CS 110
Computer Architecture

Dependability and RAID

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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

依赖性

Key locked in flat

Spare key in office

Redundancy

冗余(备份)

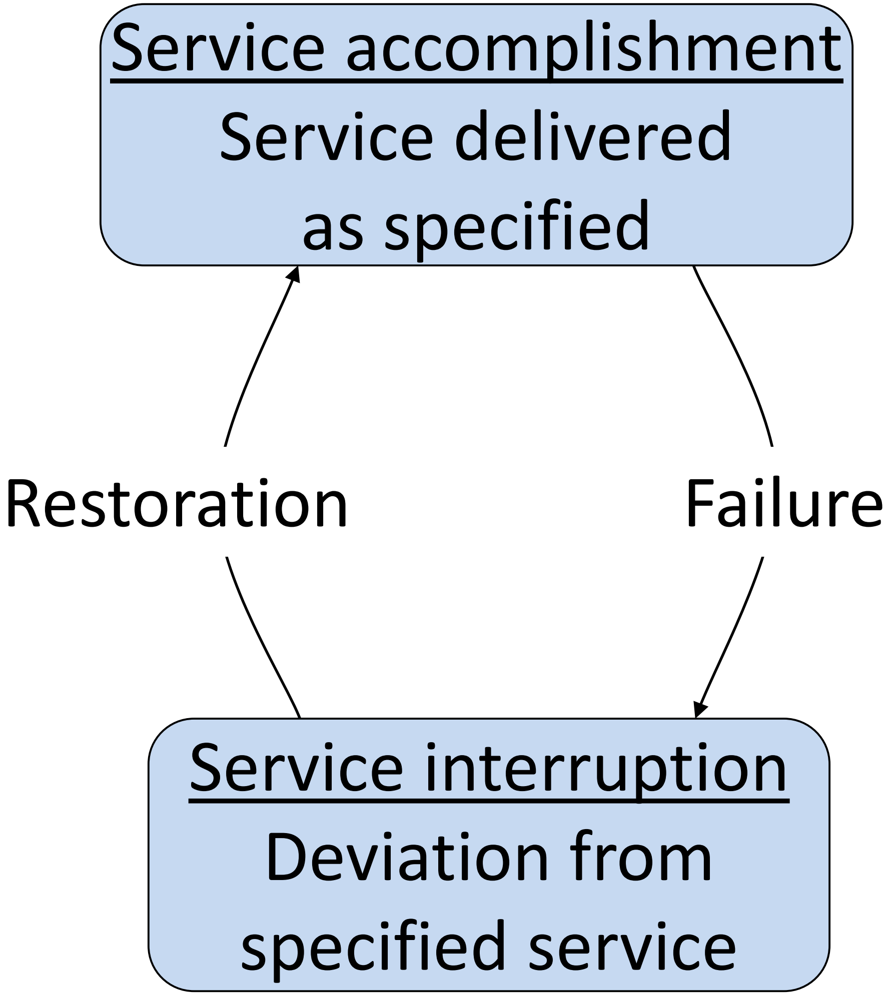
⇓

发生在error前

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 网络 多条路径可选
  - 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

空间上冗余

备份（标准3个replica）

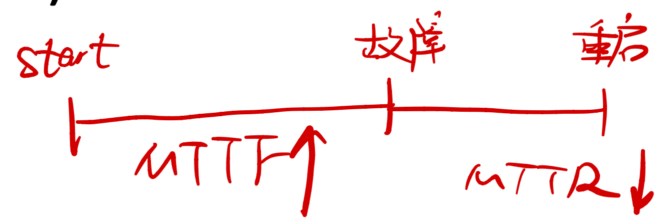
- *Spatial Redundancy* – replicated data or check information or hardware to handle hard and soft (transient) failures
- *Temporal Redundancy* – redundancy in time (retry) to handle soft (transient) failures

有计时器，若一段时间未收到回执

⇒ 重新发送(retry)

Dependability Measures

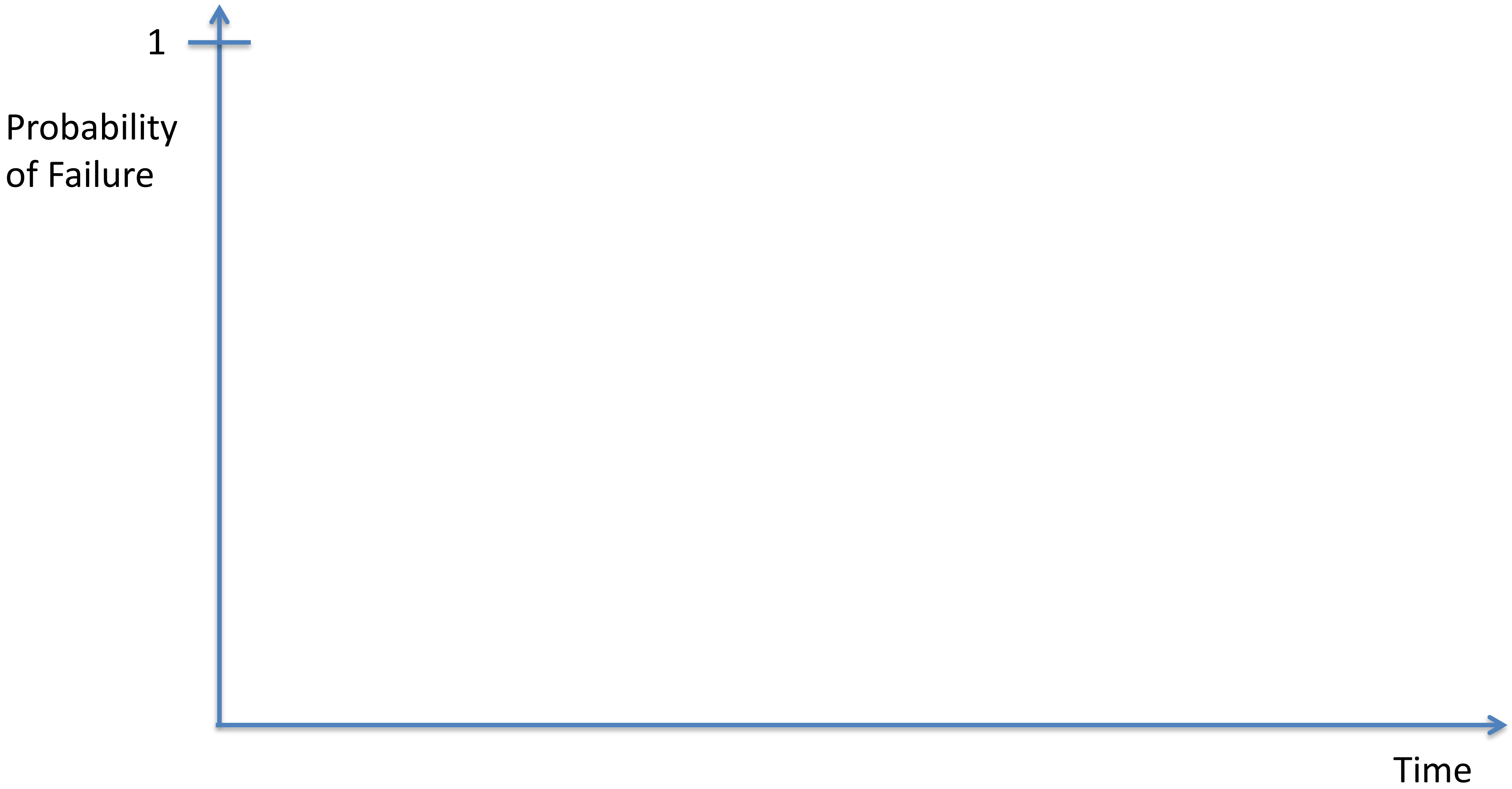
- Reliability: Mean Time To Failure (MTTF)
- Service interruption: Mean Time To Repair (MTTR)
- Mean time between failures (MTBF)
  - MTBF = MTTF + MTTR



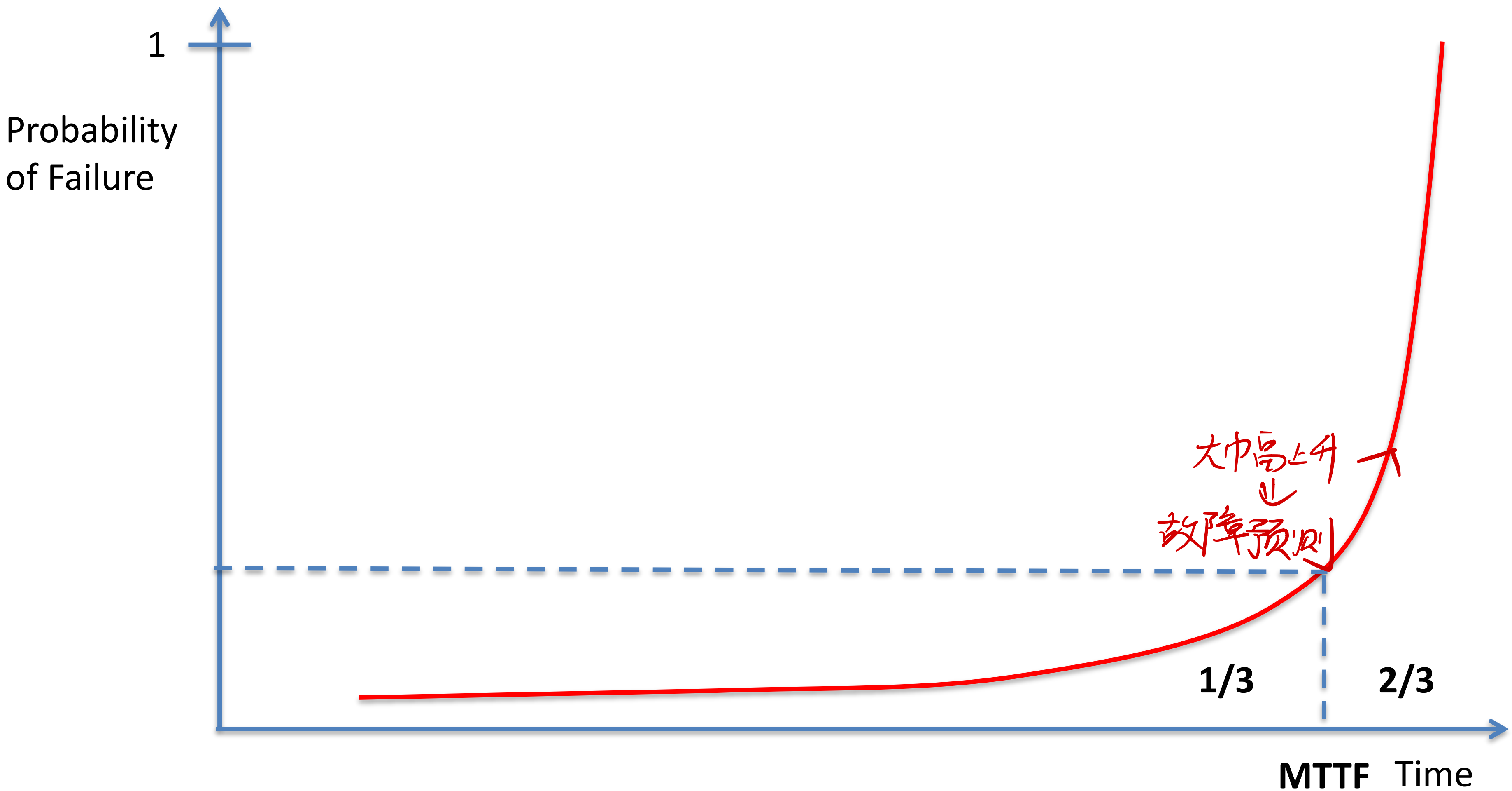
- Availability = $\frac{MTTF}{MTTF+MTTR}$
- Improving Availability
  - Increase MTTF: More reliable hardware/software + Fault Tolerance
  - 诊断

    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"

花在修复上的时间

- 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) 年化故障率
  - 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

Systematic :

- 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

    出问题的是短板
  - Dependability limited by part you do not improve

EDC / ECC

Error Detection/Correction Codes

- Memory systems generate errors (accidentally flipped-bits)
  - DRAMs store very little charge per bit

    软错 => 可修复
  - "Soft" errors occur occasionally when cells are struck by alpha particles or other environmental upsets

    不可修复
  - "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

error detected word

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) = ? 3
- 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

奇偶较验位

- 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

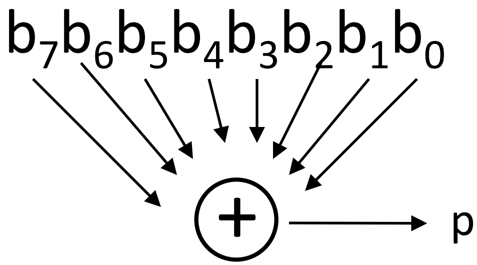
1个数为偶

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

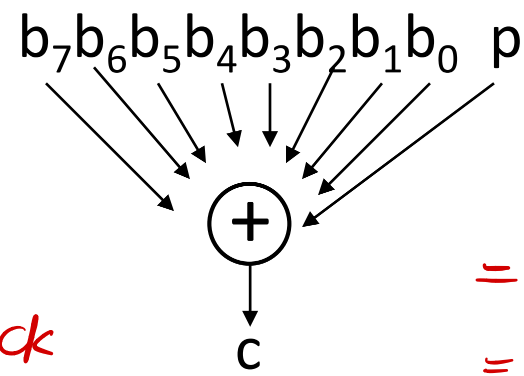
加1位,
s.t. 1有even个

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).



check

=1 一定出错

=0 可能✓

- 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

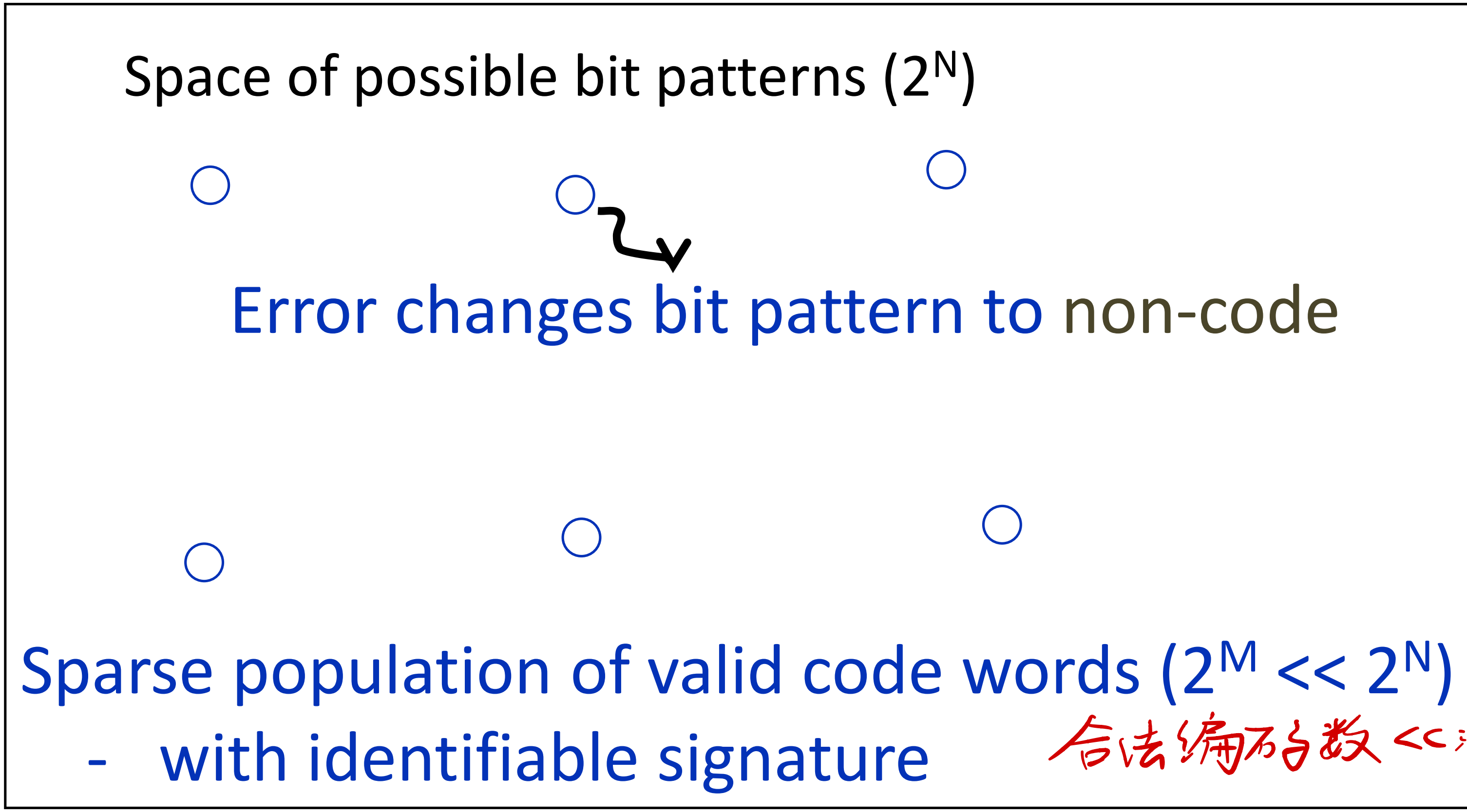
- Data 0101 0101
- 4 ones, even parity now
- Write to memory:
  0101 0101 0
  to keep parity even
- Data 0101 0111
- 5 ones, odd parity now
- Write to memory:
  0101 0111 1
  to make parity even

- Read from memory
  0101 0101 0
- 4 ones => even parity, so no error
- Read from memory
  1101 0101 0 校验位与其它bit
- 5 ones => odd parity, so error 奇数 $\Downarrow$ 出错数据相同
- 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 $1 \quad 1 \geq 3$
  - 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.

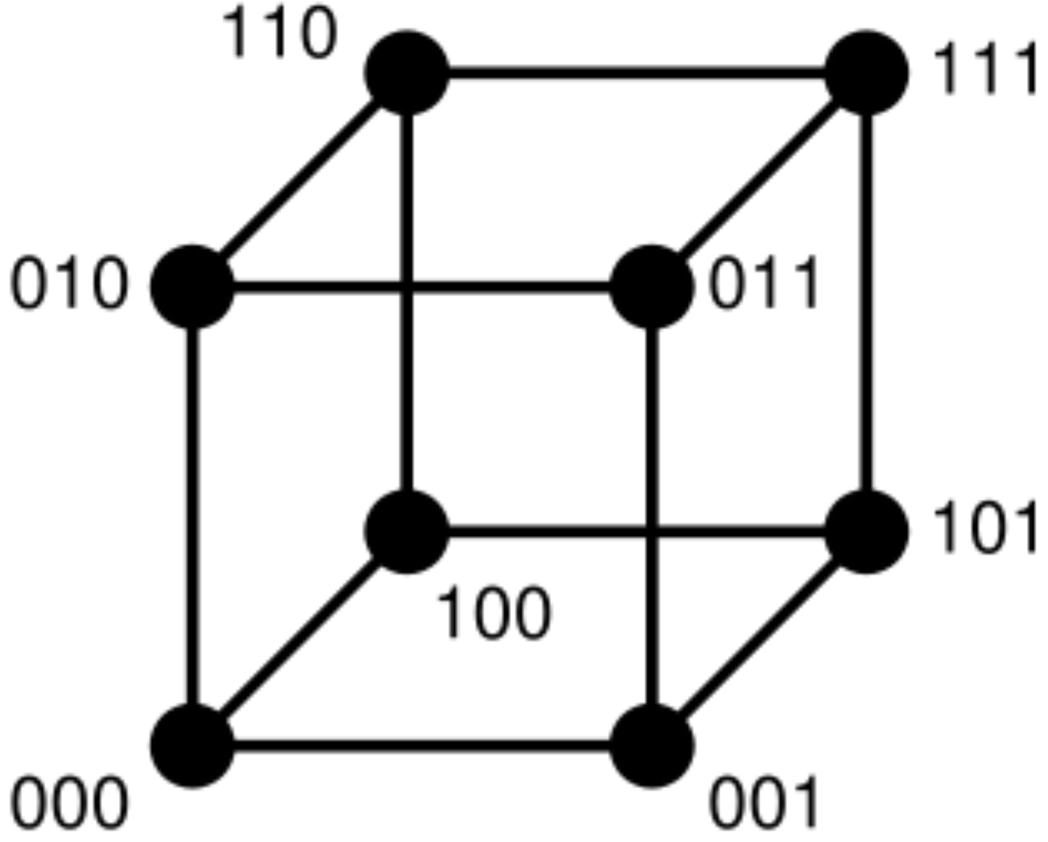
Detecting/Correcting Code Concept



合法编码数 $\ll$ 非法.

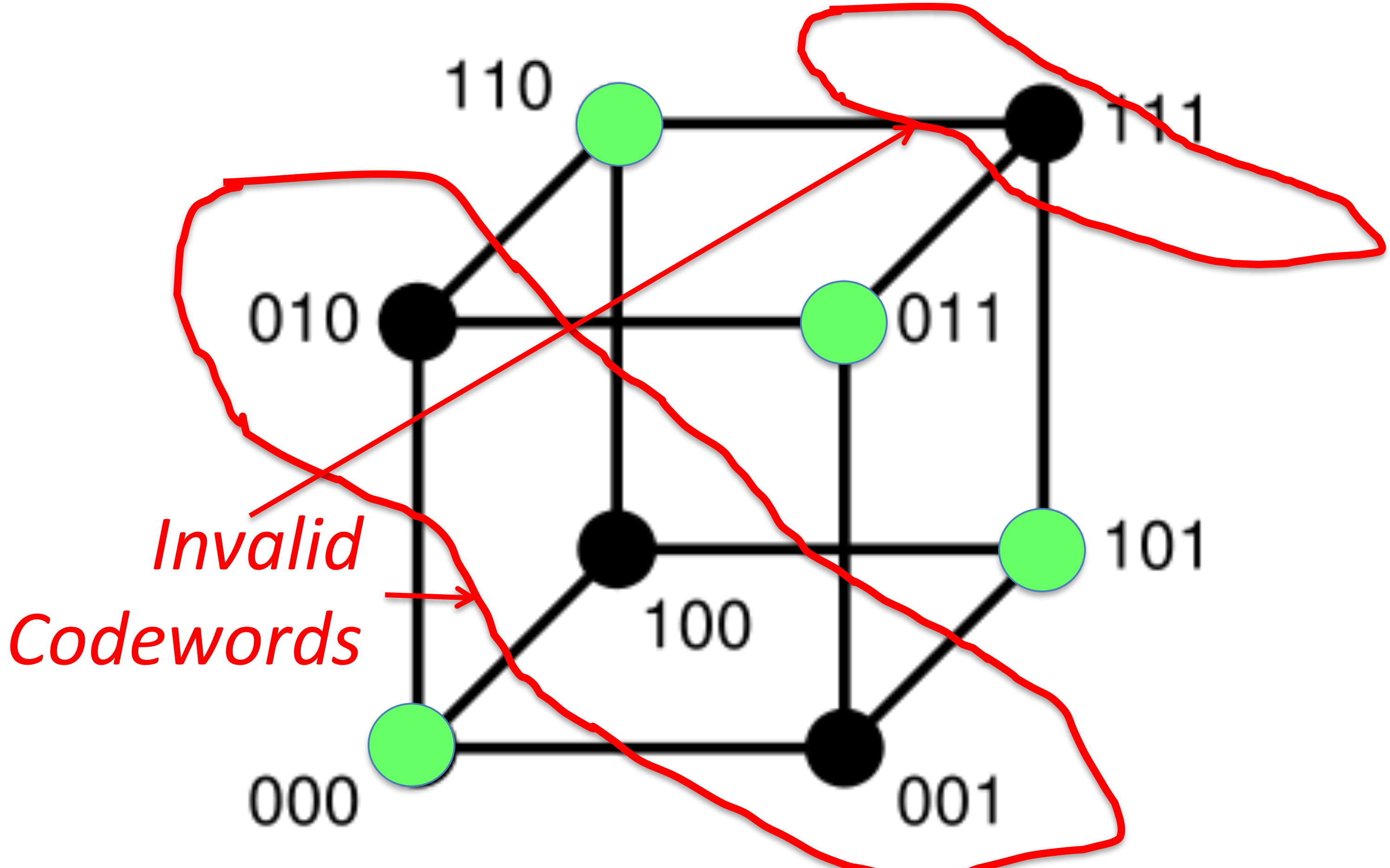
- Detection: bit pattern fails codeword check
- Correction: map to nearest valid code word

Hamming Distance: 8 code words



Hamming Distance 2: Detection

Detect Single Bit Errors

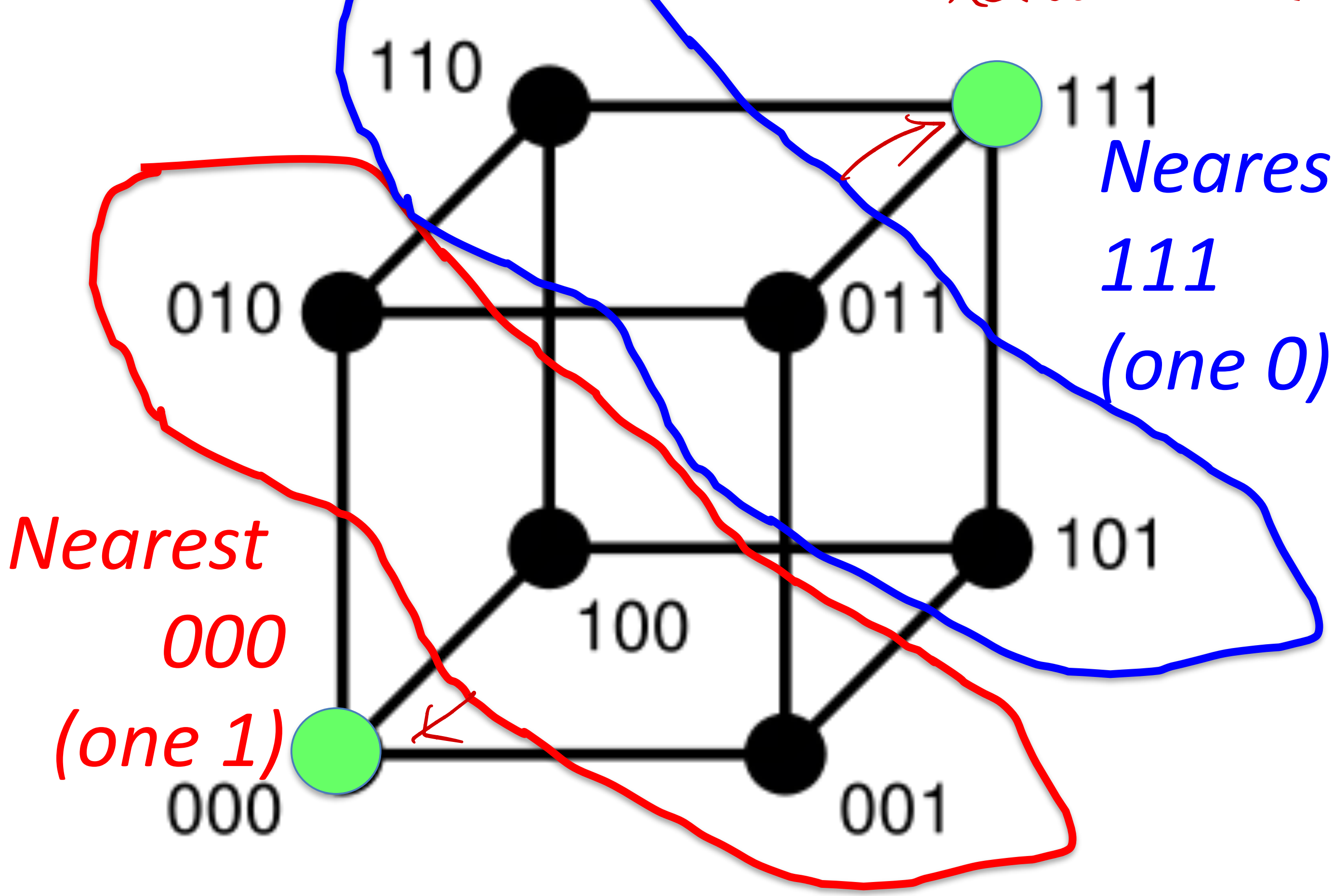


- No 1 bit error goes to another valid codeword
- ½ codewords are valid

Hamming Distance 3: Correction

Correct Single Bit Errors, Detect Double Bit Errors

定义000、111是valid的



- 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

把校验码放在第1,2,4,8,……位

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,...) 2进制最后一位为1的位 XOR
  - Bits with <u>least</u> significant bit of address = 1
- Bit 2 (0010_2): checks bits (2,3,6,7,10,11,14,15,...)
  - Bits with <u>2^{nd}</u> least significant bit of address = 1
- Bit 4 (0100_2): checks bits (4-7, 12-15, 20-23, ...)
  - Bits with <u>3^{rd}</u> least significant bit of address = 1
- Bit 8 (1000_2): checks bits (8-15, 24-31, 40-47 ,...)
  - Bits with <u>4^{th}</u> least significant bit of address = 1

Graphic of Hamming Code

1,2,4,8 奇偶校验码

从1开始

1111

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

1, 2, 4, 8 空出来

↓ XOR

填入

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

  _ 10111
  XOR = 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

  _ 1 0 1 0 1
  XOR = 1
- 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: <u>0</u><u>1</u>1<u>1</u>001<u>0</u>1010 encode
- Data word: 1 001 1010

Hamming ECC Error Check

- Suppose receive

  011100101110

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

decode

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
```

XOR → 0

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

011100101**1**10

⇓

0

Hamming ECC Error Correct

- Flip the incorrect bit …

```
0 1 1 1 0 0 1 0 1 0 1 0
```

- Double check

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

Hamming ECC Error Detect

- Suppose receive

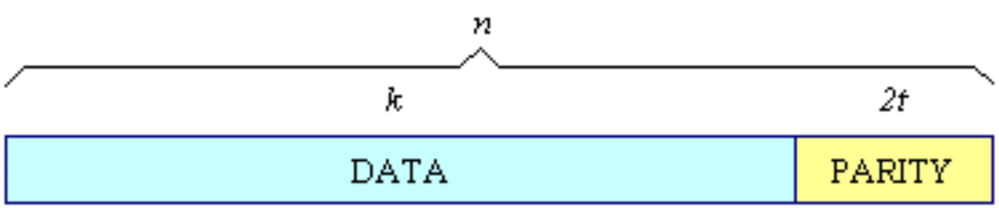
```
010100001010
0 0 0 0 1 1   √
 10  00  01   √
   1000     0 X
       01010  √
```

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

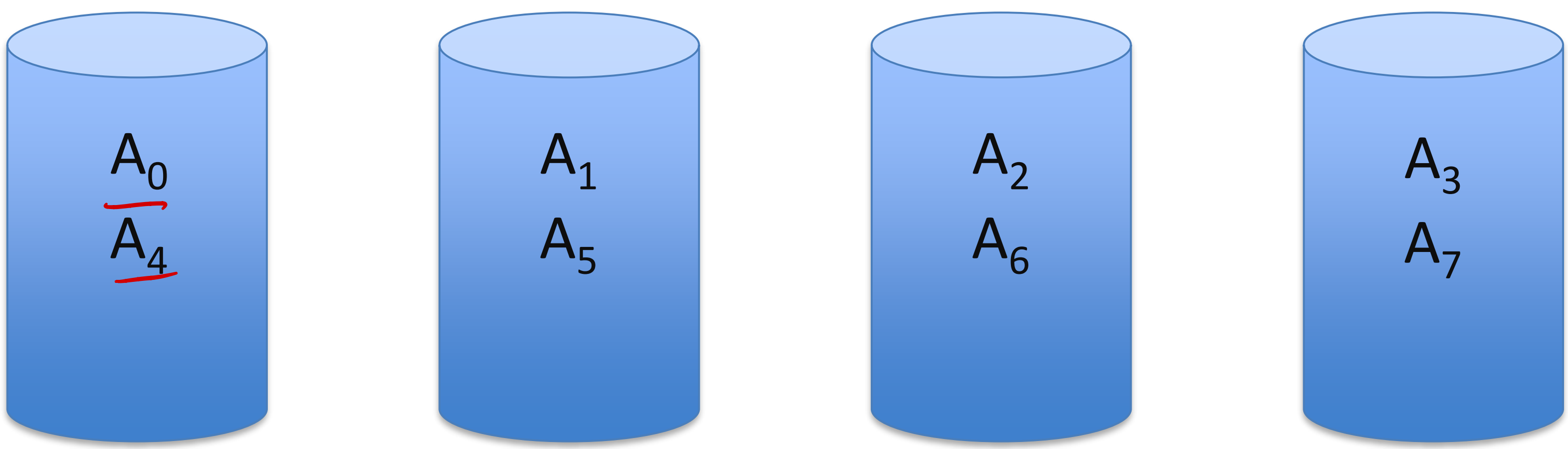
RAID: Redundant Arrays of Independent / (Inexpensive) Disks

- 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

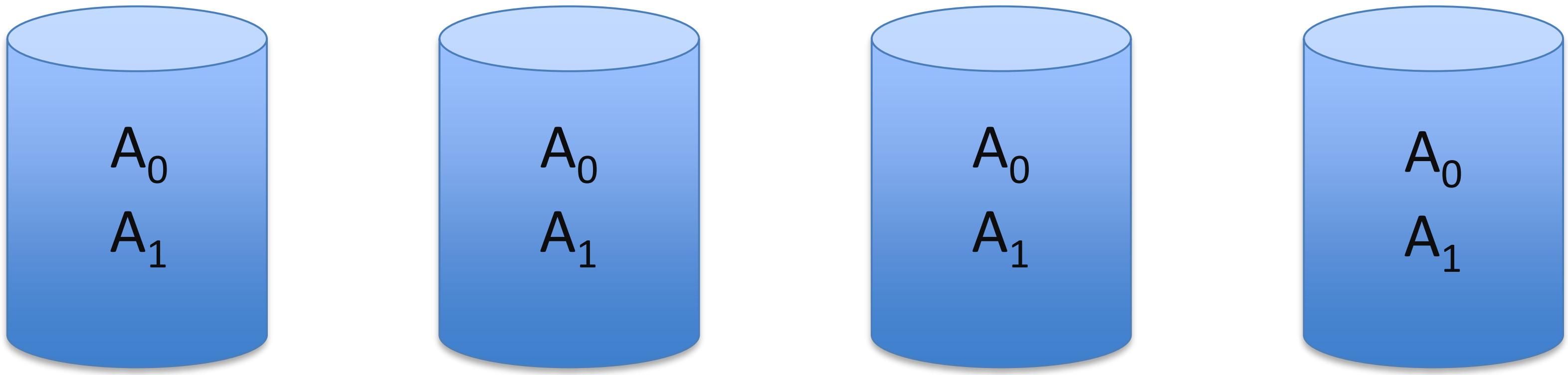
RAID 0: Striping 條

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

% 4



RAID 1: Disk Mirroring/Shadowing

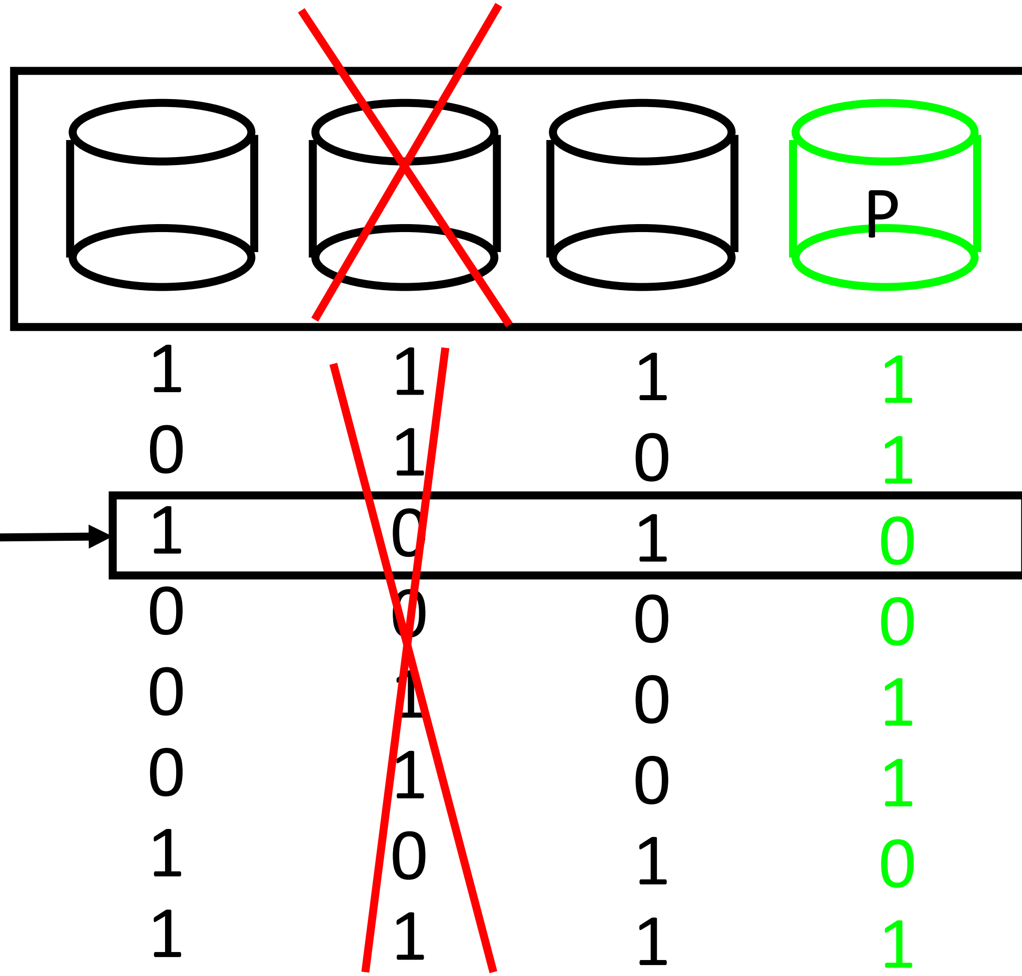


- Each disk is fully duplicated onto its "mirror(s)"
  - Very high availability can be achieved
- Bandwidth sacrifice on write:
  - Logical write = N physical writes
  - Reads may be optimized 4个盘可同时读
- Most expensive solution: 100% capacity overhead 全部备份
- RAID 10 (一零 striped mirrors), RAID 01 (零一 mirrored stripes):
  - Combinations of RAID 0 and 1.

RAID 3: Parity Disk （设想）

10010011
11001101
10010011
. . .

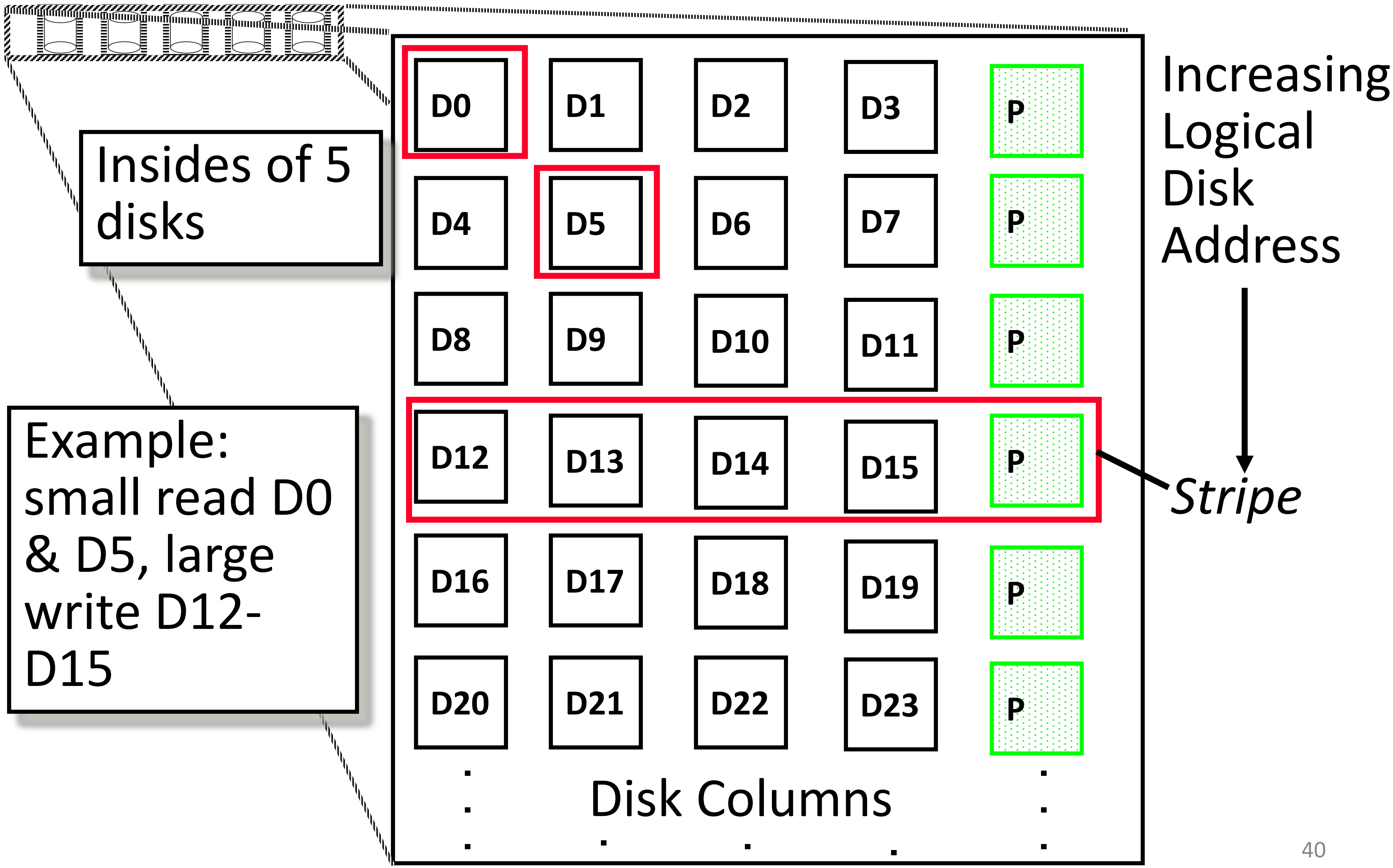
logical record
Striped physical
records



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

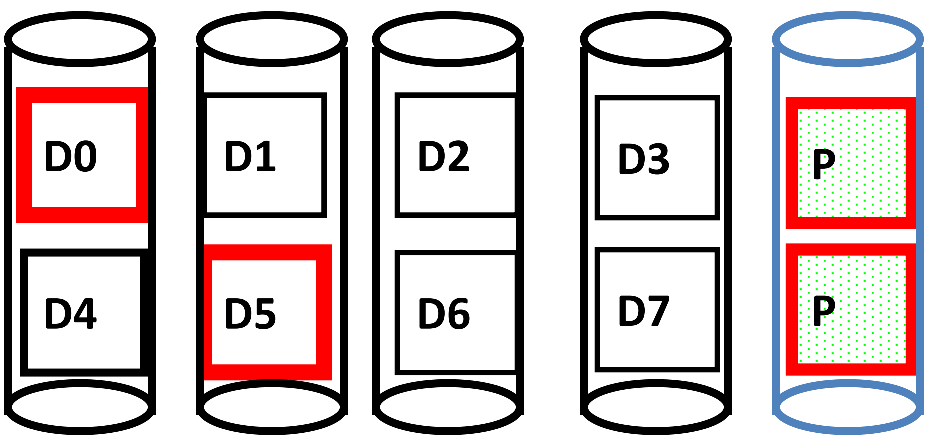
Parity单独写到一个盘上

RAID 4: High I/O Rate Parity



Inspiration for RAID 5

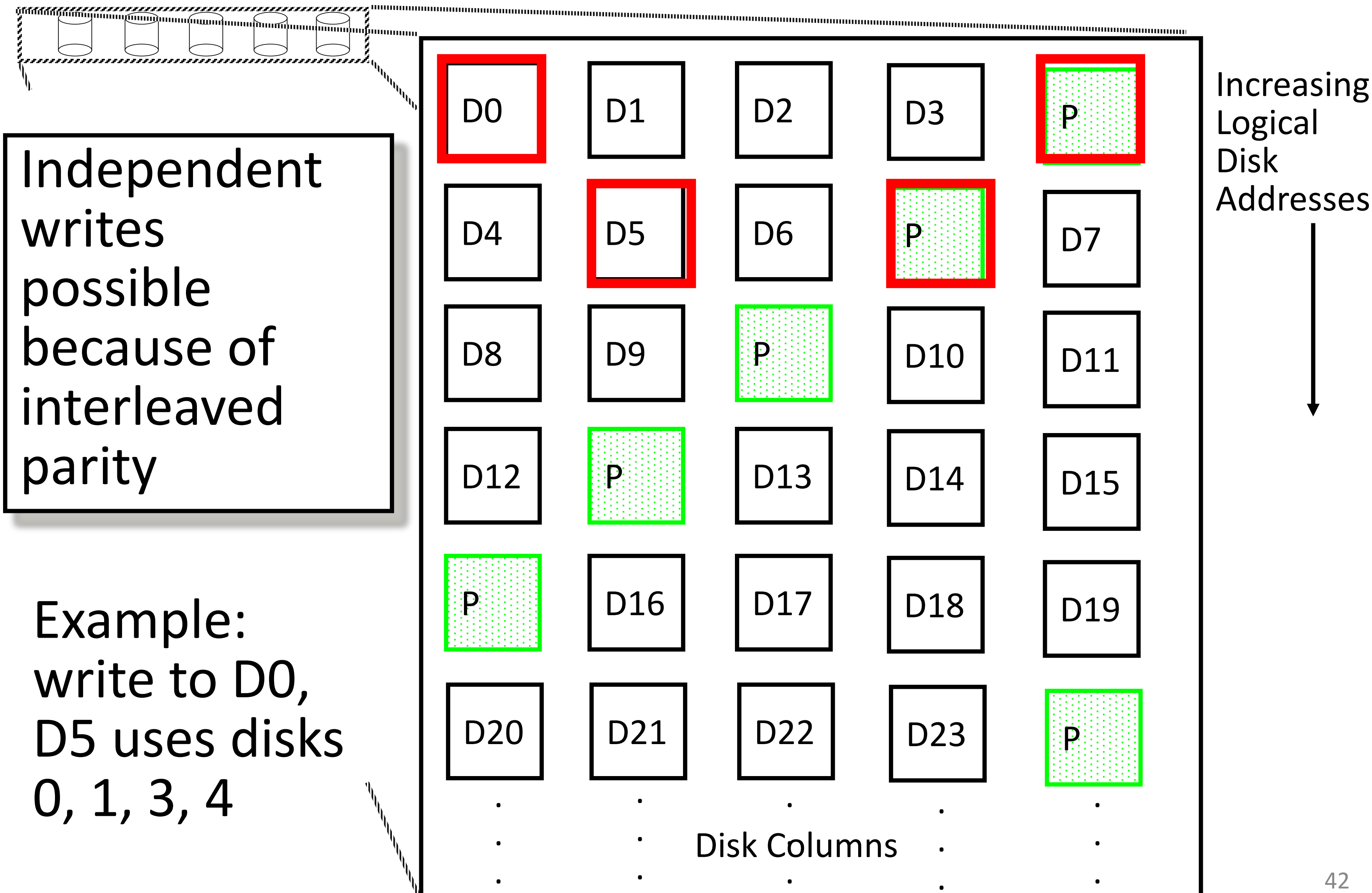
- RAID 4 works well for small reads
- Small writes (write to one disk):
  - Option 1: read other data disks, create new sum and write to Parity Disk
  - Option 2: since P has old sum, compare old data to new data, add the difference to P
- Small writes are limited by Parity Disk: Write to D0, D5 both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



RAID 5: High I/O Rate Interleaved Parity

Independent writes possible because of interleaved parity

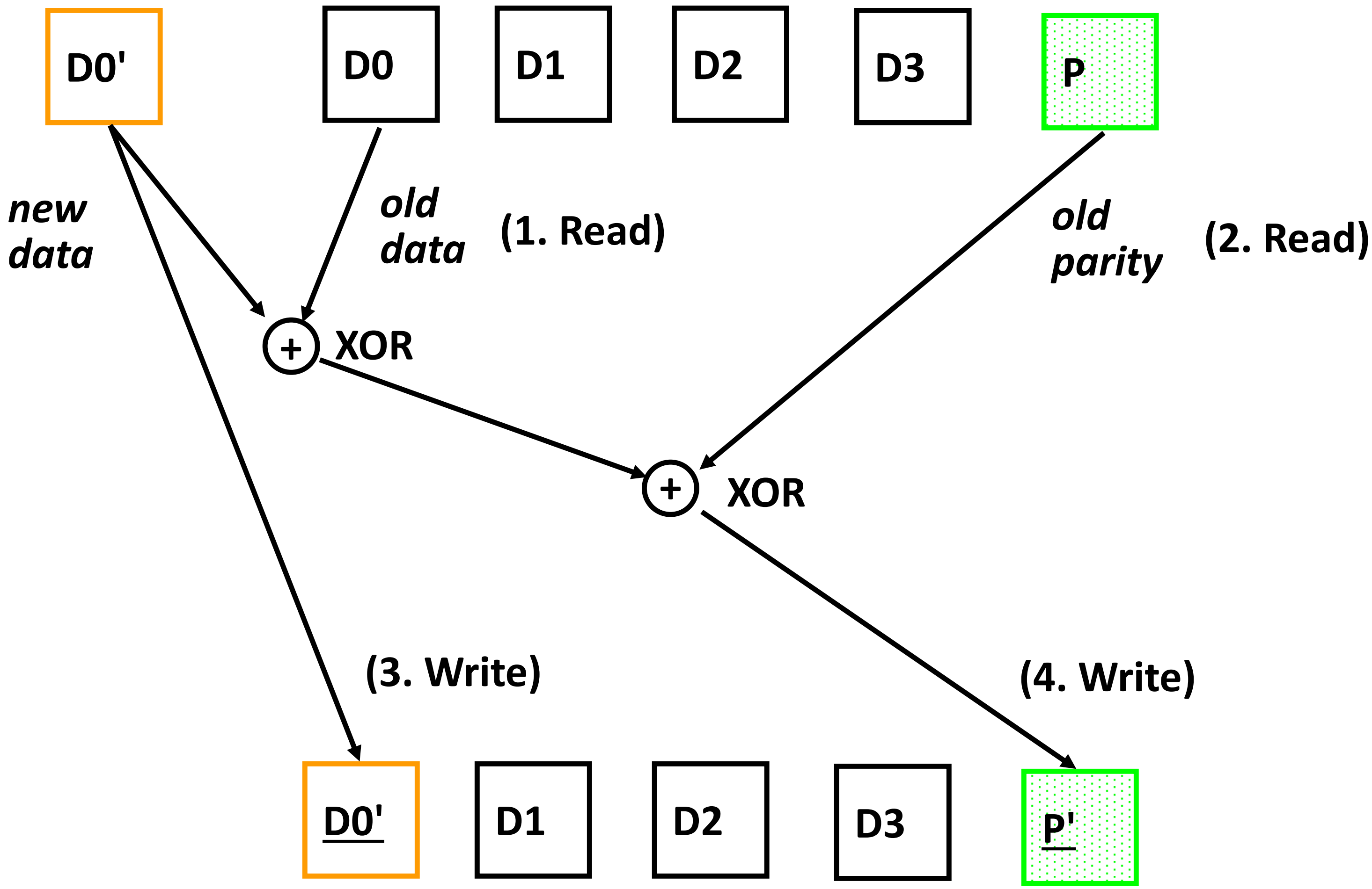
Example: write to D0, D5 uses disks 0, 1, 3, 4



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