# CS 110
# Computer Architecture

*Dependability and RAID*

Instructors:
**Chundong Wang & Siting Liu**

https://toast-lab.sist.shanghaitech.edu.cn/courses/CS110@ShanghaiTech/Spring-2023/index.html

**School of Information Science and Technology SIST**

**ShanghaiTech University**

**Slides based on UC Berkley's CS61C**

# Review

- DMA
- Disk I/Os
- Flash memory
- Network
  - Abstraction
  - Protocols

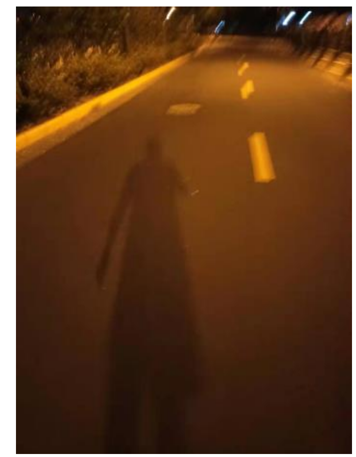
# A Story of Dependability



**Key locked in flat**

Spare key in office

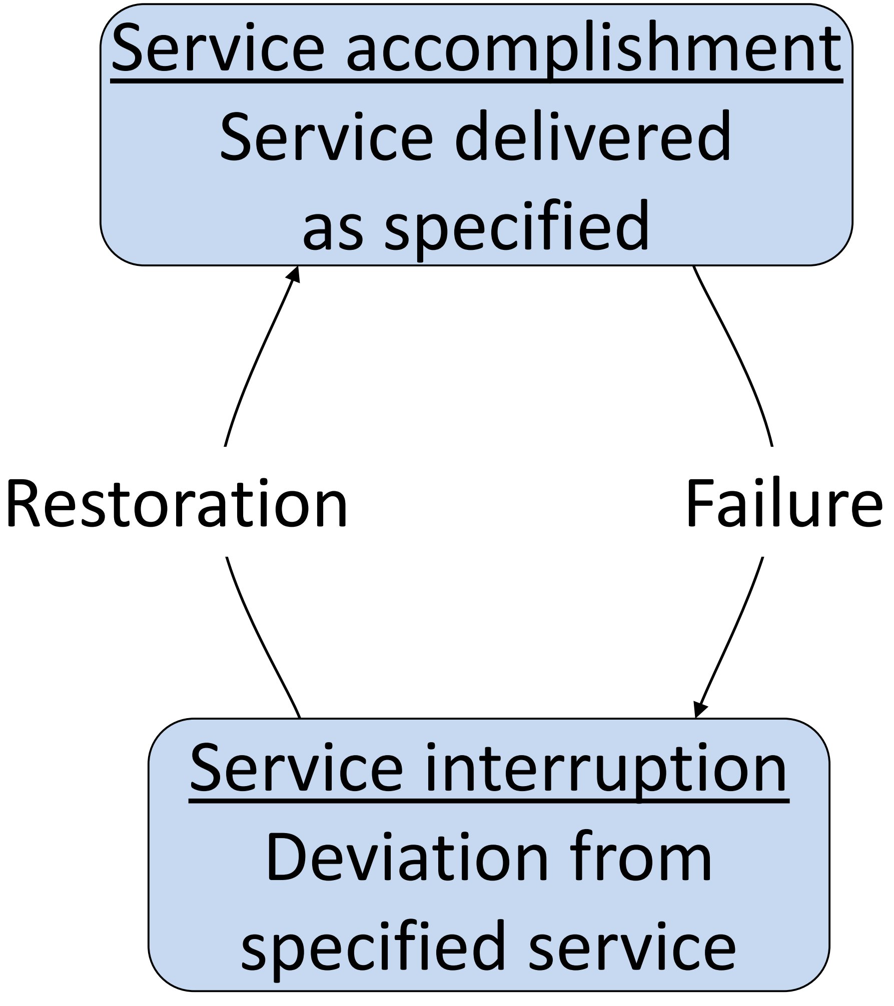
Redundancy



# 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 memory bits of so that can lose 1 bit but no data (Error Correcting Code/ECC Memory)
  - Redundant disks so that can lose 1 disk but not lose data (Redundant Arrays of Independent Disks/RAID)

# Dependability




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

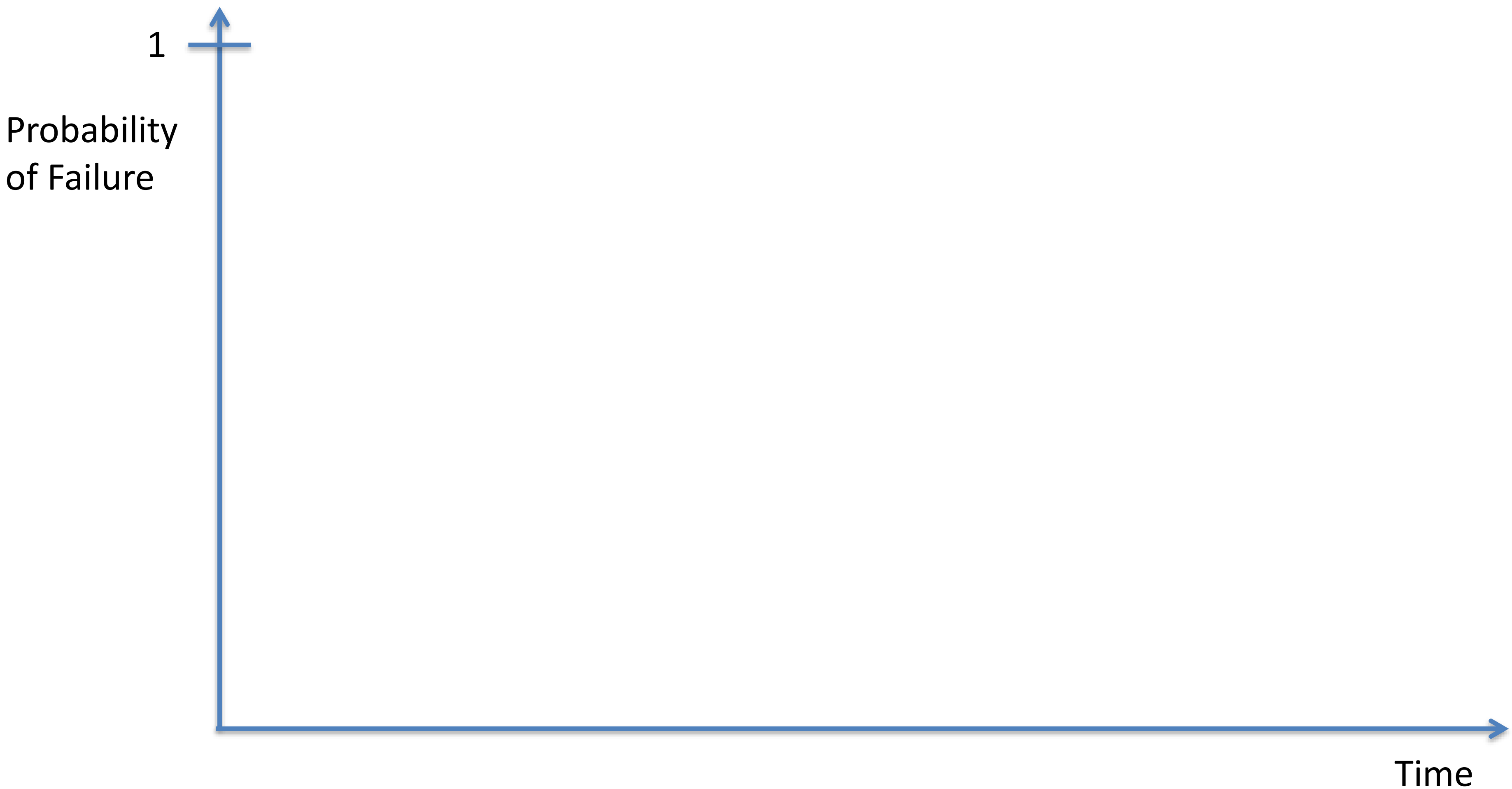
# Dependability via Redundancy: Time vs. Space

- *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

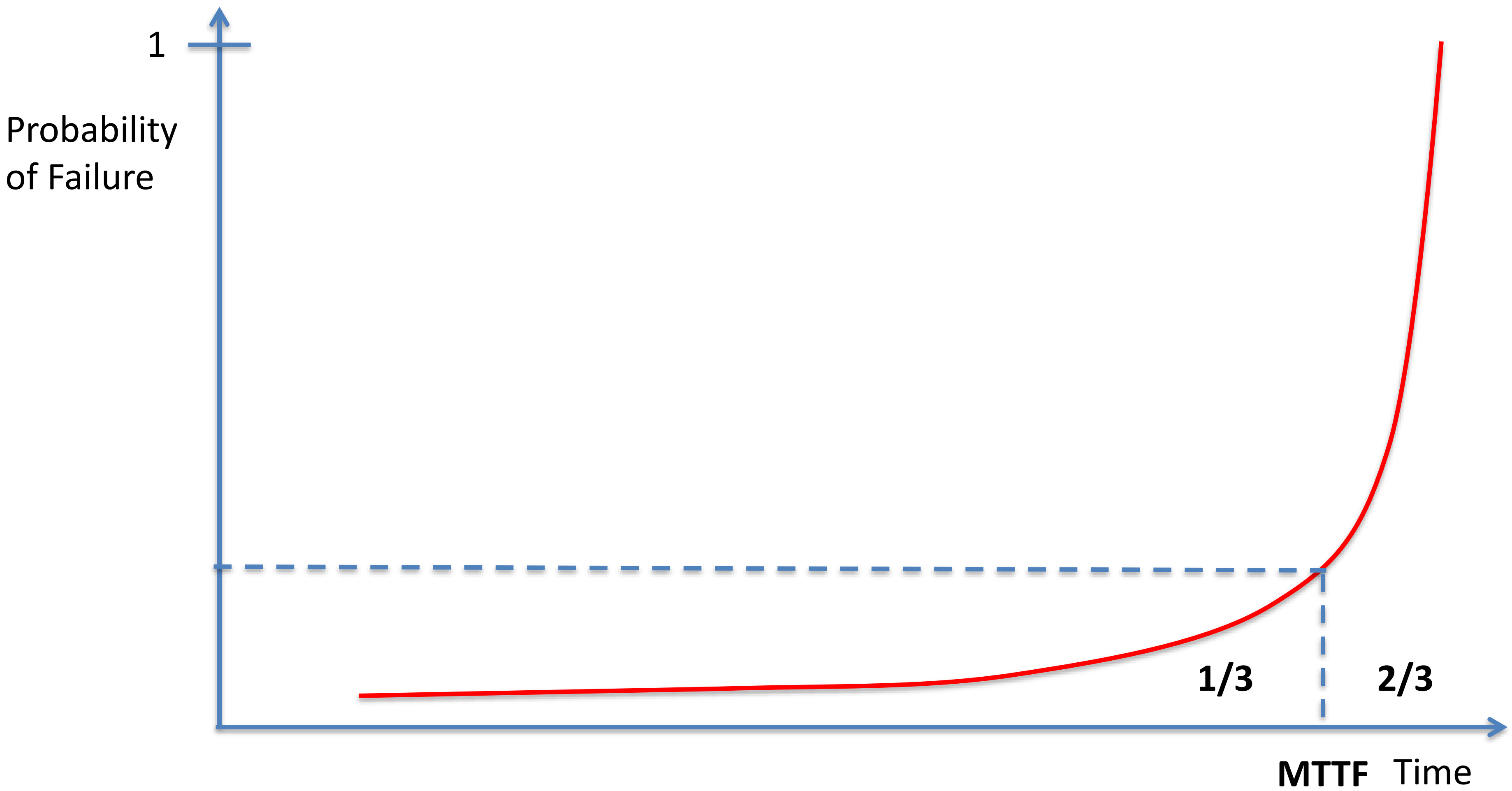
# Dependability Measures

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

# Understanding MTTF



# Understanding MTTF



# Availability Measures

- Availability = $\frac{MTTF}{MTTF+MTTR}$ 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 hours 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*

# Dependability Design Principle

- Design Principle: No single points of failure
  - "Chain is only as strong as its weakest link"
  - *Achilles' Heel*
- 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

# 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

# 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
  - There is Ham. distance between codes

Richard Hamming, 1915-98
Turing Award Winner

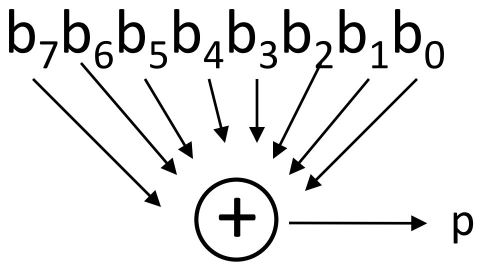
# Parity

- Parity bits are added to a word to make it
  - either odd: odd numbers of ‘1’
  - or even: even number of ‘1’
- Let us add one parity bit to three-bit word

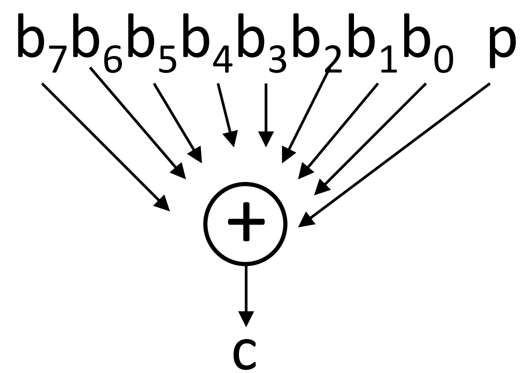
| Odd Parity | | Even Parity | |
|---|---|---|---|
| 000 | 0001 | 000 | 0000 |
| 100 | 1000 | 100 | 1001 |
| 101 | 1011 | 101 | 1010 |
| 111 | 1110 | 111 | 1111 |

# 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).




- 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
- Minimum Hamming distance of valid parity codes is 2

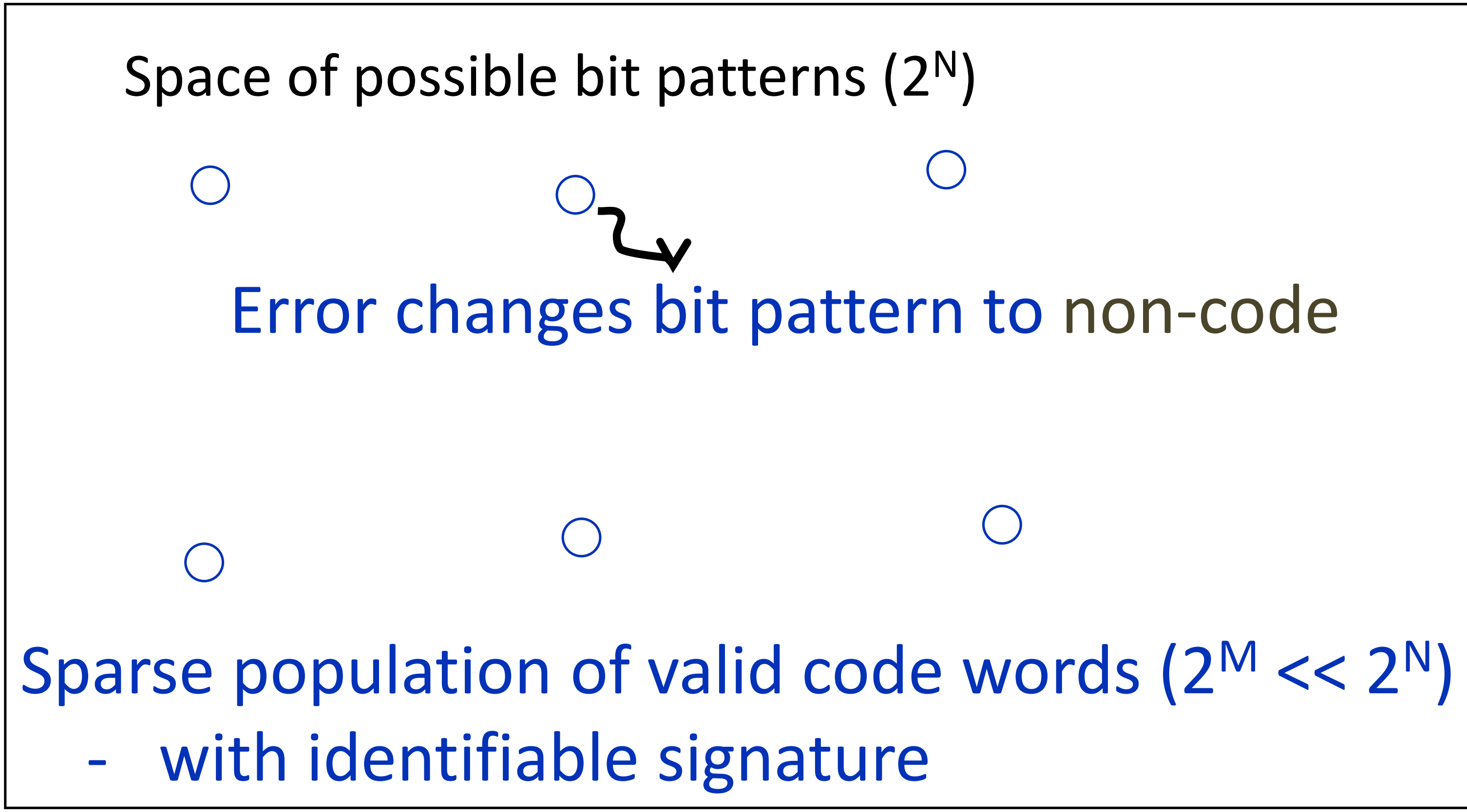
# Parity Example

- 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?

# Suppose Want to Correct 1 Error?

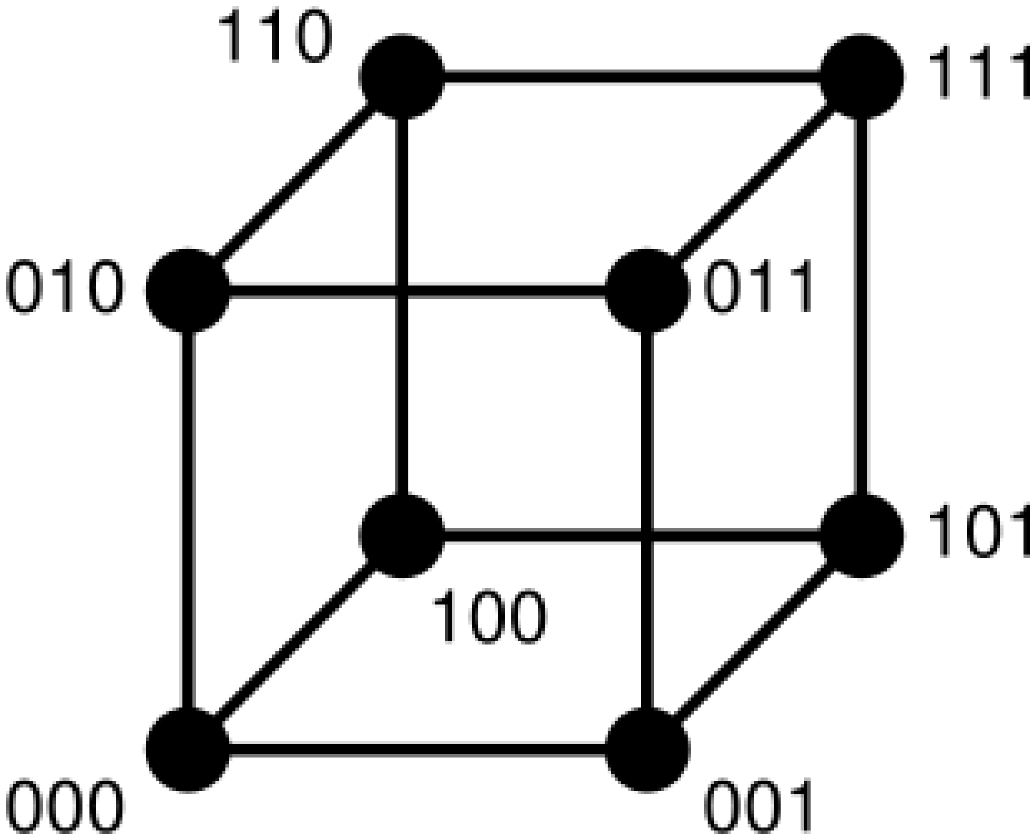
- Richard Hamming came up with simple to understand mapping to allow Error Correction at minimum distance of 3
  - Single error correction, double error detection
- Called “Hamming ECC”
  - Worked weekends on relay computer with unreliable card reader, frustrated with manual restarting
  - Got interested 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.

# Detecting/Correcting Code Concept

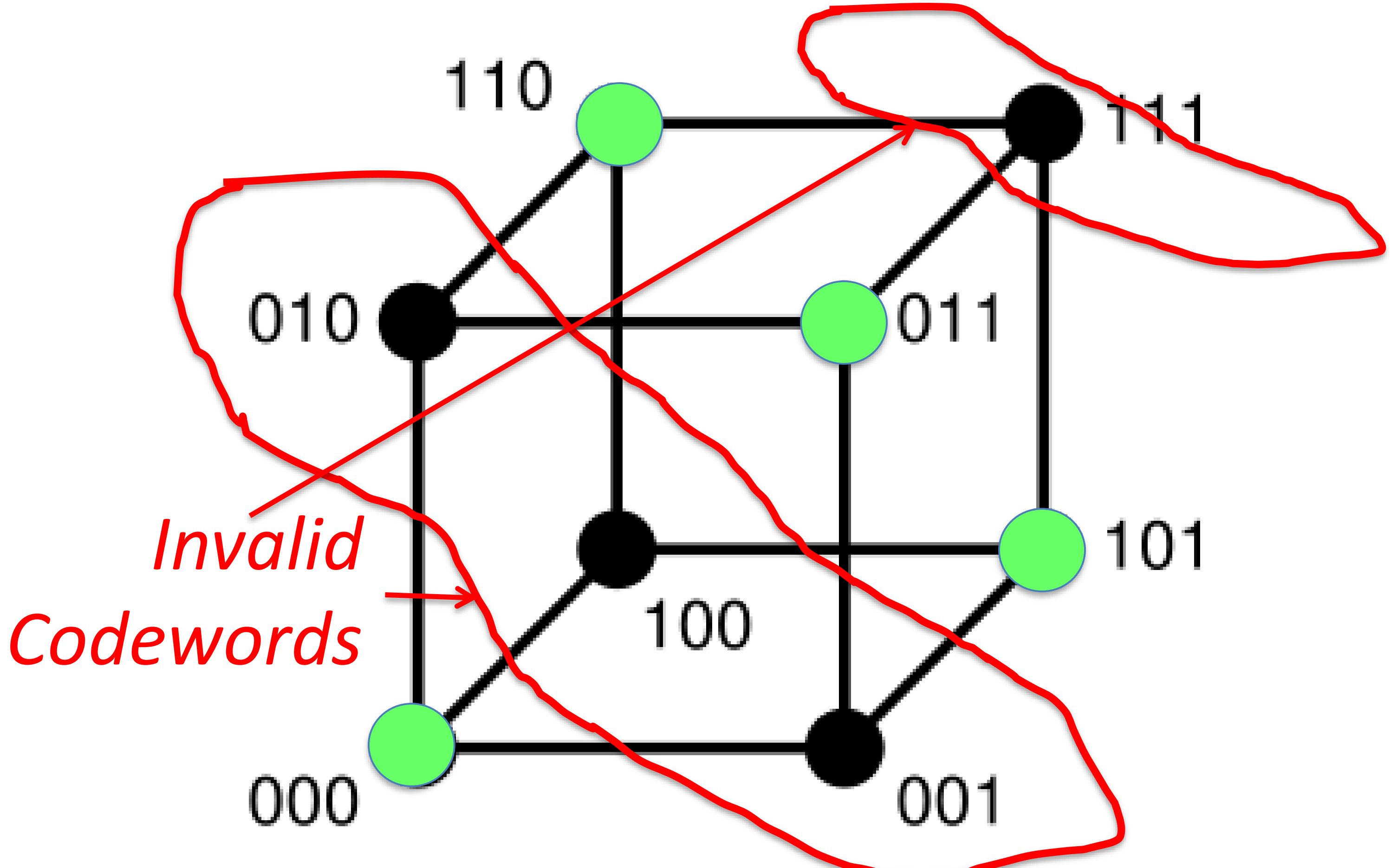



- Detection: bit pattern fails codeword check
- Correction: map to nearest valid code word

# Hamming Distance: 8 code words



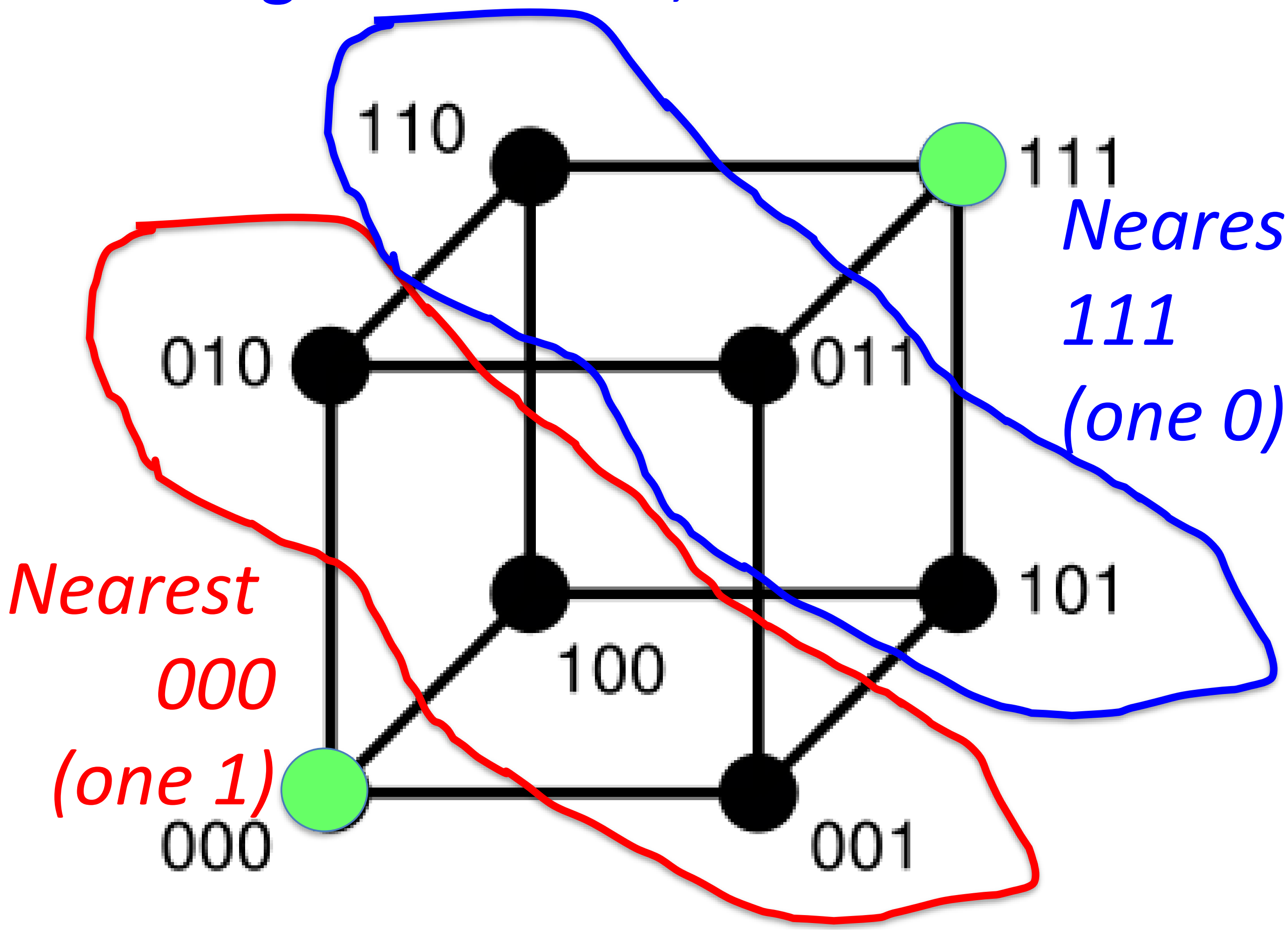
# Hamming Distance 2: Detection
## *Detect Single Bit Errors*




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

# Hamming Distance 3: Correction

## Correct Single Bit Errors, Detect Double Bit Errors




- No 2 bit error goes to another valid codeword; 1 bit error near
- 1/4 codewords are valid

# 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

# 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 $2^{nd}$ least significant bit of address = 1
- Bit 4 ($0100_2$): checks bits (4-7, 12-15, 20-23, ...)
  - Bits with $3^{rd}$ least significant bit of address = 1
- Bit 8 ($1000_2$): checks bits (8-15, 24-31, 40-47 ,...)
  - Bits with $4^{th}$ least significant bit of address = 1

# 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 | | X |
| | p2 | | X | X | | | X | X | | | X | X | | | X | X |
| | p4 | | | | X | X | X | X | | | | | X | X | X | X |
| | p8 | | | | | | | | X | X | X | X | X | X | X | X |

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

# 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

  *1 2 3 4 5 6 7 8 9 A B C*
- Calculate the parity bits

# Hamming ECC

_ _ 1 _ 0 0 1 _ 1 0 1 0

- Position 1 checks bits 1, 3, 5, 7, 9, 11:
  **?** _ **1** _ **0** 0 **1** _ **1** 0 **1** 0. set position 1:
  **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:
  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:
  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:
  - 0 1 1 1 0 0 1 **0 1 0 1 0**

# Hamming ECC

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

# Hamming ECC Error Check

- Suppose receive

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

  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 | | X |
| | p2 | | X | X | | | X | X | | | X | X | | | X | X |
| | p4 | | | | X | X | X | X | | | | | X | X | X | X |
| | p8 | | | | | | | | X | X | X | X | X | X | X | X |

# 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*

011100101**1**10

# Hamming ECC Error Correct

- Flip the incorrect bit …

```
011100101010
```

- Double check

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

# Hamming ECC Error Detect

- Suppose receive

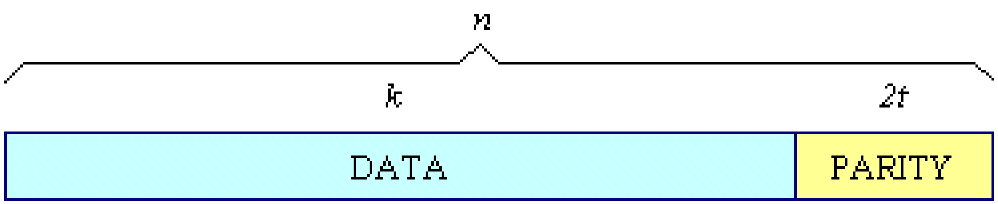
```
0 1 0 1 0 0 0 0 1 0 1 0
0   0   0   0   1   1     √
  1 0     0 0     0 1     √
      1 0 0 0         0   X
              0 1 0 1 0   √
```

Two errors can be detected, but not correctable

How about ≥3 bits error?

# Cyclic Redundancy Check

- Parity is not powerful enough to detect long runs of errors (also known as *burst errors*)
- Better Alternative: *Reed-Solomon Codes*
  - Used widely in CDs, DVDs, Magnetic Disks
  - RS(255,223) with 8-bit symbols: each codeword contains 255 code word bytes (223 bytes are data and 32 bytes are parity)




  - For this code: n = 255, k = 223, s = 8, 2t = 32, t = 16
  - Decoder can correct any errors in up to 16 bytes anywhere in the codeword

# RAID: Redundancy for Disks

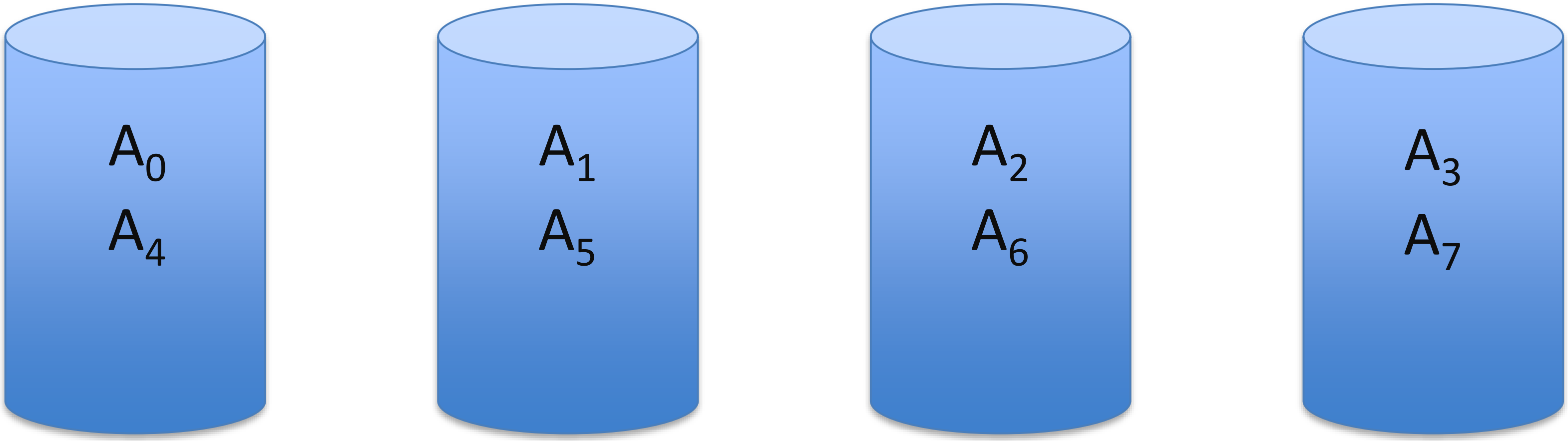
- Why we still worry about disks?
  - Trade-off: price, capacity, density, etc.
  - When you need storage space in petabytes (PB) or exabytes (EB)
    - 1 PB = 1024 TB
    - 1 EB = 1024 PB
  - Do not forget that flash-based SSDs also fail
    - Limited program/erase cycles ← wear levelling

# RAID: Redundant Arrays of (Inexpensive) Disks

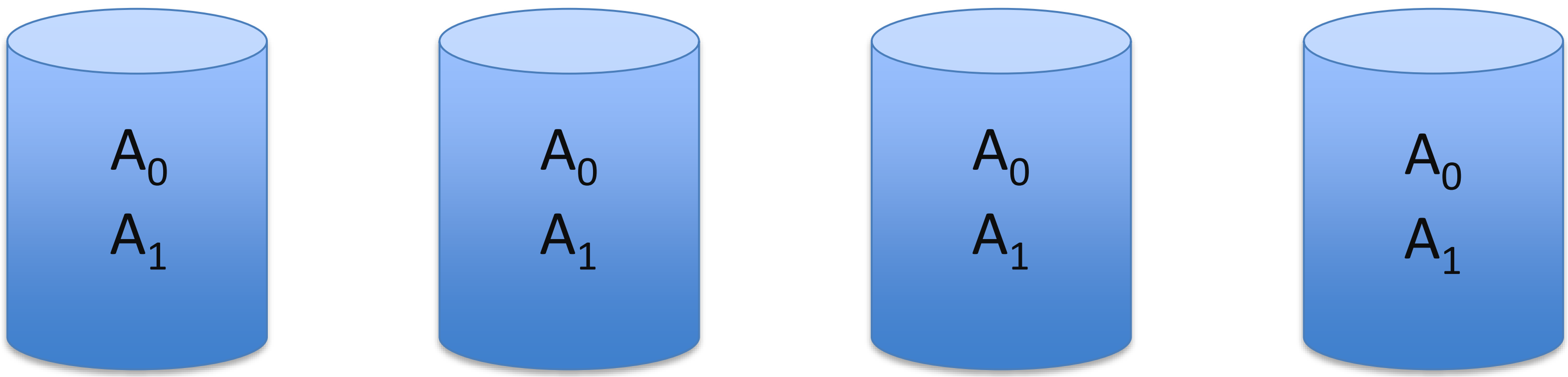
- Files are “striped” across multiple disks
- Redundancy yields high data availability
  - Availability: service still provided to user, even if some components failed
- Disks will still fail
- Contents reconstructed from data redundantly stored in the array
  - → Capacity penalty to store redundant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

# RAID 0: Striping

- RAID 0 provides **no** fault tolerance or redundancy
  - Striping, or disk spanning
  - High performance



# RAID 1: Disk Mirroring/Shadowing



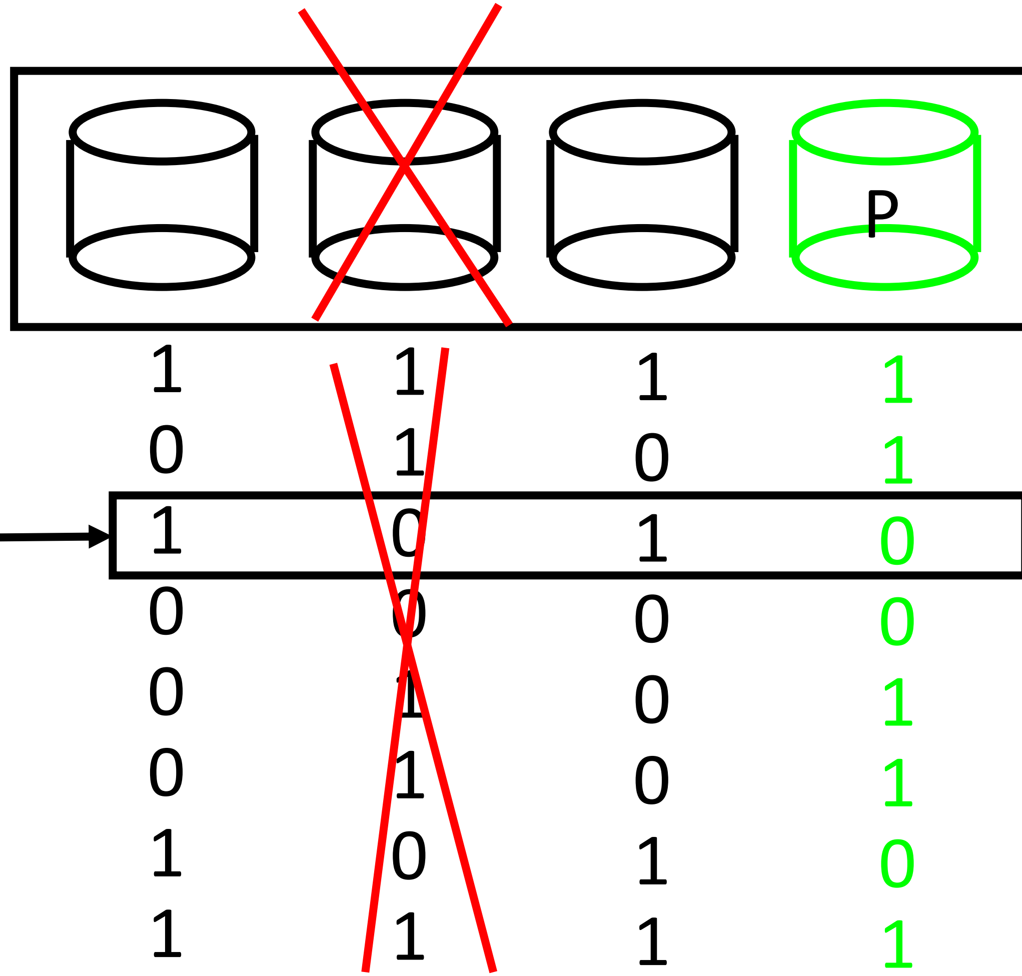

- Each disk is fully duplicated onto its "<u>mirror(s)</u>"
  - Very high availability can be achieved
- Bandwidth sacrifice on write:
  - Logical write = N physical writes
  - Reads may be optimized
- Most expensive solution: 100% capacity overhead
- RAID 10 (striped mirrors), RAID 01 (mirrored stripes):
  - Combinations of RAID 0 and 1.

# RAID 3: Parity Disk

10010011
11001101
10010011
. . .

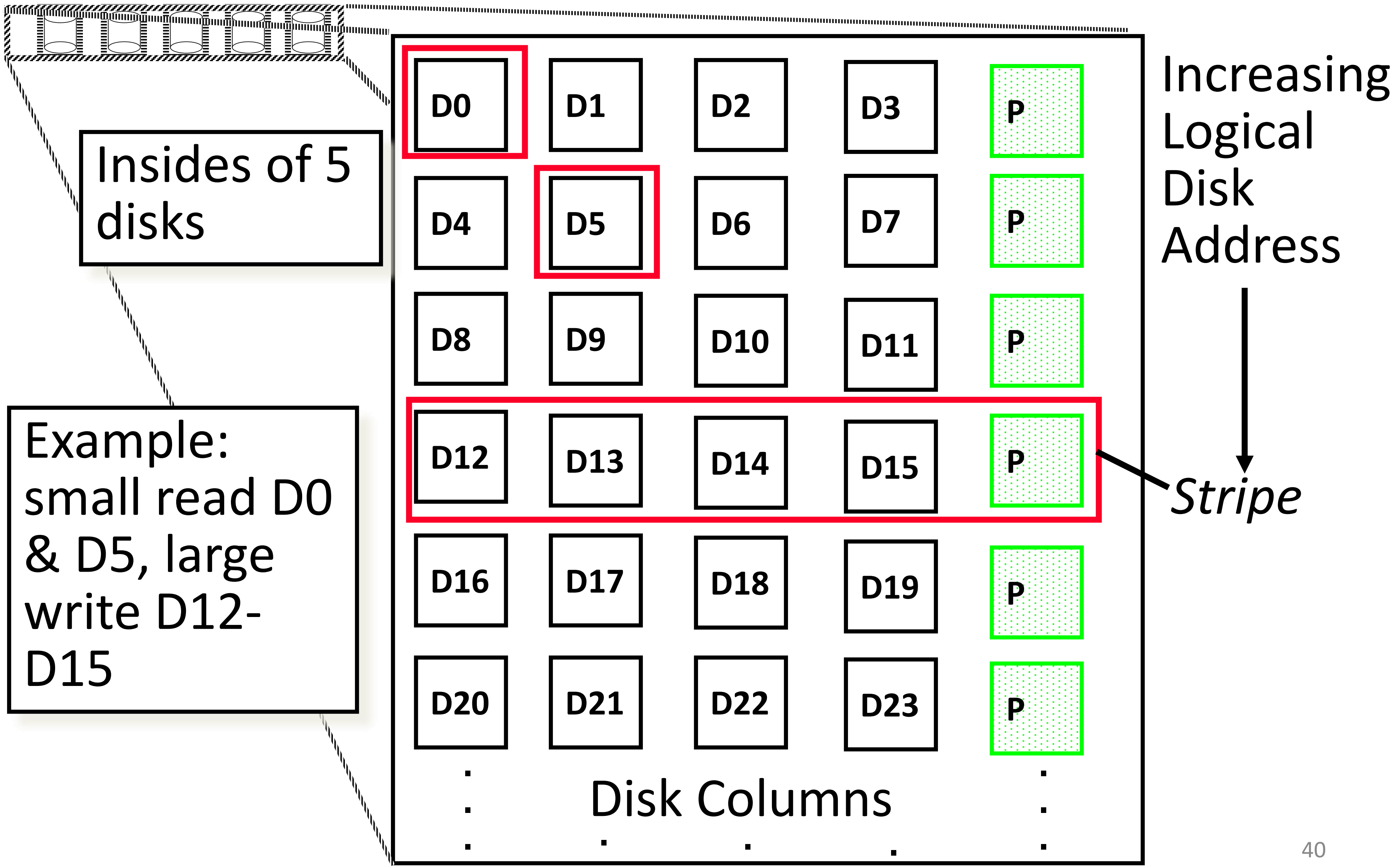
logical record

Striped physical records



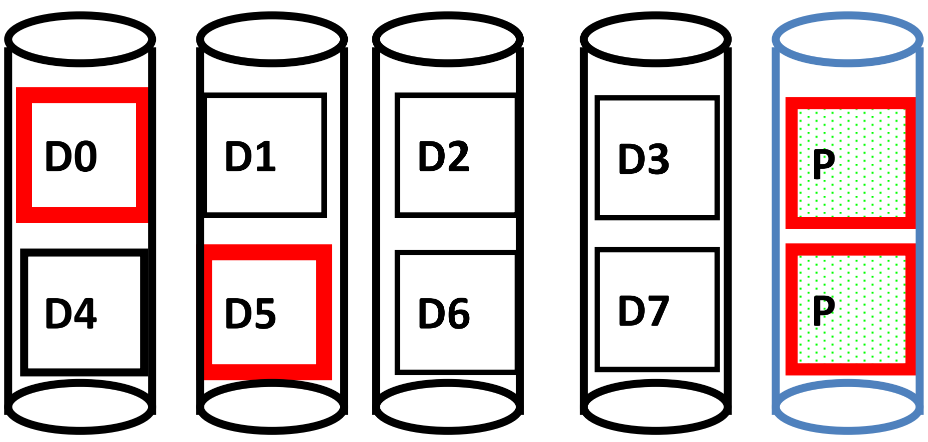

P contains sum of other disks per stripe mod 2 ("parity")
If disk fails, subtract P from sum of other disks to find missing information

# RAID 4: High I/O Rate Parity



# Inspiration for RAID 5

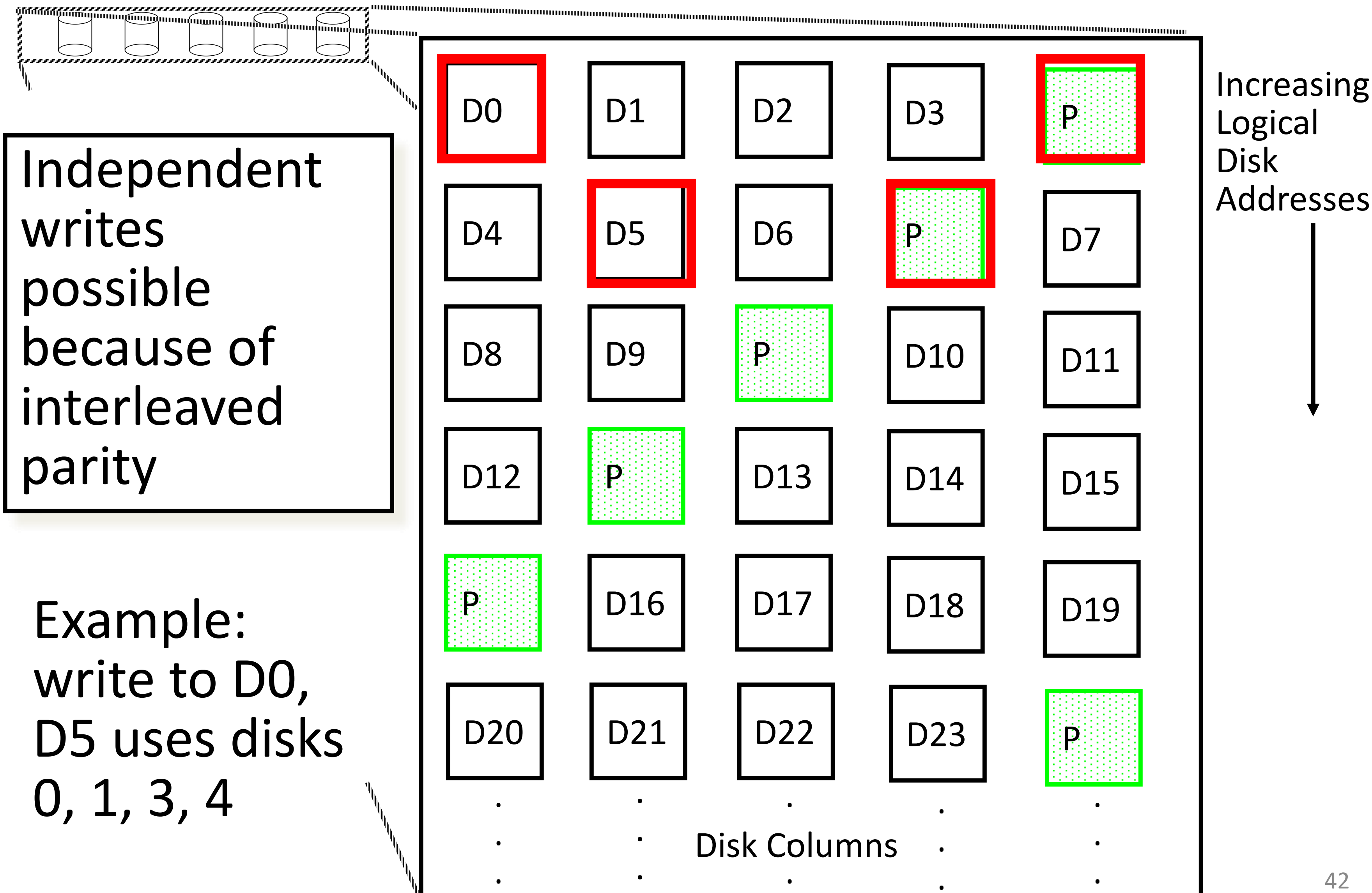
- RAID 4 works well for small reads
- Small writes (write to one disk):
  - Option 1: read other data disks, create new sum and write to Parity Disk
  - Option 2: since P has old sum, compare old data to new data, add the difference to P
- Small writes are limited by Parity Disk: Write to D0, D5 both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



# RAID 5: High I/O Rate Interleaved Parity

Independent writes possible because of interleaved parity

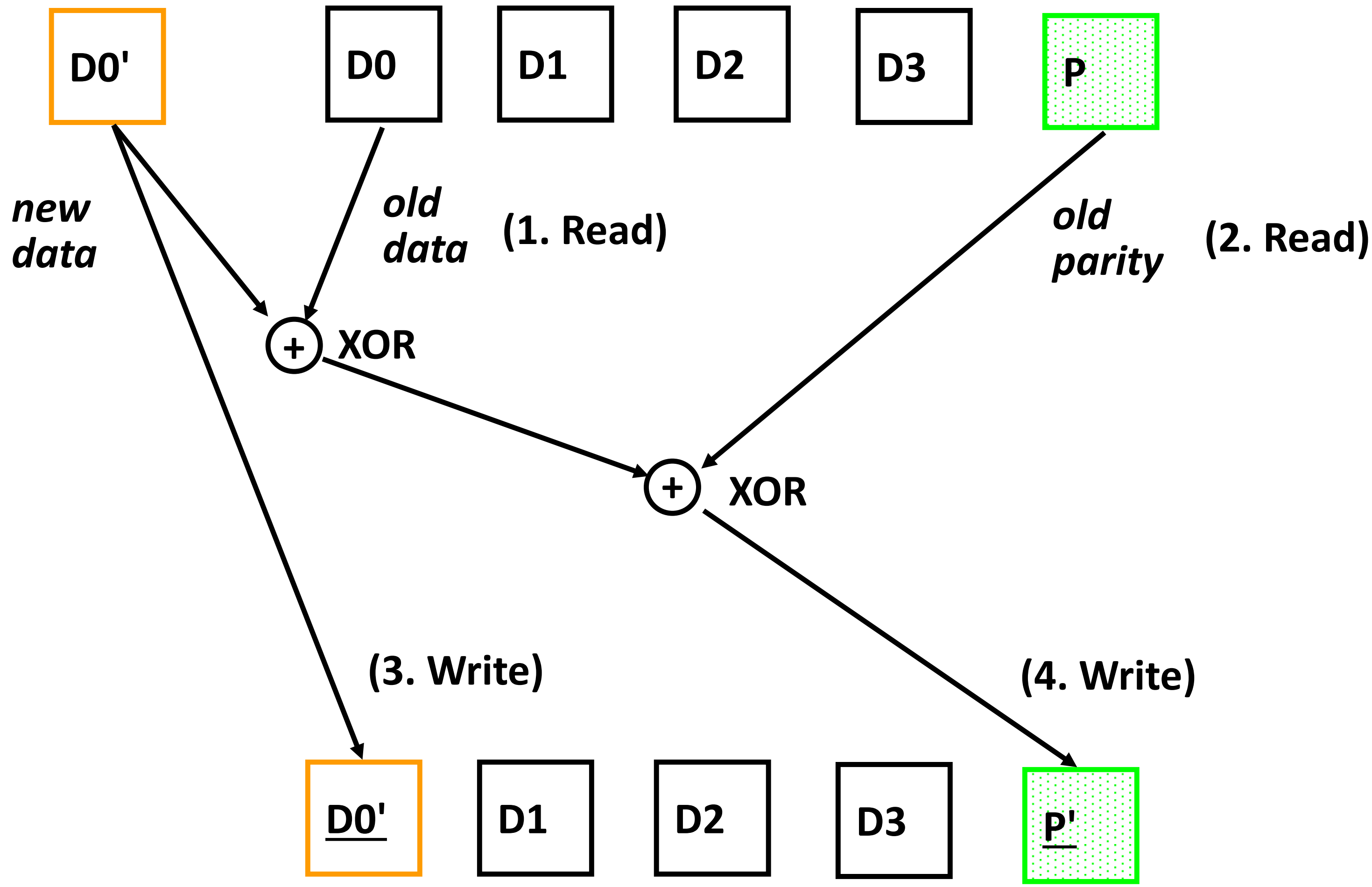
Example: write to D0, D5 uses disks 0, 1, 3, 4



# Problems of Disk Arrays: Small Writes

***RAID-5: Small Write Algorithm***

**1 Logical Write = 2 Physical Reads + 2 Physical Writes**



# 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
- Memory
  - Hamming ECC: correct single, detect double
- RAID
  - Interleaved data and parity