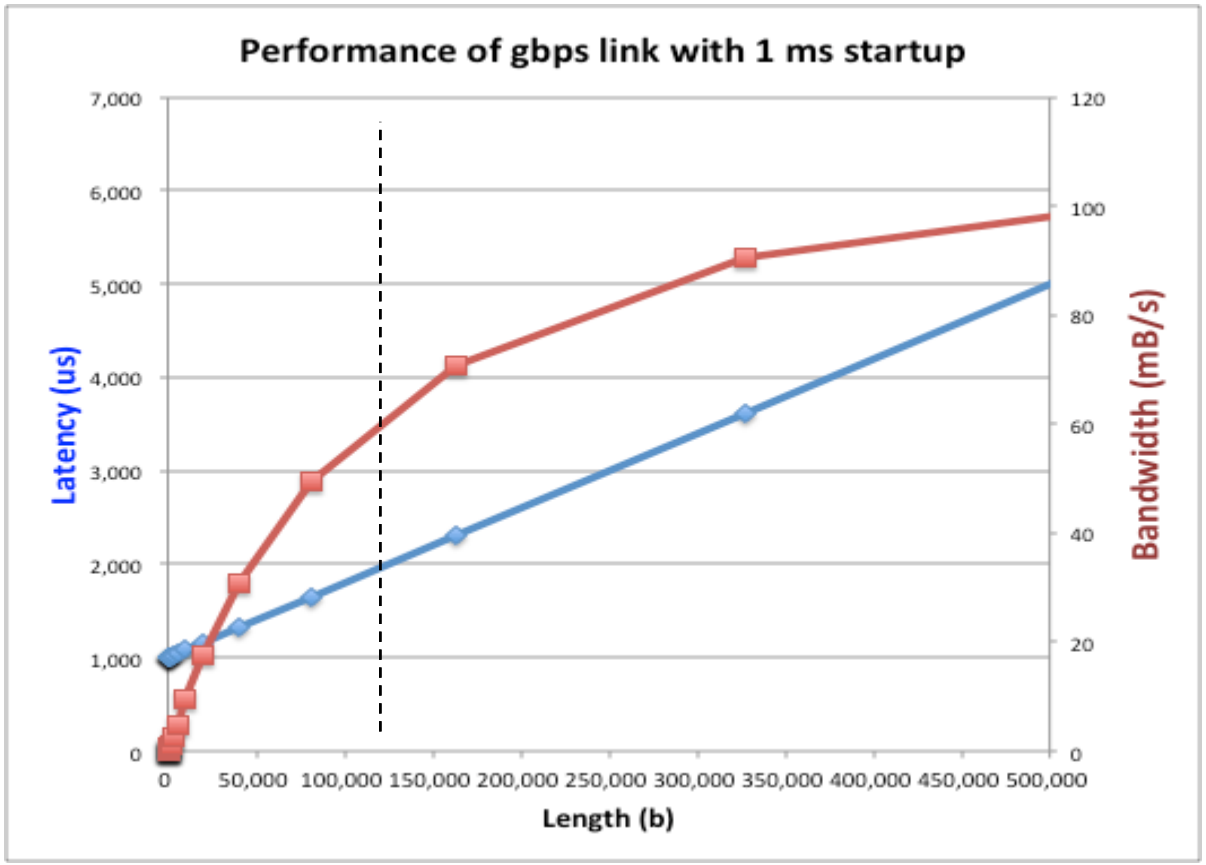
Lecture 11: File System

Bo Tang @ 2020, Spring

Clarification

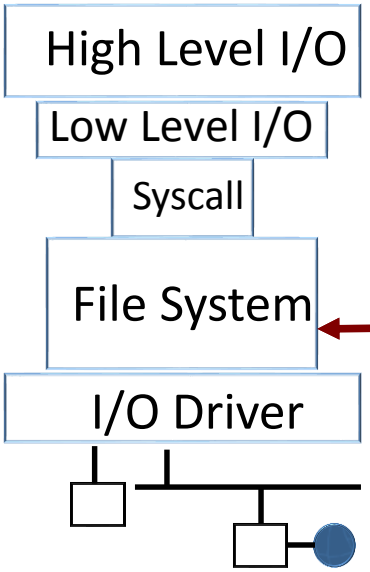
- Consider a 1 Gb/s (100Mb/s) link (Transfer capacity B = 125 MB/s)
  - With a startup cost S = 1 ms
  - What is the cost to transfer 1 GB (1024MB) data?



I/O & Storage Layers

Operations, Entities and Interface

Application / Service



streams

handles

registers

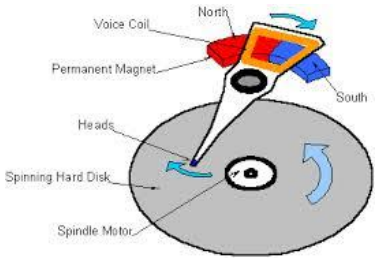
```
file_open, file_read, … on struct file * & void *
```

descriptors

we are here …

Commands and Data Transfers

Disks, Flash, Controllers, DMA



Recall: C Low level I/O

- Operations on File Descriptors – as OS object representing the state of a file
  - User has a "handle" on the descriptor

```
#include <fcntl.h>
#include <unistd.h>
#include <sys/types.h>

int open (const char *filename, int flags [, mode_t mode])
int create (const char *filename, mode_t mode)
int close (int filedes)
```

Bit vector of:
- Access modes (Rd, Wr, …)
- Open Flags (Create, …)
- Operating modes (Appends, …)

Bit vector of Permission Bits:
- User|Group|Other X R|W|X

http://www.gnu.org/software/libc/manual/html_node/Opening-and-Closing-Files.html

File System

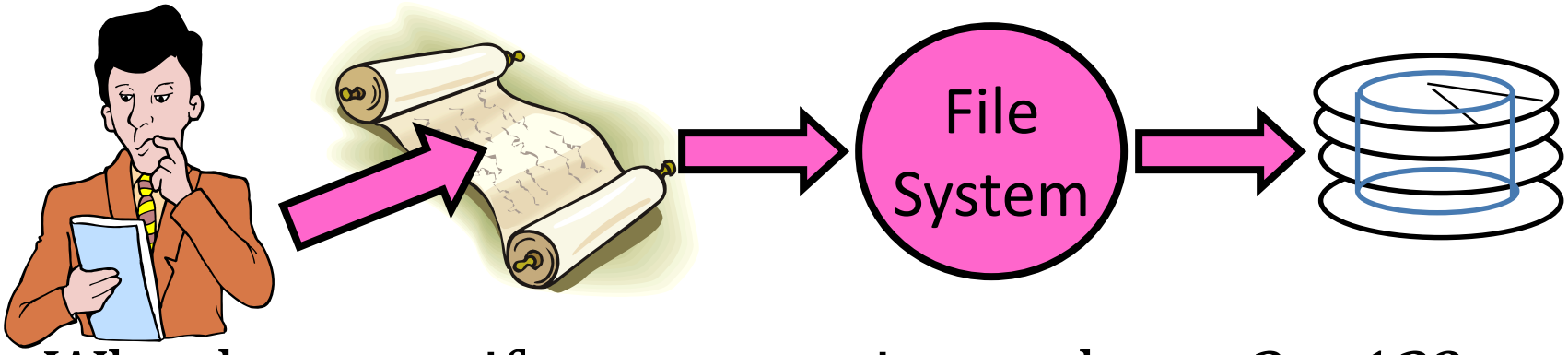
- File System: Layer of OS that transforms block interface of disks (or other block devices) into Files, Directories, etc.

- File System Components
  - **Naming:** Interface to find files by name, not by blocks
  - **Disk Management:** collecting disk blocks into files
  - **Protection:** Layers to keep data secure
  - **Reliability/Durability:** Keeping of files durable despite crashes, media failures, attacks, etc.

User vs. System View of a File

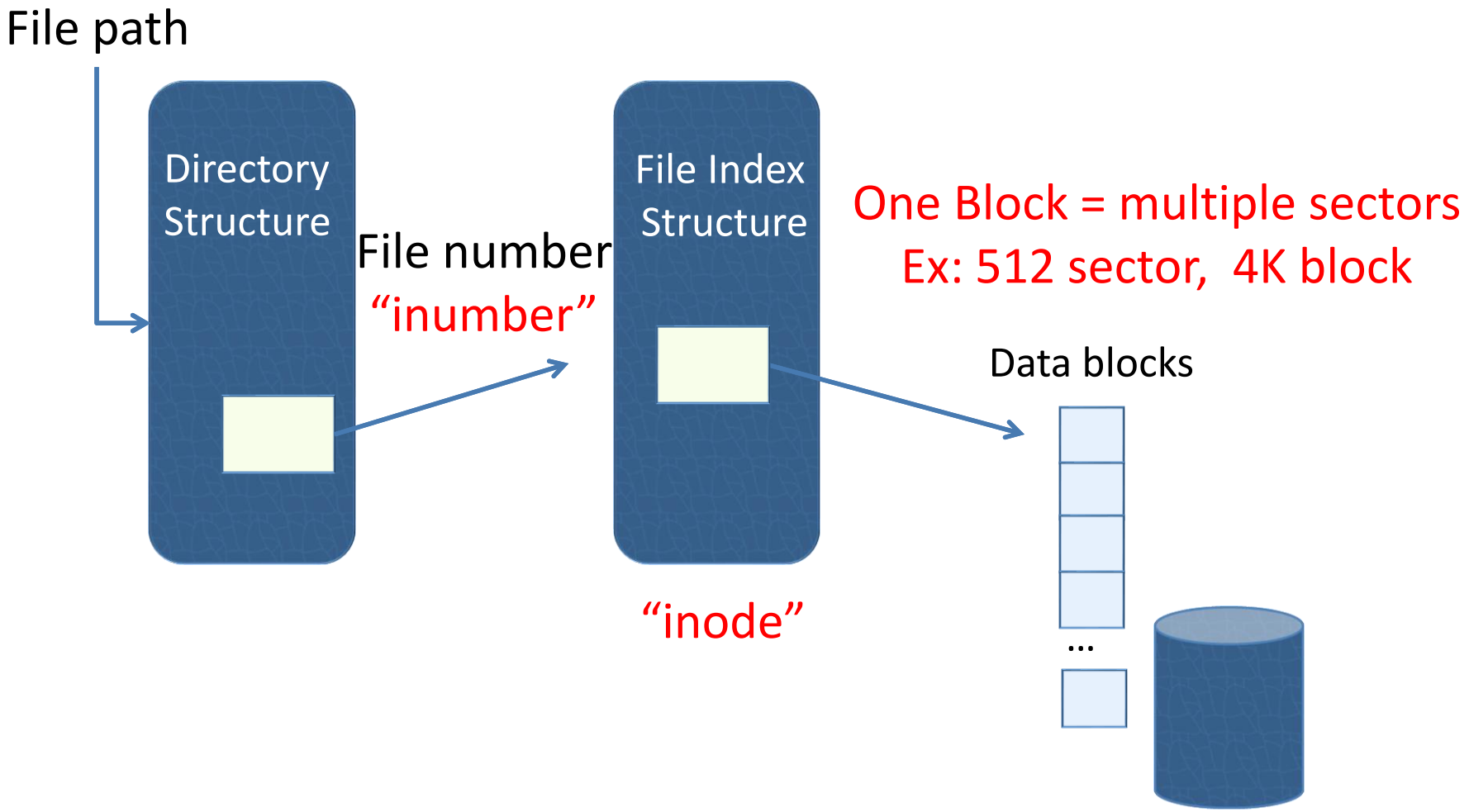
- User's view:
  - Durable Data Structures
- System's view (system call interface):
  - Collection of Bytes (UNIX)
  - Doesn't matter to system what kind of data structures you want to store on disk!
- System's view (inside OS):
  - Collection of blocks (a block is a logical transfer unit, while a sector is the physical transfer unit)
  - Block size ≥ sector size; in UNIX, block size is 4KB

Translating from User to System View



- What happens if user says: give me bytes 2—12?
  - Fetch block corresponding to those bytes
  - Return just the correct portion of the block
- What about: write bytes 2—12?
  - Fetch block
  - Modify portion
  - Write out Block
- Everything inside File System is in whole size blocks
  - For example, `getc()`, `putc()` ⇒ buffers something like 4096 bytes, even if interface is one byte at a time
- From now on, file is a collection of blocks

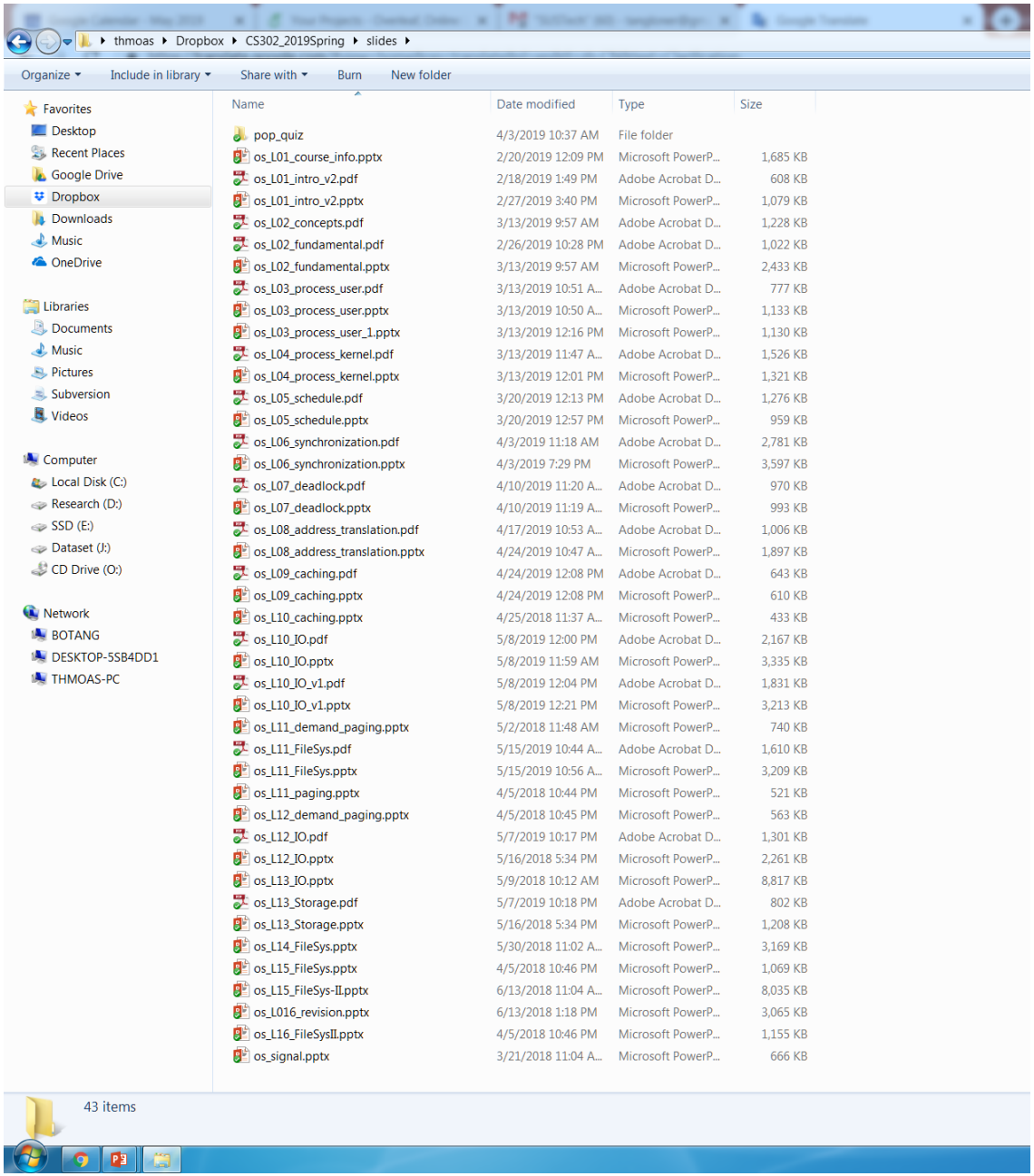
Components of a File System



Directory

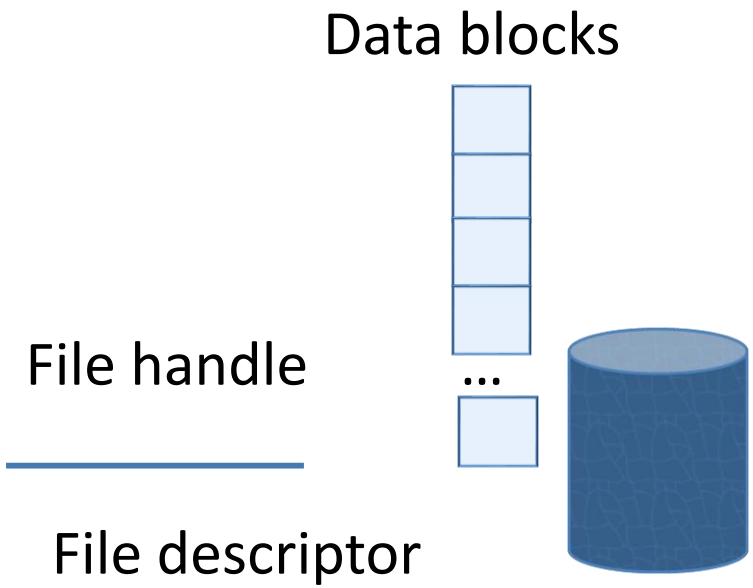
- Basically a hierarchical structure
- Each directory entry is a collection of
  - Files
  - Directories
    - A link to another entries
- Each has a name and attributes
  - Files have data
- Links (hard links) make it a DAG, not just a tree
  - Softlinks (aliases) are another name for an entry

Directories

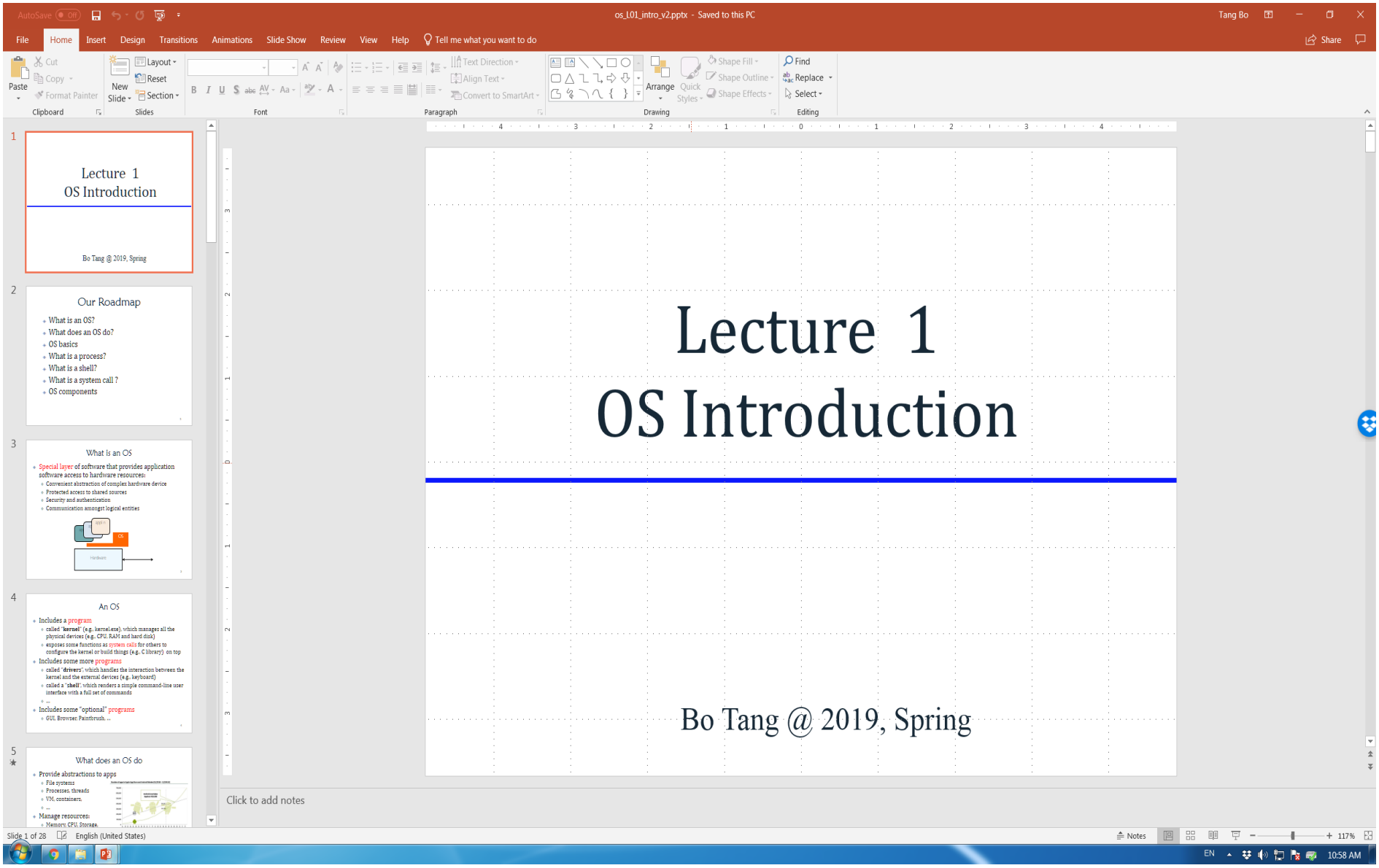


File

- Named permanent storage
- Contains
  - Data
    - Blocks on disk somewhere
  - Metadata (Attributes)
    - Owner, size, last opened, …
    - Access rights
      - R, W, X
      - Owner, Group, Other (in Unix systems)
      - Access control list in Windows system



File


os_L01_intro_v2.pptx - Saved to this PC
Tang Bo
File
Home
Insert
Design
Transitions
Animations
Slide Show
Review
View
Help
Tell me what you want to do
Share
Paste
Cut
Copy
Format Painter
New Slide
Layout
Reset
Section
Text Direction
Align Text
Convert to SmartArt
Arrange
Quick Styles
Shape Fill
Shape Outline
Shape Effects
Find
Replace
Select
Clipboard
Slides
Font
Paragraph
Drawing
Editing
1
Lecture 1
OS Introduction
Bo Tang @ 2019, Spring
2
Our Roadmap
What is an OS?
What does an OS do?
OS basics
What is a process?
What is a shell?
What is a system call ?
OS components
3
What is an OS
4
An OS
5
What does an OS do
Lecture 1
OS Introduction
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Slide 1 of 28
English (United States)
Notes
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Disk Management Policies (1/2)

- Basic entities on a disk:
  - File: user-visible group of blocks arranged sequentially in logical space
  - Directory: user-visible index mapping names to files

- Access disk as linear array of sectors.
  - Two Options:
    - Identify sectors as vectors [cylinder, surface, sector], sort in cylinder-major order, not used anymore
    - Logical Block Addressing (LBA): Every sector has integer address from zero up to max number of sectors
  - Controller translates from address $\Rightarrow$ physical position
    - First case: OS/BIOS must deal with bad sectors
    - Second case: hardware shields OS from structure of disk

Disk Management Policies (2/2)

- Need way to track free disk blocks
  - Link free blocks together ⇒ too slow today
  - Use bitmap to represent free space on disk

- Need way to structure files: File Header
  - Track which blocks belong at which offsets within the logical file structure
  - Optimize placement of files' disk blocks to match access and usage patterns

File System

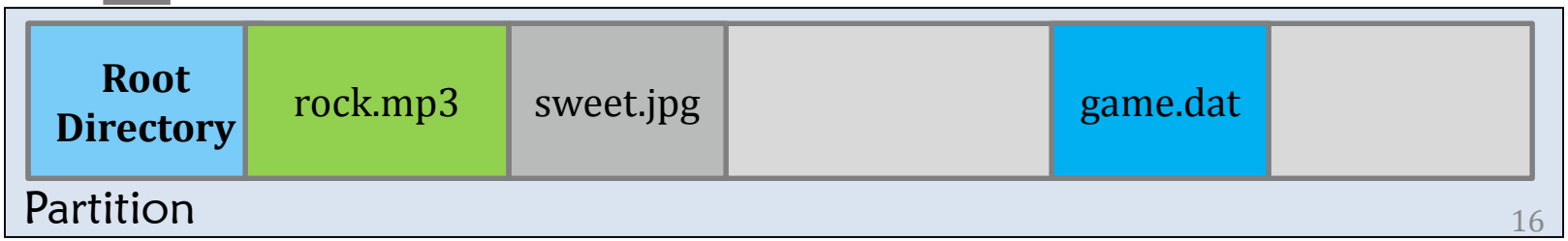
- Layout
  - contiguous allocation
  - linked allocation
  - inode allocation (next lecture)

Contiguous allocation – basics

Locate files easily.

Filename	Starting Address	Size
rock.mp3	100	1900
sweet.jpg	2001	1234
game.dat	5000	1000

Free space is here



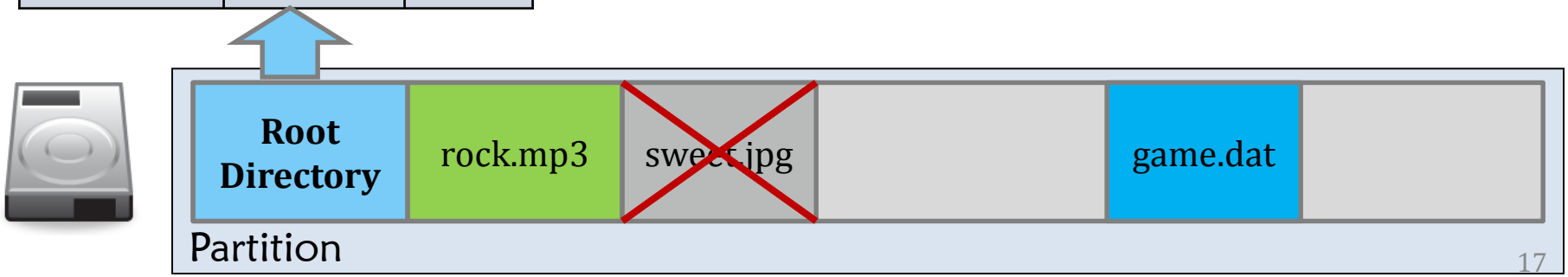
Contiguous allocation – basics

File deletion is easy! Space de-allocation is the same as updating the root directory!

Yet, how about file creation?

Filename	Starting Address	Size
~~rock.mp3~~	~~100~~	~~1900~~
sweet.jpg	2001	1234
game.dat	5000	1000

Filename	Starting Address	Size
rock.mp3	100	1900
game.dat	5000	1000

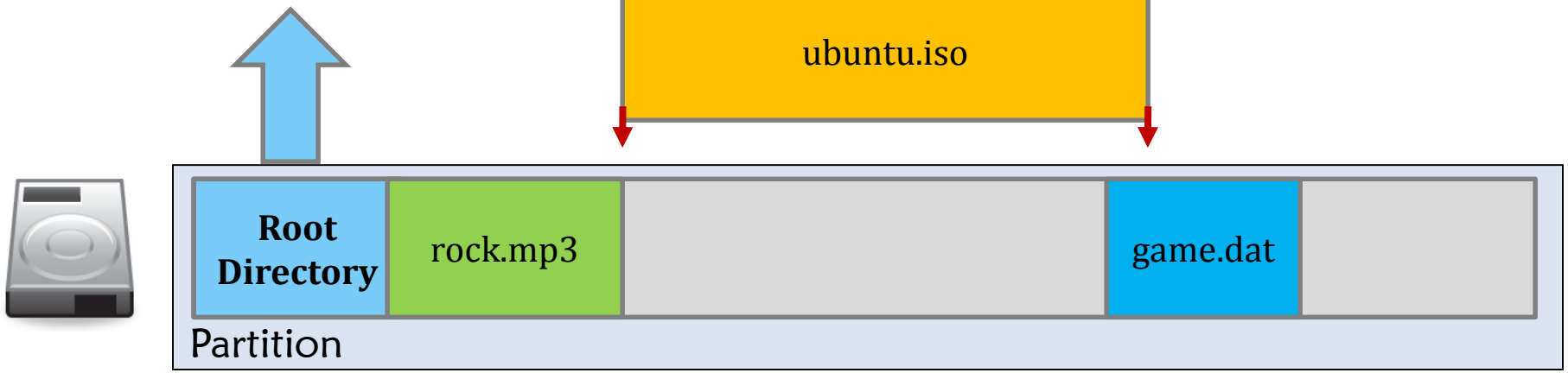


Contiguous allocation – basics

Really BAD! We have enough space, but there is no holes that I can satisfy the request. The name of the problem is called:

External Fragmentation

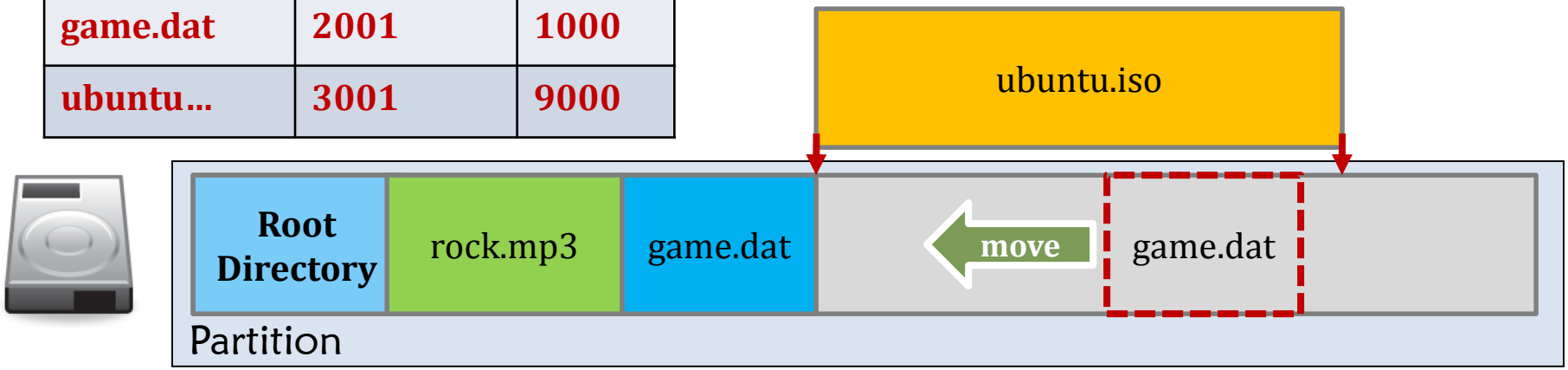
Filename	Starting Address	Size
rock.mp3	100	1900
game.dat	5000	1000



Contiguous allocation – basics

Defragmentation process may help!
You know, this is very expensive as you're working on disks.

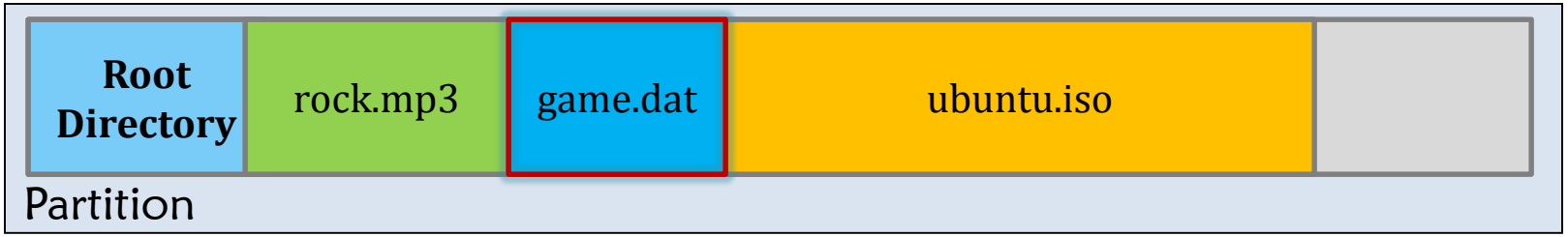
Filename	Starting Address	Size
rock.mp3	100	1900
game.dat	**2001**	**1000**
ubuntu…	**3001**	**9000**



Contiguous allocation – basics

Filename	Starting Address	Size
rock.mp3	100	1900
game.dat	2001	1000
ubuntu…	3001	9000

Growth problem!

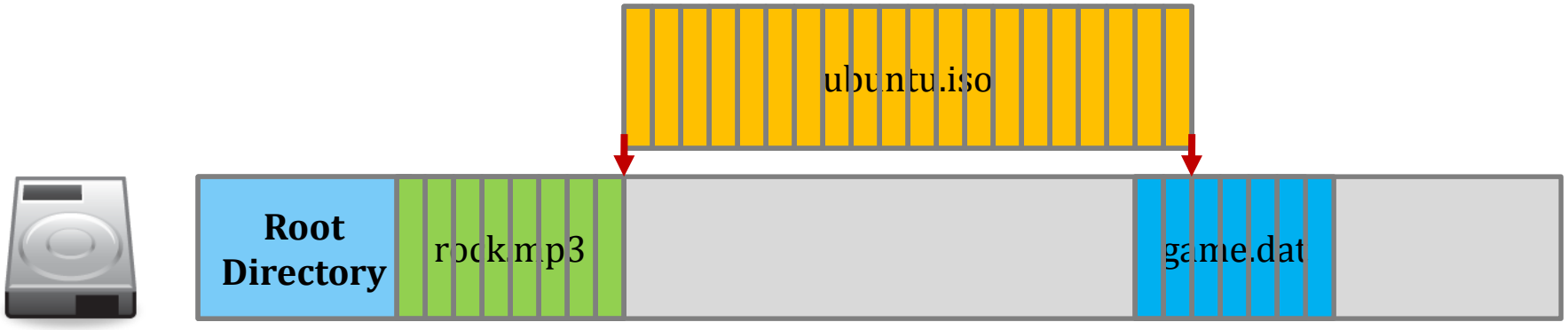


Contiguous allocation – application?

- ISO 9660
- CD-ROM
  - .iso image

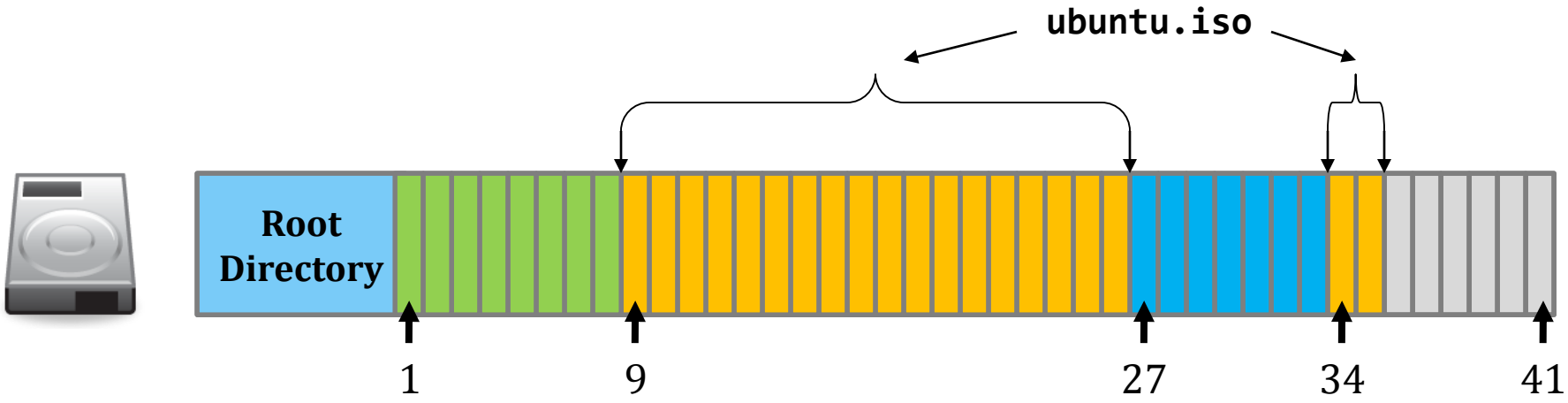
Linked allocation

- Let's borrow the idea from linked list…
  - Step (1) Chop the storage device and data into **equal-sized blocks**.



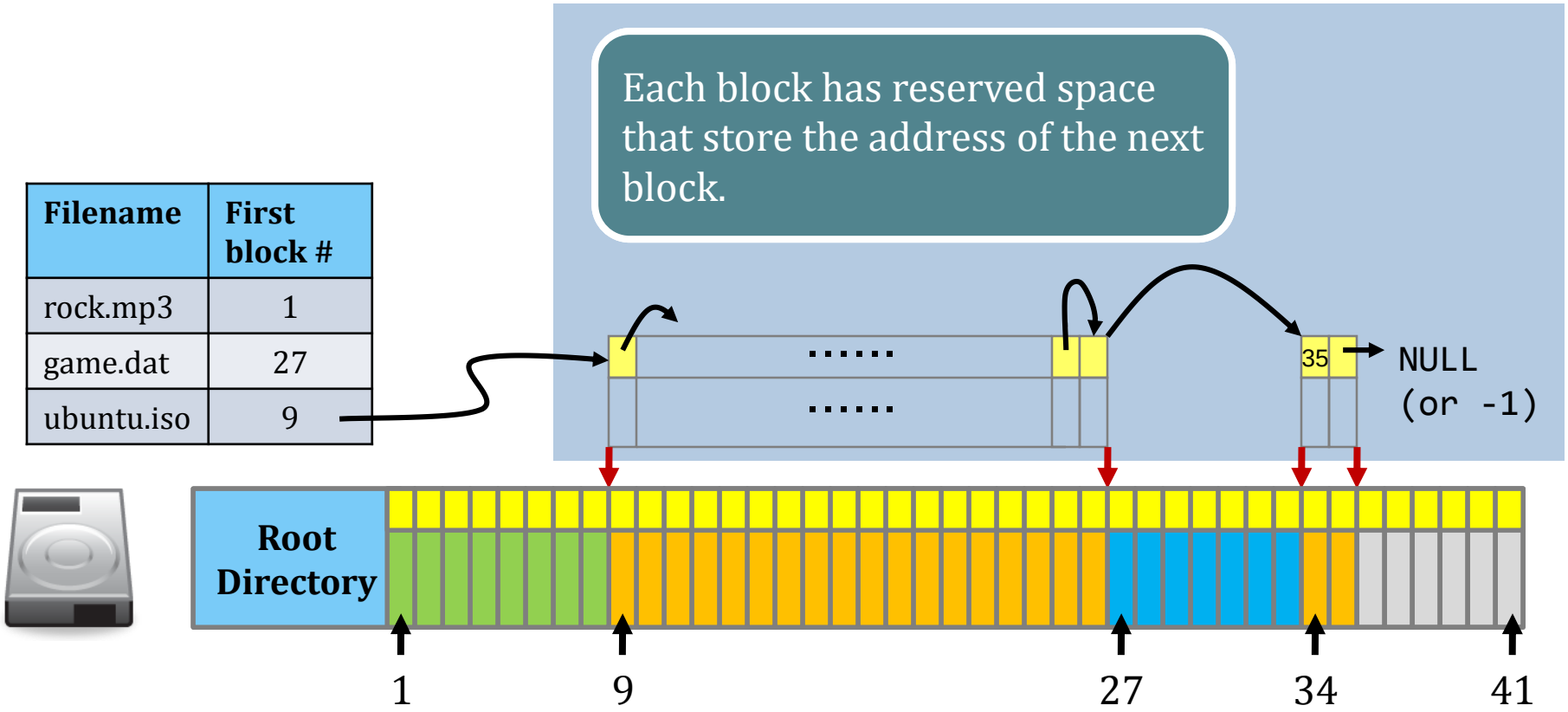
Linked allocation

- Let's borrow the idea from the linked list …
  - Step (1) Chop the storage device into **equal-sized blocks**.
  - Step (2) Fill the empty space in a **block-by-block** manner.



Linked allocation

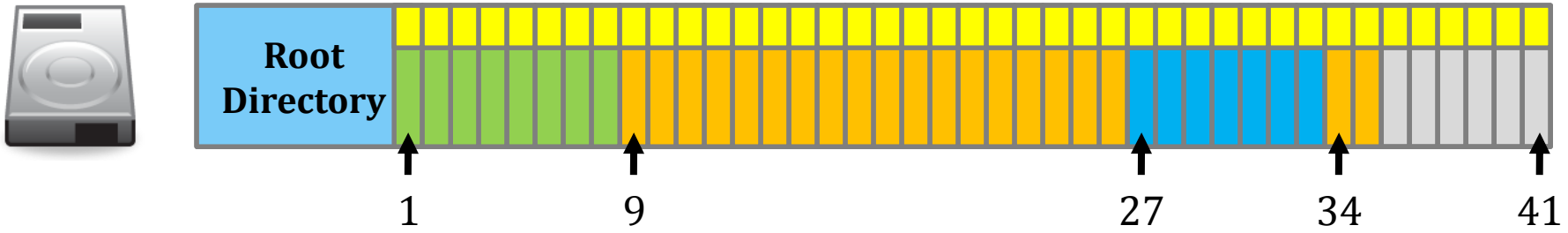
- Leave **4 bytes from each block** as the "pointer"
  - To write the block # of the next block into the first 4 bytes of each block.



Linked allocation

- Also keep the file size in the root directory table
  - To facilitate "ls –l" that lists the file size of each file
  - (otherwise needs to live counting how many blocks each file has)

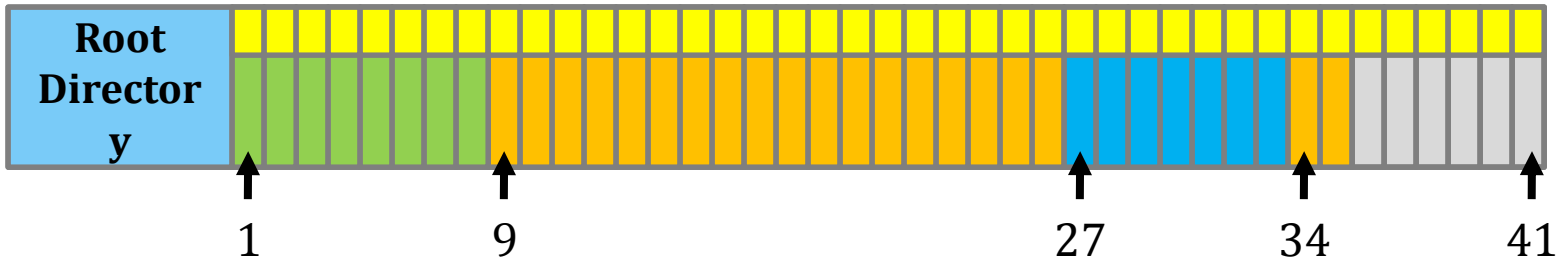
Filename	First block #	Size
rock.mp3	1	1900
game.dat	27	1000
ubuntu.iso	9	9000



Linked allocation

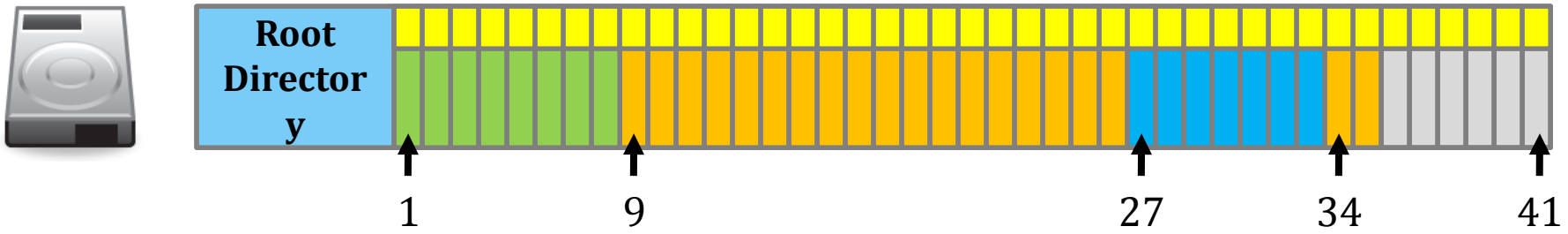
- So, how would you grade this file system?
  - External fragmentation?
  - File growth?

Filename	First block #	Size
rock.mp3	1	1900
game.dat	27	1000
ubuntu.iso	9	9000



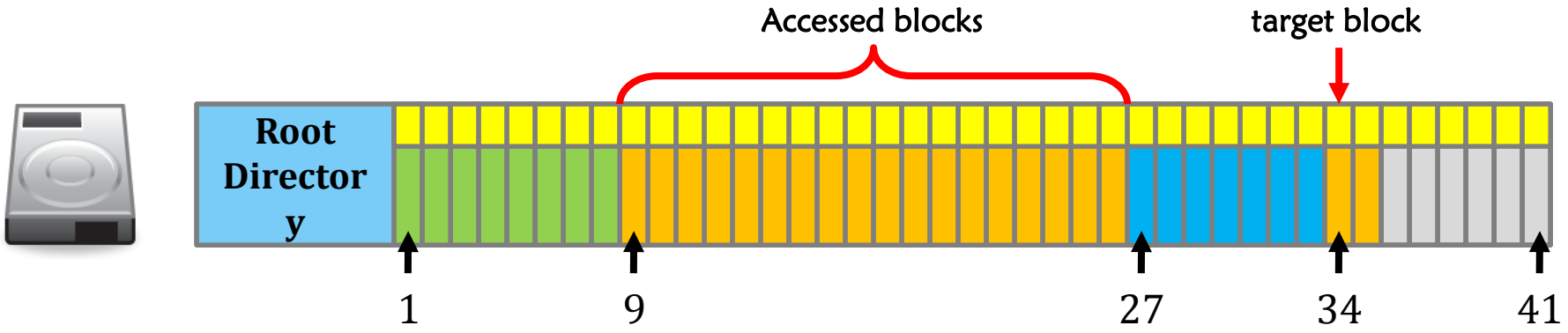
Linked allocation

- **Internal Fragmentation.**
  - A file is not always a multiple of the block size.
    - The last block of a file may not be **fully filled**.
    - E.g., a file of size 1 byte still occupies one block.
  - The remaining space will be wasted since no other files can be allowed to fill such space.



Linked allocation

- **Poor random access performance.**
  - What if I want to access the 2019-th block of ubuntu.iso?
  - **You have to access blocks 1 – 2018 of ubuntu.iso until the 2019-th block**



FAT

- Centralize all the block links as File Allocation Table

FAT

Task: read "ubuntu.iso" sequentially.

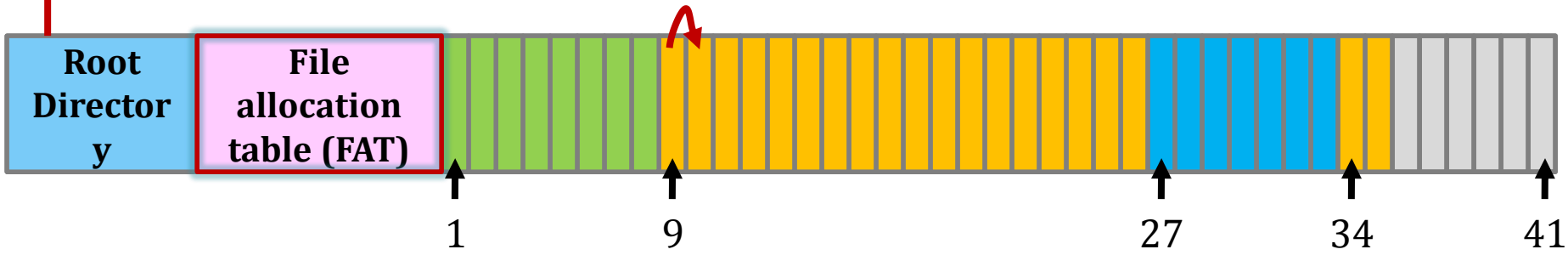
Filename	First block #	Size
rock.mp3	1	1900
game.dat	27	1000
ubuntu.iso	9	9000

Step 1. Read the root directory and retrieve the **first block number**.

Step 2. Read the FAT to determine the location of next block.

File allocation table (FAT)

Block #	1	...	7	8	9	...	26	27	...	32	33	34	35	...	41
Next Block #	2	...	8	-1	10	...	34	28	...	33	-1	35	-1	...	0



FAT

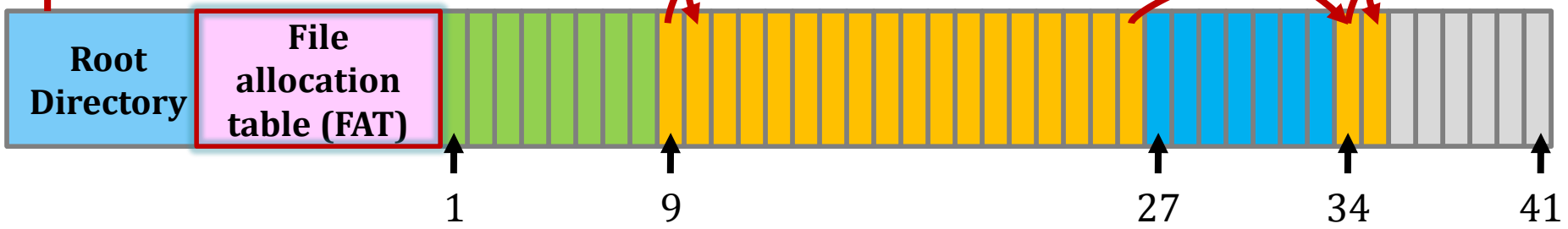
Task: read "ubuntu.iso" sequentially.

Filename	First block #	Size
rock.mp3	1	1900
game.dat	27	1000
ubuntu.iso	9	9000

Step 3. After reading the 2nd block, the process continues. Note that the blocks **may not be contiguously allocated**.

Step 4. The process stops until the FAT says the next block # is -1.

Block #	1	...	7	8	9	...	26	27	...	32	33	34	35	...	41
Next Block #	2	...	8	-1	10	...	34	28	...	33	-1	35	-1	...	0

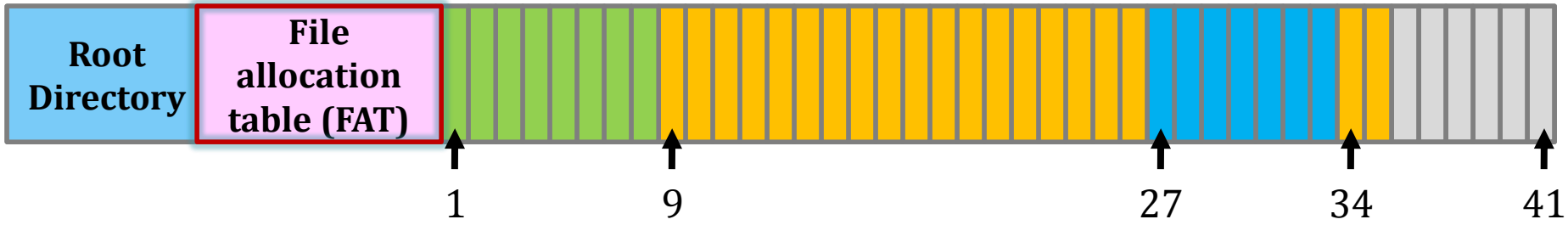


FAT

Resulting layout & file allocation.

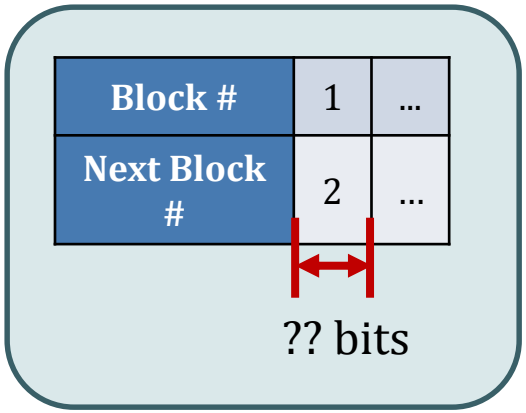
Filename	First block #	Size
rock.mp3	1	1900
game.dat	27	1000
ubuntu.iso	9	9000

Block #	1	...	7	8	9	...	26	27	...	32	33	34	35	...	41
Next Block #	2	...	8	-1	10	...	34	28	...	33	-1	35	-1	...	0



FAT

- Start from floppy disk and DOS
- On DOS, a block is called as a '**cluster**'
- E.g., FAT12
  - 12-bit cluster address
  - Can point up to 2^{12} = 4096 blocks



	FAT12	FAT16	FAT32
Cluster address length	12 bits	16 bits	28 bits
Number of clusters	2^{12} (4,096)	2^{16} (65,536)	2^{28}

MS reserves 4 bits (but nobody eventually used those)

FAT

- Size of a block (cluster):

Available block sizes (bytes)								
512	1K	2K	8K	16K	32K	64K	128K	256K

block **size: 32KB**

block **address: 28 bits**

E.g.,

File system size.

$$(32 \times 2^{10}) \times 2^{28} = 2^5 \times 2^{10} \times 2^{28}$$
$$= 2^{43} \quad (8\ TB)$$

*** but MS deliberately set its formatting tool to format it up to 32GB only to lure you to use NTFS**

FAT series – layout overview

	Propose	Size
Boot sector	FS-specific parameters	1 sector, 512 bytes
FSINFO	Free-space management	1 sector, 512 bytes
More reserved sectors	Optional	Variable, can be changed during formatting
FAT (2 pieces)	1 copy as backup	Variable, depends on disk size and cluster size.
Root directory	Start of the directory tree.	At least one cluster, depend on the number of directory entries.

Reserved sectors

A FAT partition

FAT series – directory traversal

Step (1) Read the directory file of the root directory starting from **Cluster #2**.

"**C:\windows**" starts from Cluster #123.

```
c:\> dir c:\windows
……
06/13/2007  1,033,216    gamedata.dat
08/04/2004     69,120    notepad.exe
……
c:\> _
```

A directory entry

Cluster #2		
Filename	**Attributes**	**Cluster #**
.	……	……
..	……	……
……	……	……
windows	……	123

FAT series – directory traversal

Step (2) Read the directory **file** of the "**C:\windows**" starting from **Cluster #123**.

```
c:\> dir c:\windows
……
06/13/2007   1,033,216     gamedata.dat
08/04/2004      69,120     notepad.exe
……
c:\> _
```

Cluster #123		
Filename	**Attributes**	**Cluster #**
.	……	……
..	……	……
……	……	……
notepad.exe	……	456

FAT series – directory entry

- A 32-byte directory entry in a directory file
- A directory entry is describing a file (or a sub-directory) under a particular directory

Bytes	Description
0-0	1st character of the filename (0x00 or 0xe5 means unallocated)
1-10	remaining characters of filename + extension.
11-11	File attributes (e.g., read only, hidden)
12-12	Reserved.
13-19	Creation and access time information.
20-21	High 2 bytes of the first cluster address (0 for FAT16 and FAT12).
22-25	Written time information.
26-27	Low 2 bytes of first cluster address.
28-31	File size.

Filename	Attributes	Cluster #
explorer.dat	.....	32

0	e	x	p	l	o	r	e	r	7
8	e	x	e	…	…	…	…	…	15
16	…	…	…	…	00	00	…	…	23
24	…	…	20	00	00	C4	0F	00	31

Note. This is the 8+3 naming convention.

8 characters for name +
3 characters for file extension

FAT series – directory entry

- The 1st block address of that file

Bytes	Description
0-0	1st character of the filename (0x00 or 0xe5 means unallocated)
1-10	7+3 characters of filename + extension.
11-11	File attributes (e.g., read only, hidden)
12-12	Reserved.
13-19	Creation and access time information.
20-21	High 2 bytes of the first cluster address (0 for FAT16 and FAT12).
22-25	Written time information.
26-27	Low 2 bytes of first cluster address.
28-31	File size.

Filename	Attributes	Cluster #
explorer.dat	.....	32

0	e	x	p	l	o	r	e	r	7
8	e	x	e	…	…	…	…	…	15
16	…	…	…	…	00	00	…	…	23
24	…	…	20	00	00	C4	0F	00	31

FAT series – directory entry

- Directory entry is just a structure.

Bytes	Description
0-0	1st character of the filename (0x00 or 0xe5 means unallocated)
1-10	7+3 characters of filename + extension.
11-11	File attributes (e.g., read only, hidden)
12-12	Reserved.
13-19	Creation and access time information.
20-21	High 2 bytes of the first cluster address (0 for FAT16 and FAT12).
22-25	Written time information.
26-27	Low 2 bytes of first cluster address.
28-31	File size.

Filename	Attributes	Cluster #
explorer.dat	.....	32

0	e	x	p	l	o	r	e	r	7
8	e	x	e	…	…	…	…	…	15
16	…	…	…	…	00	00	…	…	23
24	…	…	20	00	00	C4	0F	00	31

So, what is the largest size of a FAT32 file?

4G - 1 bytes

Bounded by the file size attribute!

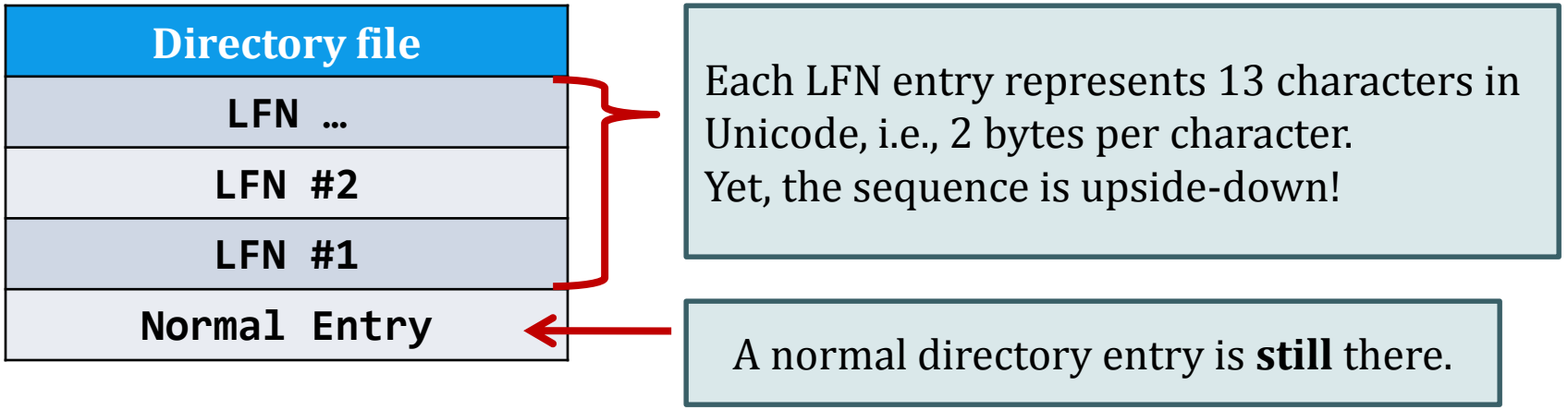
Why "– 1"?

- Imagine 3 bits: 000, 001, …, 110, 111
- Largest number is 111 = 2^3-1
- i.e., we also need to represent "0 bytes"

FAT series – LFN directory entry

- LFN: Long File Name.
  - In old days, Uncle Bill set the rule that every file should follow the 8+3 naming convention.
  - To support LFN

  - Abuse directory entries to store the file name!
  - Allow to use up to 20 entries for one LFN



FAT series – LFN directory entry

- Normal directory entry vs LFN directory entry

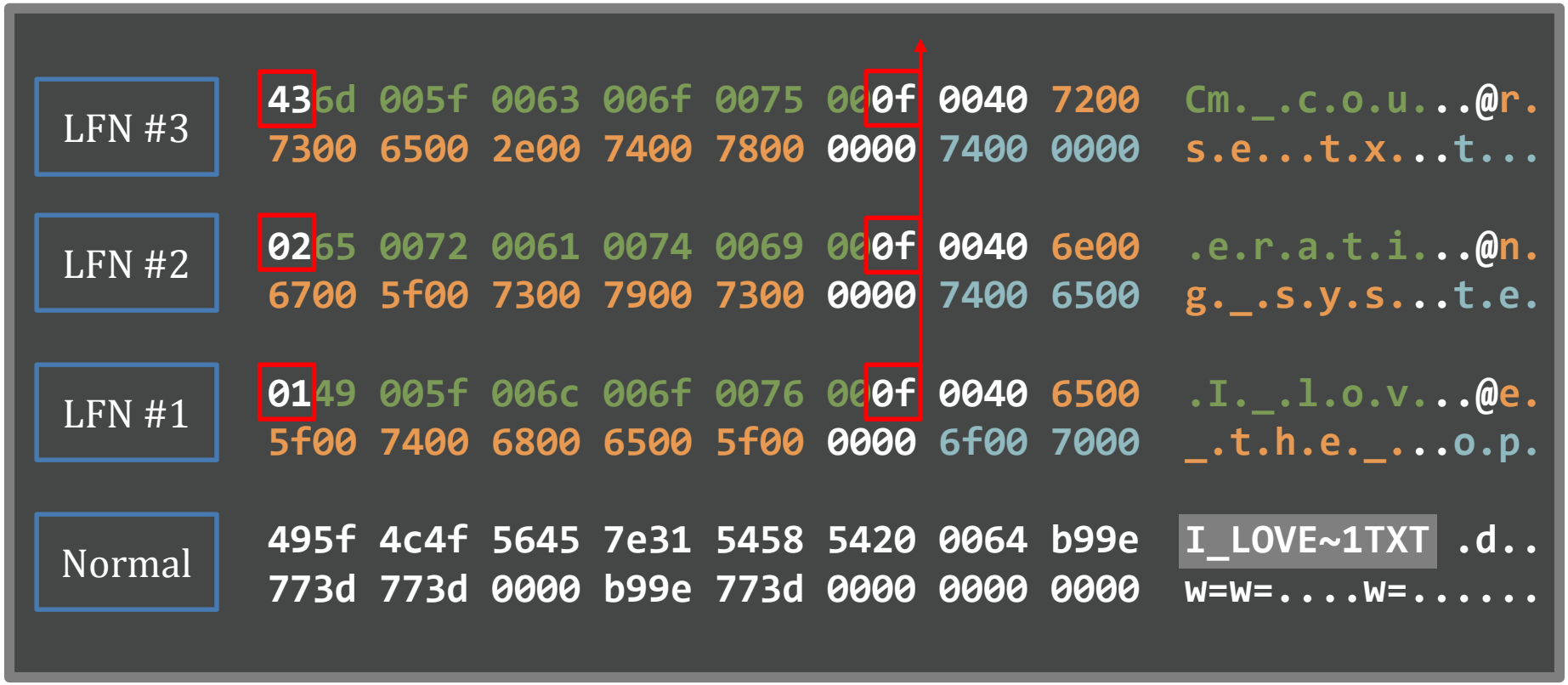
Bytes	Description
0-0	1st character of the filename (0x00 or 0xe5 means unallocated)
1-10	7+3 characters of filename + extension.
11-11	File attributes (e.g., read only, hidden)
12-12	Reserved.
13-19	Creation and access time information.
20-21	High 2 bytes of the first cluster address (0 for FAT16 and FAT12).
22-25	Written time information.
26-27	Low 2 bytes of first cluster address.
28-31	File size.

Bytes	Description
0-0	Sequence Number
1-10	File name characters (5 characters in Unicode)
11-11	File attributes - always 0x0F (to indicate it is a LFN)
12-12	Reserved.
13-13	Checksum
14-25	File name characters (6 characters in Unicode)
26-27	Reserved
28-31	File name characters (2 characters in Unicode)

FAT series – LFN directory entry

- Filename:
  "**I_love_the_operating_system_course.txt**".

Byte 11 is always 0x0F to indicate that is a LFN.



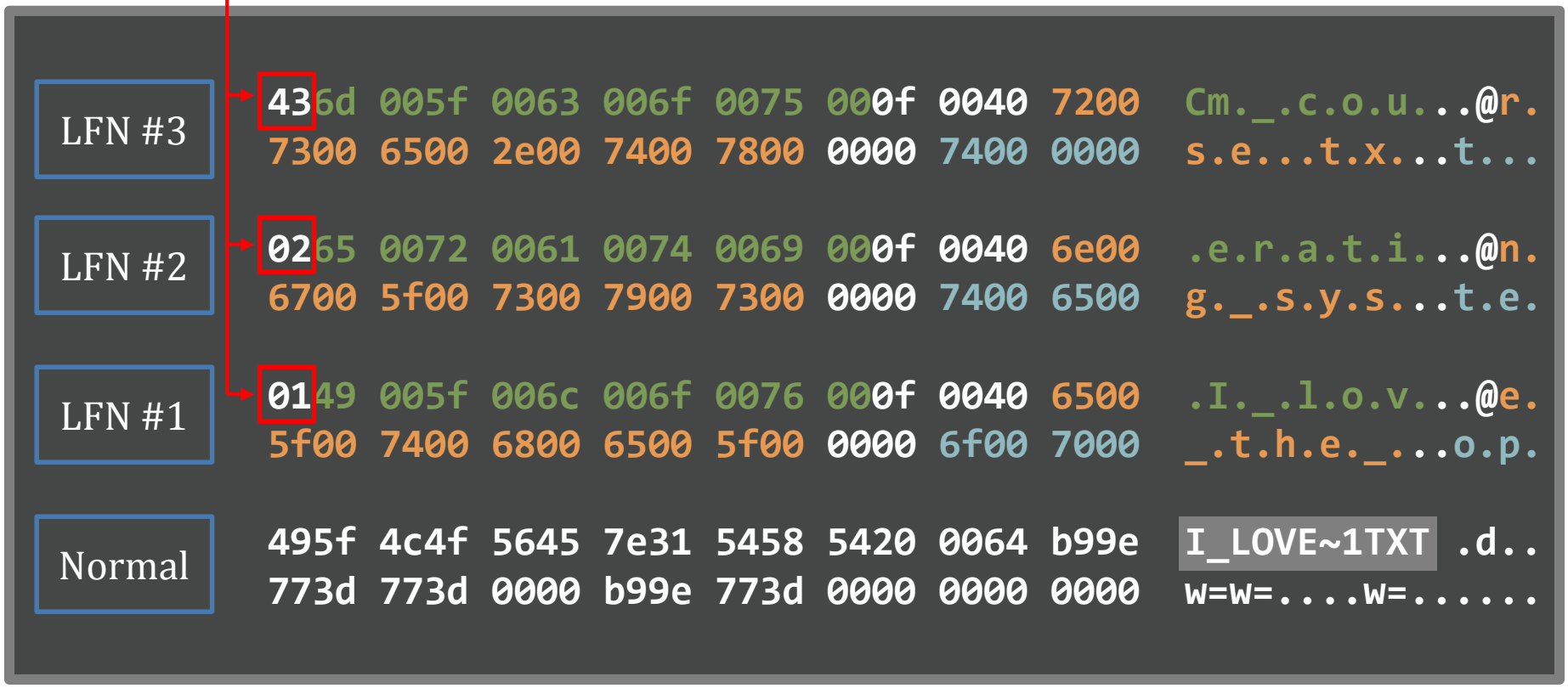
FAT series – 1 directory entry can hold

This is the sequence number, and they are arranged in descending order.

The terminating directory entry has the sequence number OR-ed with 0x40.

s

Directory file
LFN #3: “m_cou” “rse.tx” “t”
LFN #2: “erati” “ng_sys” “te”
LFN #1: “I_lov” “e_the_” “op”
Normal Entry



FAT series – directory entry: a short summary

- A directory is an extremely important part of a FAT-like file system.
  - It stores the start cluster number.
  - It stores the **file size**; without the file size, how can you know when you should stop reading a cluster?
  - It stores **all file attributes**.

FAT series – reading a file

Task: read "C:\windows\gamedata.dat" sequentially.

FAT1

0	...
1	...
...	...
32	33
33	EOF
34	0
35	0

Filename	Attributes	Cluster #
gamedata.dat	.....	32

Damaged	= 0x0ffffff7
EOF	>= 0x0ffffff8
Unallocated	= 0x0

Step 1. Read the content from Cluster #32.
Note. The **file size** may also help determining if the last cluster is reached.

Step 2. Look for the next cluster and it is Cluster #33.

FAT series – reading a file

Task: read "C:\windows\gamedata.dat" sequentially.

0	...
1	...
...	...
32	33
33	EOF
34	0
35	0

Filename	Attributes	Cluster #
gamedata.dat	.....	32

Step 3. Since the FAT has marked "EOF", we have reached the last cluster of that file.

Note. The file size help determining **how many bytes to read** from the last cluster.

FAT series – writing a file

Task: append data to "C:\windows\gamedata.dat".

0	...
1	...
...	...
32	33
33	EOF
34	0
35	0

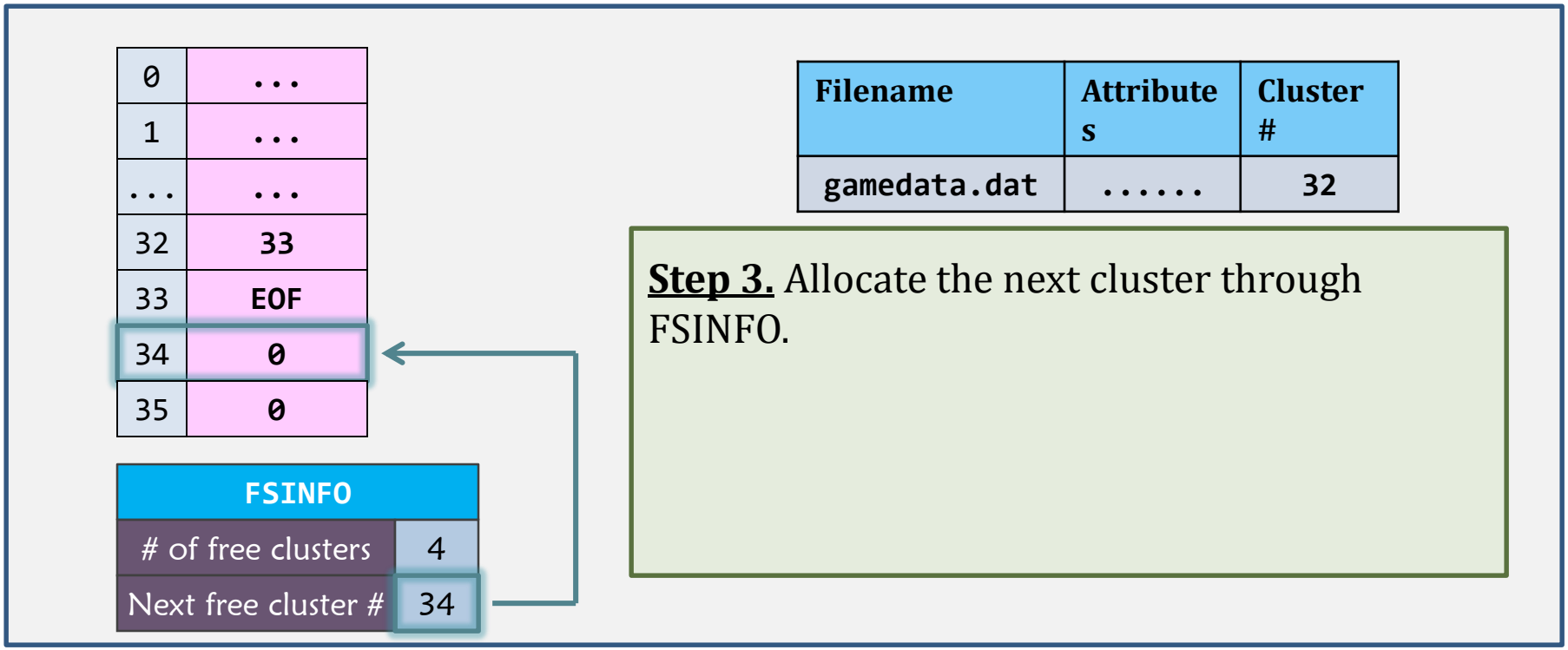
Filename	Attributes	Cluster #
gamedata.dat	.....	32

Step 1. Locate the last cluster.

Step 2. Start writing to the non-full cluster.

FAT series – writing a file

Task: append data to "C:\windows\gamedata.dat".



FAT series – writing a file

Task: append data to "C:\windows\gamedata.dat".

0	...
1	...
...	...
32	33
33	34
34	EOF
35	0

Filename	Attributes	Cluster #
gamedata.dat	.....	32

Step 3. Allocate the next cluster through FSINFO.

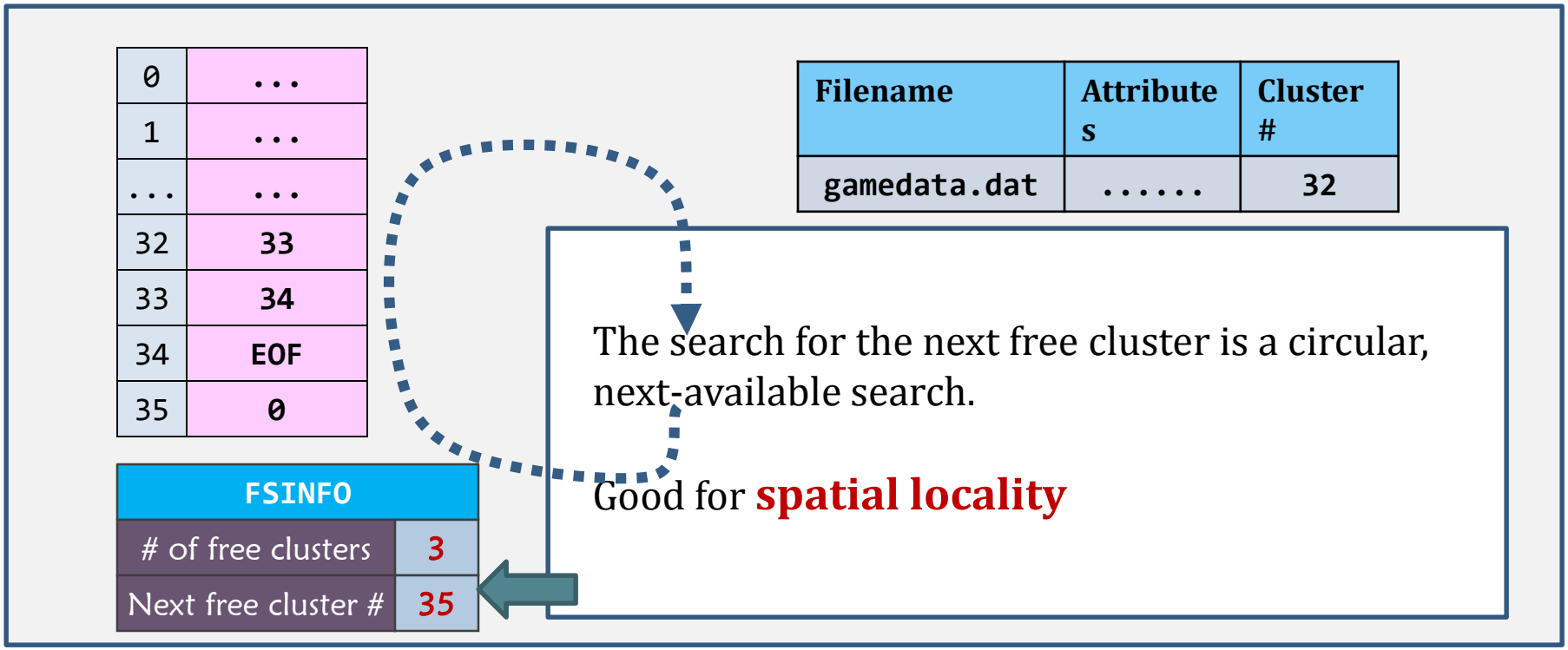
Step 4. Update the FATs and FSINFO.

Step 5. When write finishes, update the file size.

FSINFO	
# of free clusters	3
Next free cluster #	35

FAT series – writing a file

Task: append data to "C:\windows\gamedata.dat".



FAT series – delete a file

Task: delete "C:\windows\gamedata.dat".

0	...
1	...
...	...
32	33
33	34
34	EOF
35	0

0	...
1	...
...	...
32	0
33	0
34	0
35	0

Filename	Attributes	Cluster #
gamedata.dat	.....	32

Step 1. De-allocate all the blocks involved. Update FSINFO and FATs.

FSINFO	
# of free clusters	3
Next free cluster #	35

FSINFO	
# of free clusters	6
Next free cluster #	32

FAT series – delete a file

Task: delete "C:\windows\gamedata.dat".

Directory "windows"		
Filename	**Attributes**	**Cluster #**
.	.....	?
..	.....	?
_amedata.dat	.....	32
notepad.exe	.....	456

Step 2. Change the first byte of the directory entry to _ (0xE5)

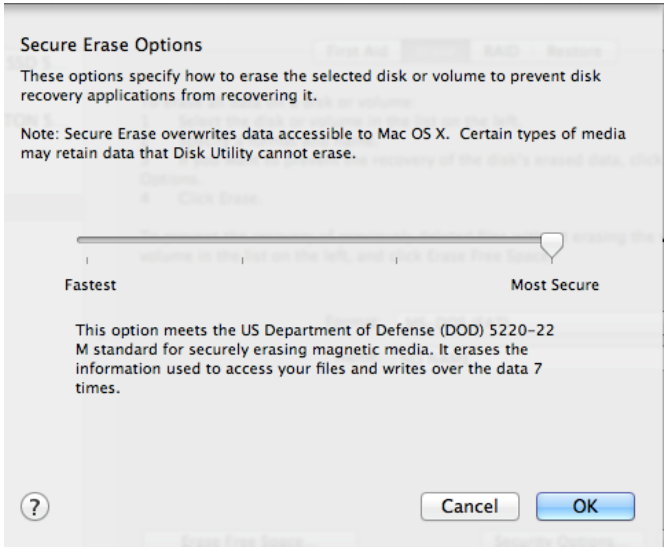
That's the end of deletion!

FAT series – really delete a file?

- Can you see that: **the file is not really removed from the FS layout?**
  - Perform a search in all the free space. Then, you will find all deleted file contents.
- "*Deleted data*" persists until the de-allocated clusters **are reused**.
  - This is an issue between performance (during deletion) and security.
- Any way(s) to delete a file **securely**?

FAT series – really delete a file?

Mac OS X Secure Disk Erase



Hard disk Degausser?
http://www.youtube.com/watch?v=5zKjGQAPhUs

Brute Force?
http://www.ohgizmo.com/2009/06/01/manual-hard-drive-destroyer-looks-like-fun/

FAT series – how to recover a deleted file?

- If you're really care about the deleted file, then…
  - **PULL THE POWER PLUG AT ONCE!**
  - Pulling the power plug stops the target clusters from being over-written.

File size is within one block (cluster)	Because **the first cluster address** in the direct is still readable, the recovery is having a very high successful rate.
File size spans more than 1 block	Because of the next-available search, clusters of a file are likely to be contiguous allocated. This provides a hint in looking for deleted blocks. Can you devise an undelete algorithm for FAT32?

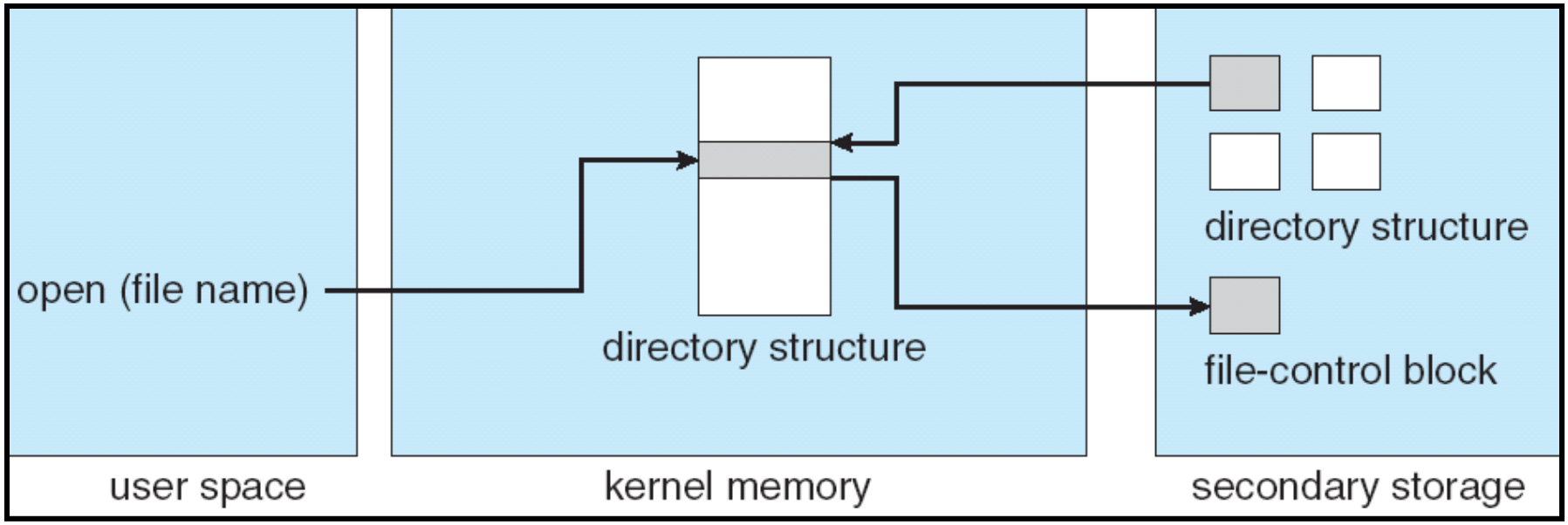
FAT series – conclusion

- Space efficient:
  - 4 bytes overhead (FAT entry) per data cluster.
- Delete:
  - Lazy delete efficient
  - Insecure
    - designed for single-user 20+ years ago
- Deployment: (FAT32 and FAT12)
  - It is everywhere: CF cards, SD cards, USB drives
- Search:
  - Block addresses of a file may scatter discontinuously
  - To locate the 888-th block of a file?
    - Start from the first FAT entry and follow 888 pointers
- The most commonly used filesystem in the world

Designing a File System …

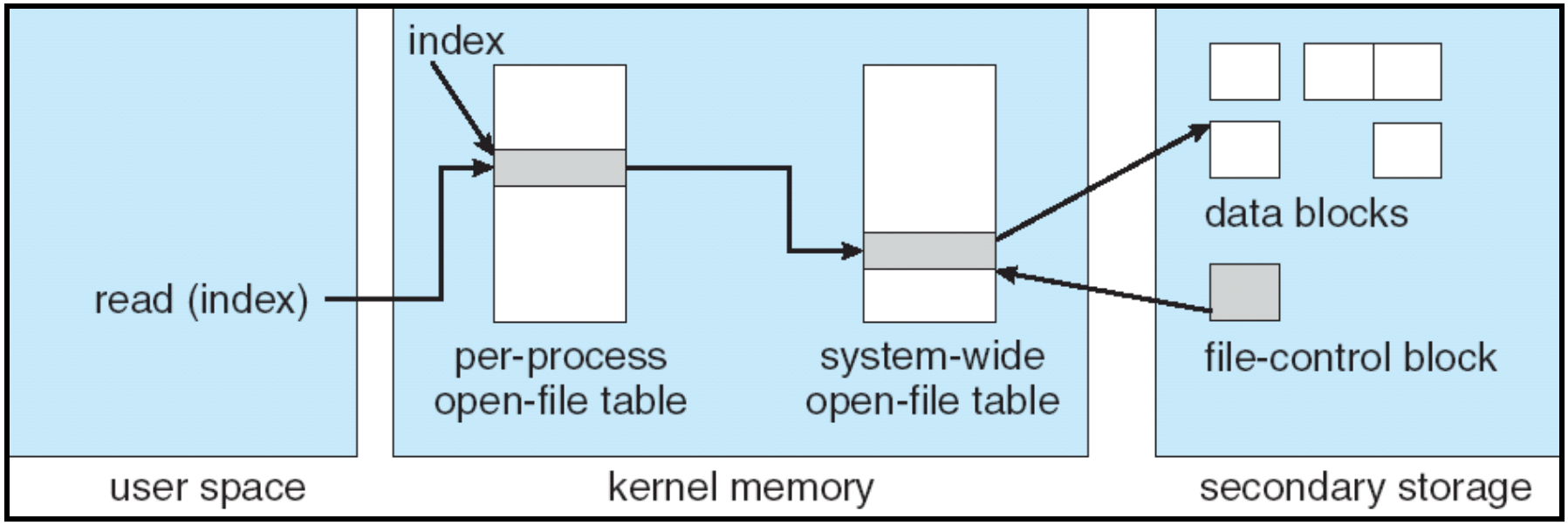
- What factors are critical to the design choices?
- Durable data store => it's all on disk
- (Hard) Disks Performance !!!
  - Maximize sequential access, minimize seeks
- Open before Read/Write
  - Can perform protection checks and look up where the actual file resource are, in advance
- Size is determined as they are used !!!
  - Can write (or read zeros) to expand the file
  - Start small and grow, need to make room
- Organized into directories
  - What data structure (on disk) for that?
- Need to allocate / free blocks
  - Such that access remains efficient

In-Memory File System Structures



- Open system call:
  - Resolves file name, finds file control block
  - Makes entries in per-process and system-wide tables
  - Returns index (called “file handle”) in open-file table

In-Memory File System Structures



- Read/write system calls:
  - Use file handle to locate inode
  - Perform appropriate reads or writes

Summary

- File System:
  - Transforms blocks into Files and Directories
  - Optimize for access and usage patterns
  - Maximize sequential access, allow efficient random access
- File (and directory) defined by header, called “inode”
- File Allocation Table (FAT) Scheme
  - Linked-list approach
  - Very widely used: Cameras, USB drives, SD cards
  - Simple to implement, but poor performance and no security
- Look at actual file access patterns – many small files, but large files take up all the space!

Thank You!