CS 370: Operating Systems
[Mass Storage]

Shrideep Pallickara
Computer Science
Colorado State University

Computer Science Department   Colorado State University

1

Frequently asked questions from the previous class survey

- For contiguous allocation on HDDs, does it all have to be on the same track?
- Wouldn't there always be some level of fragmentation for a file that is continuously growing?
- If the metadata for a filesystem is lost (e.g., iNode array, MFT records) would that mean you lose all data on that disk?
- iNodes
  - Cannot hold any data, correct?
  - Are the FCB?
- Is the table for linked list allocations referencing logical or physical addresses?
- What is the purpose of a hard link?

Colorado State University   Professor: Shrideep Pallickara Computer Science Department   Mass Storage   L29.2

2

Topics covered in this lecture

- Wrap-up of File Systems
  - NTFS
- Flash Memory
- RAID

3

WINDOWS NEW TECHNOLOGY FILE SYSTEM (NTFS)

4

New Technology File System (NTFS)

- NTFS was first released in 1993
- Improved on Microsoft's FAT file system with many new features
  - Including new index structures to improve performance, more flexible file metadata, improved security, and reliability

NTFS: Extents and flexible trees

- Rather than tracking individual file blocks, NTFS tracks **extents**
  - Variable-sized regions of files that are each stored in a contiguous region on the storage device
- Whereas UFS tracks file blocks with a fixed tree, NTFS tracks extents with flexible trees
  - Many other recent file systems such as Linux ext4 and btrfs now leverage this idea as well

Representation of files

- Each file in NTFS is represented by a **variable-depth tree**
- The extent pointers for a file with a small number of extents can be stored in a **shallow tree**, even if the file, itself, is large
- Deeper trees are only needed if the file becomes badly fragmented

The NTFS Master File Table (MFT)

- The roots of these trees are stored in an MFT similar to the UFS/FFS inode array
- NTFS uses **attribute records** to store both data and metadata — both are just considered attributes of a file
- NTFS's MFT stores an **array of 1 KB MFT records**, each of which stores a sequence of variable-size attribute records
- An MFT record has a flexible format that can include range of different attributes

In addition to data attributes, an MFT record has three common metadata attribute types [1/2]

- **Standard information**
  - Needed for all files and includes the file's creation time, modification time, access time, owner ID, and security specifier
  - Also includes a set of flags indicating basic information like whether the file is a read only file, a hidden file, or a system file
- **File name**
  - Holds the file's name and the file number of its parent directory
  - Because a file can have multiple names (e.g., if there are multiple hard links to the file), it may have multiple file name attributes in its MFT record

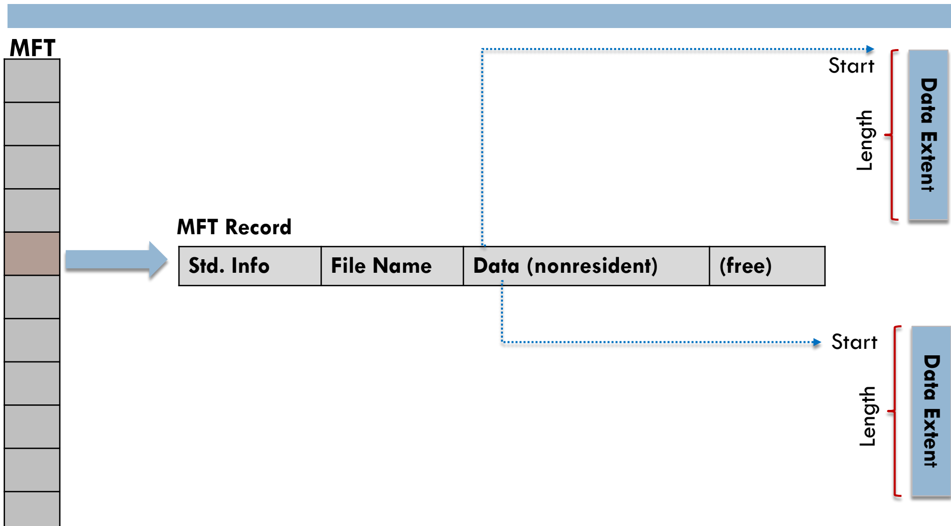
In addition to data attributes, an MFT record has three common metadata attribute types [2/2]

- **Attributes list**
  - A file's metadata may include a *variable number* of variable sized attributes
  - Thus, a file's metadata may be larger than a single MFT record can hold
    - Store the attributes multiple records
    - The attribute list is stored in the first record

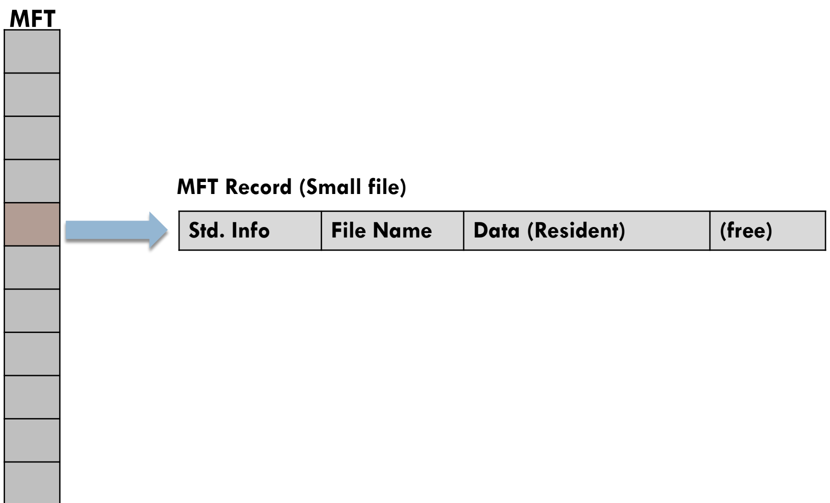
Resident and non-resident attribute records

- Some attributes can be too large to fit in an MFT record (e.g., data extents)
  - While some can be small enough to fit (e.g., a file's last modified time)
- An attribute can therefore be **resident** or **non-resident**
  - A resident attribute stores its contents directly in the MFT record
  - A non-resident attribute stores extent pointers in its MFT record and stores its contents in those extents

NTFS index structure for basic file with 2 data extents



A small file's data can be resident, meaning the file's data is stored in the MFT record



Metadata files

- NTFS stores almost *all of its metadata* in about a **dozen ordinary files** with well-known low-numbered file numbers
  - File number 2, log of metadata changes
  - File number 3 (volume), 4 (attribute definitions)
  - File number 5 is the root directory
  - File number 6 is the free space bitmap, 7 (volume boot record)
  - File number 8 contains a list of the volume's bad blocks
  - File number 9, called `$Secure`, contains security and access control info
  - File number 10 (Unicode upper case table), 11 (optional extensions)

How is the MFT stored? [1/2]

- Even the master file table, itself, is stored as a file, **file number 0**, called **$MFT**
  - File number 1 is a **mirror** of the $MFT
- So, we need to find the first entry of the MFT in order to read the MFT!
- To locate the MFT, the **first sector of an NTFS volume** includes a pointer to the first entry of the MFT

How is the MFT stored? [2/2]

- Storing the MFT in a file avoids the need to statically allocate all MFT entries as a fixed array in a predetermined location
- Instead, NTFS starts with a small MFT and grows it as new files are created and new entries are needed

NTFS Reserve Areas [1/2]

- To avoid having the master file table file ($MFT) become fragmented, NTFS **reserves part of the start of the volume**
  - E.g., the first 12.5% of the volume, for MFT expansion
- NTFS does not place file blocks in the MFT reserve area until the non-reserved area is full
  - At which point it halves the size of the MFT reserve area and continues

NTFS Reserve Areas [2/2]

- As the volume continues to fill, NTFS continues to halve the reserve area until it reaches the point where the remaining reserve area is more than half full
- Finally, Microsoft operating systems with NTFS include a **defragmentation utility** that takes fragmented files and rewrites them to contiguous regions of disk

NTFS: Locality heuristics

- Rather than trying to keep the allocation bitmap for the entire disk in memory
  - The system caches the allocation status for a smaller region of the disk and searches that region first

COLORADO STATE UNIVERSITY Professor: SHRIDEEP PALLICKARA COMPUTER SCIENCE DEPARTMENT MASS STORAGE L29.19

19

20

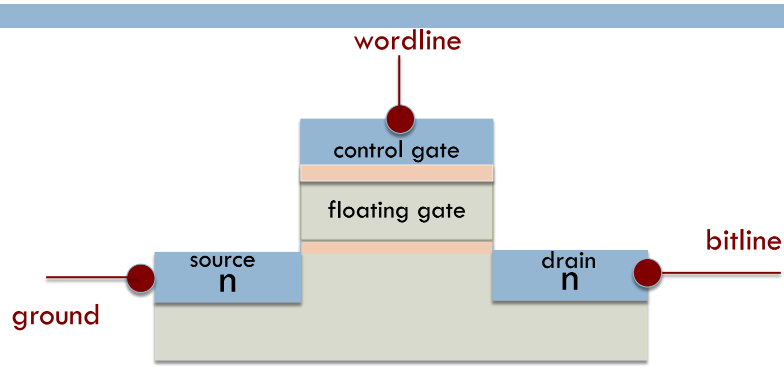
Flash memory is a type of a solid-state storage

- No moving parts … and stores data using electrical circuits
  - Can have better random I/O performance than HDDs, use less power, and is less vulnerable to physical damage
  - But significantly more expensive per byte

Transistors

- It takes one transistor to store a bit
- Ordinary transistors are electronic switches
  - Turned on and off by electricity
- Strength: Computer can store information simply by **passing patterns of electricity** through its memory circuits
- Weakness: As soon as power is turned off, transistors revert to their original state (loses all information)
  - Electronic amnesia!

Transistors in flash memory



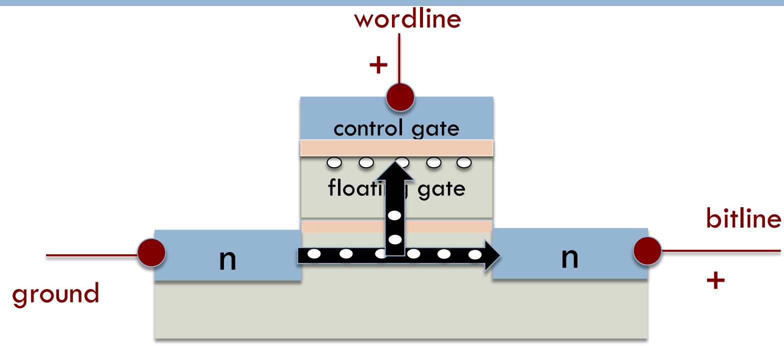
The source and drain regions are rich in electrons (n-type silicon)

Electrons cannot flow from source to drain, because of the electron-deficient p-type material between them

A gate that floats?

- The extra gate in our transistor "floats" — it is not connected to any circuit
- Since the floating gate is <u>entirely surrounded</u> by an **insulator**, it will hold an electrical charge for months or years without requiring any power
- Even though the floating gate is not electrically connected to anything, it can be charged or discharged
  - Via **electron tunneling** by running a sufficiently high-voltage current near it

Transistors in flash memory



The presence of electrons on the floating gate is how a flash transistor stores a **one**

Electrons stay there indefinitely, even when positive voltages are removed AND whether power is supplied to the unit or not

Electrons can be flushed out by putting a negative voltage on the wordline. REPELS electrons back.

How do you read what is stored in the floating gate?

- The floating gate's state of charge affects the transistor's threshold voltage for activation
- State can be detected by applying an **intermediate voltage** to the transistor's control gate
  - Intermediate voltage will only be sufficient to activate the transistor if the floating gate is charged

Flash storage: Erasure blocks

- Before flash memory can be written, it must be *erased* by setting each cell to a logical "1"
- Can only be erased in large units called **erasure blocks** (128-512 KB)
- Slow operation: takes several milliseconds
- Erasing an erasure block is what gives "flash memory" its name ...
  - Resemblance to the flash of a camera

Write page and read page

- Write Page:
  - Once erased, flash memory can be written on a page-by-page basis
  - Each page is typically 2-4 KB
  - Writing a page takes about 10s of microseconds
- Read page
  - Flash memory is read on a page-by-page basis
  - Reading a page takes about 10s of microseconds

Challenges in writing to a page

- To write a page, it's **entire erasure block** must first be erased
  - Erasure is slow and affects a large number of pages
- Flash translation layer (FTL)
  - Maps logical flash pages to different physical pages on the flash device
  - When logical page is overwritten, the FTL writes the new version to a free, already-erased physical page
    - … and remaps logical page to that physical page
  - Write remapping significantly improves performance

Durability [1/2]

- Normally, flash memory can retain state for months or years without power
- However, **high current loads** from flashing and writing memory *causes circuits to degrade*
  - After a few 1000~1,000,000 erase cycles, **a cell may wear out** … cannot reliably store a bit

Durability [2/2]

- Reading a flash memory cell a large number of times causes surrounding cells' charges to be **disturbed**
  - **Read disturb error**: Location in memory read too many times without surrounding memory being rewritten

Improving durability

- Error correcting codes
- Bad page and bad erasure block management
  - Firmware stops storing data on defective blocks
- **Wear leveling**
  - Move logical pages to different physical pages to ensure *no physical page gets inordinate number of writes* and wears out prematurely
  - Some algorithms also migrate unmodified pages to protect against read disturb errors
- Spare pages and erasure blocks

Parameters for the Intel 710 Series SSD

- Capacity 300 GB
- Page Size 4 KB

- Performance
  - Bandwidth (Sequential Reads) 270 MB/s
  - Bandwidth (Sequential Writes) 210 MB/s
  - Read/ Write Latency 75 μs
  - Random Reads Per Second 38,500
  - Random Writes Per Second 2,000
    - 2,400 with 20% space reserve

Parameters for the Intel 710 Series SSD

- Interface SATA 3 Gb/ s

- Endurance
  - Endurance 1.1 PB
  - 1.5 PB with 20% space reserve

- Power
  - Power Consumption Active/ Idle 3.7 W / 0.7 W

RAID STRUCTURE

COMPUTER SCIENCE DEPARTMENT — COLORADO STATE UNIVERSITY

35

RAID involves using large number of disks in parallel

- Improves **rate** at which data be can read/written
- Increases **reliability** of storage
  - Redundant information can be stored on multiple disks
  - Failure of 1 disk should not result in loss of data
- Redundant Array of ~~Inexpensive~~ **Independent** Disks

COLORADO STATE UNIVERSITY — Professor: SHRIDEEP PALLICKARA, COMPUTER SCIENCE DEPARTMENT — MASS STORAGE — L29.36

36

RAID levels

- Standardized by the Storage Networking Industry Association (SNIA)
  - In the Common RAID Disk Drive Format (DDF) standard
- Originally there were 5 levels
- There are other nested levels

Reliability through redundancy

- Store information that is <u>not normally needed</u>
- Can be used in the event of disk failure
  - **Rebuild** lost information
- Simplest approach: **Mirroring**
  - Duplicate every disk
  - Data lost only if 2nd disk fails BEFORE 1st one is replaced
  - Watch for: Correlated failures

RAID parallelism

- **Stripe** data across disks
- Objectives
  1. Increase throughput
  2. Reduce response times of large accesses

RAID Parallelism: Stripe data across disks **Bit level** striping

- **Split bits** of each byte across multiple disks
  - 8 disks: Bit `i` of each byte written to disk `i`
  - Bit 3 written to disk 3
- Array of 8 disks treated as a single disk
  - 8 times the access rate
  - Every disk participates in every read/write

RAID Parallelism: Block-level striping

- **Blocks** of a file are striped across multiple disks
- When there are `n` disks
  - Block `i` of the file written to …
  - Disk: `(i mod n) + 1`
    - 4 disks: Block 8 of file goes to disk 1
    - 4 disks: Block 9 of file goes to disk 2

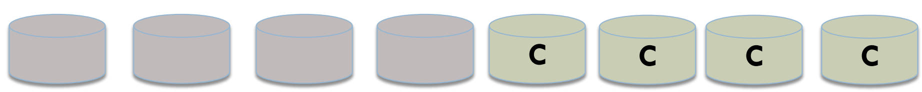
RAID levels

- Striping improves transfer rates
  - BUT not reliability
- Disk striping usually combined with **parity**
- Different schemes classified according to levels
  - RAID levels

RAID 0: Stripe blocks without redundancy

- No mirroring
- No parity

RAID 1: Disk mirroring

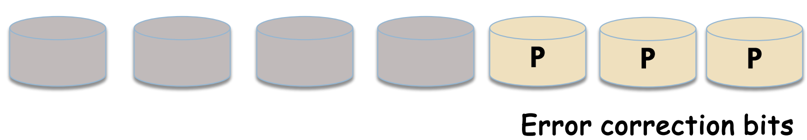


- Each disk is mirrored

RAID 2: Memory style error correcting code

- **Parity bit** records number of 1 bits in byte
  - Even: parity 0
  - Odd: parity 1
- Use to detect single-bit errors
- Error correcting schemes
  - 2 or more extra bits to recover from single-bit errors

RAID 2: Error Correcting Codes

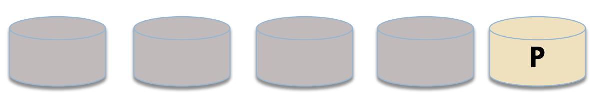


- **If one disk fails:**
- Remaining bits of the byte **+** error correction bits
  - Read from other disks
- **Reconstruct** damaged data

RAID 3: Single parity bit used for error correction

- We can identify damaged sector
- Figure out if any bit in sector is 0 or 1
  - Compute parity of corresponding bits from other sectors
    - If parity of remaining bits == stored parity
      - Missing bit = 0
    - Otherwise, missing bit = 1

RAID 3: Single parity bit used for error correction



Error correction bits

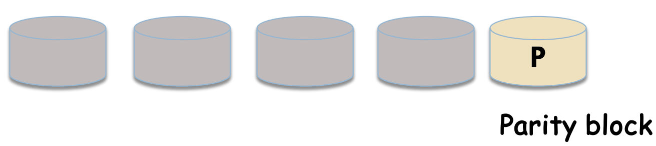
Issues

- Fewer I/Os per-second since every disk participates in every I/O
- Overheads for computing parity bits

RAID-4
Block interleaved parity

- Block-level striping
  - Block read accesses only one disk
  - Data transfer rate slower for each access
  - Multiple reads proceed in parallel
    - Higher overall I/O rate
- **Parity block** on a separate disk

RAID 4:
Block interleaved parity



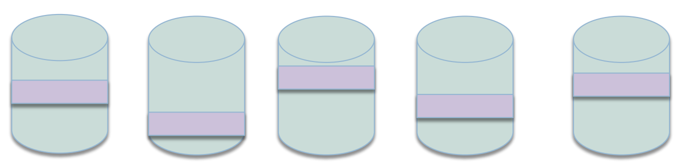
If one disk fails

- Parity block used with corresponding blocks
  - Restore blocks of failed disk

RAID-5
Block interleaved **distributed** parity

- **Spread** data and parity among all **N+1** disks
  - Avoid overuse of single parity disk
- Parity block does not store parity for blocks on the same disk

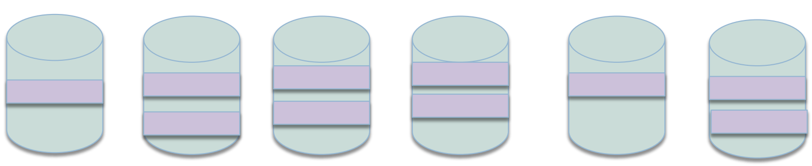
RAID 5:
Block interleaved distributed parity



RAID-6

- Store extra redundant information
  - Guard against **multiple** disk failures
- Error correcting codes are used
  - Reed-Solomon codes
- 2-bits of redundant data
  - For every 4-bits of data

RAID-6



In the computer science department

- RAID 1
  - To mirror the root disks of the servers
- RAID 5
  - For all the "no_back_up" partitions
- RAID 6
  - For all data disks

The contents of this slide-set are based on the following references

- *Thomas Anderson and Michael Dahlin. Operating Systems: Principles & Practice. 2nd edition. ISBN: 978-0-9856735-2-9 [Chapter 12, 13]*
- *Avi Silberschatz, Peter Galvin, Greg Gagne. Operating Systems Concepts, 9th edition. John Wiley & Sons, Inc. ISBN-13: 978-1118063330.* [Chapter 10, 11]
- *Andrew S Tanenbaum and Herbet Bos. Modern Operating Systems. 4th Edition, 2014. Prentice Hall. ISBN: 013359162X/ 978-0133591620. [Chapter 5]*
- *Chris Woodford. Flash Memory. http://www.explainthatstuff.com/flashmemory.html*