

CS 61C: Great Ideas in Computer Architecture (Machine Structures)

Dependability and RAID

Instructor:

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<http://inst.eecs.Berkeley.edu/~cs61c/fa13>

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Great Ideas in Computer Architecture

1. Layers of Representation/Interpretation
2. Moore's Law
3. Principle of Locality/Memory Hierarchy
4. Parallelism
5. Performance Measurement & Improvement
- 6. Dependability via Redundancy**

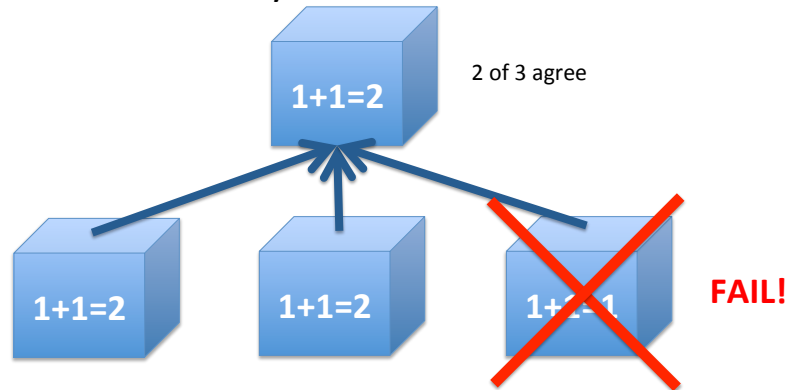
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Great Idea #6: Dependability via Redundancy

- Redundancy so that a failing piece doesn't make the whole system fail



Increasing transistor density reduces the cost of redundancy

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Great Idea #6: Dependability via Redundancy

- Applies to everything from datacenters to memory
 - Redundant datacenters so that can lose 1 datacenter but Internet service stays online
 - Redundant routes so can lose nodes but Internet doesn't fail
 - Redundant disks so that can lose 1 disk but not lose data (Redundant Arrays of Independent Disks/RAID)
 - Redundant memory bits of so that can lose 1 bit but no data (Error Correcting Code/ECC Memory)



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Agenda

- Dependability, Reliability, Availability metrics
- Codes for Redundancy
- Administrivia
- Error Detection and Correction in Memory
- RAID

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Agenda

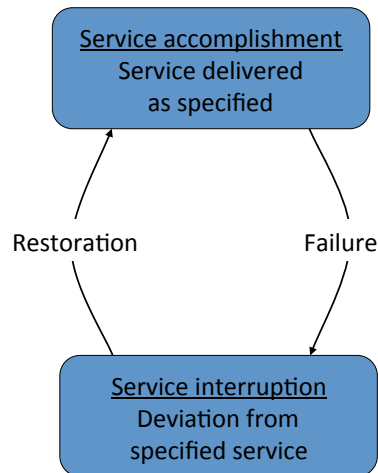
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Dependability



- **Fault:** failure of a component
 - May or may not lead to system failure

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Dependability via Redundancy: Time vs. Space

- ***Spatial Redundancy*** – replicated data or check information or hardware to handle hard and soft (transient) failures
- ***Temporal Redundancy*** – redundancy in time (retry) to handle soft (transient) failures

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Dependability Measures

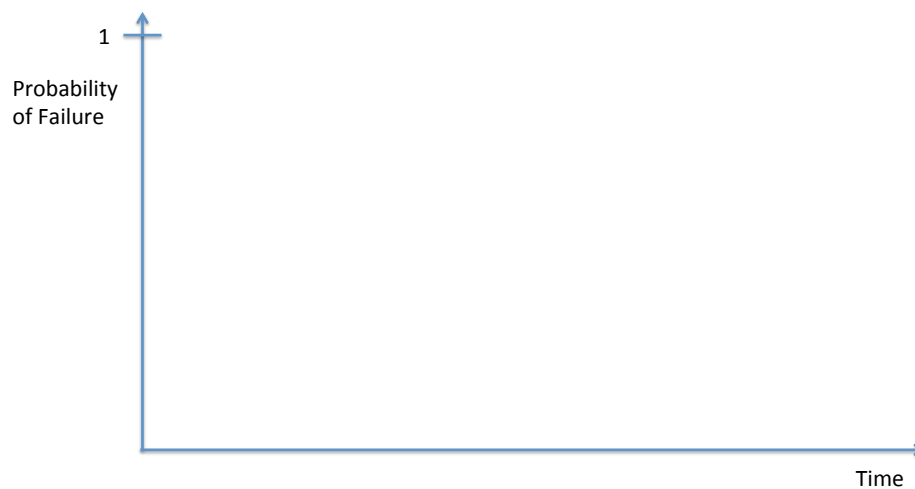
- Reliability: Mean Time To Failure (**MTTF**)
- Service interruption: Mean Time To Repair (**MTTR**)
- Mean time between failures (**MTBF**)
 - $MTBF = MTTF + MTTR$
- Availability = $MTTF / (MTTF + MTTR)$
- Improving Availability
 - Increase MTTF: More reliable hardware/software + Fault Tolerance
 - Reduce MTTR: improved tools and processes for diagnosis and repair

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Understanding MTTF

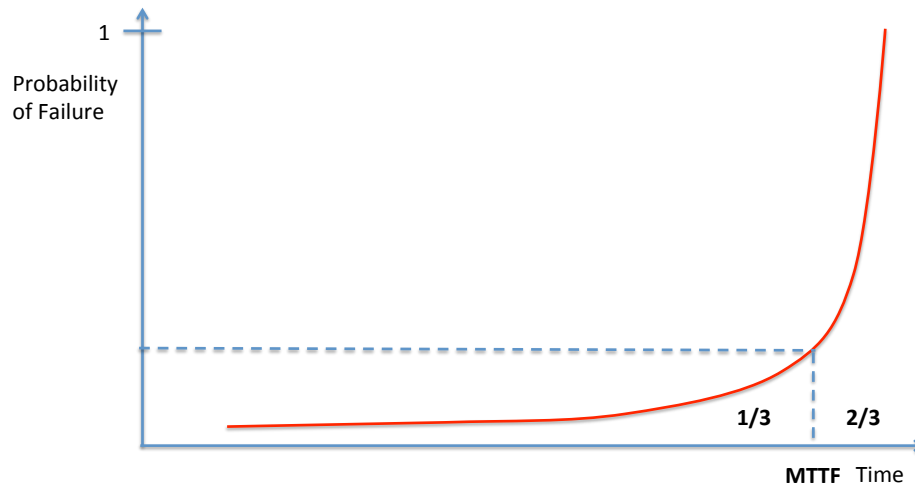


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Understanding MTTF



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Availability Measures

- Availability = $\text{MTTF} / (\text{MTTF} + \text{MTTR})$ as %
 - MTTF, MTBF usually measured in hours
- Since hope rarely down, shorthand is “number of 9s of availability per year”
- 1 nine: 90% => 36 days of repair/year
- 2 nines: 99% => 3.6 days of repair/year
- 3 nines: 99.9% => 526 minutes of repair/year
- 4 nines: 99.99% => 53 minutes of repair/year
- 5 nines: 99.999% => 5 minutes of repair/year

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Reliability Measures

- Another is average number of failures per year: **Annualized Failure Rate (AFR)**
 - E.g., 1000 disks with 100,000 hour MTTF
 - 365 days * 24 hours = 8760 hours
 - $(1000 \text{ disks} * 8760 \text{ hrs/year}) / 100,000 = 87.6$ failed disks per year on average
 - $87.6/1000 = 8.76\%$ annual failure rate
- Google's 2007 study* found that actual AFRs for individual drives ranged from 1.7% for first year drives to over 8.6% for three-year old drives

**research.google.com/archive/disk_failures.pdf*

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Dependability Design Principle

- Design Principle: No single points of failure
 - “Chain is only as strong as its weakest link”
- Dependability Corollary of Amdahl’s Law
 - Doesn’t matter how dependable you make one portion of system
 - Dependability limited by part you do not improve

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Error Detection/Correction Codes

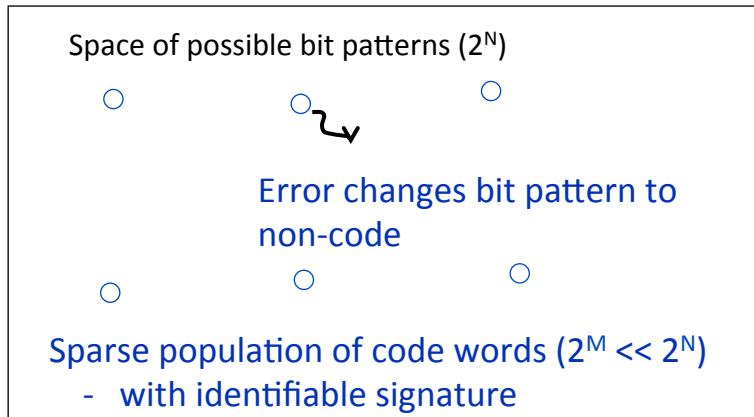
- Memory systems generate errors (accidentally flipped-bits)
 - DRAMs store very little charge per bit
 - “Soft” errors occur occasionally when cells are struck by alpha particles or other environmental upsets
 - “Hard” errors can occur when chips permanently fail.
 - Problem gets worse as memories get denser and larger
- Memories protected against failures with EDC/ECC
- Extra bits are added to each data-word
 - Used to detect and/or correct faults in the memory system
 - Each data word value mapped to unique *code word*
 - A fault changes valid code word to invalid one, which can be detected

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Detecting/Correcting Code Concept



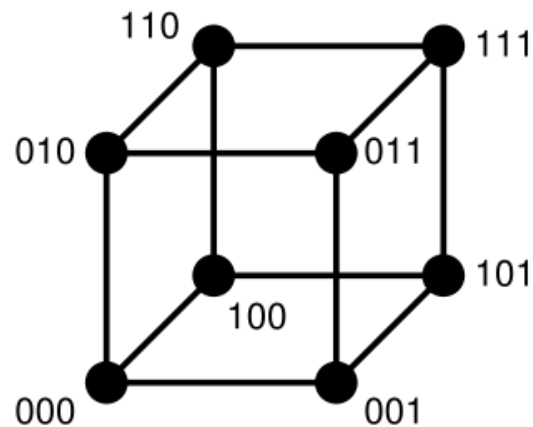
- **Detection:** bit pattern fails codeword check
- **Correction:** map to nearest valid code word

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Hamming Distance: 8 code words



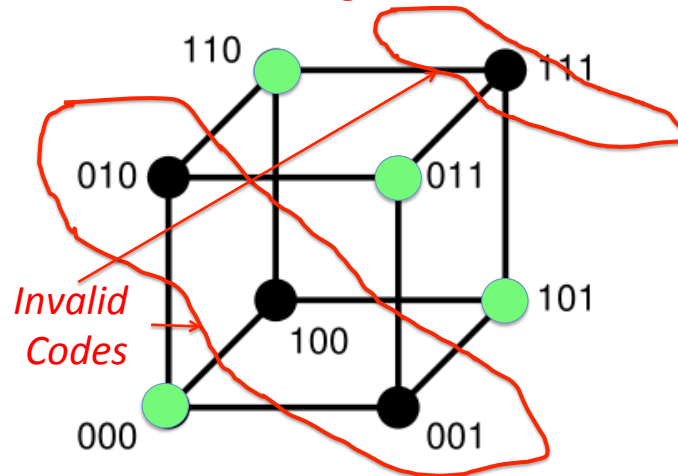
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Hamming Distance 2: Detection

Detect Single Bit Errors



- No 1 bit error goes to another valid code
- $\frac{1}{2}$ codes are valid

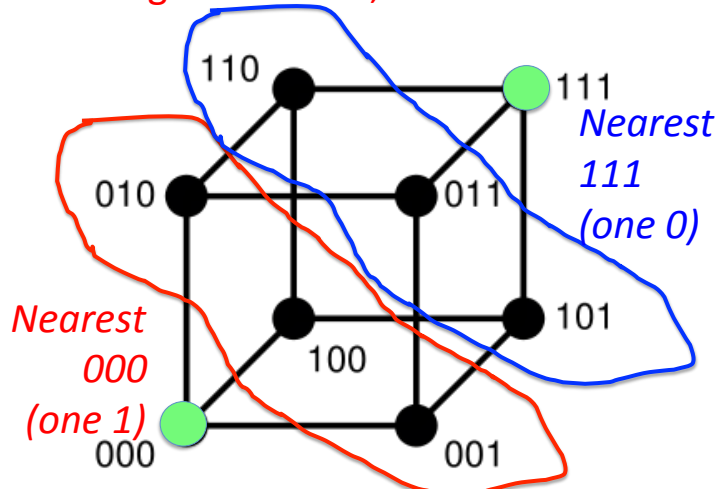
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Hamming Distance 3: Correction

Correct Single Bit Errors, Detect Double Bit Errors



- No 2 bit error goes to another valid code; 1 bit error near
- $\frac{1}{8}$ codes are valid

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Agenda

- Dependability, Reliability, Availability metrics
- Codes for Redundancy
- **Administrivia**
- Error Detection and Correction in Memory
- RAID

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Administrivia

- **Final Exam**
 - Friday, December 20, 8:00-11:00 TBD
 - Short answer, fill in the blank, multiple choice, mix and match: 100 points/minutes
 - Room 220/230/242 Hearst Gym (assigned by course account login)
 - Comprehensive, but concentrated on material since midterm examination
 - Closed book/note, open crib sheet as before, MIPS Green Card provided
 - *Special consideration students, please contact*

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Agenda

- Dependability, Reliability, Availability metrics
- Codes for Redundancy
- Administrivia
- Error Detection and Correction in Memory
- RAID

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Block Code Principles

- Hamming distance = difference in # of bits
- $p = 0\underline{1}1\underline{0}11$, $q = 0\underline{0}1\underline{1}11$, Ham. distance $(p,q) = 2$
- $p = 011011$,
 $q = 110001$, [Student Roulette](#)
distance $(p,q) = ?$
- Can think of extra bits as creating a code with the data
- What if minimum distance between members of code is 2 and get a 1 bit error?



Richard Hamming, 1915-98
Turing Award Winner²⁴

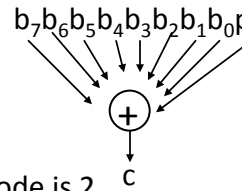
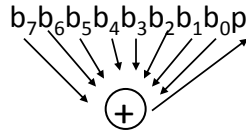
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Parity: Simple Error Detection Coding

- Each data value, before it is written to memory is “tagged” with an extra bit to force the stored word to have *even* parity:
- Each word, as it is read from memory is “checked” by finding its parity (including the parity bit).

parity:



- Minimum Hamming distance of parity code is 2
- A non-zero parity indicates an error occurred:
 - 2 errors (on different bits) are not detected
 - nor any even number of errors, just odd numbers of errors are detected

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Parity Example

- Data 0101 0101
- 4 ones, even parity now
- Write to memory: 0101 0101 0
to keep parity even
- Data 0101 0111
- 5 ones, odd parity now
- Write to memory: 0101 0111 1
to make parity even
- Read from memory 0101 0101 0
- 4 ones => even parity, so no error
- Read from memory 1101 0101 0
- 5 ones => odd parity, so error
- What if error in parity bit?

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Suppose Want to Correct 1 Error?

- Richard Hamming came up with simple to understand mapping to allow Error Correction at minimum distance of 3
 - Single error correction, double error detection
- Called “Hamming ECC”
 - Worked weekends on relay computer with unreliable card reader, frustrated with manual restarting
 - Got interested in error correction; published 1950
 - R. W. Hamming, “Error Detecting and Correcting Codes,” *The Bell System Technical Journal*, Vol. XXVI, No 2 (April 1950) pp 147-160.

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Hamming Error Correction Code

- Use of **extra parity bits** to allow the position identification of a single error
1. Mark all bit positions that are **powers of 2** as parity bits (positions 1, 2, 4, 8, 16, ...)
 - Start numbering bits at 1 at left (not at 0 on right)
 2. All **other bit positions** are data bits (positions 3, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, ...)
 3. Each data bit is covered by 2 or more parity bits

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Hamming ECC

4. The **position of parity** bit determines sequence of data bits that it checks
- **Bit 1 (0001_2):** checks bits (1,3,5,7,9,11,...)
 - Bits with least significant bit of address = 1
 - **Bit 2 (0010_2):** checks bits (2,3,6,7,10,11,14,15,...)
 - Bits with 2nd least significant bit of address = 1
 - **Bit 4 (0100_2):** checks bits (4-7, 12-15, 20-23, ...)
 - Bits with 3rd least significant bit of address = 1
 - **Bit 8 (1000_2):** checks bits (8-15, 24-31, 40-47, ...)
 - Bits with 4th least significant bit of address = 1

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Graphic of Hamming Code

Bit position	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Encoded data bits	p1	p2	d1	p4	d2	d3	d4	p8	d5	d6	d7	d8	d9	d10	d11
Parity bit coverage	p1	X		X		X		X		X		X		X	
	p2		X	X			X	X			X	X			X
	p4				X	X	X	X					X	X	X
	p8								X	X	X	X	X	X	X

- http://en.wikipedia.org/wiki/Hamming_code

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Hamming ECC

5. Set parity bits to create **even parity** for each group

- A byte of data: 10011010
- Create the coded word, leaving spaces for the parity bits:
- $_ _ 1 _ 0 0 1 _ 1 0 1 0$
 $0 0 0 0 0 0 0 0 0 1 1 1$
 $1 2 3 4 5 6 7 8 9 0 1 2$
- Calculate the parity bits

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Hamming ECC

- Position 1 checks bits 1,3,5,7,9,11 (bold):
 $? _ \mathbf{1} _ 0 0 \mathbf{1} _ \mathbf{1} 0 \mathbf{1} 0$. set position 1 to a $_$:
 $_ _ \mathbf{1} _ 0 0 \mathbf{1} _ \mathbf{1} 0 \mathbf{1} 0$
- Position 2 checks bits 2,3,6,7,10,11 (bold):
 $0 ? \mathbf{1} _ 0 0 \mathbf{1} _ 1 0 \mathbf{1} 0$. set position 2 to a $_$:
 $0 _ \mathbf{1} _ 0 0 \mathbf{1} _ 1 0 \mathbf{1} 0$
- Position 4 checks bits 4,5,6,7,12 (bold):
 $0 1 1 ? 0 0 \mathbf{1} _ 1 0 1 \mathbf{0}$. set position 4 to a $_$:
 $0 1 1 _ 0 0 \mathbf{1} _ 1 0 1 \mathbf{0}$
- Position 8 checks bits 8,9,10,11,12:
 $0 1 1 1 0 0 1 ? \mathbf{1} 0 \mathbf{1} 0$. set position 8 to a $_$:
 $0 1 1 1 0 0 1 _ \mathbf{1} 0 \mathbf{1} 0$

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Hamming ECC

- Position 1 checks bits 1,3,5,7,9,11:
 ? 1 0 0 1 1 0 1 0. set position 1 to a **0**:
0 1 0 0 1 1 0 1 0
- Position 2 checks bits 2,3,6,7,10,11:
 0 ? 1 0 0 1 1 0 1 0. set position 2 to a **1**:
 0 **1** 1 0 0 1 1 0 1 0
- Position 4 checks bits 4,5,6,7,12:
 0 1 1 ? 0 0 1 1 0 1 0. set position 4 to a **1**:
 0 1 1 **1** 0 0 1 1 0 1 0
- Position 8 checks bits 8,9,10,11,12:
 0 1 1 1 0 0 1 ? 1 0 1 0. set position 8 to a **0**:
 0 1 1 1 0 0 1 **0** 1 0 1 0

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Hamming ECC

- **Final** code word: 011100101010
- Data word: 1 001 1010

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Hamming ECC Error Check

- Suppose receive
0111001011110

0 1 1 1 0 0 1 0 1 1 1 0

Bit position	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Encoded data bits	p1	p2	d1	p4	d2	d3	d4	p8	d5	d6	d7	d8	d9	d10	d11
Parity bit coverage	p1	X		X		X		X		X		X		X	
	p2		X	X			X	X			X	X			X
	p4				X	X	X	X					X	X	X
	p8								X	X	X	X	X	X	X

Hamming ECC Error Check

- Suppose receive
0111001011110

Hamming ECC Error Check

- Suppose receive

011100101110

0 1 0 1 1 1 √

11 01 11 X-Parity 2 in error

1001 0 √

01110 X-Parity 8 in error

- *Implies position $8+2=10$ is in error*

011100101110

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Hamming ECC Error Correct

- Flip the incorrect bit ...

011100101010

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Hamming ECC Error Correct

- Suppose receive

```

011100101010
0 1 0 1 1 1  ✓
  11  01  01  ✓
    1001    0  ✓
      01010 ✓
  
```

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Hamming ECC

- **Finding and fixing a corrupted bit:**
- Suppose receive 011100101110
123456789012
- Parity 1_, Parity 2_, Parity 4_, Parity 8_
(Bits numbers $xxx1_{two}$, $xx1x_{two}$, $x1xx_{two}$, $1xxx_{two}$)
- Parity bits 2 and 8 incorrect. As $2 + 8 = 10$, bit position 10 is location of bad bit: flip value!
- Corrected value: 011100101010
- Why does Hamming ECC work?

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Hamming Error Correcting Code

- Overhead involved in single error correction code
- Let p be total number of parity bits and d number of data bits in $p + d$ bit word
- If p error correction bits are to point to error bit ($p + d$ cases) + indicate that no error exists (1 case), we need:

$$2^p \geq p + d + 1,$$

$$\text{thus } p \geq \log(p + d + 1)$$

for large d , p approaches $\log(d)$

- 8 bits data $\Rightarrow d = 8$, $2^p = p + 8 + 1 \Rightarrow p = 4$
- 16 data $\Rightarrow 5$ parity,
- 32 data $\Rightarrow 6$ parity,
- 64 data $\Rightarrow 7$ parity

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Hamming Single Error Correction, Double Error Detection (SEC/DED)

- Adding extra parity bit covering the entire word provides double error **detection** as well as single error correction

1 2 3 4 5 6 7 8

p_1 p_2 d_1 p_3 d_2 d_3 d_4 p_4

- Hamming parity bits H (p_1 p_2 p_3) are computed (even parity as usual) plus the even parity over the entire word, p_4 :

$H=0$ $p_4=0$, no error

$H \neq 0$ $p_4=1$, correctable single error (odd parity if 1 error $\Rightarrow p_4=1$)

$H \neq 0$ $p_4=0$, double error occurred (even parity if 2 errors $\Rightarrow p_4=0$)

$H=0$ $p_4=1$, single error occurred in p_4 bit, not in rest of word

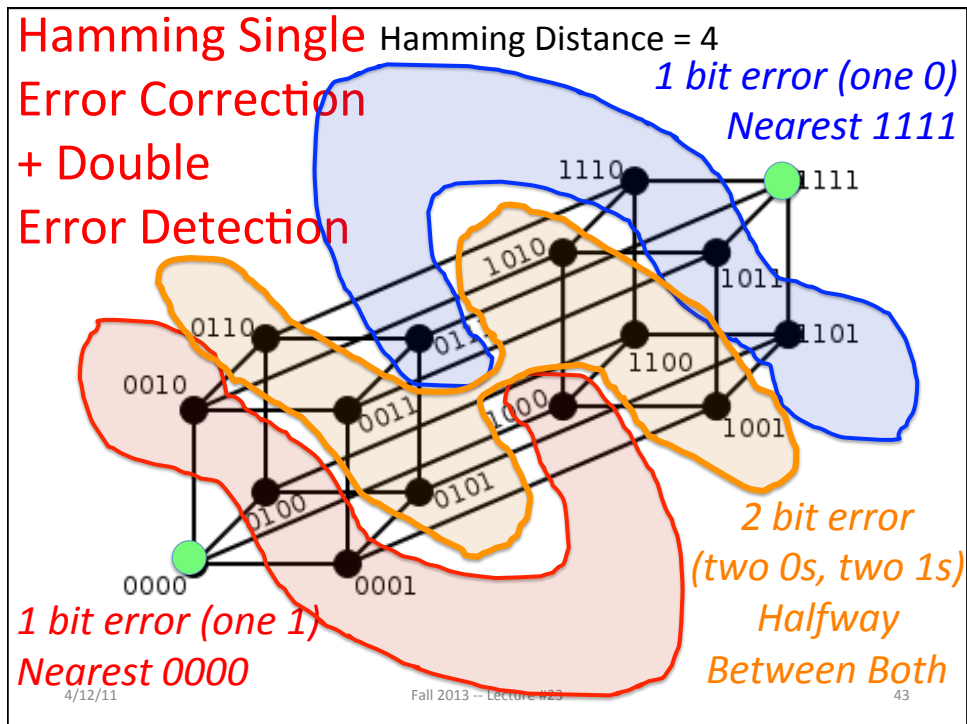
Typical modern codes in DRAM memory systems:

64-bit data blocks (8 bytes) with 72-bit code words (9 bytes).

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What if More Than 2 Bit Errors?

- Network transmissions, disks, distributed storage common failure mode is bursts of bit errors, not just one or two bit errors
 - contiguous *sequence of B* bits in which first, last and any number of intermediate bits are in error
 - caused by impulse noise or by fading in wireless
 - effect is greater at higher data rates

Cyclic Redundancy Check

- For block of k bits, transmitter generates an $n-k$ bit frame check sequence
- Transmits n bits exactly divisible by some number
- Receiver divides frame by that number
 - If no remainder, assume no error
 - Easy to calculate division for some binary numbers with shift register
- Disks detect *and correct* blocks of 512 bytes with called Reed Solomon codes \approx CRC

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(In More Depth: Code Types)

- Linear Codes: $\bar{C} = \bar{G} \cdot \bar{d}$ $\bar{S} = \bar{H} \cdot \bar{C}$
Code is *generated* by G and in *null-space* of H
- Hamming Codes: Design the H matrix
 - $d = 3 \Rightarrow$ Columns nonzero, Distinct
 - $d = 4 \Rightarrow$ Columns nonzero, Distinct, Odd-weight
- Reed-solomon codes:
 - Based on polynomials in $GF(2^k)$ (i.e. k -bit symbols)
 - Data as coefficients, code space as values of polynomial:
 - $P(x) = a_0 + a_1x^1 + \dots + a_{k-1}x^{k-1}$
 - Coded: $P(0), P(1), P(2), \dots, P(n-1)$
 - Can recover polynomial as long as get *any* k of n
 - Alternatively: as long as no more than $n-k$ coded symbols erased, can recover data.
- Side note: Multiplication by constant in $GF(2^k)$ can be represented by $k \times k$ matrix: $a \cdot x$
 - Decompose unknown vector into k bits: $x = x_0 + 2x_1 + \dots + 2^{k-1}x_{k-1}$
 - Each column is result of multiplying a by 2^i

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Hamming ECC on your own

- Test if these Hamming-code words are correct. If one is incorrect, indicate the correct **code word**. Also, indicate what the original **data** was.
- 110101100011 [Student Roulette](#)
- 111110001100
- 000010001010

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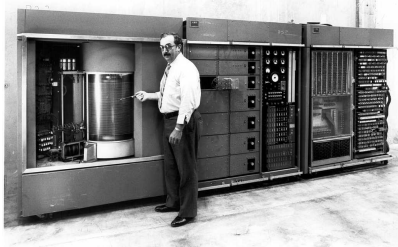
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Evolution of the Disk Drive



IBM 3390K, 1986



11/14/13 IBM RAMAC 305, 1956



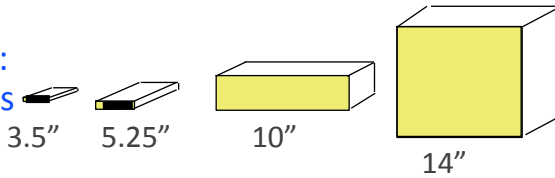
Apple SCSI, 1986 49

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Arrays of Small Disks

Can smaller disks be used to close gap in performance between disks and CPUs?

Conventional:
4 disk designs



Low End → High End

Disk Array:
1 disk design



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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 have potential for large data and I/O rates, high MB per cu. ft., high MB per KW, but what about reliability?

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RAID: Redundant Arrays of (Inexpensive) Disks

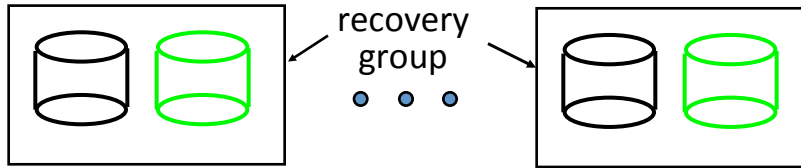
- Files are "striped" across multiple disks
- Redundancy yields high data availability
 - Availability: service still provided to user, even if some components failed
- Disks will still fail
- Contents reconstructed from data redundantly stored in the array
 - ⇒ Capacity penalty to store redundant info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

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Redundant Arrays of Inexpensive Disks RAID 1: Disk Mirroring/Shadowing



- Each disk is fully duplicated onto its “mirror”
Very high availability can be achieved
- Bandwidth sacrifice on write:
Logical write = two physical writes
Reads may be optimized
- Most expensive solution: 100% capacity overhead

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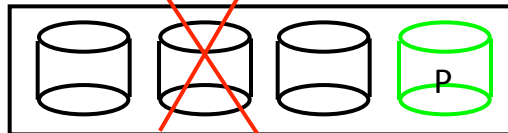
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Redundant Array of Inexpensive Disks RAID 3: Parity Disk

```

10010011
11001101
10010011
...
    
```



logical record
Striped physical records

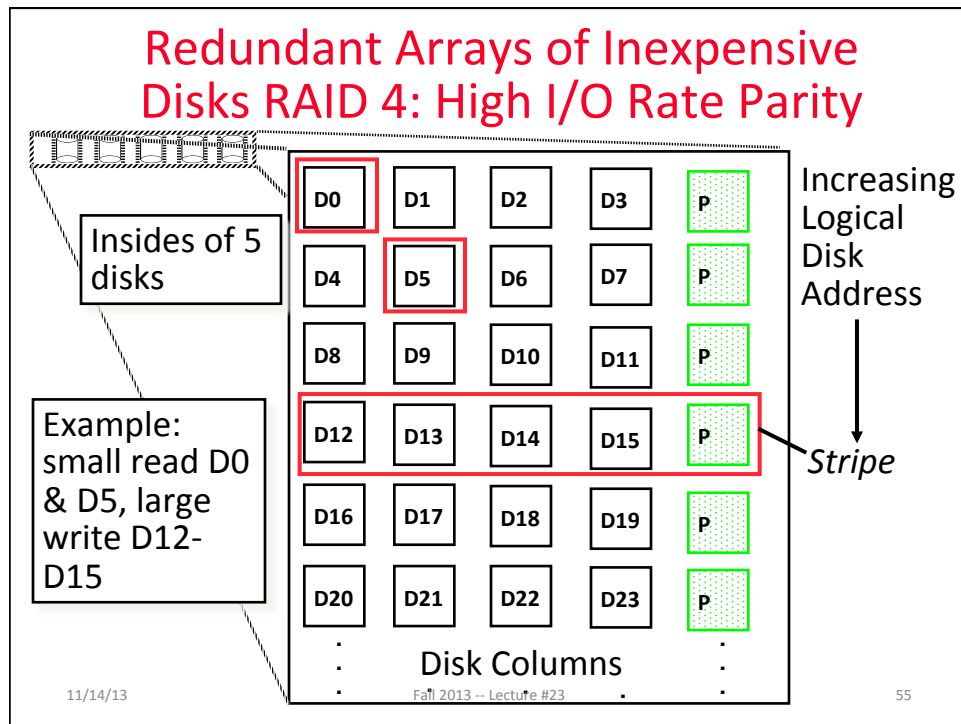
1	1	1	1
0	1	0	1
1	0	1	0
0	0	0	0
0	1	0	1
0	1	0	1
1	0	1	0
1	1	1	1

P contains sum of other disks per stripe mod 2 (“parity”)
If disk fails, subtract P from sum of other disks to find missing information

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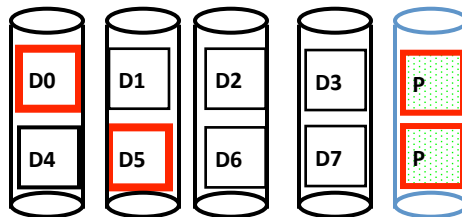
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Inspiration for RAID 5

- RAID 4 works well for small reads
- Small writes (write to one disk):
 - Option 1: read other data disks, create new sum and write to Parity Disk
 - Option 2: since P has old sum, compare old data to new data, add the difference to P
- Small writes are limited by Parity Disk: Write to D0, D5 both also write to P disk



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RAID 5: High I/O Rate Interleaved Parity

Independent writes possible because of interleaved parity

Example: write to D0, D5 uses disks 0, 1, 3, 4



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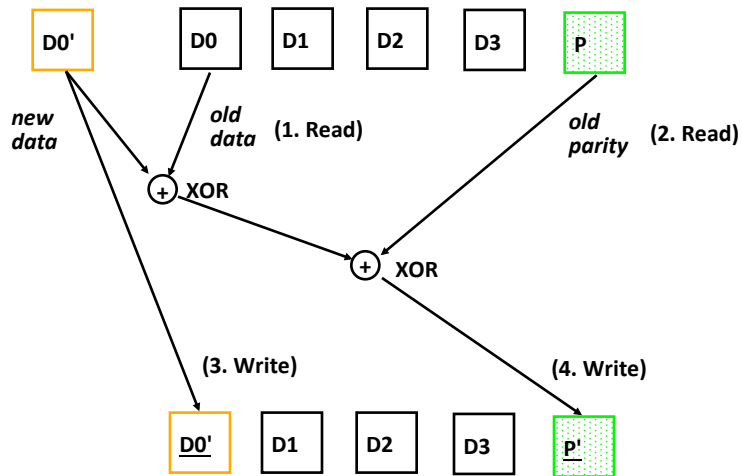
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Problems of Disk Arrays: Small Writes

RAID-5: Small Write Algorithm

1 Logical Write = 2 Physical Reads + 2 Physical Writes



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Tech Report Read 'Round the World (December 1987)

A Case for Redundant Arrays of Inexpensive Disks (RAID)

David A. Paterson, Garth Gibson, and Randy H. Katz

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Case for Raid



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Articles

[\[book\] A case for redundant arrays of inexpensive disks \(RAID\)](#)

DA Patterson, G Gibson, RH Katz - 1988 - dl.acm.org

Legal documents

Abstract Increasing performance of CPUs and memories will be squandered if not matched by a similar performance increase in I/O. While the capacity of Single Large Expensive Disks (SLED) has grown rapidly, the performance improvement of SLED has been modest. ...

Any time

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Expensive Disk (SLED) has grown rapidly, the performance improvement of SLED has been modest. Redundant Arrays of Inexpensive Disks (RAID), based on the magnetic disk technology developed for personal computers, offers an attractive alternative to SLED, promising improvements of an order of magnitude in performance, reliability, power consumption, and scalability.

This paper introduces five levels of RAID's, giving their relative cost/performance, and compares RAID's to an IBM 3380 and a Fujitsu Super Eagle.

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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



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RAID II

- 1990-1993
- Early Network Attached Storage (NAS) System running a Log Structured File System (LFS)
- Impact:
 - \$25 Billion/year in 2002
 - Over \$150 Billion in RAID device sold since 1990-2002
 - 200+ RAID companies (at the peak)
 - Software RAID a standard component of modern OSs

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RAID II



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And, in Conclusion, ...

- Great Idea: Redundancy to Get Dependability
 - Spatial (extra hardware) and Temporal (retry if error)
- Reliability: MTTF & Annualized Failure Rate (AFR)
- Availability: % uptime (MTTF-MTTR/MTTF)
- Memory
 - Hamming distance 2: Parity for Single Error Detect
 - Hamming distance 3: Single Error Correction Code + encode bit position of error
- Treat disks like memory, except you know when a disk has failed—erasure makes parity an Error Correcting Code
- RAID-2, -3, -4, -5: Interleaved data and parity

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And, in Conclusion, ...

- Logical-to-physical block mapping, parity striping, read-modify-write processing
- Embedded caches and orchestrating data staging between network interfaces, parity hardware, and file server interfaces
- Failed disk replacement, hot spares, background copies and backup
- Embedded log-structured file systems, compression on the fly
- Software complexity dominates hardware!

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