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# CS61C

## Great Ideas in Computer Architecture
(a.k.a. Machine Structures)

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# Dependability

# 6 Great Ideas in Computer Architecture

1. Abstraction (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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# 6 Great Ideas in Computer Architecture

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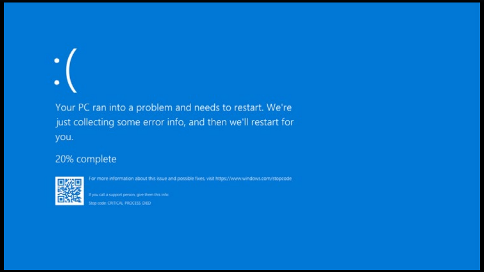
# Computers Fail…

- May fail transiently…




- …or permanently

We will discuss hardware failures and methods to mitigate them



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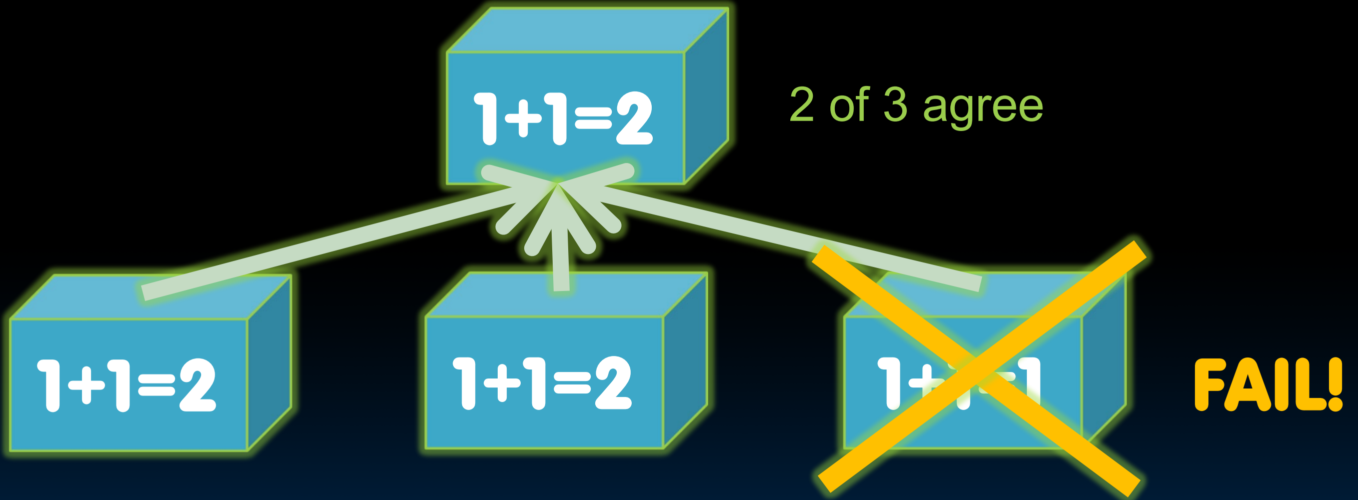
# Great Idea #6: Dependability via Redundancy

- 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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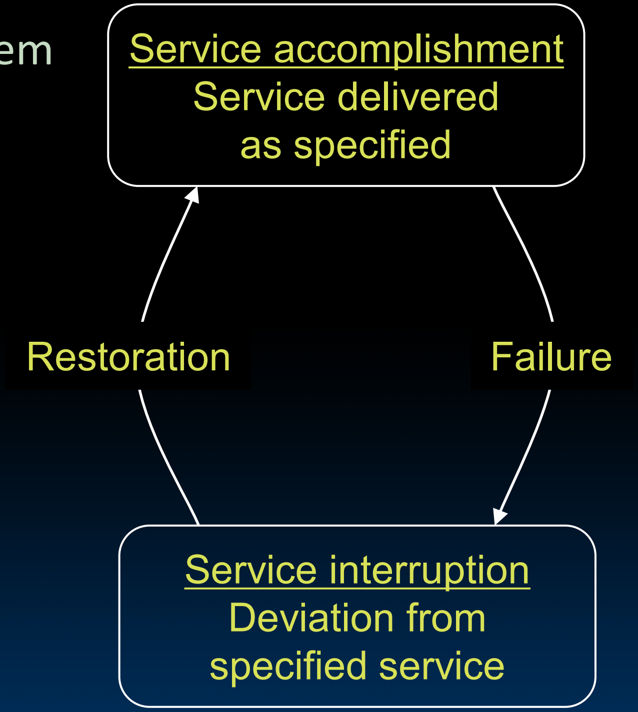
# Great Idea #6: Dependability via Redundancy

- Applies to everything from datacenters to storage to memory to instructors
  - Redundant datacenters so that can lose 1 datacenter but Internet service stays online
  - 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)


# Dependability Metrics

# 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

# 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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# Availability Measures

- Availability = MTTF / (MTTF + 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

# 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 disks * 8760 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*

# Hard Drive Failures

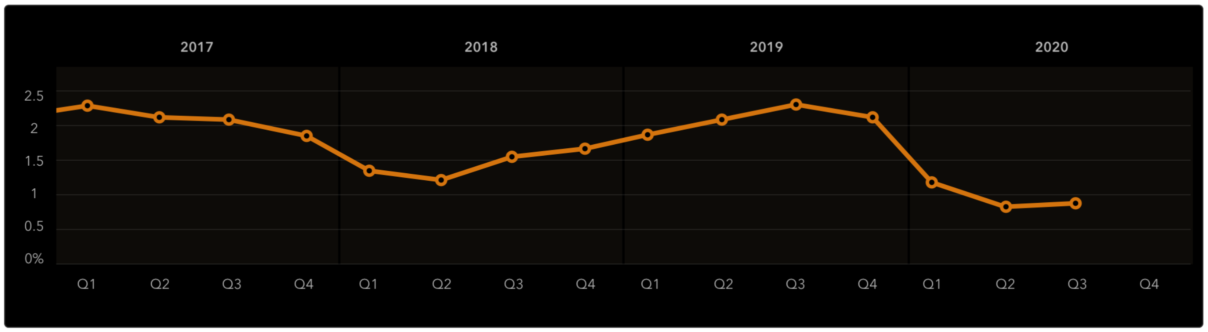
Annualized hard-drive failure rates

**Backblaze Lifetime Annualized Hard Drive Failure Rates**

Reporting period: April 20, 2013 through 30 September 2020 inclusive

| MFG | Model | Drive Size | Avg Age | Drive Count | Drive Days | Drive Failures | AFR |
|---|---|---|---|---|---|---|---|
| HGST | HMS5C4040ALE640 | 4TB | 53.8 | 3,023 | 12,476,131 | 170 | 0.50% |
| HGST | HMS5C4040BLE640 | 4TB | 47.5 | 12,737 | 23,069,669 | 270 | 0.43% |
| HGST | HUH728080ALE600 | 8TB | 33.2 | 1,032 | 1,113,086 | 20 | 0.66% |
| HGST | HUH721212ALE600 | 12TB | 12.1 | 2,600 | 908,168 | 10 | 0.40% |
| Seagate | ST14000NM001G | 14TB | 0.7 | 2,400 | 21,120 | - | 0.00% |
| Seagate | ST16000NM001G | 16TB | 9.9 | 60 | 15,895 | 1 | 2.30% |
| Seagate | ST18000NM000J | 18TB | 0.4 | 60 | 300 | - | 0.00% |
| Toshiba | MD04ABA400V | 4TB | 64.3 | 99 | 261,874 | 5 | 0.70% |
| Toshiba | MG07ACA14TA | 14TB | 5.9 | 17,318 | 2,983,751 | 84 | 1.03% |
| | | | TOTALS | 150,757 | 175,830,635 | 7,628 | 1.58% |

BACKBLAZE



# Failures In Time (FIT) Rate

- The **Failures In Time** (**FIT**) rate of a device is the number of failures that can be expected in one billion ($10^9$) device-hours of operation
  - Or 1000 devices for 1 million hours, 1 million devices for 1000 hours each
- MTBF = 1,000,000,000 x 1/FIT
- Relevant: Automotive safety integrity level (ASIL) defines FT rates for different classes of components in vehicles



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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

# 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 soft errors 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

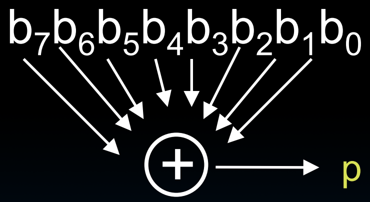
# Block Code Principles

- Hamming distance = difference in # of bits
- p = 011011, q = 001111, Ham. distance (p,q) = 2
- p = 011011,
  q = 110001,
  distance (p,q) = ?
- Can think of extra bits as creating a code with the data
- What if minimum distance between codewords is 2 and get a 1-bit error?

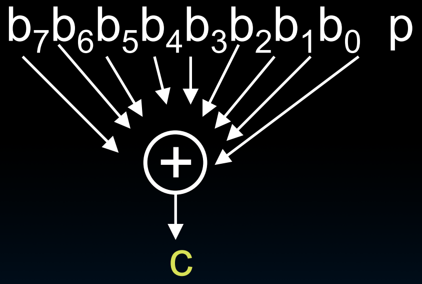
Richard Hamming, 1915-98
Turing Award Winner

# 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).




- Minimum Hamming distance of parity code is 2
- A non-zero parity check 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

# Parity Example

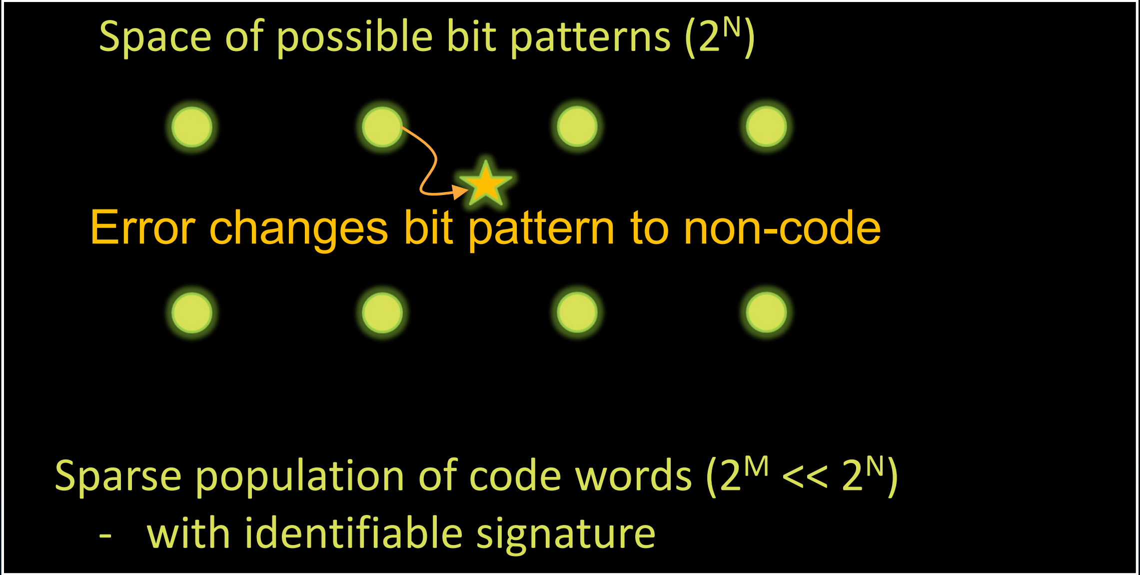
- Data 0101 0101
- 4 ones, even parity now
- Write to memory:
  0101 0101 0
  to keep parity even
- Data 0101 0111
- 5 ones, odd parity now
- Write to memory:
  0101 0111 1
  to make parity even
- Read from memory
  0101 0101 0
- 4 ones => even parity, so no error
- Read from memory
  1101 0101 0
- 5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

# ERROR DETECTION AND CORRECTION

# Suppose Want to Correct One Error?

- Hamming came up with simple to understand mapping to allow Error Correction at minimum distance of three
  - 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.

# Detecting/Correcting Code Concept




- Detection: bit pattern fails codeword check
- Correction: map to nearest valid code word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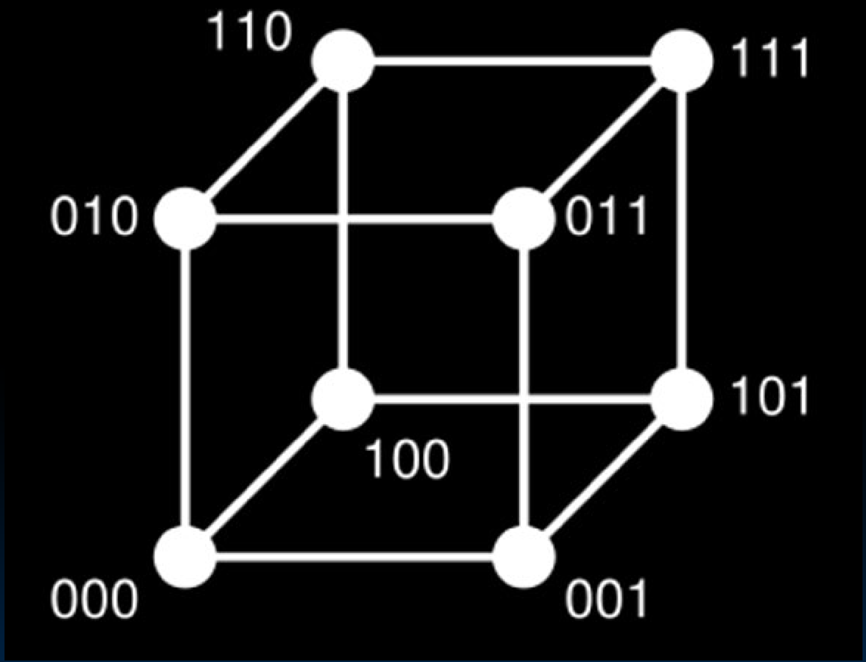
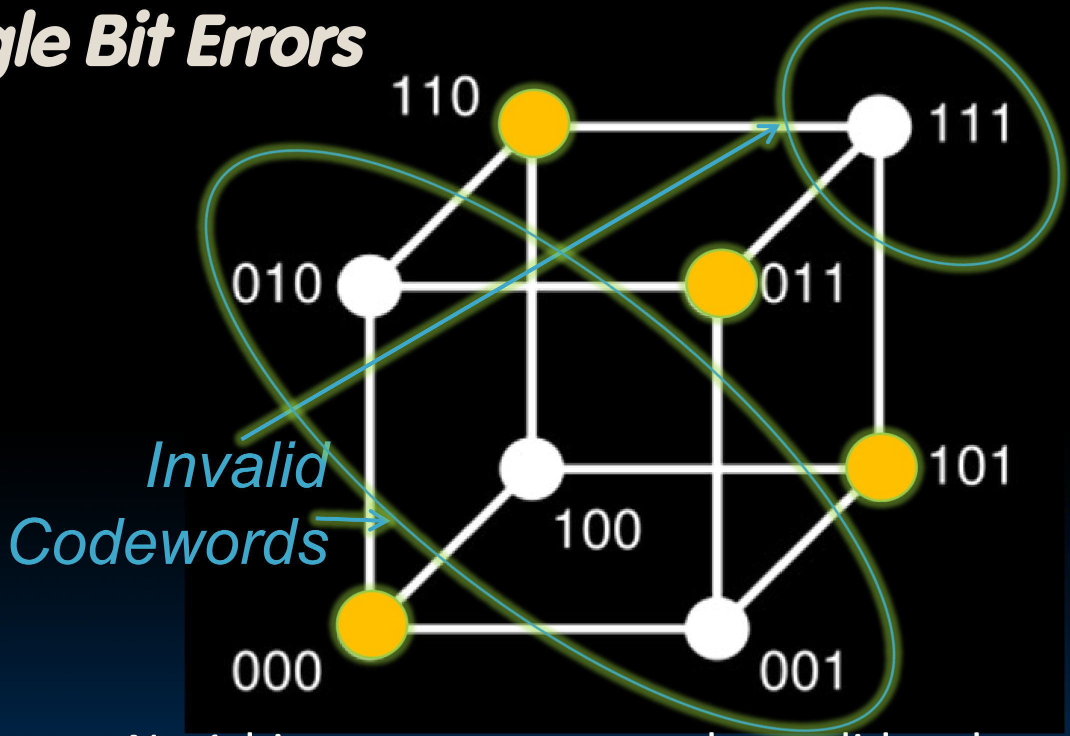
# Hamming Distance: Eight Code Words



# Hamming Distance 2: Detection

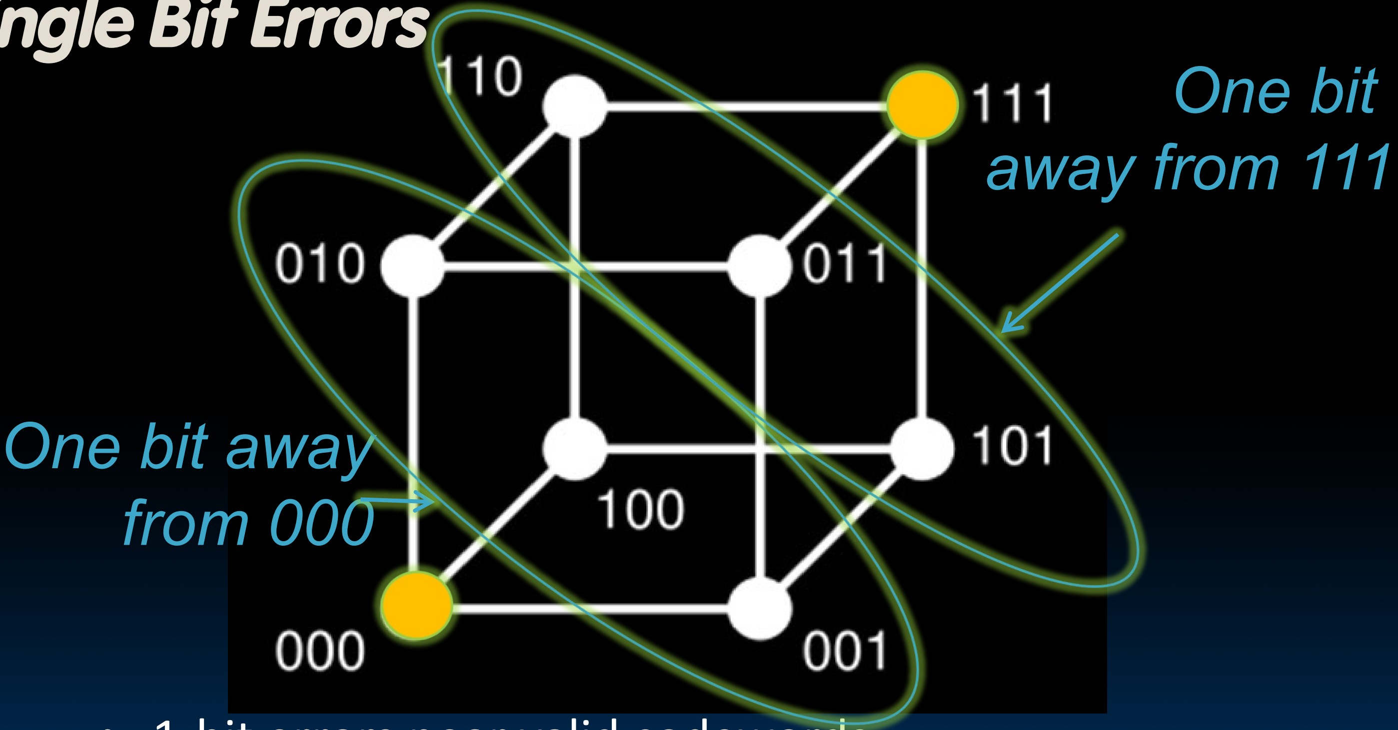
## *Detect Single Bit Errors*




- No 1-bit error goes to another valid codeword
- ½ codewords are valid

# Hamming Distance 2: Detection

## *Correct Single Bit Errors*




- 1-bit errors near valid codewords
- ¼ codewords are valid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# ECC EXAMPLE

# Hamming ECC

- Interleave data and parity bits
- Place parity bits at binary positions 1, 10, 100, etc
  - p1 covers all positions with LSB = 1
  - p2 covers all positions with next to LSB = 1, etc
  - Can continue indefinitely

| Bit position | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Encoded data bits | | p1 | p2 | d1 | p4 | d2 | d3 | d4 | p8 | d5 | d6 | d7 | d8 | d9 | d10 | d11 | p16 | d12 | d13 | d14 | d15 | |
| Parity bit coverage | p1 | | | | | | | | | | | | | | | | | | | | | |
| | p2 | | | | | | | | | | | | | | | | | | | | | ... |
| | p4 | | | | | | | | | | | | | | | | | | | | | |
| | p8 | | | | | | | | | | | | | | | | | | | | | |
| | p16 | | | | | | | | | | | | | | | | | | | | | |


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# Hamming ECC

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

1 2 3 4 5 6 7 8 9 a b c – bit position

- Calculate the parity bits

# 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 _:

- Position 2 checks bits **2,3,6,7,10,11**:
  0 **? 1** _ 0 **0 1** _ 1 **0 1** 0. set position 2 to a _:

- Position 4 checks bits **4,5,6,7,12**:
  0 1 1 **? 0 0 1** _ 1 0 1 **0**. set position 4 to a _:

- 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 _:

# Hamming ECC

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

# Hamming ECC

- Suppose receive
  011100101110

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 | 16 | 17 | 18 | 19 | 20 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Encoded data bits | | p1 | p2 | d1 | p4 | d2 | d3 | d4 | p8 | d5 | d6 | d7 | d8 | d9 | d10 | d11 | p16 | d12 | d13 | d14 | d15 | |
| Parity bit coverage | p1 | | | | | | | | | | | | | | | | | | | | | |
| | p2 | | | | | | | | | | | | | | | | | | | | | ... |
| | p4 | | | | | | | | | | | | | | | | | | | | | |
| | p8 | | | | | | | | | | | | | | | | | | | | | |
| | p16 | | | | | | | | | | | | | | | | | | | | | |


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# Hamming ECC Error Check

- Suppose receive
  011100101110

# 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

# Hamming ECC Error Correct

- Flip the incorrect bit …
  0111001010**0**10

# Hamming ECC Error Correct

- Suppose receive

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

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# What if More Than 2-Bit Errors?

- Use double-error correction, triple-error detection (DECTED)
- 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
- Solve with Cyclic Redundancy Check (CRC), interleaving or other more advanced codes


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# REDUNDANCY WITH RAID

# RAID: Redundant Arrays of (Inexpensive) Disks

- Data is stored across multiple 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
- Writes limited by single-disk speed
- Reads may be optimized

Most expensive solution: 100% capacity overhead


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# RAID 3: Parity Disk

10010011
11001101
10010011
. . .

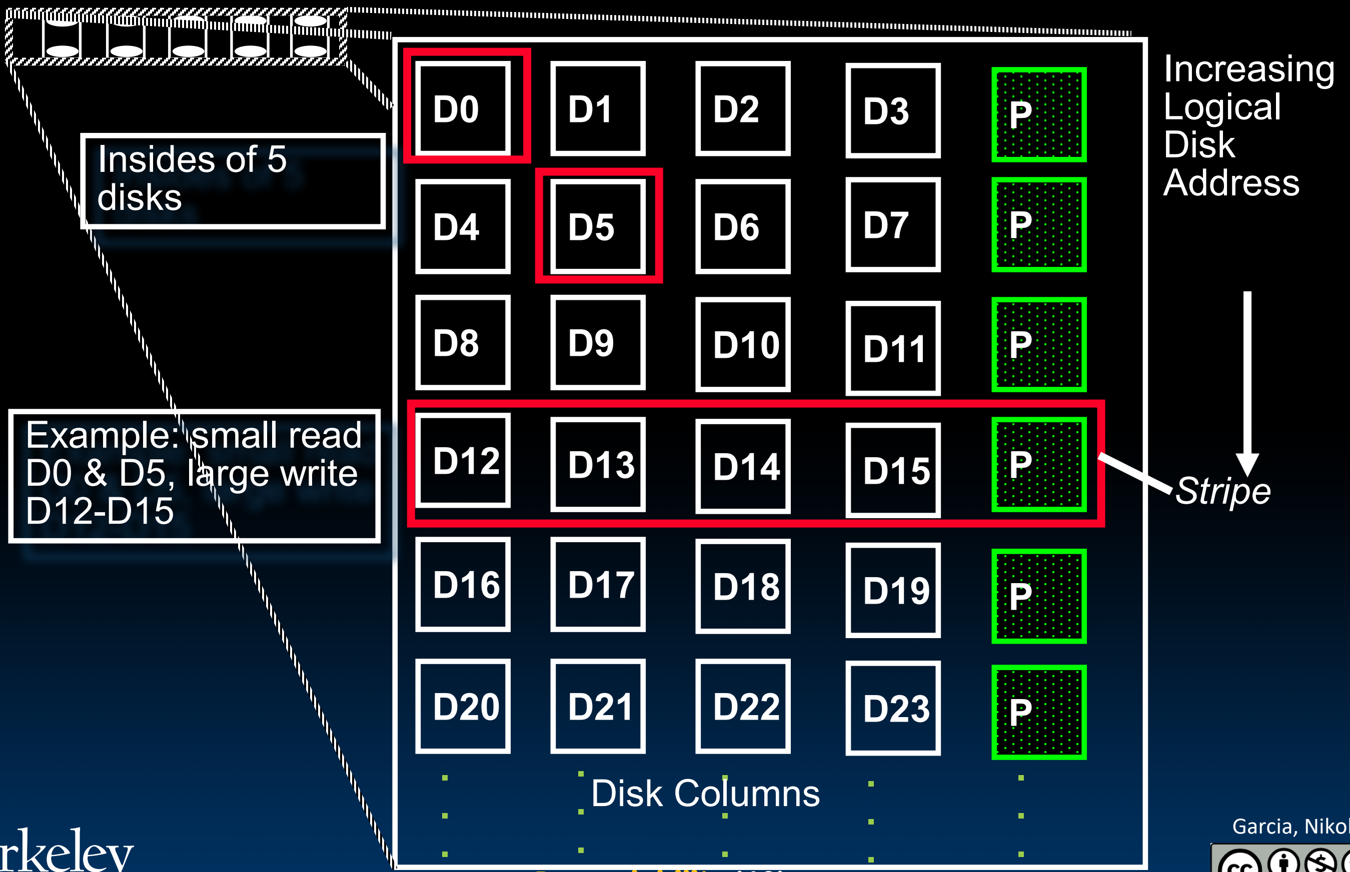
logical record


| | | | |
|---|---|---|---|
| 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 |

Striped physical records

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

# RAID 4: High I/O Rate Parity

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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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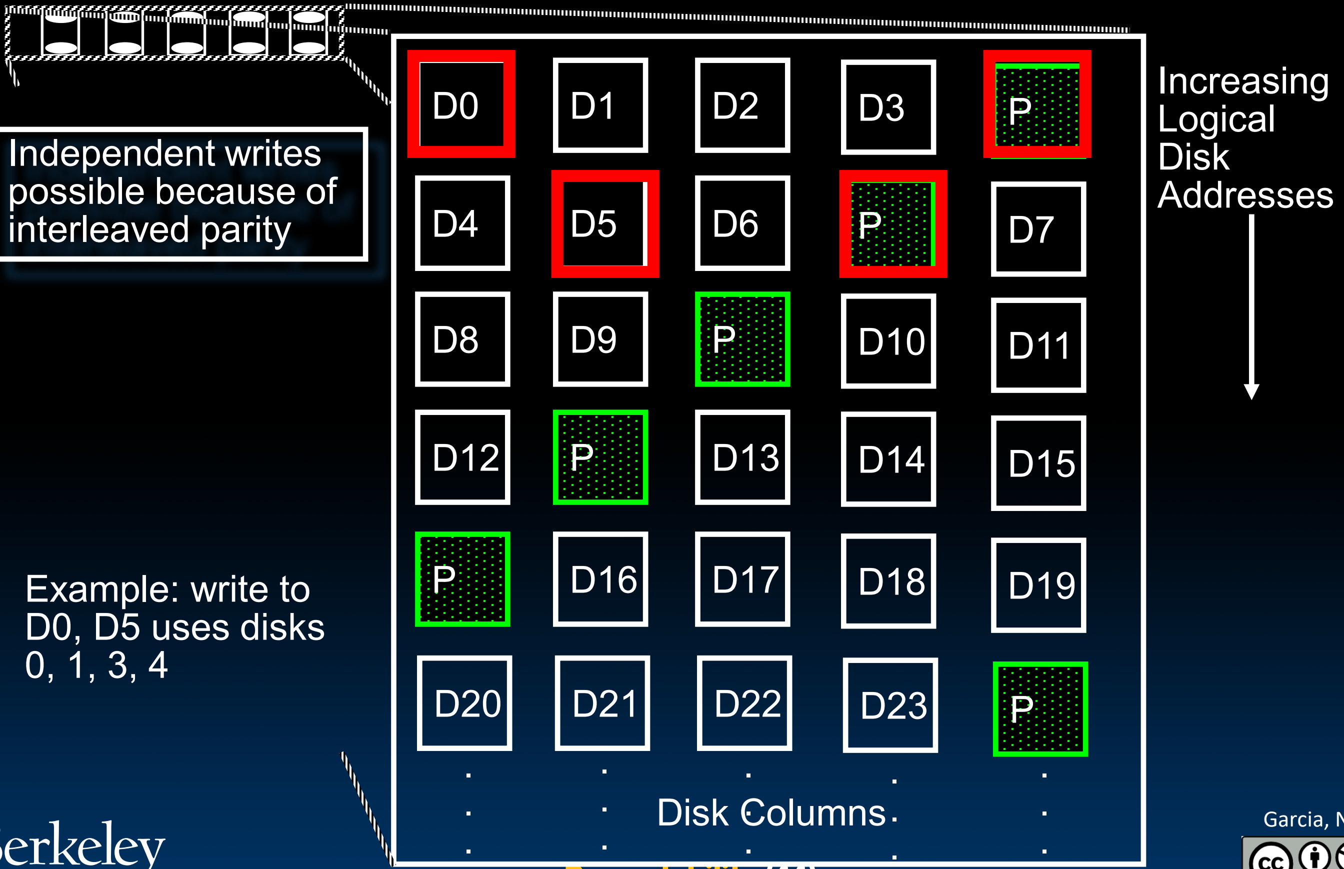
# RAID 5: High I/O Rate Interleaved Parity

Independent writes possible because of interleaved parity

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



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# "And in Conclusion…"

- Great Idea: Redundancy to Get Dependability
  - Spatial (extra hardware) and Temporal (retry if error)
- Reliability: MTTF, Annualized Failure Rate (AFR), and FIT
- Availability: % uptime (MTTF/MTTF+MTTR)
- 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 (and -6, -10): Interleaved data and parity