inst.eecs.berkeley.edu/~cs61c

CS61C : Machine Structures

Lecture #26

RAID & Performance

CPS today!

2005-12-05

There is one handout today at the front and back of the room!

Lecturer PSOE, new dad Dan Garcia

www.cs.berkeley.edu/~ddgarcia

Samsung pleads guilty! ⇒

They were convicted of "price-fixing" DRAM from 1999-04 to 2002-06 through emails, etc & ordered to pay $0.3 Billion (2nd largest fine in criminal antitrust case).

www.cnn.com/2005/TECH/biztech/12/01/samsung.price.fixing.ap

Review

- Protocol suites allow heterogeneous networking
  - Another form of principle of abstraction
  - Protocols ⇒ operation in presence of failures
  - Standardization key for LAN, WAN
- Magnetic Disks continue rapid advance: 60%/yr capacity, 40%/yr bandwidth, slow on seek, rotation improvements, MB/$ improving 100%/yr?
  - Designs to fit high volume form factor

State of the Art: Two camps (2005)

- Performance
  - Enterprise apps, servers
- E.g., Seagate Cheetah 15K.4
  - Serial-Attached SCSI, Ultra320 SCSI, 2Gbit Fibre Channel interface
  - 146 GB, 3.5-inch disk
  - 15,000 RPM
  - 4 discs, 8 heads
  - 13 watts (idle)
  - 3.5 ms avg. seek
  - 200 MB/s transfer rate
  - 1.4 Million hrs MTBF
  - 5 year warrantee
  - $1000 = $6.8 / GB

- Capacity
  - Mainstream, home uses
- E.g., Seagate Barracuda 7200.9
  - Serial ATA 3Gb/s, Ultra ATA/100
  - 500 GB, 3.5-inch disk
  - 7,200 RPM
  - ? discs, ? heads
  - 7 watts (idle)
  - 8.5 ms avg. seek
  - 300 MB/s transfer rate
  - ? Million hrs MTBF
  - 5 year warrantee
  - $330 = $0.66 / GB

source: www.seagate.com

1 inch disk drive!

- 2005 Hitachi Microdrive:
  - 40 x 30 x 5 mm, 13g
  - 8 GB, 3600 RPM, 1 disk, 10 MB/s, 12 ms seek
  - 400G operational shock, 2000G non-operational
  - Can detect a fall in 4” and retract heads to safety
  - For iPods, cameras, phones
- 2006 MicroDrive?
  - 16 GB, 12 MB/s!
  - Assuming past trends continue

www.hitachigst.com

Where does Flash memory come in?

- Microdrives and Flash memory (e.g., CompactFlash) are going head-to-head
  - Both non-volatile (no power, data ok)
  - Flash benefits: durable & lower power (no moving parts)
  - Flash limitations: finite number of write cycles (wear on the insulating oxide layer around the charge storage mechanism)
    - OEMs work around by spreading writes out
- How does Flash memory work?
  - NMOS transistor with an additional conductor between gate and source/drain which “traps” electrons. The presence/absence is a 1 or 0.
  - `wikipedia.org/wiki/Flash_memory`

What does Apple put in its iPods?

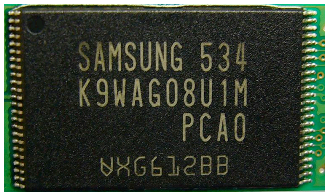
Thanks to Andy Dahl for the tip

shuffle

Toshiba 0.5,1GB flash

nano

Samsung 2,4GB flash



mini

Hitachi 1 inch 4,6GB MicroDrive

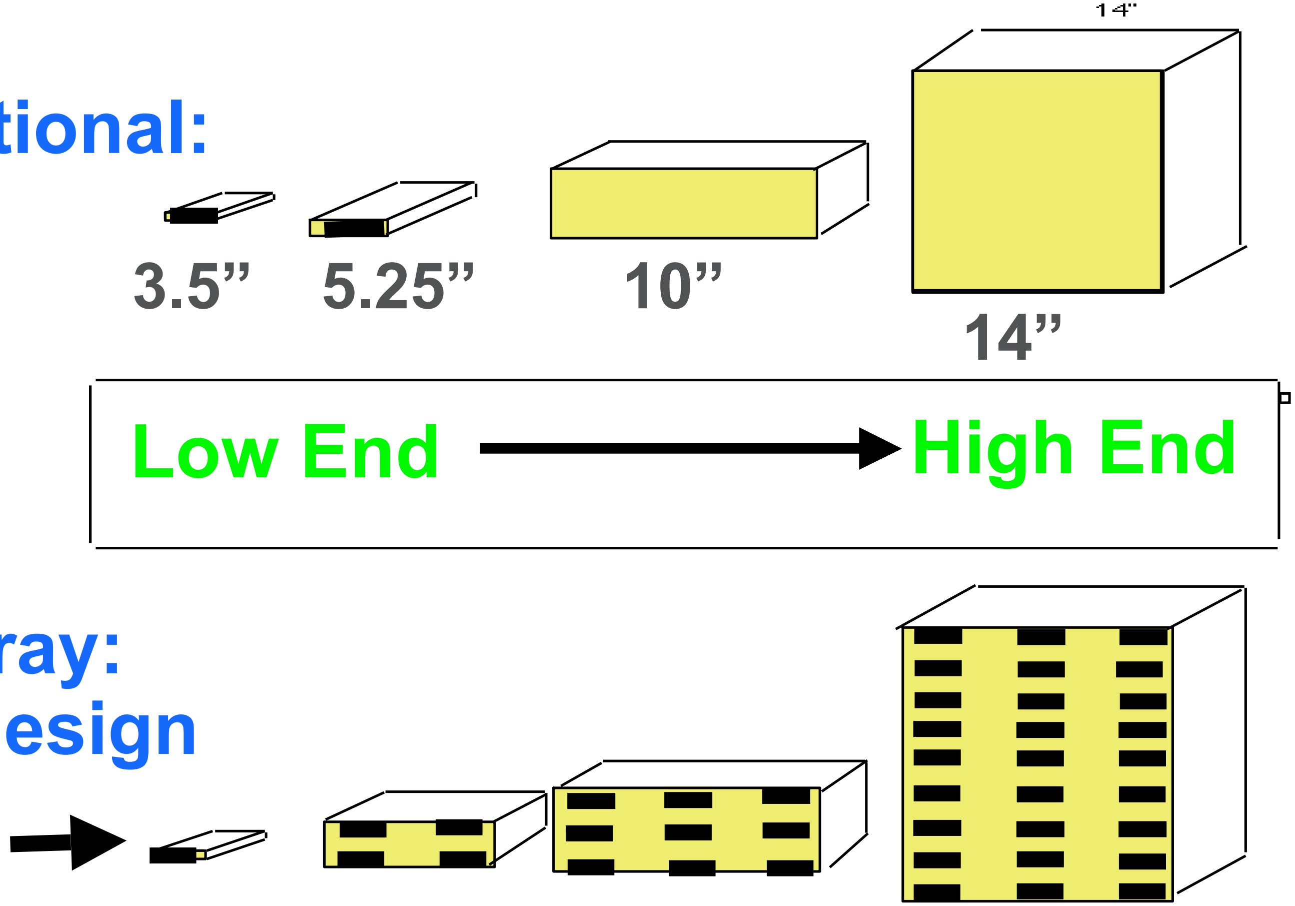
iPod

Toshiba 1.8-inch 30,60GB (MK1504GAL)

Use Arrays of Small Disks…

- Katz and Patterson asked in 1987:
  - Can smaller disks be used to close gap in performance between disks and CPUs?

Conventional:
4 disk designs



3.5”

5.25”

10”

14”

Low End → High End

Disk Array:
1 disk design

3.5”

Replace Small Number of Large Disks with Large Number of Small Disks! (1988 Disks)

	IBM 3390K	IBM 3.5" 0061	x70	
Capacity	20 GBytes	320 MBytes	23 GBytes	
Volume	97 cu. ft.	0.1 cu. ft.	11 cu. ft.	9X
Power	3 KW	11 W	1 KW	3X
Data Rate	15 MB/s	1.5 MB/s	120 MB/s	8X
I/O Rate	600 I/Os/s	55 I/Os/s	3900 IOs/s	6X
MTTF	250 KHrs	50 KHrs	??? Hrs	
Cost	$250K	$2K	$150K	

Disk Arrays potentially high performance, high MB per cu. ft., high MB per KW,

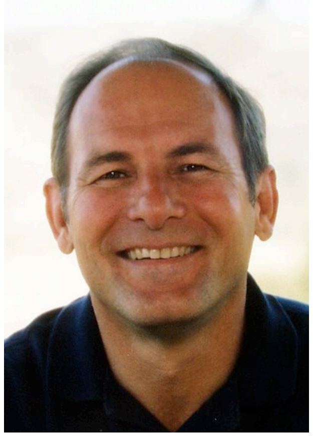
but what about reliability?

Array Reliability

- **Reliability** - whether or not a component has failed
  - measured as Mean Time To Failure (MTTF)
- Reliability of N disks = Reliability of 1 Disk ÷ N (assuming failures independent)
  - 50,000 Hours ÷ 70 disks = 700 hour
- Disk system MTTF: Drops from 6 years to 1 month!
- Disk arrays too unreliable to be useful!

Review

- Magnetic disks continue rapid advance: 2x/yr capacity, 2x/2-yr bandwidth, slow on seek, rotation improvements, MB/$ 2x/yr!
  - Designs to fit high volume form factor
- RAID
  - Motivation: In the 1980s, there were 2 classes of drives: expensive, big for enterprises and small for PCs. They thought "make one big out of many small!"
  - Higher performance with more disk arms per $
  - Adds option for small # of extra disks (the "R")
  - Started @ Cal by CS Profs Katz & Patterson



Redundant Arrays of (Inexpensive) Disks

- Files are "striped" across multiple disks
- Redundancy yields high data availability
  - **Availability**: service still provided to user, even if some components failed
- Disks will still fail
- Contents reconstructed from data redundantly stored in the array

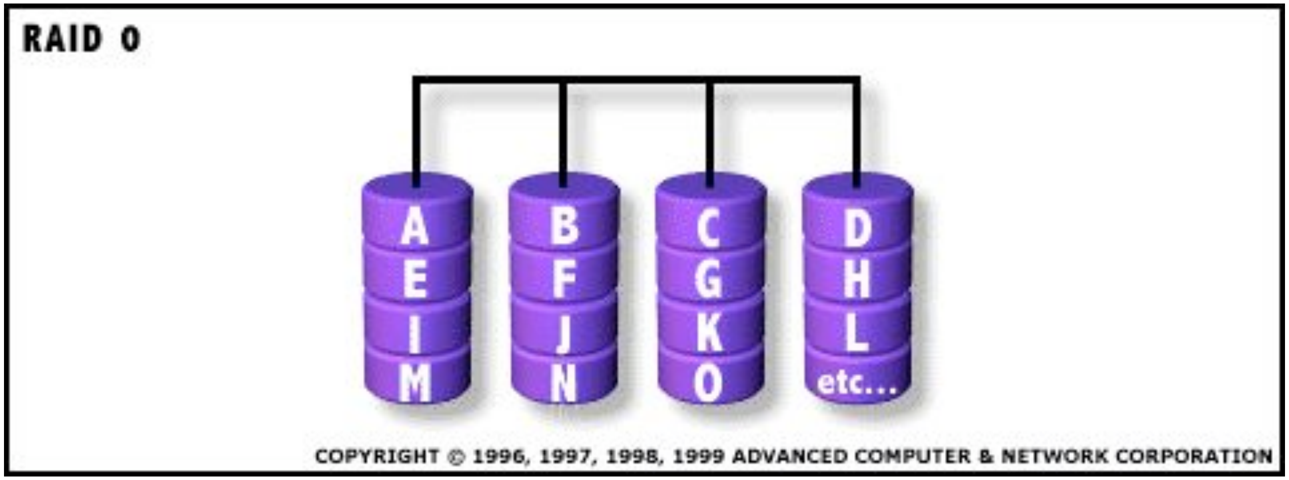
  ⇒ Capacity penalty to store redundant info

  ⇒ Bandwidth penalty to update redundant info

Berkeley History, RAID-I

- RAID-I (1989)
  - Consisted of a Sun 4/280 workstation with 128 MB of DRAM, four dual-string SCSI controllers, 28 5.25-inch SCSI disks and specialized disk striping software
- Today RAID is > $32 billion dollar industry, 80% nonPC disks sold in RAIDs

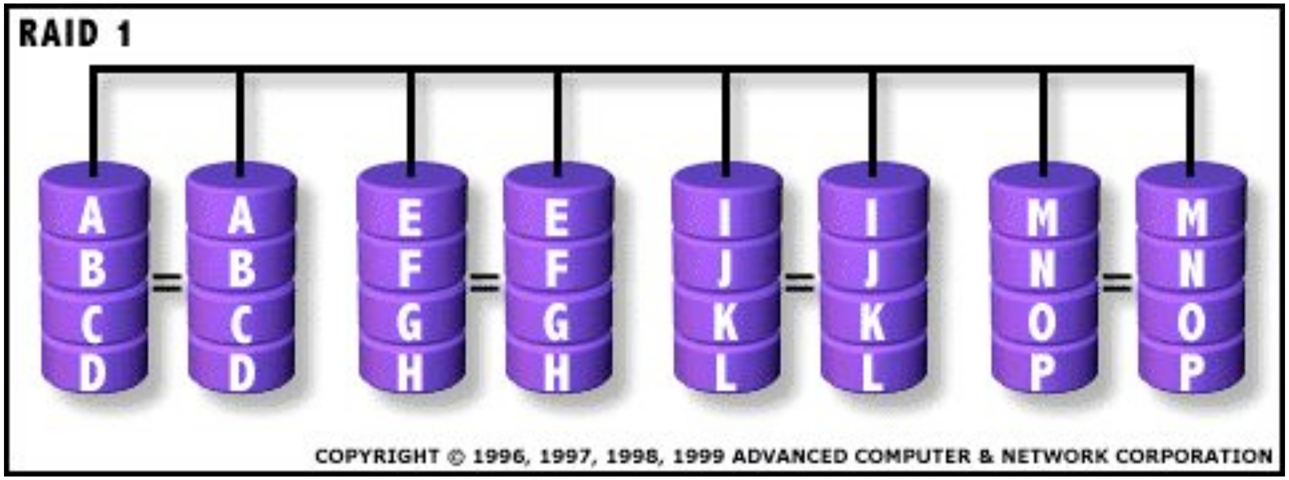
"RAID 0": No redundancy = "AID"


RAID 0
A
E
I
M
B
F
J
N
C
G
K
O
D
H
L
etc...
COPYRIGHT © 1996, 1997, 1998, 1999 ADVANCED COMPUTER & NETWORK CORPORATION

- Assume have 4 disks of data for this example, organized in blocks
- Large accesses faster since transfer from several disks at once

This and next 5 slides from RAID.edu, http://www.acnc.com/04_01_00.html

RAID 1: Mirror data


RAID 1
A
B
C
D
=
A
B
C
D
E
F
G
H
=
E
F
G
H
I
J
K
L
=
I
J
K
L
M
N
O
P
=
M
N
O
P
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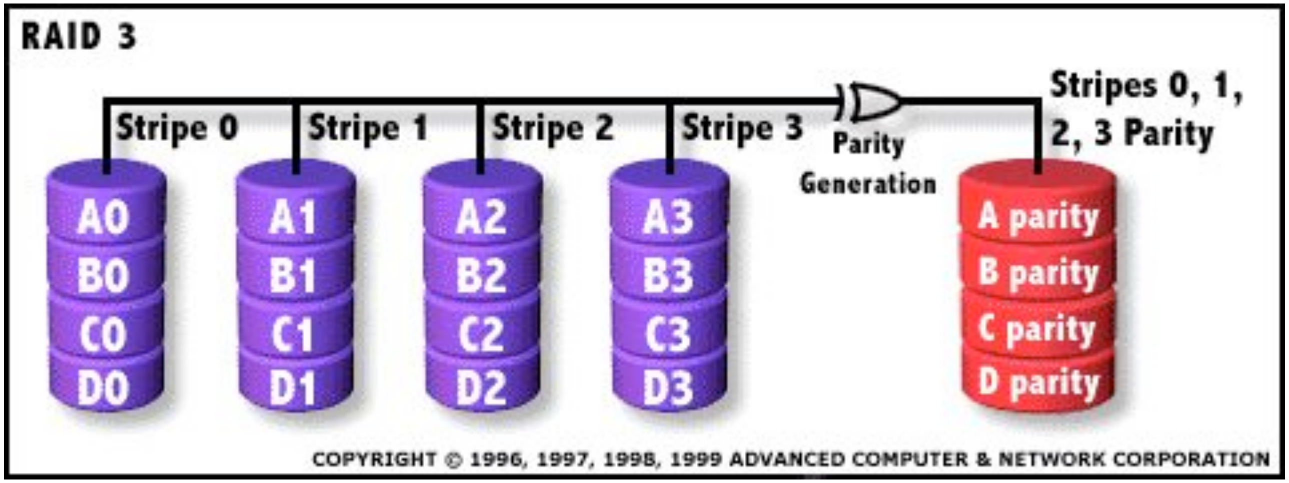
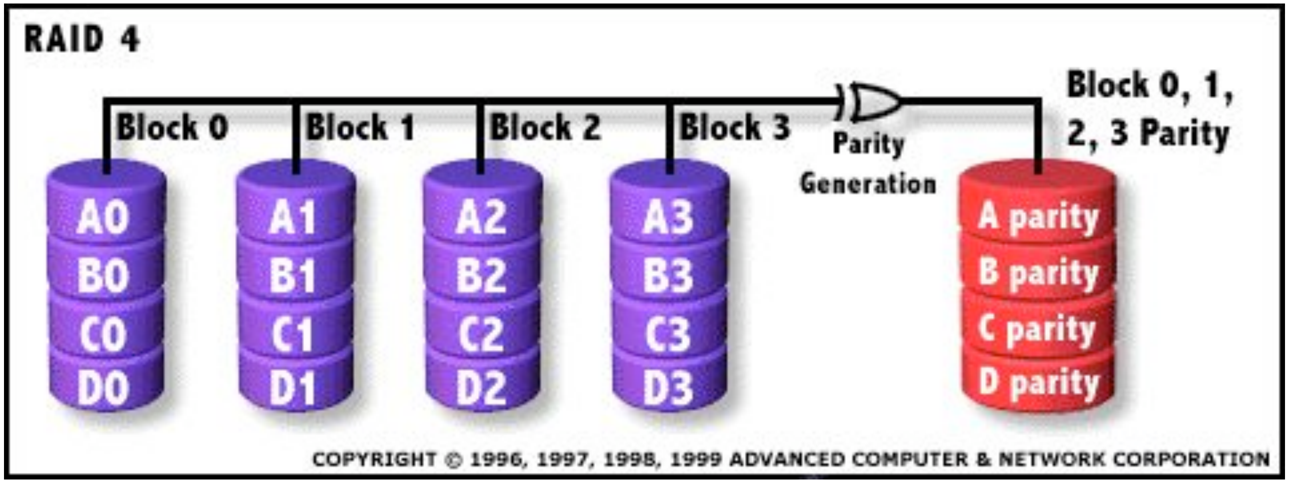
- Each disk is fully duplicated onto its "mirror"
  - Very high availability can be achieved
- Bandwidth reduced on write:
  - 1 Logical write = 2 physical writes
- Most expensive solution: 100% capacity overhead

RAID 3: Parity (RAID 2 has bit-level striping)



- Parity computed across group to protect against hard disk failures, stored in P disk
- Logically, a single high capacity, high transfer rate disk
- 25% capacity cost for parity in this example vs. 100% for RAID 1 (5 disks vs. 8 disks)

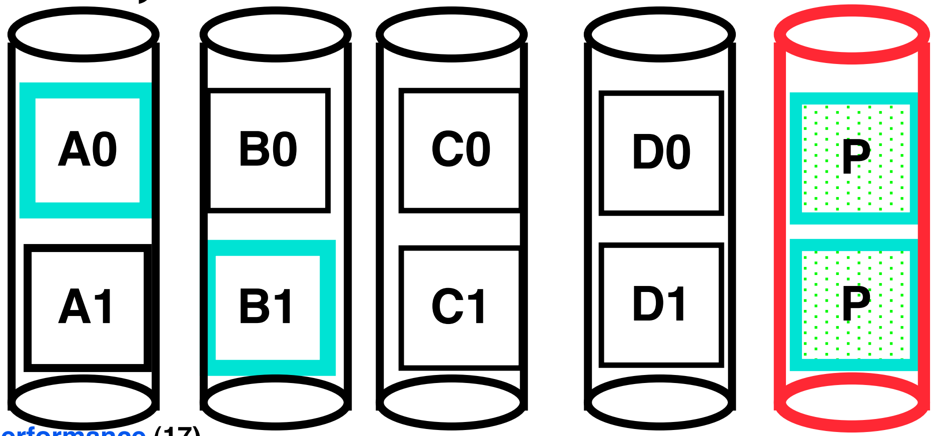
RAID 4: parity plus small sized accesses



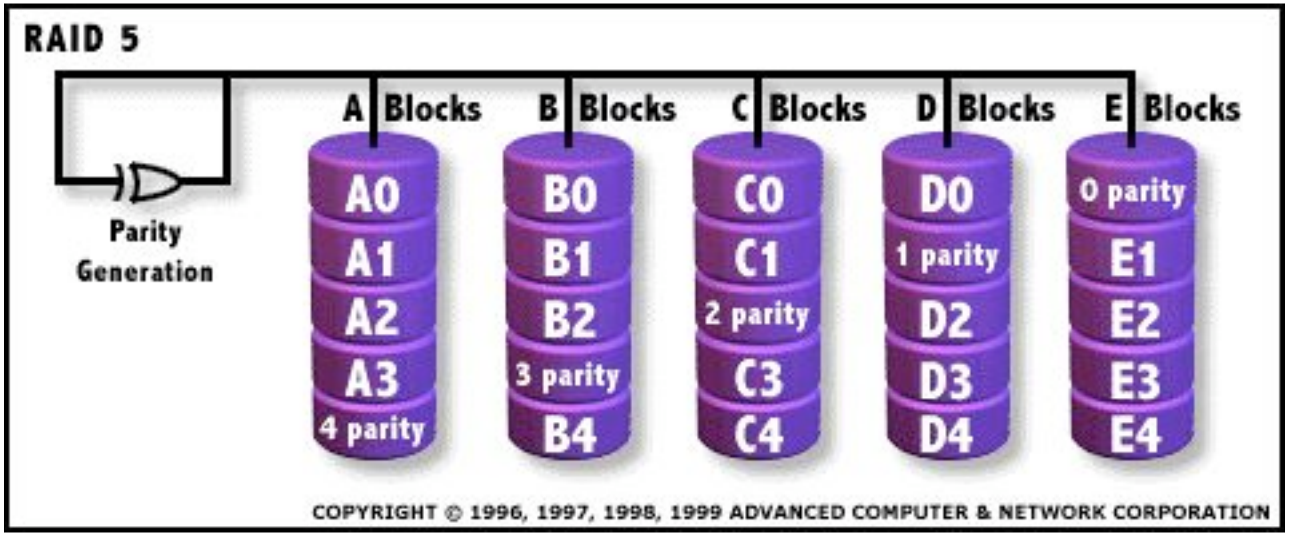
- RAID 3 relies on parity disk to discover errors on Read
- But every sector has an error detection field
- Rely on error detection field to catch errors on read, not on the parity disk
- Allows small independent reads to different disks simultaneously

Inspiration for RAID 5

- Small writes (write to one disk):
  - Option 1: read other data disks, create new sum and write to Parity Disk (access all disks)
  - Option 2: since P has old sum, compare old data to new data, add the difference to P: 1 logical write = 2 physical reads + 2 physical writes to 2 disks
- Parity Disk is bottleneck for Small writes: Write to A0, B1 => both write to P disk

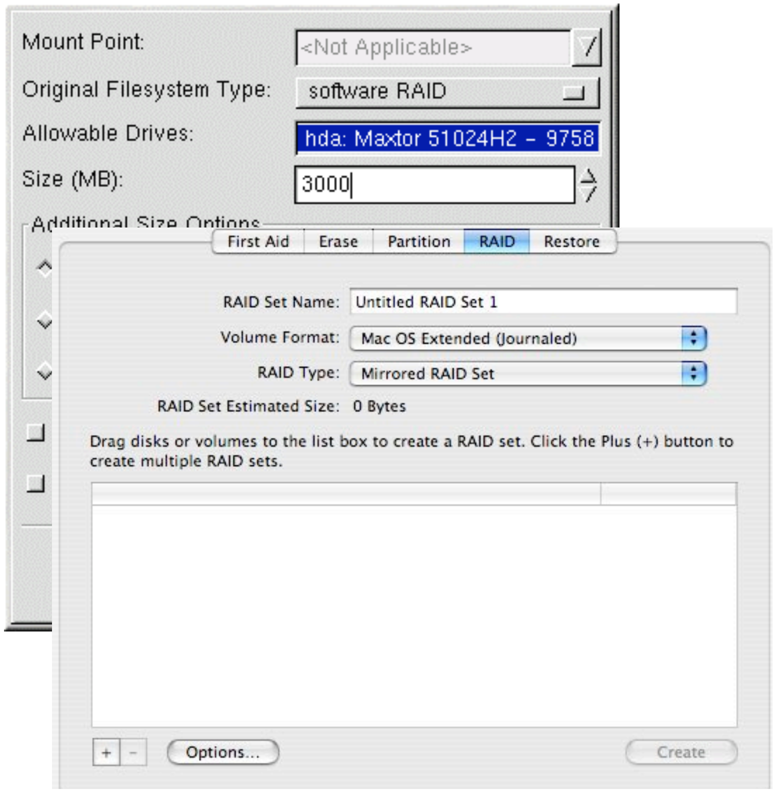


RAID 5: Rotated Parity, faster small writes



- Independent writes possible because of interleaved parity
  - Example: write to A0, B1 uses disks 0, 1, 4, 5, so can proceed in parallel
  - Still 1 small write = 4 physical disk accesses

RAID products: Software, Chips, Systems



Mount Point: <Not Applicable>

Original Filesystem Type: software RAID

Allowable Drives: hda: Maxtor 51024H2 - 9758

Size (MB): 3000

Additional Size Options

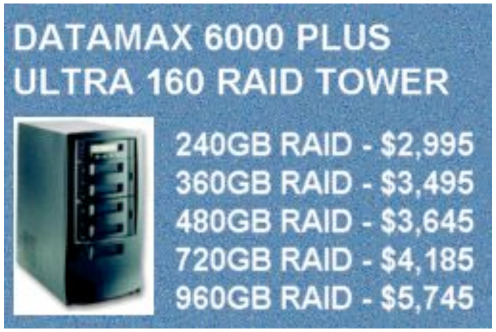
RAID Set Name: Untitled RAID Set 1

Volume Format: Mac OS Extended (Journaled)

RAID Type: Mirrored RAID Set

RAID Set Estimated Size: 0 Bytes

Drag disks or volumes to the list box to create a RAID set. Click the Plus (+) button to create multiple RAID sets.

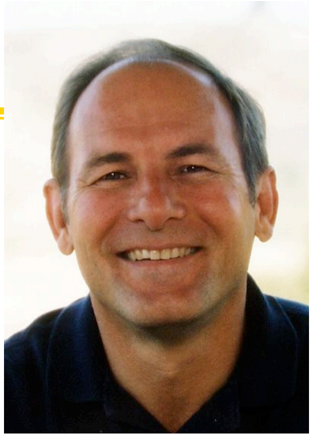


DATAMAX 6000 PLUS
ULTRA 160 RAID TOWER

240GB RAID	$2,995
360GB RAID	$3,495
480GB RAID	$3,645
720GB RAID	$4,185
960GB RAID	$5,745

RAID was $32 B industry in 2002, 80% nonPC disks sold in RAIDs

Margin of Safety in CS&E?



- Patterson reflects…
  - Operator removing good disk vs. bad disk
  - Temperature, vibration causing failure before repair
  - In retrospect, suggested RAID 5 for what we anticipated, but should have suggested RAID 6 (double failure OK) for unanticipated/safety margin…

Peer Instruction

1. RAID 1 (mirror) and 5 (rotated parity) help with performance and availability
2. RAID 1 has higher cost than RAID 5
3. Small writes on RAID 5 are slower than on RAID 1

	ABC
1:	FFF
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

Peer Instruction Answer

1. All RAID (0-5) helps with performance, only RAID 0 doesn't help availability. TRUE

2. Surely! Must buy 2x disks rather than 1.25x (from diagram, in practice even less) TRUE

3. RAID5 (2R,2W) vs. RAID1 (2W). Latency worse, throughput (ll writes) better. TRUE

1. RAID 1 (mirror) and 5 (rotated parity) help with performance and availability

2. RAID 1 has higher cost than RAID 5

3. Small writes on RAID 5 are slower than on RAID 1

	ABC
1:	FFF
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

Administrivia

- Please attend Wednesday's lecture!
  - HKN Evaluations at the end
- Compete in the Performance contest!
  - Deadline is Mon, 2005-12-12 @ 11:59pm, 1 week from now
- Sp04 Final exam + solutions online!
- Final Review: 2005-12-11 @ 2pm in 10 Evans
- Final: 2005-12-17 @ 12:30pm in 2050 VLSB
  - Only bring pen{,cil}s, two 8.5"x11" handwritten sheets + green. Leave backpacks, books,

Upcoming Calendar

Week #	Mon	Wed	Thu Lab	Sat
#15 Last Week o' Classes	Performance	LAST CLASS Summary, Review, & HKN Evals	I/O Networking & 61C Feedback Survey	
#16 Sun 2pm Review 10 Evans	Performance competition due tonight @ midnight			FINAL EXAM SAT 12-17 @ 12:30pm-3:30pm 2050 VLSB Performance awards

Performance

- Purchasing Perspective: given a collection of machines (or upgrade options), which has the
  - best performance ?
  - least cost ?
  - best performance / cost ?
- Computer Designer Perspective: faced with design options, which has the
  - best performance improvement ?
  - least cost ?
  - best performance / cost ?
- All require basis for comparison and metric for evaluation
- Solid metrics lead to solid progress!

Two Notions of "Performance"

Plane	DC to Paris	Top Speed	Passen-gers	Throughput (pmph)
Boeing 747	6.5 hours	610 mph	470	286,700
BAD/Sud Concorde	3 hours	1350 mph	132	178,200

- Which has higher performance?
  - Time to deliver 1 passenger?
  - Time to deliver 400 passengers?
- In a computer, time for 1 job called

  Response Time or Execution Time
- In a computer, jobs per day called

  Throughput or Bandwidth

Definitions

- Performance is in units of things per sec
  - bigger is better
- If we are primarily concerned with response time
  - performance(x) = $\dfrac{1}{\text{execution\_time(x)}}$

" F(ast) is *n* times faster than S(low) " means…

$$n = \frac{\text{performance(F)}}{\text{performance(S)}} = \frac{\text{execution\_time(S)}}{\text{execution\_time(F)}}$$

Example of Response Time v. Throughput

- Time of Concorde vs. Boeing 747?
  - Concord is 6.5 hours / 3 hours = 2.2 times faster
- Throughput of Boeing vs. Concorde?
  - Boeing 747: 286,700 pmph / 178,200 pmph = 1.6 times faster
- Boeing is 1.6 times ("60%") faster in terms of throughput
- Concord is 2.2 times ("120%") faster in terms of flying time (response time)

We will focus primarily on execution time for a single job

Confusing Wording on Performance

- Will (try to) stick to “n times faster”; its less confusing than “m % faster”
- As faster means both increased performance and decreased execution time, to reduce confusion we will (and you should) use “improve performance” or “improve execution time”

What is Time?

- Straightforward definition of time:
  - Total time to complete a task, including disk accesses, memory accesses, I/O activities, operating system overhead, ...
  - "real time", "response time" or "elapsed time"
- Alternative: just time processor (CPU) is working only on your program (since multiple processes running at same time)
  - "CPU execution time" or "CPU time"
  - Often divided into system CPU time (in OS) and user CPU time (in user program)

How to Measure Time?

- User Time ⇒ seconds
- CPU Time: Computers constructed using a clock that runs at a constant rate and determines when events take place in the hardware
    - These discrete time intervals called clock cycles (or informally clocks or cycles)
    - Length of clock period: clock cycle time (e.g., 2 nanoseconds or 2 ns) and clock rate (e.g., 500 megahertz, or 500 MHz), which is the inverse of the clock period; use these!

Measuring Time using Clock Cycles (1/2)

- CPU execution time for a program

$$= \text{Clock Cycles for a program} \\ \text{x Clock Cycle Time}$$

- or

$$= \frac{\text{Clock Cycles for a program}}{\text{Clock Rate}}$$

Measuring Time using Clock Cycles (2/2)

- One way to define clock cycles:

Clock Cycles for program

= Instructions for a program
(called "Instruction Count")

x Average Clock cycles Per Instruction
(abbreviated "CPI")

- CPI one way to compare two machines with same instruction set, since Instruction Count would be the same

Performance Calculation (1/2)

- CPU execution time for program
  = Clock Cycles for program
  x Clock Cycle Time
- Substituting for clock cycles:

CPU execution time for program
= (Instruction Count x CPI)
x Clock Cycle Time

= Instruction Count x CPI x Clock Cycle Time

Performance Calculation (2/2)

$$\text{CPU time} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Cycle}}$$

$$\text{CPU time} = \frac{\cancel{\text{Instructions}}}{\text{Program}} \times \frac{\text{Cycles}}{\cancel{\text{Instruction}}} \times \frac{\text{Seconds}}{\text{Cycle}}$$

$$\text{CPU time} = \frac{\cancel{\text{Instructions}}}{\text{Program}} \times \frac{\cancel{\text{Cycles}}}{\cancel{\text{Instruction}}} \times \frac{\text{Seconds}}{\cancel{\text{Cycle}}}$$

$$\text{CPU time} = \frac{\text{Seconds}}{\text{Program}}$$

- Product of all 3 terms: if missing a term, can’t predict time, the real measure of performance

How Calculate the 3 Components?

- **Clock Cycle Time**: in specification of computer (Clock Rate in advertisements)
- **Instruction Count**:
  - Count instructions in loop of small program
  - Use simulator to count instructions
  - Hardware counter in spec. register
    - (Pentium II,III,4)
- **CPI**:
  - Calculate: $\dfrac{\text{Execution Time / Clock cycle time}}{\text{Instruction Count}}$
  - Hardware counter in special register (PII,III,4)

Calculating CPI Another Way

- First calculate CPI for each individual instruction (`add`, `sub`, `and`, etc.)
- Next calculate frequency of each individual instruction
- Finally multiply these two for each instruction and add them up to get final CPI (the weighted sum)

Example (RISC processor)

Op	Freq$_i$	CPI$_i$	Prod	(% Time)
ALU	50%	1	.5	(23%)
Load	20%	5	1.0	(45%)
Store	10%	3	.3	(14%)
Branch	20%	2	.4	(18%)
			2.2	

Instruction Mix

(Where time spent)

- **What if Branch instructions twice as fast?**

"And in conclusion…"

- RAID
  - Motivation: In the 1980s, there were 2 classes of drives: expensive, big for enterprises and small for PCs. They thought "make one big out of many small!"
  - Higher performance with more disk arms/$, adds option for small # of extra disks (the R)
  - Started @ Cal by CS Profs Katz & Patterson
- Latency v. Throughput
- Performance doesn't depend on any single factor: need Instruction Count, Clocks Per Instruction (CPI) and Clock Rate to get valid estimations
- User Time: time user waits for program to execute: depends heavily on how OS switches between tasks
- CPU Time: time spent executing a single program: depends solely on processor design (datapath, pipelining effectiveness, caches, etc.)

$$\text{CPU time} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Cycle}}$$