - Embedded storage
    - » smaller, cheaper, more reliable, lower power
  - Data utilities
    - » high capacity, hierarchically managed storage

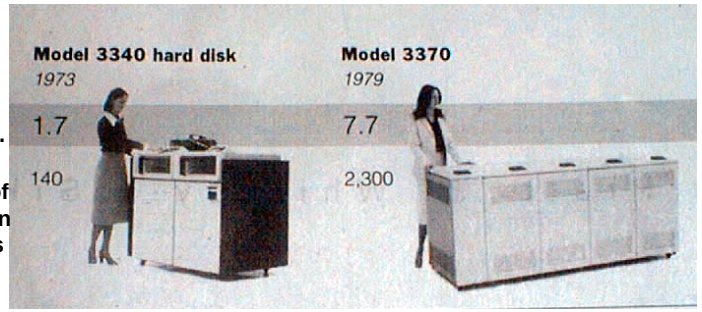
Historical Perspective

- 1956 IBM Ramac — early 1970s Winchester
  - Developed for mainframe computers, proprietary interfaces
  - Steady shrink in form factor: 27 in. to 14 in.
- 1970s developments
  - 5.25 inch floppy disk formfactor (microcode into mainframe)
  - early emergence of industry standard disk interfaces
    - » ST506, SASI, SMD, ESDI
- Early 1980s
  - PCs and first generation workstations
- Mid 1980s
  - Client/server computing
  - Centralized storage on file server
    - » accelerates disk downsizing: 8 inch to 5.25 inch
  - Mass market disk drives become a reality
    - » industry standards: SCSI, IPI, IDE
    - » 5.25 inch drives for standalone PCs, End of proprietary interfaces

Disk History

Data density Mbit/sq. in.

Capacity of Unit Shown Megabytes



1973:
1. 7 Mbit/sq. in
140 MBytes

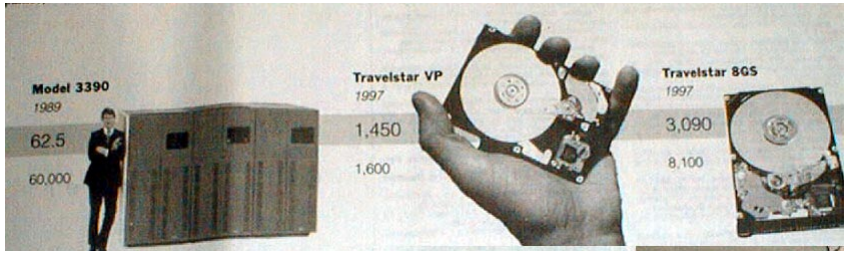
1979:
7. 7 Mbit/sq. in
2,300 MBytes

source: New York Times, 2/23/98, page C3,
"Makers of disk drives crowd even mroe data into even smaller spaces"

Historical Perspective

- Late 1980s/Early 1990s:
  - Laptops, notebooks, (palmtops)
  - 3.5 inch, 2.5 inch, (1.8 inch formfactors)
  - Formfactor plus capacity drives market, not so much performance
    - » Recently Bandwidth improving at 40%/ year
  - Challenged by DRAM, flash RAM in PCMCIA cards
    - » still expensive, Intel promises but doesn't deliver
    - » unattractive MBytes per cubic inch
  - Optical disk fails on performace (e.g., NEXT) but finds niche (CD ROM)

Disk History



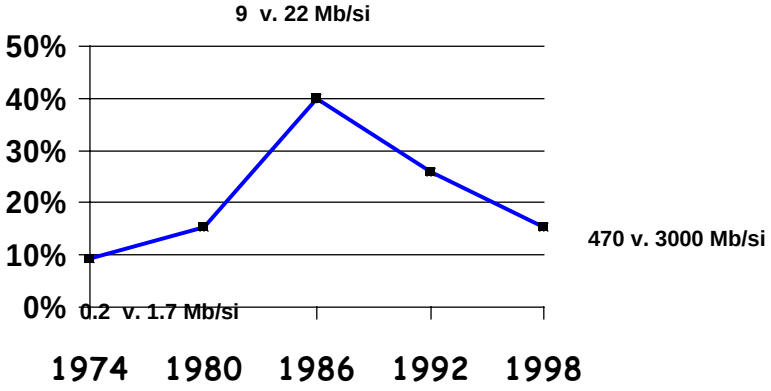
1989:
63 Mbit/sq. in
60,000 MBytes

1997:
1450 Mbit/sq. in
2300 MBytes

1997:
3090 Mbit/sq. in
8100 MBytes

source: New York Times, 2/23/98, page C3,
"Makers of disk drives crowd even mroe data into even smaller spaces"

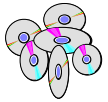
MBits per square inch: DRAM as % of Disk over time



source: New York Times, 2/23/98, page C3,
"Makers of disk drives crowd even mroe data into even smaller spaces"

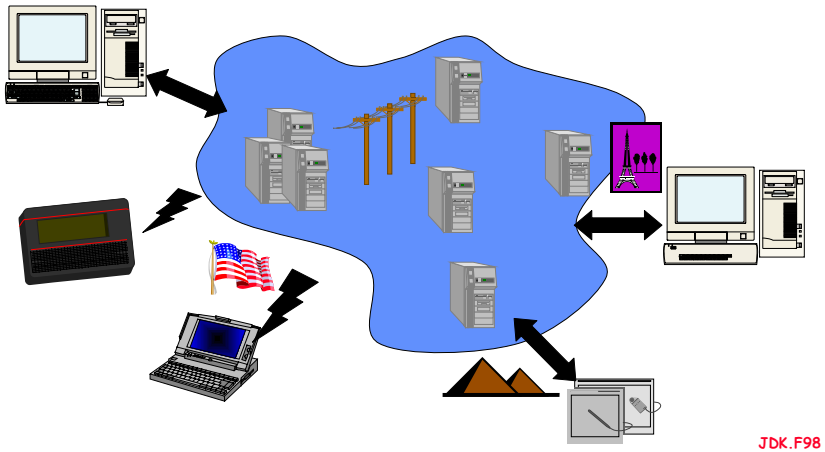
Alternative Data Storage Technologies: Early 1990s

Access Technology	Cap (MB)	BPI	TPI	BPI*TPI (Million)	Data Xfer (KByte/s)	Time
Conventional Tape:						
Cartridge (.25")	150	12000	104	1.2	92	minutes
IBM 3490 (.5")	800	22860	38	0.9	3000	seconds
Helical Scan Tape:						
Video (8mm)	4600	43200	1638	71	492	45 secs
DAT (4mm)	1300	61000	1870	114	183	20 secs
Magnetic & Optical Disk:						
Hard Disk (5.25")	1200	33528	1880	63	3000	18 ms
IBM 3390 (10.5")	3800	27940	2235	62	4250	20 ms
Sony MO (5.25")	640	24130	18796	454	88	100 ms



The ÆtherStore View

(World-wide data)

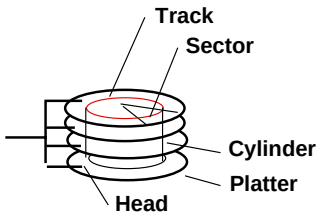


Properties of ÆtherStore

- Serverless, Homeless, Encrypted data
  - Easy sharing of information between anyone, anywhere
  - Caching of data anywhere
  - Dynamic construction of data distribution trees
  - Storage can be contributed by many different companies, just like phone service.
- Separating the "Where" from the "What"
  - View world as "ocean of data"
- Highly-available: data always duplicated
  - Higher-probability access.
  - Disaster recovery: "big-one" in California doesn't destroy your data.
- *Wireless devices plug in anywhere!*

Devices: Magnetic Disks

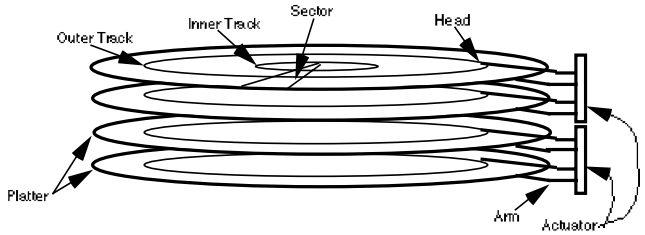
- Purpose:
  - Long-term, nonvolatile storage
  - Large, inexpensive, slow level in the storage hierarchy
- Characteristics:
  - Seek Time (~10> anq ms avg)
    - » positional latency
    - » rotational latency
- Transfer rate
  - About a sector per ms (5-15 MB/s)
  - Blocks
- Capacity
  - Gigabytes
  - Quadruples every 3 years (aerodynamics)



7200 RPM = 120 RPS => 8 ms per rev
ave rot. latency = 4 ms
128 sectors per track => 0.0625 ms per sector
1 KB per sector => 16 MB / s

Response time
= Queue + Controller + Seek + Rot + Xfer
Service time

Disk Device Terminology



Disk Latency = Queuing Time + Seek Time + Rotation Time + Xfer Time

Order of magnitude times for 4K byte transfers:

Seek: 12 ms or less

Rotate: 4.2 ms @ 7200 rpm (8.3 ms @ 3600 rpm)

Xfer: 1 ms @ 7200 rpm (2 ms @ 3600 rpm)

CS 252 Administrivia

- Upcoming schedule of project events in CS 252
  - Wednesday Dec 2: finish I/O.
  - Friday Dec 4: Esoteric computation. Quantum/DNA computing
  - Mon/Tue Dec 7/8 for oral reports
  - Friday Dec 11: project reports due.

Get moving!!!

Tape vs. Disk

- Longitudinal tape uses same technology as hard disk; tracks its density improvements
- Disk head flies above surface, tape head lies on surface
- Disk fixed, tape removable
- Inherent cost-performance based on geometries: fixed rotating platters with gaps
  (random access, limited area, 1 media / reader)

vs.

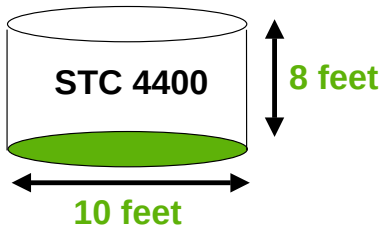
removable long strips wound on spool
(sequential access, "unlimited" length, multiple / reader)

- New technology trend:
  Helical Scan (VCR, Camcoder, DAT)
  Spins head at angle to tape to improve density

Current Drawbacks to Tape

- Tape wear out:
  - Helical 100s of passes to 1000s for longitudinal
- Head wear out:
  - 2000 hours for helical
- Both must be accounted for in economic / reliability model
- Long rewind, eject, load, spin-up times; not inherent, just no need in marketplace (so far)
- Designed for archival

Automated Cartridge System



6000 x 0.8 GB 3490 tapes = 5 TBytes in 1992
$500,000 O.E.M. Price

6000 x 10 GB D3 tapes = 60 TBytes in 1998

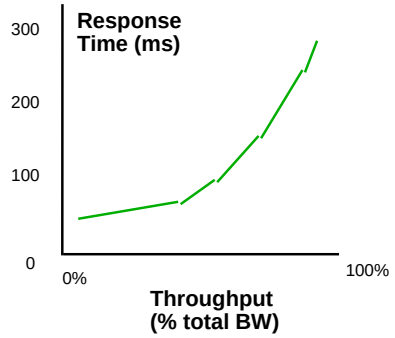
Library of Congress: all information in the world; in 1992, ASCII of all books = 30 TB

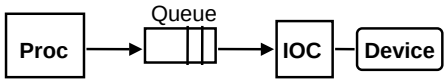
Relative Cost of Storage Technology—Late 1995/Early 1996

Magnetic Disks			
5.25"	9.1 GB	$2129	$0.23/MB
		$1985	$0.22/MB
3.5"	4.3 GB	$1199	$0.27/MB
		$999	$0.23/MB
2.5"	514 MB	$299	$0.58/MB
	1.1 GB	$345	$0.33/MB
Optical Disks			
5.25"	4.6 GB	$1695+199	$0.41/MB
		$1499+189	$0.39/MB
PCMCIA Cards			
Static RAM	4.0 MB	$700	$175/MB
Flash RAM	40.0 MB	$1300	$32/MB
	175 MB	$3600	$20.50/MB

Disk I/O Performance

Metrics:
- Response Time
- Throughput



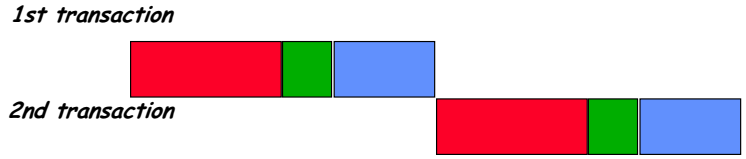


Response time = Queue + Device Service time

Response Time vs. Productivity

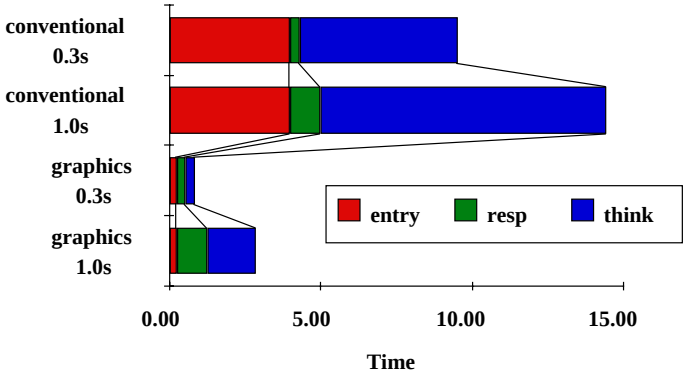
- Interactive environments:

  Each interaction or *transaction* has 3 parts:
  - *Entry Time*: time for user to enter command
  - *System Response Time*: time between user entry & system replies
  - *Think Time*: Time from response until user begins next command



- What happens to transaction time as shrink system response time from 1.0 sec to 0.3 sec?
  - With Keyboard: 4.0 sec entry, 9.4 sec think time
  - With Graphics: 0.25 sec entry, 1.6 sec think time

Response Time & Productivity



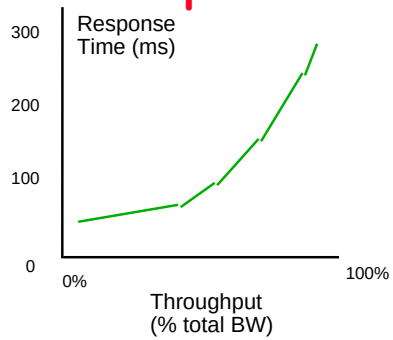
- 0.7sec off response saves 4.9 sec (34%) and 2.0 sec (70%) total time per transaction => greater productivity
- Another study: everyone gets more done with faster response, but novice with fast response = expert with slow

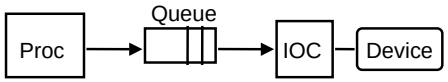
Disk Time Example

- Disk Parameters:
  - Transfer size is 8K bytes
  - Advertised average seek is 12 ms
  - Disk spins at 7200 RPM
  - Transfer rate is 4 MB/sec
- Controller overhead is 2 ms
- Assume that disk is idle so no queuing delay
- What is Average Disk Access Time for a Sector?
  - Ave seek + ave rot delay + transfer time + controller overhead
  - 12 ms + 0.5/(7200 RPM/60) + 8 KB/4 MB/s + 2 ms
  - 12 + 4.15 + 2 + 2 = 20 ms
- Advertised seek time assumes no locality: typically 1/4 to 1/3 advertised seek time: 20 ms => 12 ms

But: What about queue time? Or: why nonlinear response

Metrics:
- Response Time
- Throughput





Response time = Queue + Device Service time

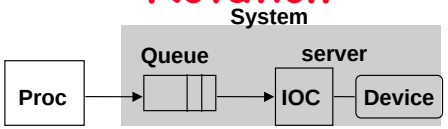
Departure to discuss queueing theory

(On board)

Introduction to Queueing Theory

- More interested in long term, steady state than in startup => Arrivals = Departures
- Little's Law:
  Mean number tasks in system = arrival rate x mean reponse time
  - Observed by many, Little was first to prove
- Applies to any system in equilibrium, as long as nothing in black box is creating or destroying tasks

A Little Queuing Theory: Notation

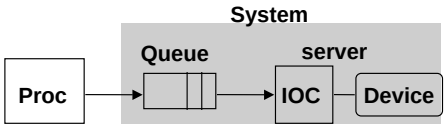


- Queuing models assume state of equilibrium: input rate = output rate
- Notation:

r	average number of arriving customers/second
T_{ser}	average time to service a customer (tradtionally $\mu = 1/T_{ser}$)
u	server utilization (0..1): $u = r \times T_{ser}$ (or $u = r / T_{ser}$)
T_q	average time/customer in queue
T_{sys}	average time/customer in system: $T_{sys} = T_q + T_{ser}$
L_q	average length of queue: $L_q = r \times T_q$
L_{sys}	average length of system: $L_{sys} = r \times T_{sys}$

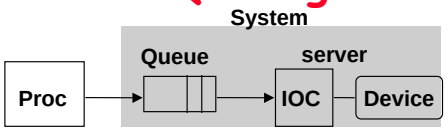
- Little's Law: $Length_{system} = rate \times Time_{system}$
  (Mean number customers = arrival rate x mean service time)

A Little Queuing Theory



- Service time completions vs. waiting time for a busy server: randomly arriving event joins a queue of arbitrary length when server is busy, otherwise serviced immediately
  - Unlimited length queues key simplification
- A *single server queue*: combination of a servicing facility that accomodates 1 customer at a time (*server*) + waiting area (*queue*): together called a *system*
- Server spends a variable amount of time with customers; *how do you characterize variability?*
  - Distribution of a random variable: histogram? curve?

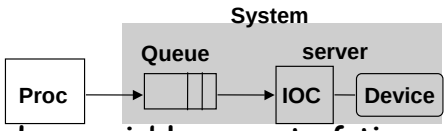
A Little Queuing Theory



- Server spends a variable amount of time with customers
  - Weighted mean *m1* = (f1 x T1 + f2 x T2 +...+ fn x Tn)/F (F=f1 + f2...)
  - *variance* = (f1 x $T1^2$ + f2 x $T2^2$ +...+ fn x Tn^2)/F – $m1^2$
    - » Must keep track of unit of measure (100 ms^2 vs. 0.1 s^2)
  - *Squared coefficient of variance*: *C = variance/$m1^2$*
    - » Unitless measure (100 ms^2 vs. 0.1 s^2)

- Exponential distribution *C = 1* : most short relative to average, few others long; 90% < 2.3 x average, 63% < average
- Hypoexponential distribution *C < 1* : most close to average, C=0.5 => 90% < 2.0 x average, only 57% < average
- Hyperexponential distribution *C > 1* : further from average C=2.0 => 90% < 2.8 x average, 69% < average

A Little Queuing Theory: Variable Service Time



- Server spends a variable amount of time with customers
  - Weighted mean *m1* = (f1xT1 + f2xT2 +...+ fnXTn)/F (F=f1+f2+...)
  - Squared coefficient of variance *C*
- Disk response times *C - 1.5* (majority seeks < average)
- Yet usually pick *C = 1.0* for simplicity
- Another useful value is average time must wait for server to complete task: *m1(z)*
  - Not just 1/2 x m1 because doesn't capture variance
  - Can derive *m1(z) = 1/2 x m1 x (1 + C)*
  - *No variance => C= 0 => m1(z) = 1/2 x m1*

A Little Queuing Theory: Average Wait Time

- Calculating average wait time in queue T_q
  - If something at server, it takes to complete on average *m1(z)*
  - Chance server is busy = u; average delay is *u* x *m1(z)*
  - All customers in line must complete; each avg T_{ser}

$$T_q = u \times \underline{m1(z)} + L_q \times T_{ser} = 1/2 \times u \times T_{ser} \times (1 + C) + \underline{L_q} \times T_{ser}$$

$$T_q = 1/2 \times u \times T_{ser} \times (1 + C) + \underline{r} \times T_q \times \underline{T_{ser}}$$

$$T_q = 1/2 \times u \times T_{ser} \times (1 + C) + \underline{u \times T_q}$$

$$T_q \times \underline{(1 - u)} = T_{ser} \times u \times (1 + C) /2$$

$$T_q = T_{ser} \times u \times (1 + C) / (2 \times (1 - u))$$

- Notation:

r	average number of arriving customers/second
T_{ser}	average time to service a customer
u	server utilization (0..1): $u = r \times T_{ser}$
T_q	average time/customer in queue
L_q	average length of queue: $L_q = r \times T_q$

A Little Queuing Theory: M/G/1 and M/M/1

- Assumptions so far:
  - System in equilibrium
  - Time between two successive arrivals in line are random
  - Server can start on next customer immediately after prior finishes
  - No limit to the queue: works First-In-First-Out
  - Afterward, all customers in line must complete; each avg T_{ser}
- Described "memoryless" or Markovian request arrival (M for C=1 exponentially random), General service distribution (no restrictions), 1 server: *M/G/1 queue*
- When Service times have C = 1, *M/M/1 queue*

$T_q = T_{ser} \times u \times (1 + C) / (2 \times (1 - u)) = T_{ser} \times u / (1 - u)$

T_{ser} average time to service a customer
u server utilization (0..1): $u = r \times T_{ser}$
T_q average time/customer in queue

A Little Queuing Theory: An Example

- processor sends 10 x 8KB disk I/Os per second, requests & service exponentially distrib., avg. disk service = 20 ms
- On average, how utilized is the disk?
  - What is the number of requests in the queue?
  - What is the average time spent in the queue?
  - What is the average response time for a disk request?
- Notation:

r average number of arriving customers/second = 10
T_{ser} average time to service a customer = 20 ms (0.02s)
u server utilization (0..1): $u = r \times T_{ser}$ = 10/s x .02s = 0.2
T_q average time/customer in queue $= T_{ser} \times u / (1 - u)$
= 20 x 0.2/(1-0.2) = 20 x 0.25 = 5 ms (0 .005s)
T_{sys} average time/customer in system: $T_{sys} = T_q + T_{ser}$ = 25 ms
L_q average length of queue: $L_q = r \times T_q$
= 10/s x .005s = 0.05 requests in queue
L_{sys} average # tasks in system: $L_{sys} = r \times T_{sys}$ = 10/s x .025s = 0.25

A Little Queuing Theory: Another Example

- processor sends 20 x 8KB disk I/Os per sec, requests & service exponentially distrib., avg. disk service = 12 ms
- On average, how utilized is the disk?
  - What is the number of requests in the queue?
  - What is the average time a spent in the queue?
  - What is the average response time for a disk request?
- Notation:

r average number of arriving customers/second= 20
T_{ser} average time to service a customer= 12 ms
u server utilization (0..1): $u = r \times T_{ser}$= 20/s x .012s = 0.24
T_q average time/customer in queue $= T_{ser} \times u / (1 - u)$
= 12 x 0.24/(1-0.24) = 12 x 0.32 = 3.8 ms
T_{sys} average time/customer in system: $T_{sys} = T_q + T_{ser}$= 15.8 ms
L_q average length of queue: $L_q = r \times T_q$
= 20/s x .0038s = 0.076 requests in queue
L_{sys} average # tasks in system : $L_{sys} = r \times T_{sys}$ = 20/s x .016s = 0.32

A Little Queuing Theory: Yet Another Example

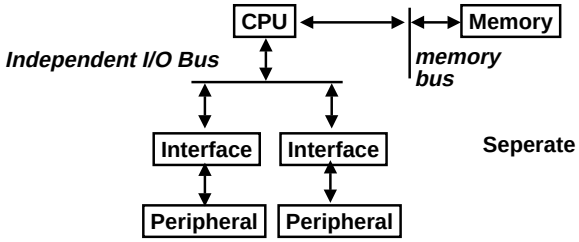
- Suppose processor sends 10 x 8KB disk I/Os per second, squared coef. var.(C) = 1.5, avg. disk service time = 20 ms
- On average, how utilized is the disk?
  - What is the number of requests in the queue?
  - What is the average time a spent in the queue?
  - What is the average response time for a disk request?
- Notation:

r average number of arriving customers/second= 10
T_{ser} average time to service a customer= 20 ms
u server utilization (0..1): $u = r \times T_{ser}$= 10/s x .02s = 0.2
T_q average time/customer in queue $= T_{ser} \times u \times (1 + C) / (2 \times (1 - u))$
= 20 x 0.2(2.5)/2(1 – 0.2) = 20 x 0.32 = 6.25 ms
T_{sys} average time/customer in system: $T_{sys} = T_q + T_{ser}$= 26 ms
L_q average length of queue: $L_q = r \times T_q$
= 10/s x .006s = 0.06 requests in queue
L_{sys} average # tasks in system : $L_{sys} = r \times T_{sys}$ = 10/s x .026s = 0.26

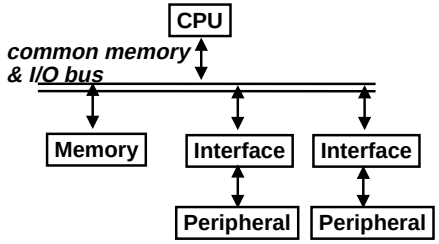
Processor Interface Issues

- Processor interface
  - Interrupts
  - Memory mapped I/O
- I/O Control Structures
  - Polling
  - Interrupts
  - DMA
  - I/O Controllers
  - I/O Processors
- Capacity, Access Time, Bandwidth
- Interconnections
  - Busses

I/O Interface



Seperate I/O instructions (in,out)



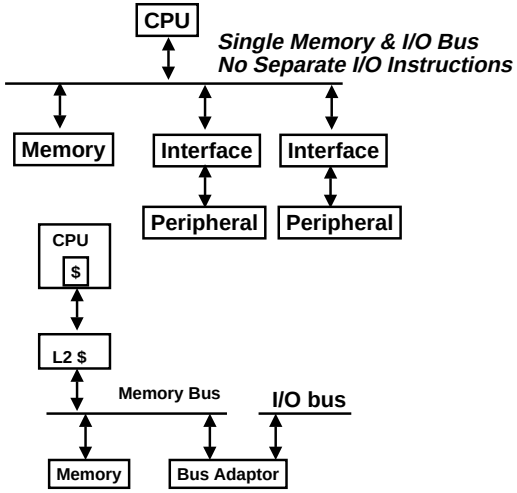
Lines distinguish between I/O and memory transfers

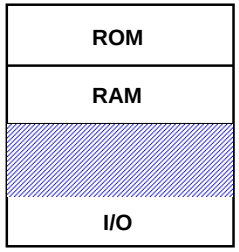
VME bus
Multibus-II
Nubus

40 Mbytes/sec optimistically

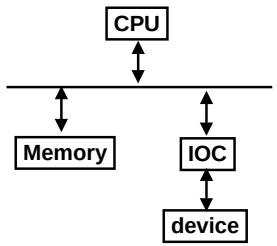
10 MIP processor completely saturates the bus!

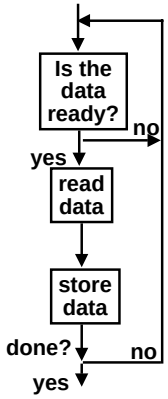
Memory Mapped I/O





Programmed I/O (Polling)

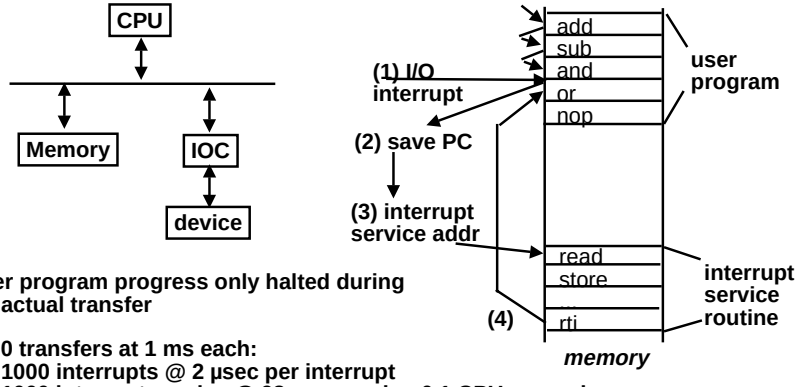




busy wait loop not an efficient way to use the CPU unless the device is very fast!

but checks for I/O completion can be dispersed among computationally intensive code

Interrupt Driven Data Transfer



User program progress only halted during actual transfer

1000 transfers at 1 ms each:
- 1000 interrupts @ 2 µsec per interrupt
- 1000 interrupt service @ 98 µsec each = 0.1 CPU seconds

Device xfer rate = 10 MBytes/sec => 0 .1 x 10^{-6} sec/byte => 0.1 µsec/byte
=> 1000 bytes = 100 µsec

1000 transfers x 100 µsecs = 100 ms = 0.1 CPU seconds

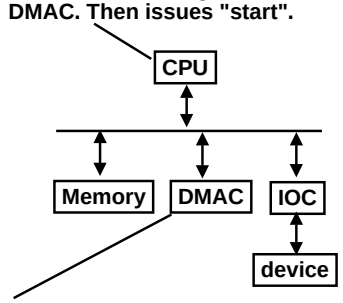
Still far from device transfer rate! 1/2 in interrupt overhead

Direct Memory Access

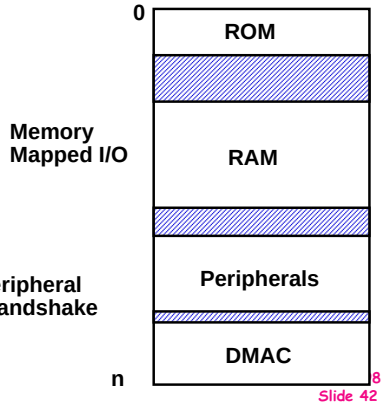
Time to do 1000 xfers at 1 msec each:
- 1 DMA set-up sequence @ 50 µsec
- 1 interrupt @ 2 µsec
- 1 interrupt service sequence @ 48 µsec

.0001 second of CPU time

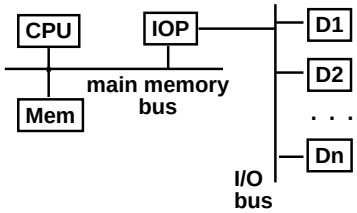
CPU sends a starting address, direction, and length count to DMAC. Then issues "start".

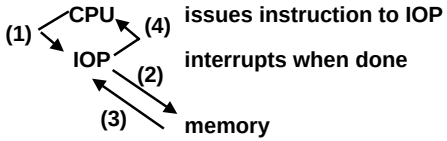


DMAC provides handshake signals for Peripheral Controller, and Memory Addresses and handshake signals for Memory.



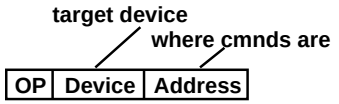
Input/Output Processors



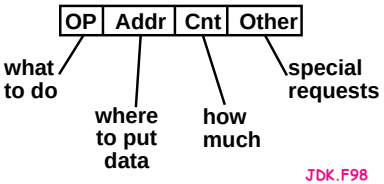


Device to/from memory transfers are controlled by the IOP directly.

IOP steals memory cycles.



looks in memory for commands



Relationship to Processor Architecture

- I/O instructions have largely disappeared
- Interrupt vectors have been replaced by jump tables
  PC <- M [IVA + interrupt number]
  PC <- IVA + interrupt number
- Interrupts:
  - Stack replaced by shadow registers
  - Handler saves registers and re-enables higher priority int's
  - Interrupt types reduced in number; handler must query interrupt controller

Relationship to Processor Architecture

- Caches required for processor performance cause problems for I/O
  - Flushing is expensive, I/O polutes cache
  - Solution is borrowed from shared memory multiprocessors "snooping"
- Virtual memory frustrates DMA
- Load/store architecture at odds with atomic operations
  - load locked, store conditional
- Stateful processors hard to context switch

Summary

- Disk industry growing rapidly, improves:
  - bandwidth 40%/yr ,
  - areal density 60%/year, $/MB faster?
- queue + controller + seek + rotate + transfer
- Advertised average seek time benchmark much greater than average seek time in practice
- Response time vs. Bandwidth tradeoffs
- Queueing theory: $W = \left(\frac{\frac{1}{2}(1+C)\bar{x}\xi}{1-\xi} \right)$ or $W = \left(\frac{\bar{x}\xi}{1-\xi} \right)$
- Value of faster response time:
  - 0.7sec off response saves 4.9 sec and 2.0 sec (70%) total time per transaction => greater productivity
  - everyone gets more done with faster response, but novice with fast response = expert with slow

Summary: Relationship to Processor Architecture

- I/O instructions have disappeared
- Interrupt vectors have been replaced by jump tables
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- Caches required for processor performance cause problems for I/O
- Virtual memory frustrates DMA
- Load/store architecture at odds with atomic operations
- Stateful processors hard to context switch