Lecture 12: File System

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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

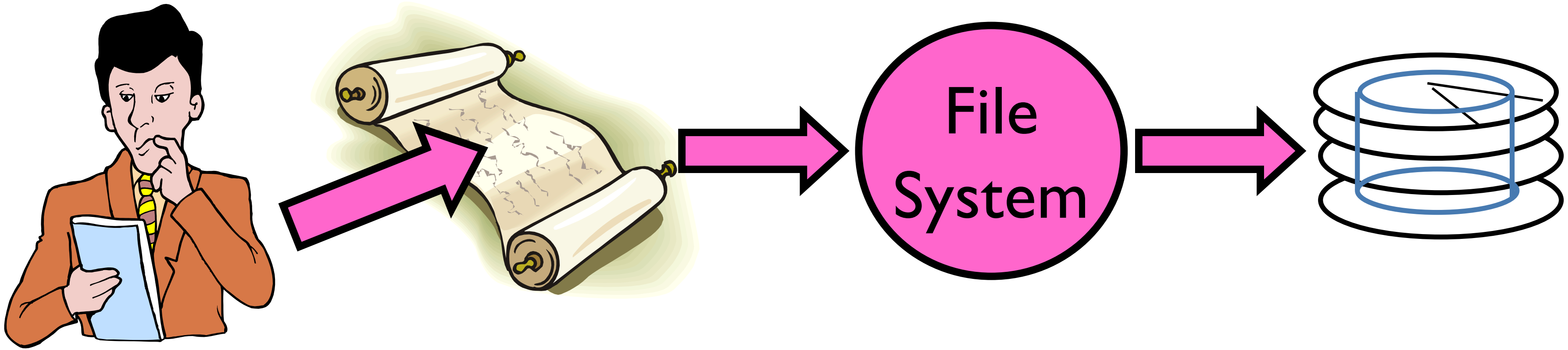
- File System: Layer of OS that transforms block interface of disks (or other block devices) into Files, Directories, etc.

- 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

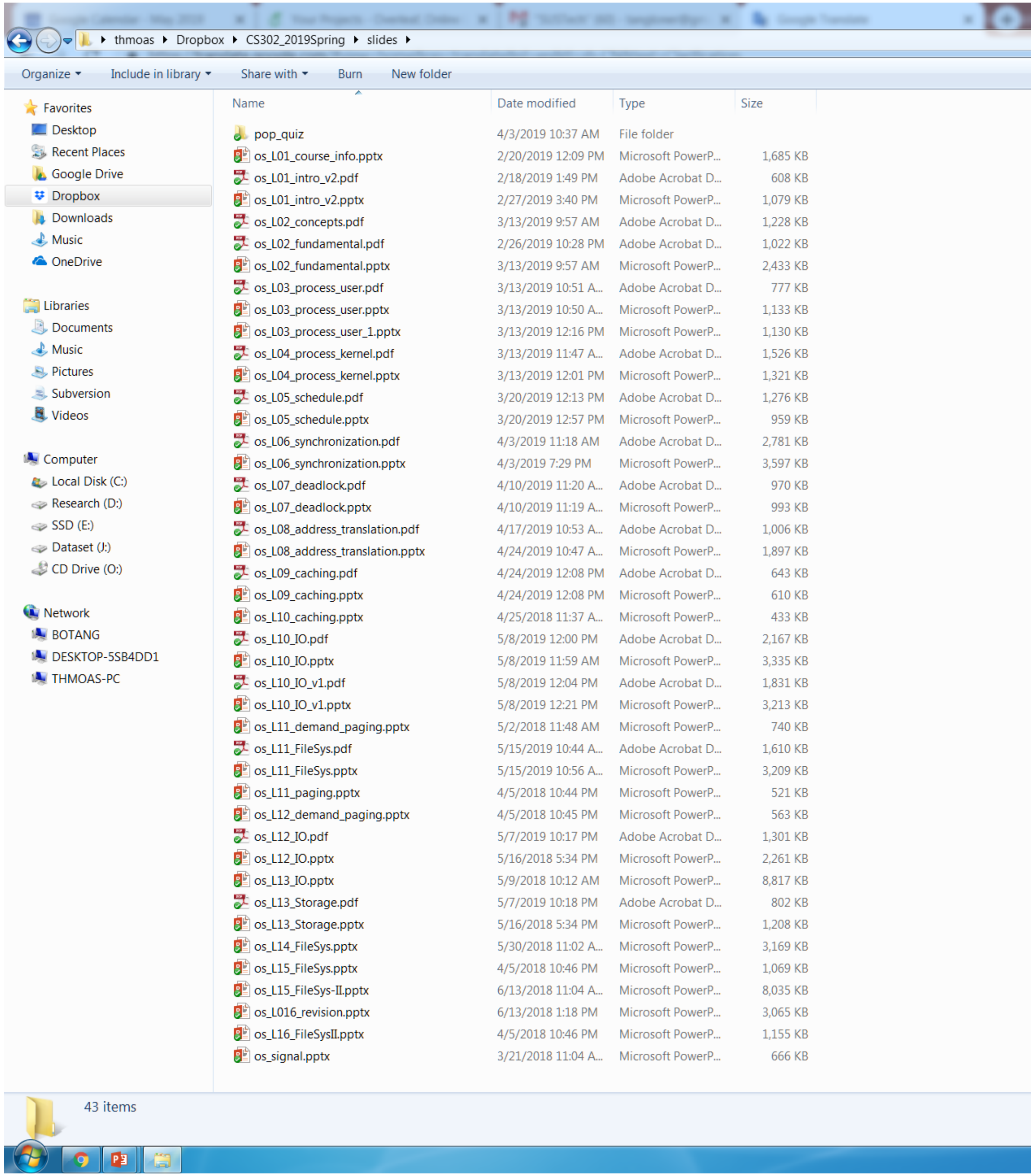


- What happens if user says: give me bytes 2—12?
  - Fetch block corresponding to those bytes
  - Return just the correct portion of the block
- What about: write bytes 2—12?
  - Fetch block
  - Modify portion
  - Write out Block
- Everything inside File System is in whole size blocks
  - For example, `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

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

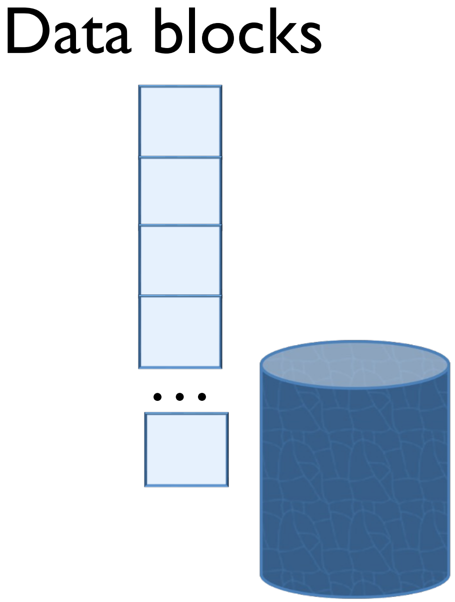
Directories



Name	Date modified	Type	Size
pop_quiz	4/3/2019 10:37 AM	File folder	
os_L01_course_info.pptx	2/20/2019 12:09 PM	Microsoft PowerP...	1,685 KB
os_L01_intro_v2.pdf	2/18/2019 1:49 PM	Adobe Acrobat D...	608 KB
os_L01_intro_v2.pptx	2/27/2019 3:40 PM	Microsoft PowerP...	1,079 KB
os_L02_concepts.pdf	3/13/2019 9:57 AM	Adobe Acrobat D...	1,228 KB
os_L02_fundamental.pdf	2/26/2019 10:28 PM	Adobe Acrobat D...	1,022 KB
os_L02_fundamental.pptx	3/13/2019 9:57 AM	Microsoft PowerP...	2,433 KB
os_L03_process_user.pdf	3/13/2019 10:51 A...	Adobe Acrobat D...	777 KB
os_L03_process_user.pptx	3/13/2019 10:50 A...	Microsoft PowerP...	1,133 KB
os_L03_process_user_1.pptx	3/13/2019 12:16 PM	Microsoft PowerP...	1,130 KB
os_L04_process_kernel.pdf	3/13/2019 11:47 A...	Adobe Acrobat D...	1,526 KB
os_L04_process_kernel.pptx	3/13/2019 12:01 PM	Microsoft PowerP...	1,321 KB
os_L05_schedule.pdf	3/20/2019 12:13 PM	Adobe Acrobat D...	1,276 KB
os_L05_schedule.pptx	3/20/2019 12:57 PM	Microsoft PowerP...	959 KB
os_L06_synchronization.pdf	4/3/2019 11:18 AM	Adobe Acrobat D...	2,781 KB
os_L06_synchronization.pptx	4/3/2019 7:29 PM	Microsoft PowerP...	3,597 KB
os_L07_deadlock.pdf	4/10/2019 11:20 A...	Adobe Acrobat D...	970 KB
os_L07_deadlock.pptx	4/10/2019 11:19 A...	Microsoft PowerP...	993 KB
os_L08_address_translation.pdf	4/17/2019 10:53 A...	Adobe Acrobat D...	1,006 KB
os_L08_address_translation.pptx	4/24/2019 10:47 A...	Microsoft PowerP...	1,897 KB
os_L09_caching.pdf	4/24/2019 12:08 PM	Adobe Acrobat D...	643 KB
os_L09_caching.pptx	4/24/2019 12:08 PM	Microsoft PowerP...	610 KB
os_L10_caching.pptx	4/25/2018 11:37 A...	Microsoft PowerP...	433 KB
os_L10_IO.pdf	5/8/2019 12:00 PM	Adobe Acrobat D...	2,167 KB
os_L10_IO.pptx	5/8/2019 11:59 AM	Microsoft PowerP...	3,335 KB
os_L10_IO_v1.pdf	5/8/2019 12:04 PM	Adobe Acrobat D...	1,831 KB
os_L10_IO_v1.pptx	5/8/2019 12:21 PM	Microsoft PowerP...	3,213 KB
os_L11_demand_paging.pptx	5/2/2018 11:48 AM	Microsoft PowerP...	740 KB
os_L11_FileSys.pdf	5/15/2019 10:44 A...	Adobe Acrobat D...	1,610 KB
os_L11_FileSys.pptx	5/15/2019 10:56 A...	Microsoft PowerP...	3,209 KB
os_L11_paging.pptx	4/5/2018 10:44 PM	Microsoft PowerP...	521 KB
os_L12_demand_paging.pptx	4/5/2018 10:45 PM	Microsoft PowerP...	563 KB
os_L12_IO.pdf	5/7/2019 10:17 PM	Adobe Acrobat D...	1,301 KB
os_L12_IO.pptx	5/16/2018 5:34 PM	Microsoft PowerP...	2,261 KB
os_L13_IO.pptx	5/9/2018 10:12 AM	Microsoft PowerP...	8,817 KB
os_L13_Storage.pdf	5/7/2019 10:18 PM	Adobe Acrobat D...	802 KB
os_L13_Storage.pptx	5/16/2018 5:34 PM	Microsoft PowerP...	1,208 KB
os_L14_FileSys.pptx	5/30/2018 11:02 A...	Microsoft PowerP...	3,169 KB
os_L15_FileSys.pptx	4/5/2018 10:46 PM	Microsoft PowerP...	1,069 KB
os_L15_FileSys-II.pptx	6/13/2018 11:04 A...	Microsoft PowerP...	8,035 KB
os_L016_revision.pptx	6/13/2018 1:18 PM	Microsoft PowerP...	3,065 KB
os_L16_FileSysII.pptx	4/5/2018 10:46 PM	Microsoft PowerP...	1,155 KB
os_signal.pptx	3/21/2018 11:04 A...	Microsoft PowerP...	666 KB

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



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 ⇒ 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

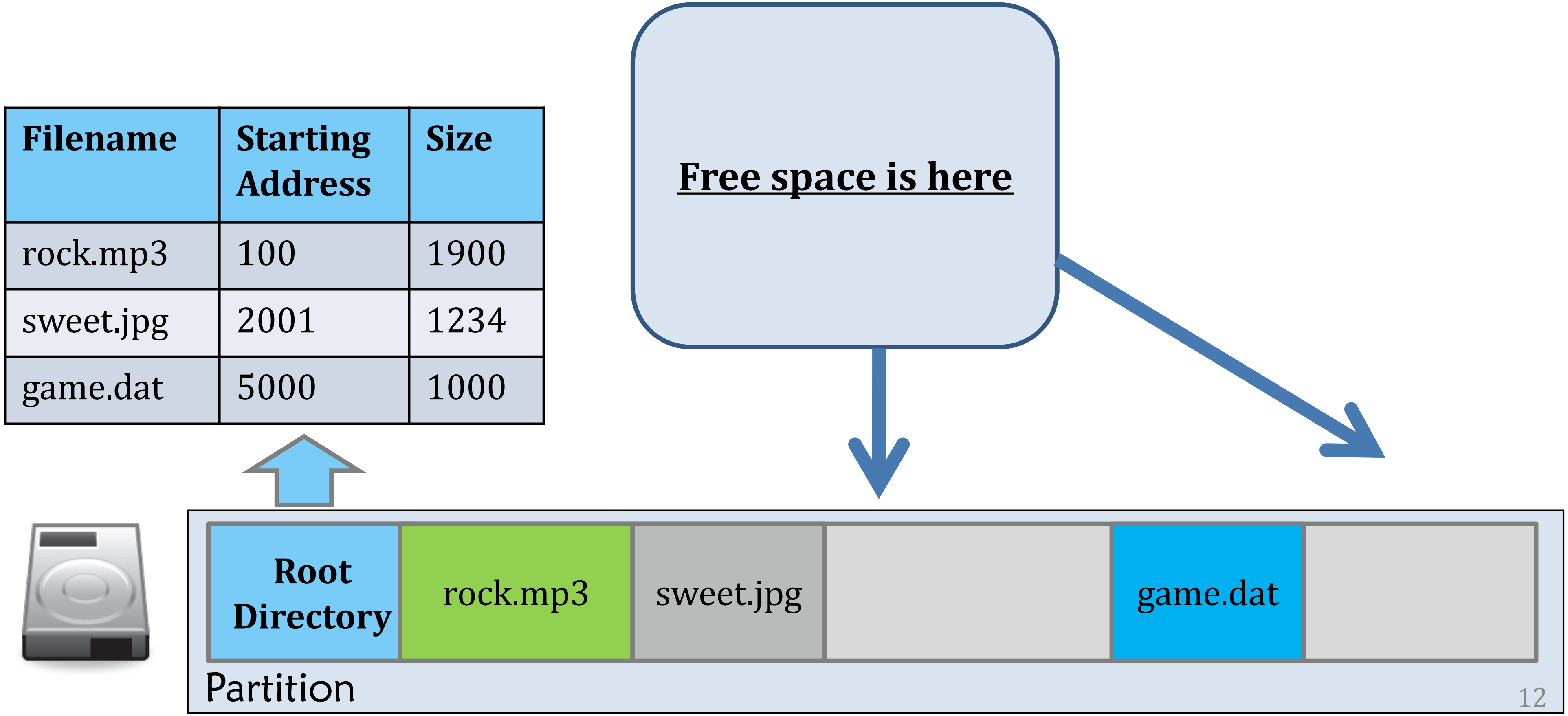
File System

- Layout
  - contiguous allocation
  - linked allocation
  - inode allocation

Contiguous allocation – basics

Locate files easily.

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



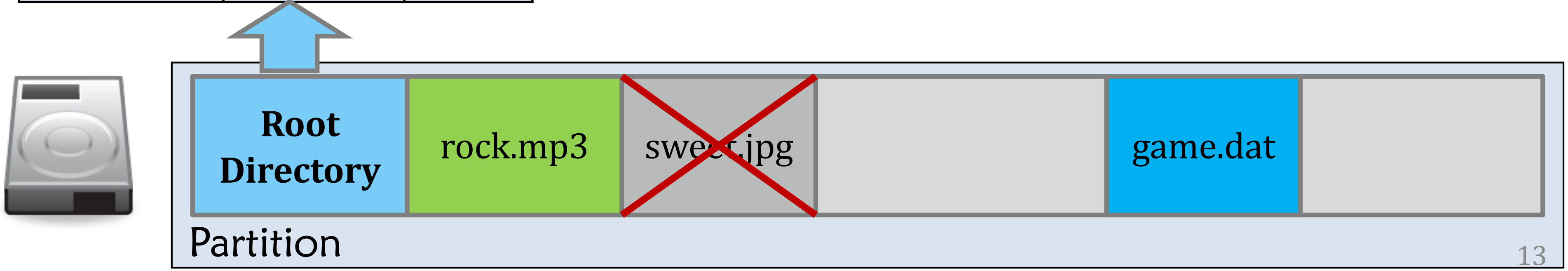
Contiguous allocation – basics

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

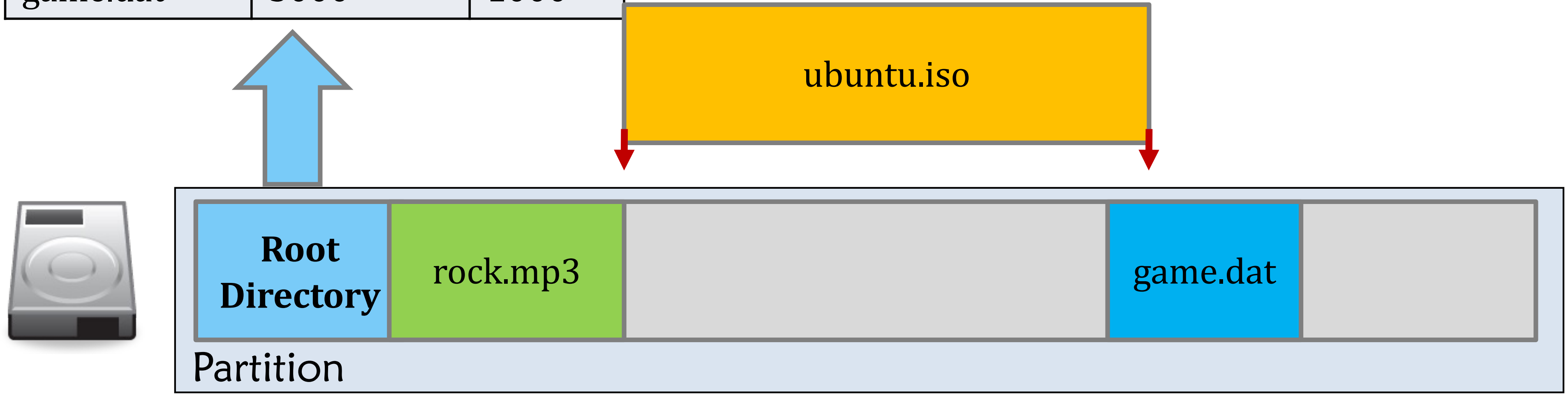


Contiguous allocation – basics

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

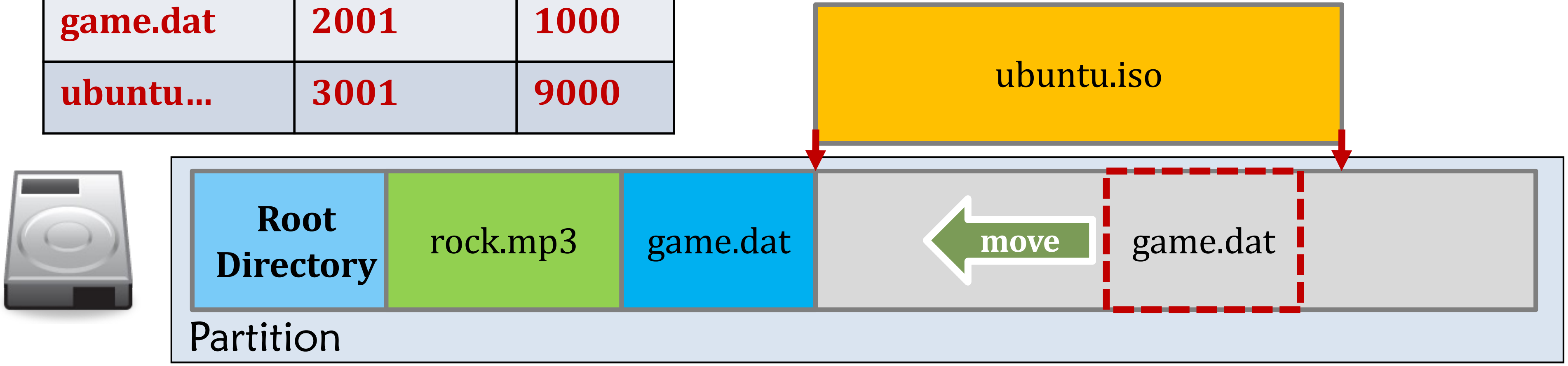
Filename	**Starting Address**	**Size**
rock.mp3	100	1900
game.dat	5000	1000



Contiguous allocation – basics

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

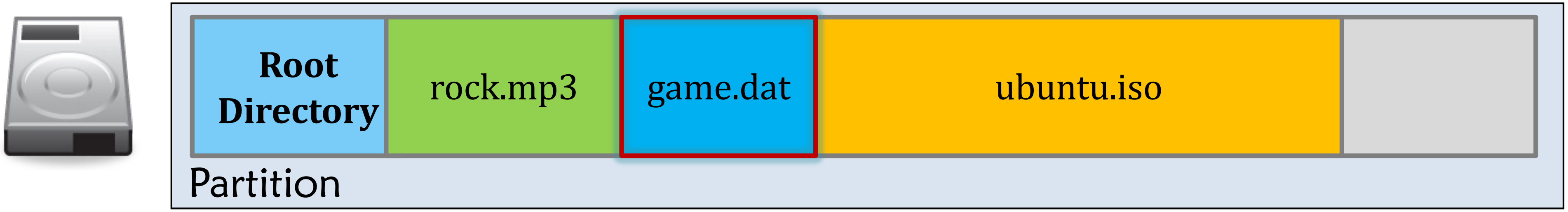
Filename	Starting Address	Size
rock.mp3	100	1900
game.dat	**2001**	**1000**
ubuntu...	**3001**	**9000**



Contiguous allocation – basics

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

Growth problem!

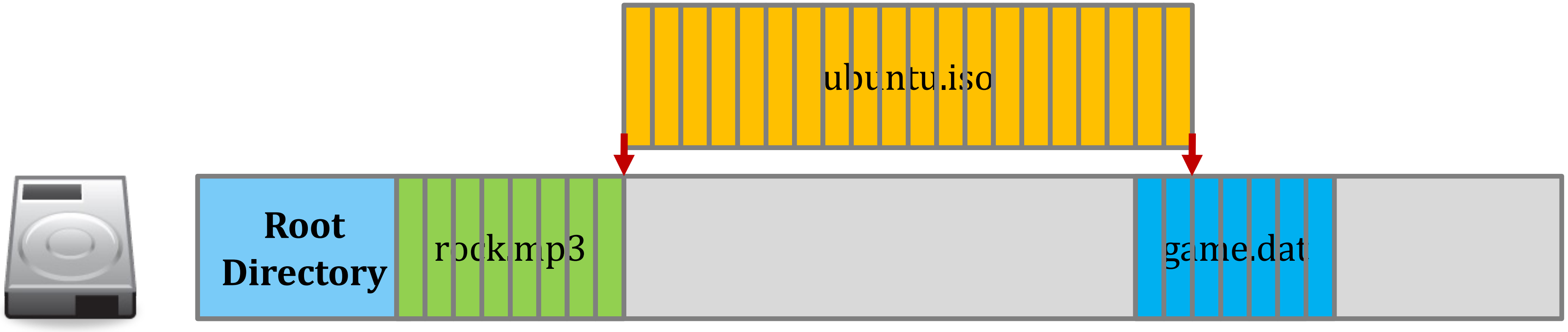


Contiguous allocation – application?

- ISO 9660
- CD-ROM
  - .iso image

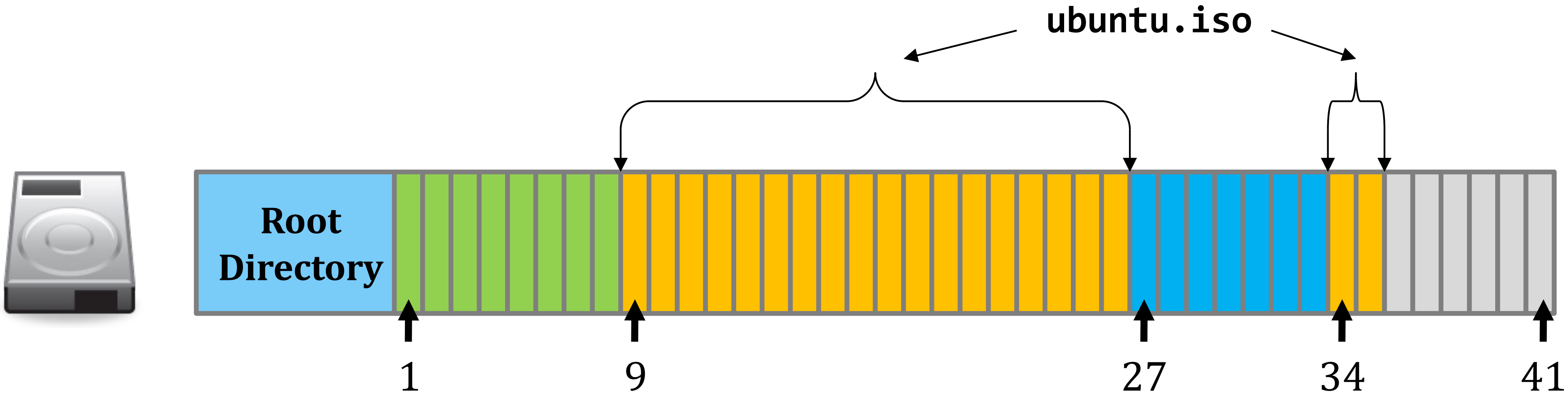
Linked allocation

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



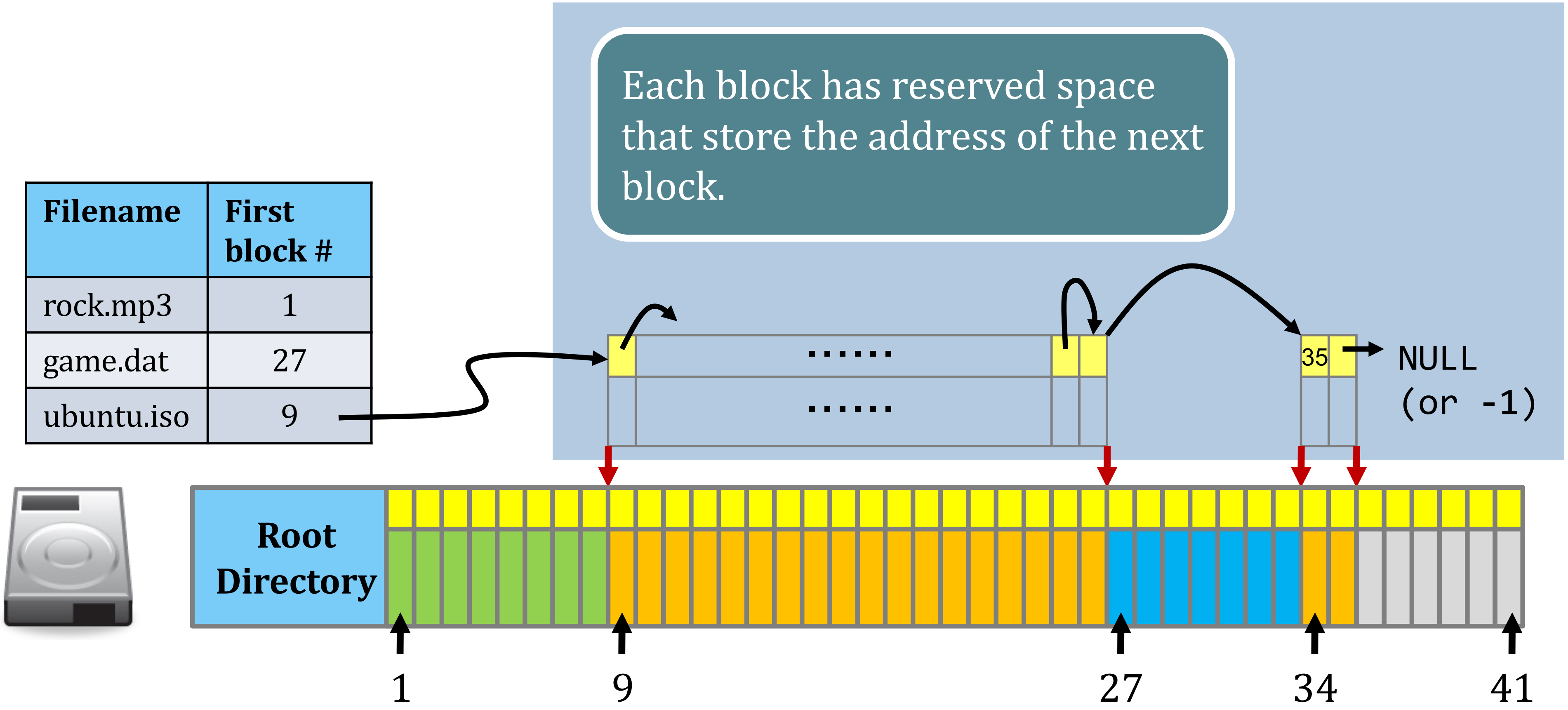
Linked allocation

- 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 **<u>4 bytes from each block</u>** as the “pointer”
    - To write the block # of the next block into the first 4 bytes of each block.



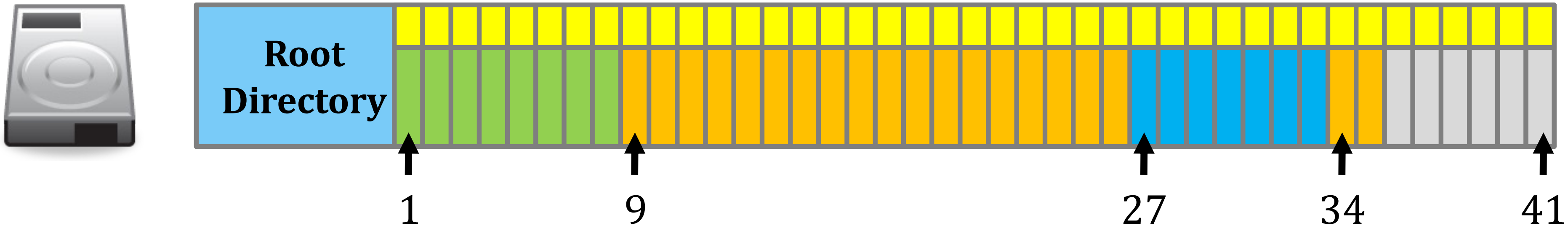
Filename	First block #
rock.mp3	1
game.dat	27
ubuntu.iso	9

Each block has reserved space that store the address of the next 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)

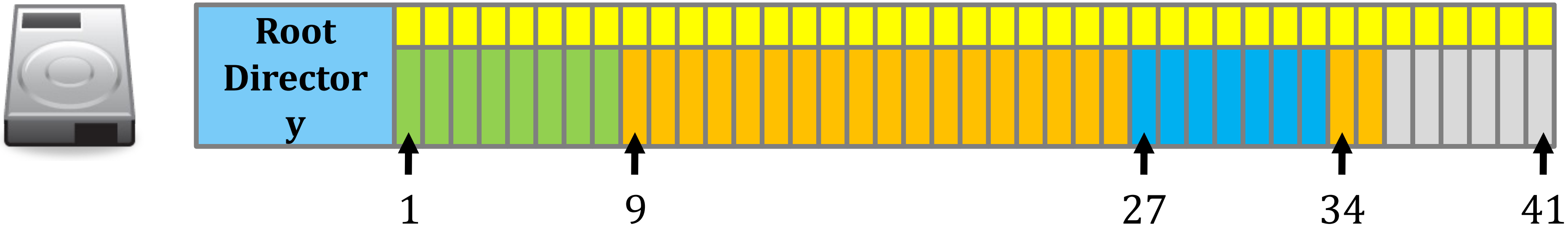
Filename	First block #	Size
rock.mp3	1	1900
game.dat	27	1000
ubuntu.iso	9	9000



Linked allocation

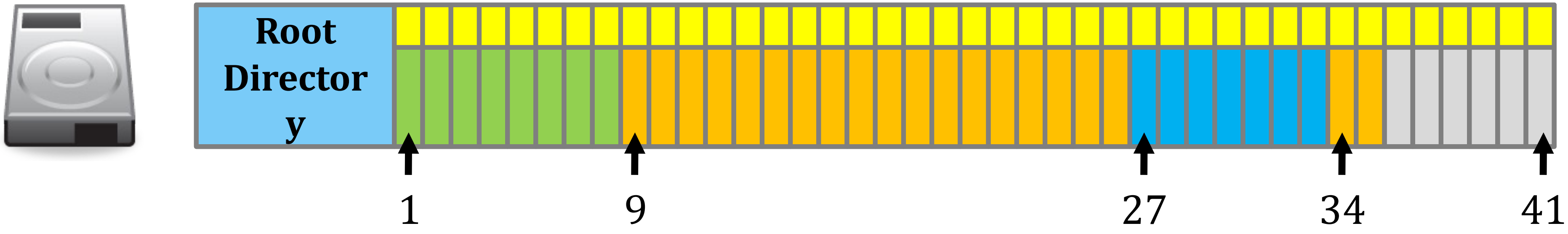
- So, how would you grade this file system?
  - External fragmentation?
  - File growth?

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



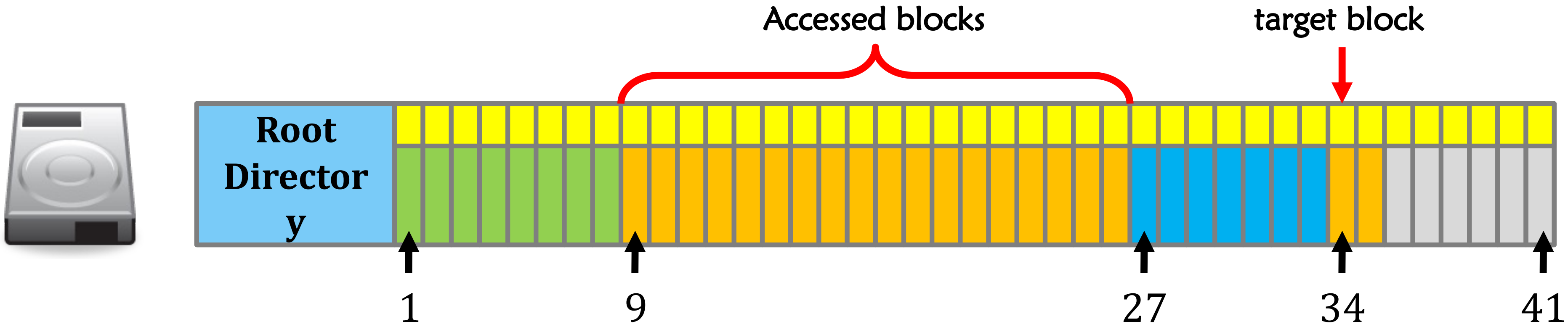
Linked allocation

- **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.



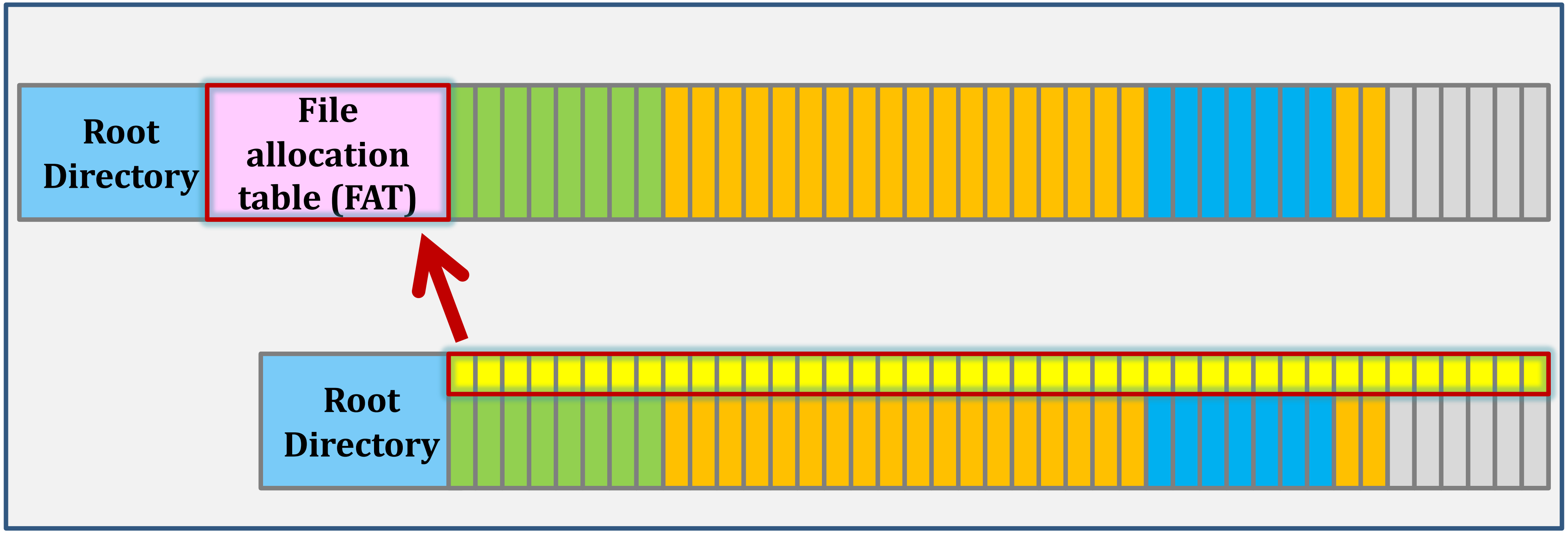
Linked allocation

- **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

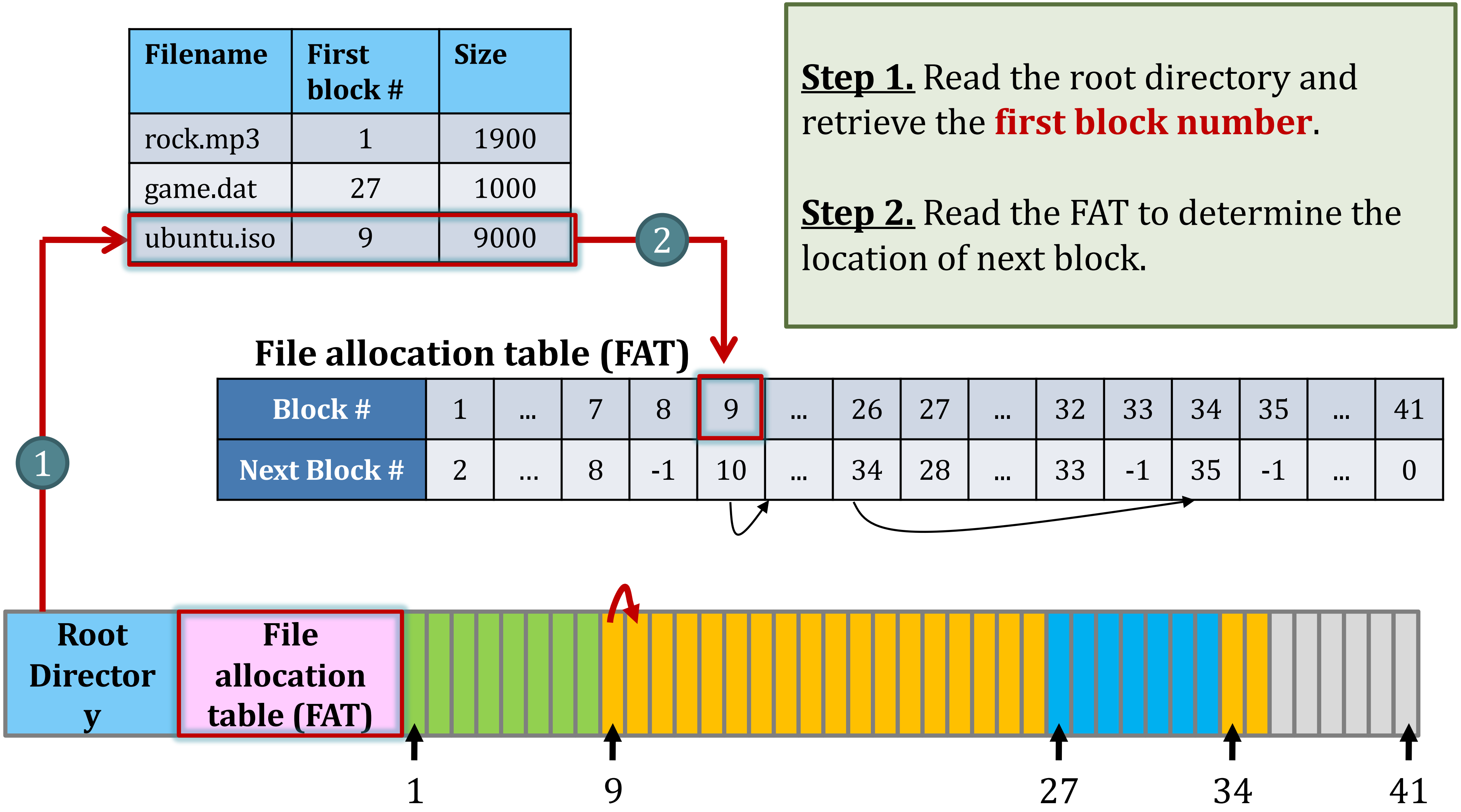


FAT

Task: read "ubuntu.iso" sequentially.

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

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



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

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

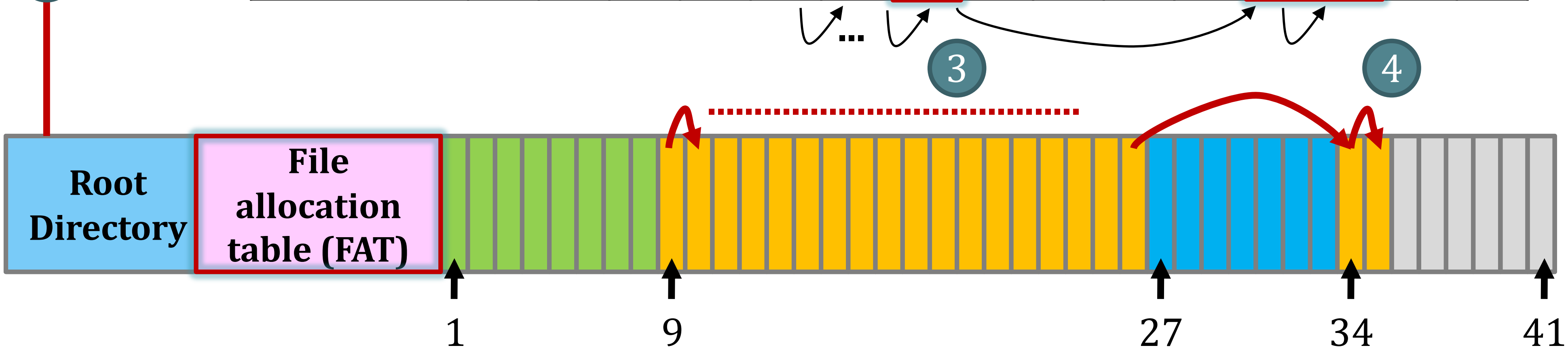
Task: read "ubuntu.iso" sequentially.

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.

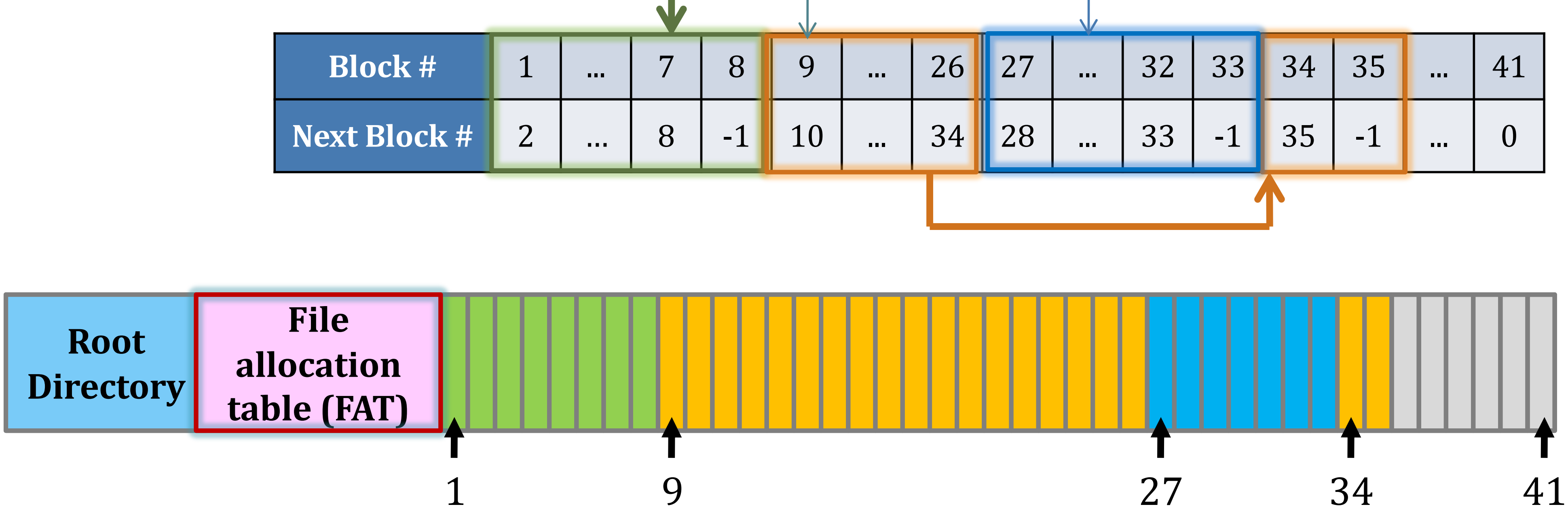
Block #	1	...	7	8	9	...	26	27	...	32	33	34	35	...	41
Next Block #	2	...	8	-1	10	...	34	28	...	33	-1	35	-1	...	0



FAT

Resulting layout & file allocation.

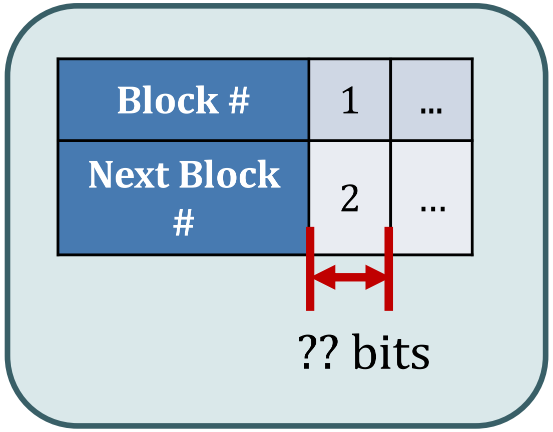
Filename	First block #	Size
rock.mp3	1	1900
game.dat	27	1000
ubuntu.iso	9	9000



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



Block #	1	…
Next Block #	2	…

?? bits

	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.

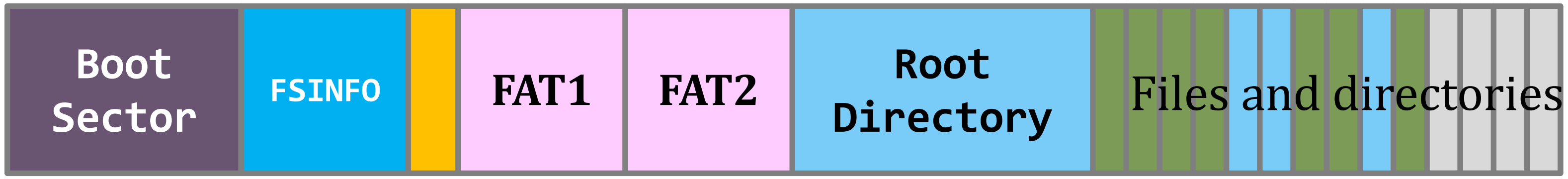
$$\begin{aligned}(32 \times 2^{10}) \times 2^{28} &= 2^{5} \times 2^{10} \times 2^{28} \\ &= 2^{43} \quad (8\ TB)\end{aligned}$$

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

FAT series – layout overview

Reserved sectors

	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.

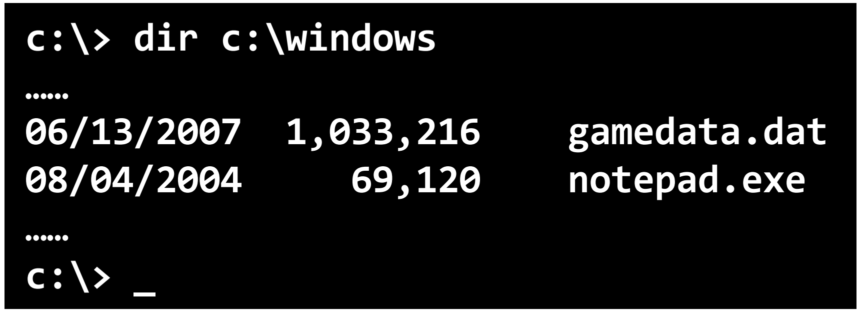


A FAT partition

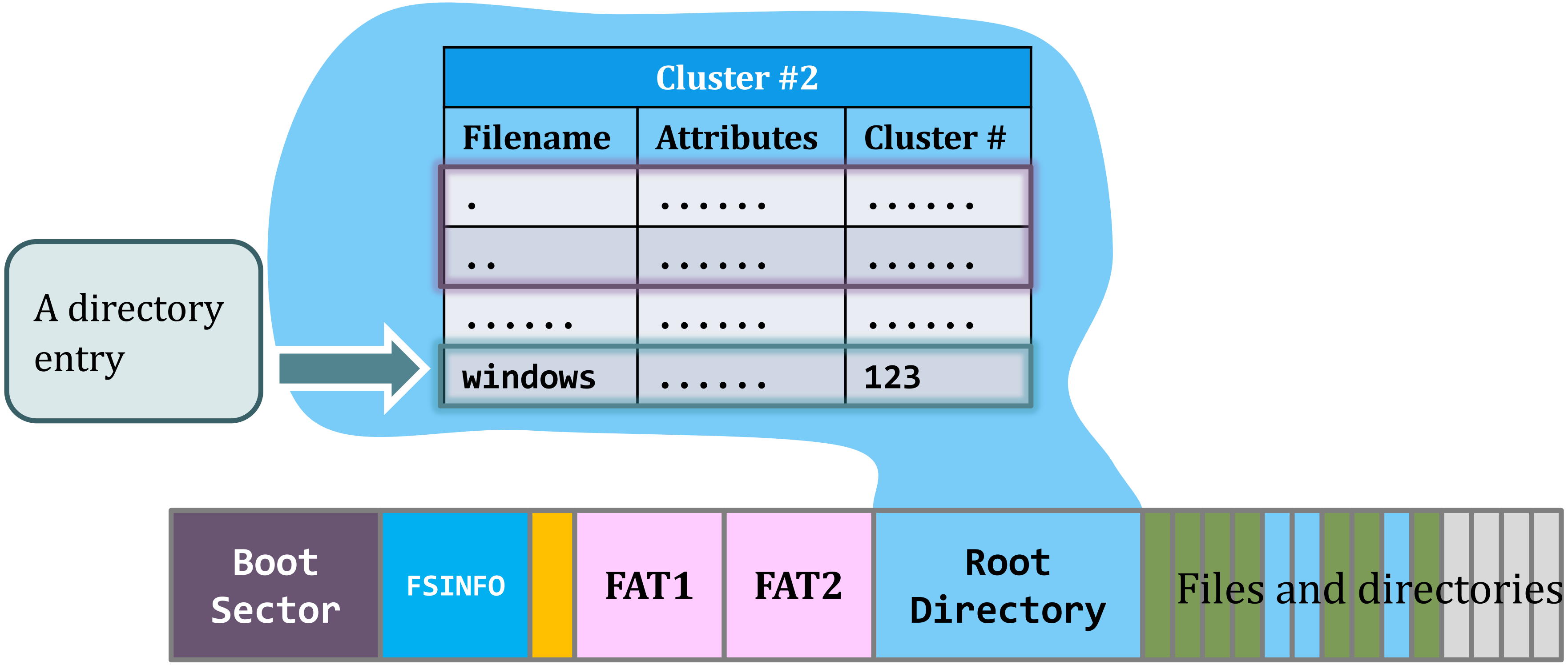
FAT series – directory traversal

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

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



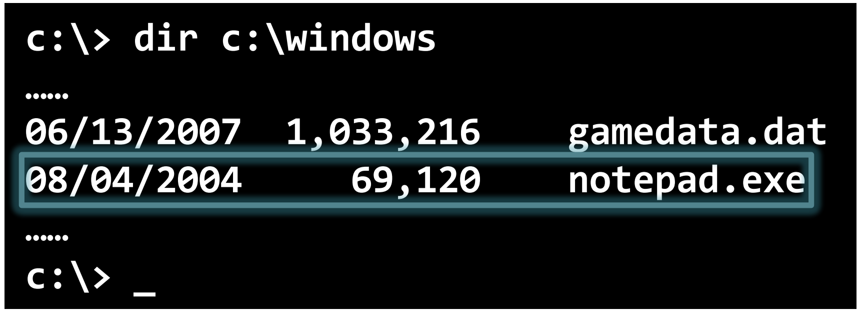
```
c:\> dir c:\windows
……
06/13/2007  1,033,216    gamedata.dat
08/04/2004     69,120    notepad.exe
……
c:\> _
```



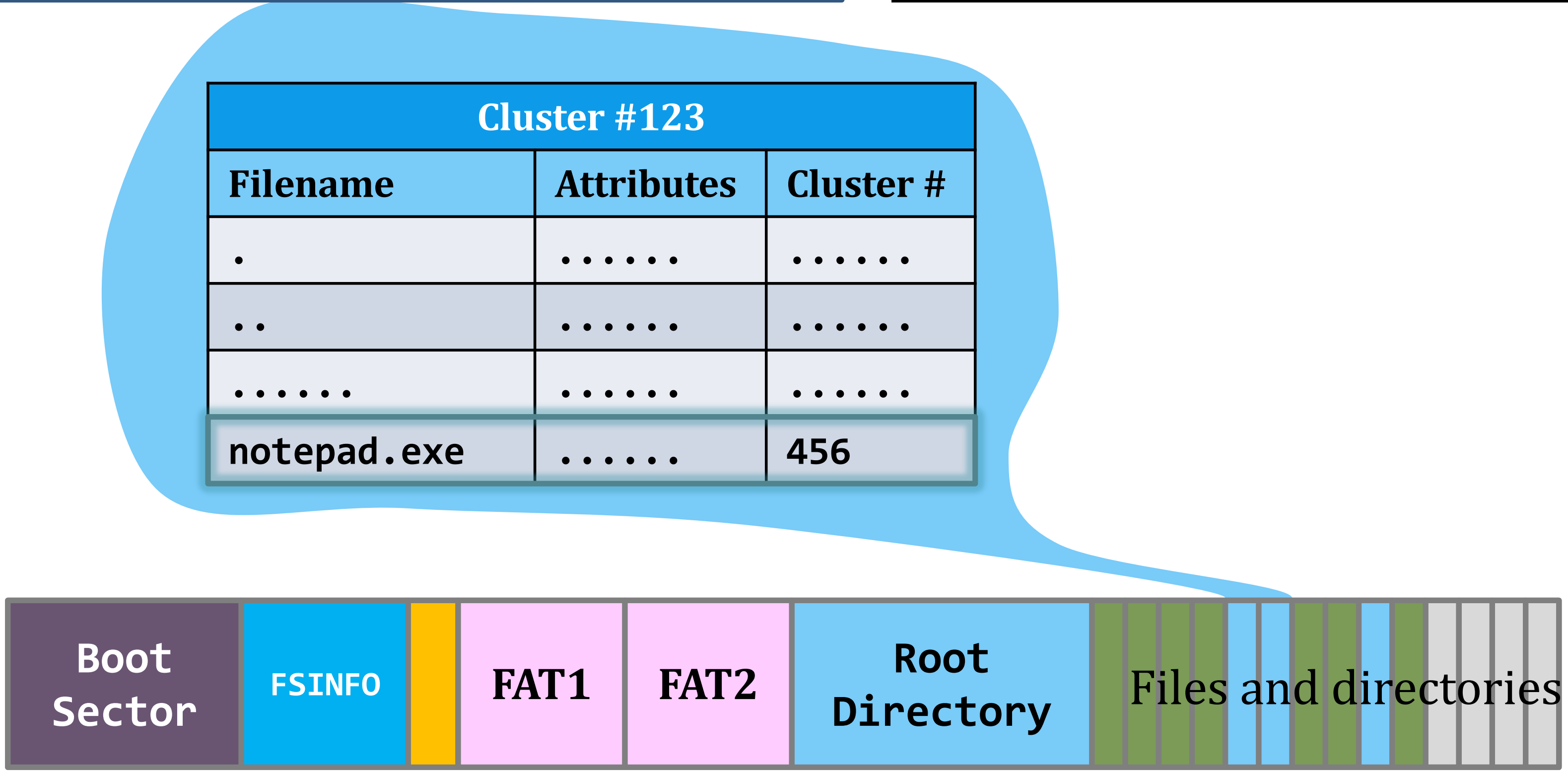
Cluster #2		
Filename	Attributes	Cluster #
.	……	……
..	……	……
……	……	……
windows	……	123

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!

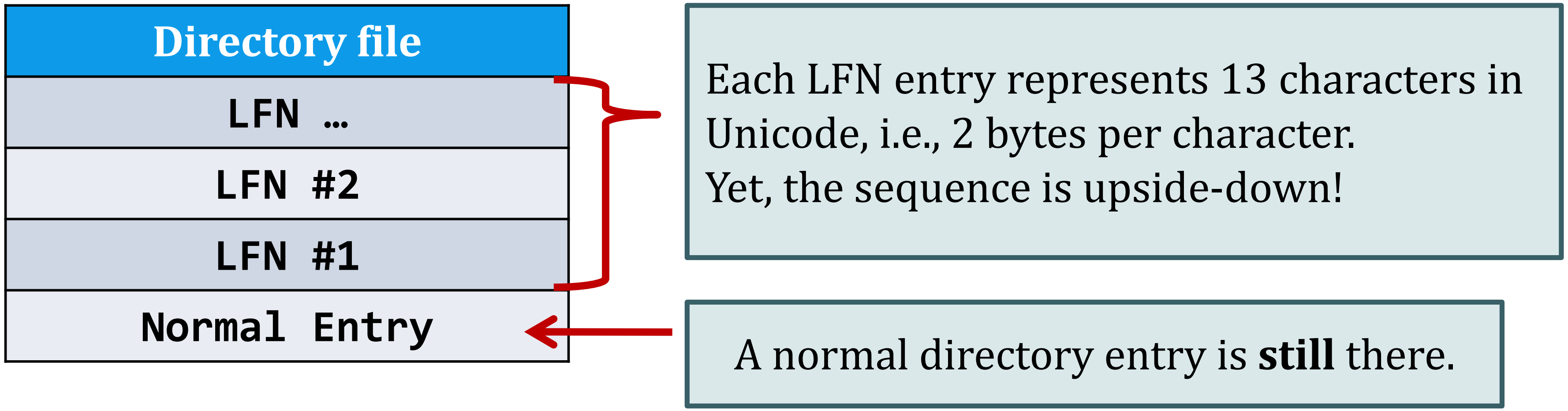
Why "– 1"?

- 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



Directory file

LFN …

LFN #2

LFN #1

Normal Entry

Each LFN entry represents 13 characters in Unicode, i.e., 2 bytes per character.
Yet, the sequence is upside-down!

A normal directory entry is **still** there.

FAT series – LFN directory entry

- Normal directory entry vs LFN directory entry

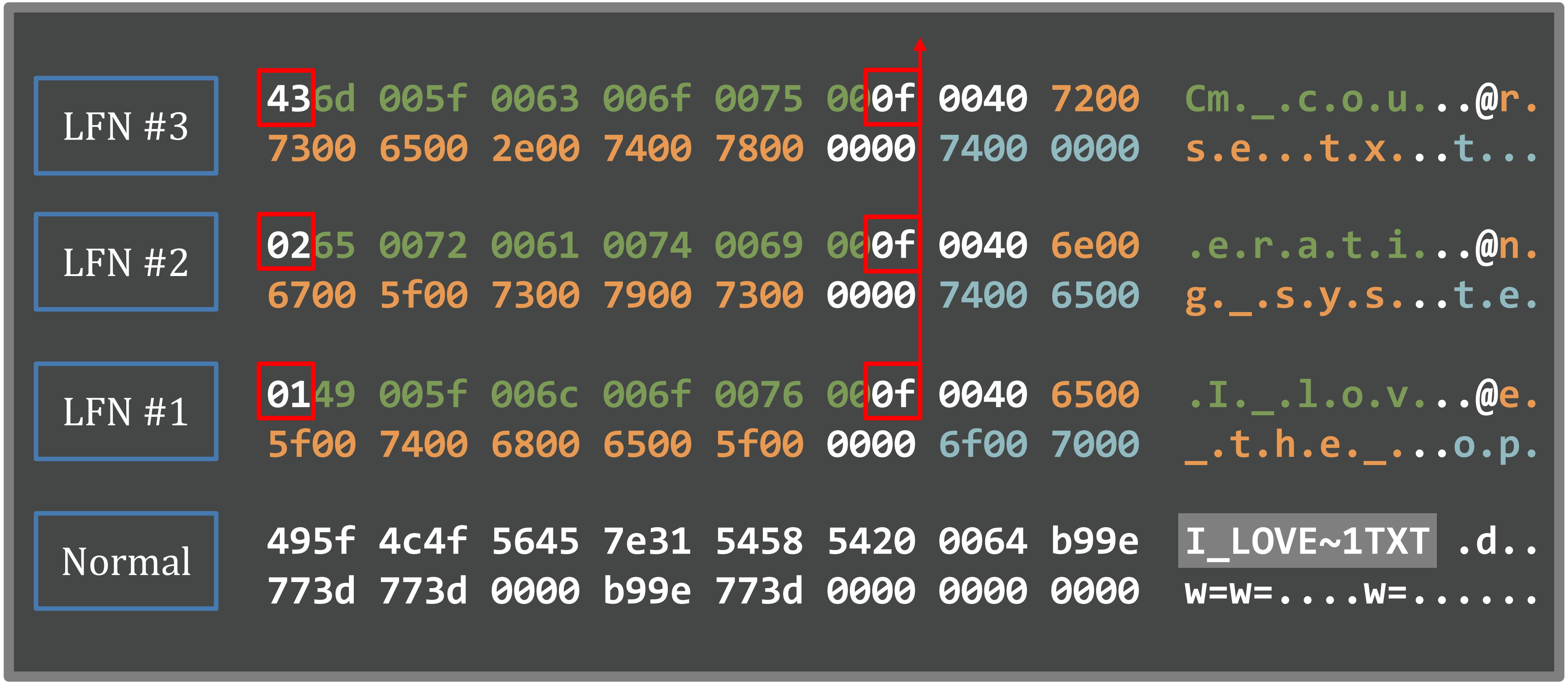
Bytes	Description
0-0	1st character of the filename (0x00 or 0xe5 means unallocated)
1-10	7+3 characters of filename + extension.
11-11	File attributes (e.g., read only, hidden)
12-12	Reserved.
13-19	Creation and access time information.
20-21	High 2 bytes of the first cluster address (0 for FAT16 and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



```
LFN #3   436d 005f 0063 006f 0075 000f 0040 7200  Cm._.c.o.u...@r.
         7300 6500 2e00 7400 7800 0000 7400 0000  s.e...t.x...t...

LFN #2   0265 0072 0061 0074 0069 000f 0040 6e00  .e.r.a.t.i...@n.
         6700 5f00 7300 7900 7300 0000 7400 6500  g._.s.y.s...t.e.

LFN #1   0149 005f 006c 006f 0076 000f 0040 6500  .I._.l.o.v...@e.
         5f00 7400 6800 6500 5f00 0000 6f00 7000  _.t.h.e._...o.p.

Normal   495f 4c4f 5645 7e31 5458 5420 0064 b99e  I_LOVE~1TXT .d..
         773d 773d 0000 b99e 773d 0000 0000 0000  w=w=....w=......
```

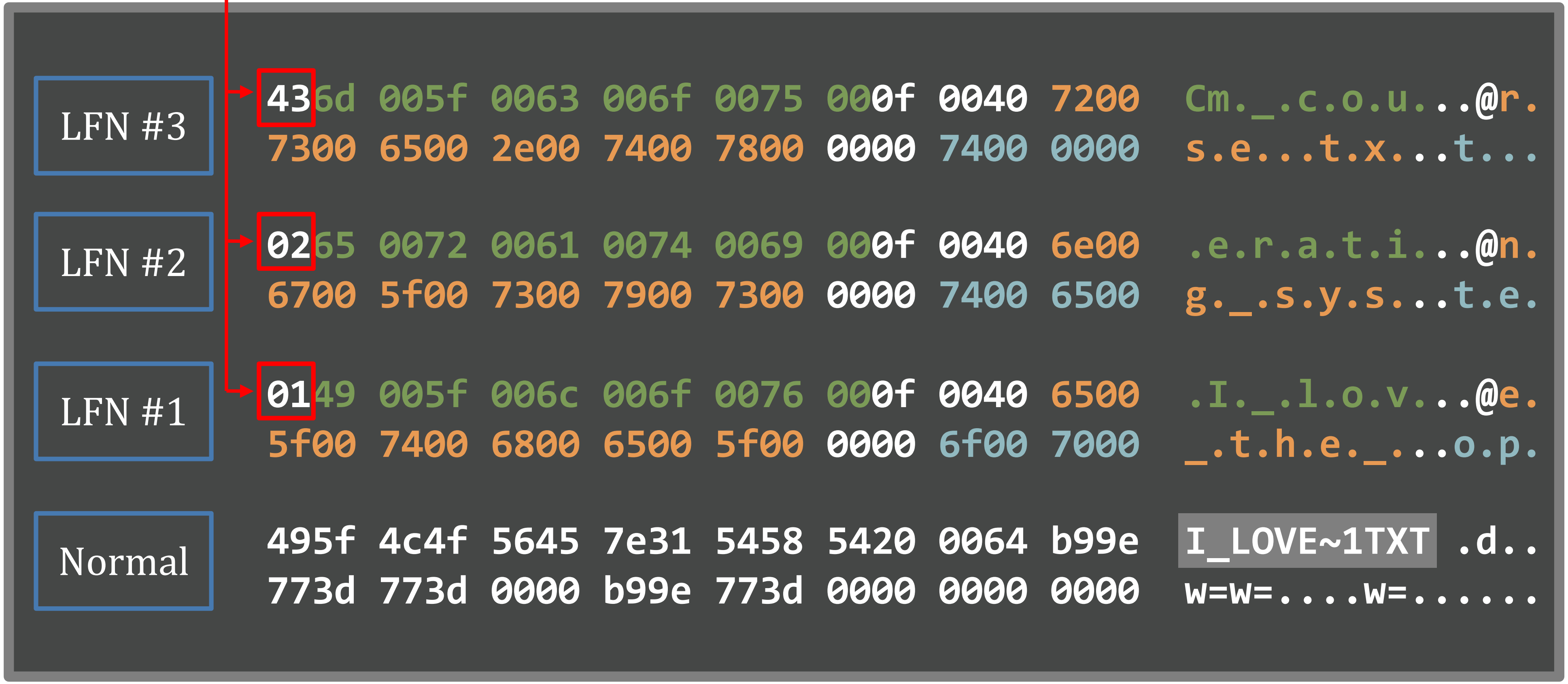
FAT series – 1 directory entry can hold

s

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

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

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



```
LFN #3   436d 005f 0063 006f 0075 000f 0040 7200  Cm._.c.o.u...@r.
         7300 6500 2e00 7400 7800 0000 7400 0000  s.e...t.x...t...

LFN #2   0265 0072 0061 0074 0069 000f 0040 6e00  .e.r.a.t.i...@n.
         6700 5f00 7300 7900 7300 0000 7400 6500  g._.s.y.s...t.e.

LFN #1   0149 005f 006c 006f 0076 000f 0040 6500  .I._.l.o.v...@e.
         5f00 7400 6800 6500 5f00 0000 6f00 7000  _.t.h.e._...o.p.

Normal   495f 4c4f 5645 7e31 5458 5420 0064 b99e  I_LOVE~1TXT .d..
         773d 773d 0000 b99e 773d 0000 0000 0000  w=w=....w=......
```

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

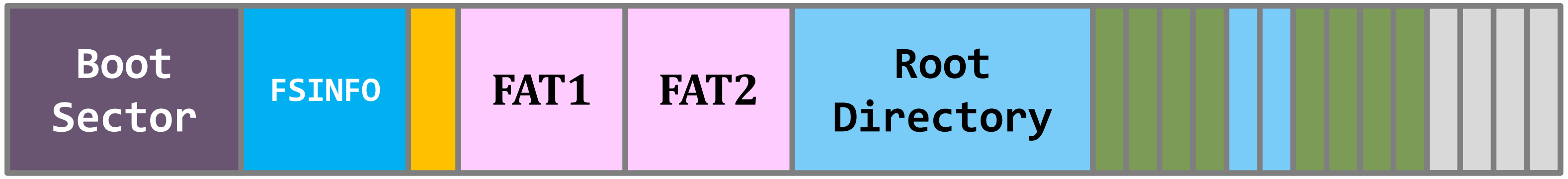
0	...
1	...
...	...
32	**33**
33	EOF
34	0
35	0

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

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.

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



FAT series – reading a file

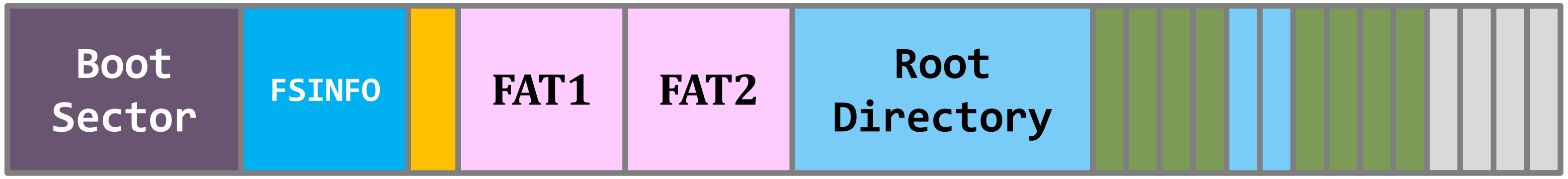
Task: read “C:\windows\gamedata.dat” sequentially.

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 – appending a file

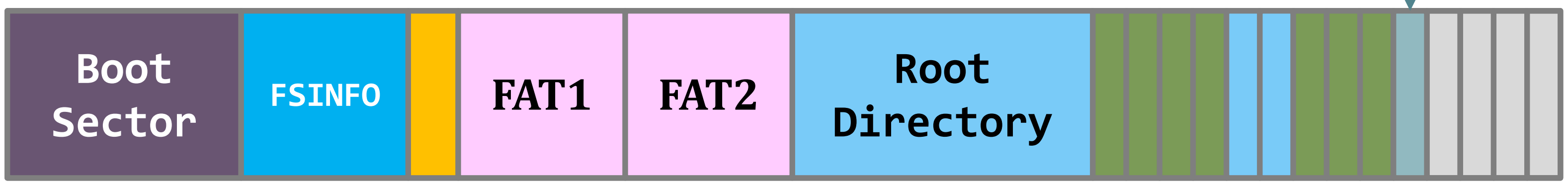
Task: append data to "C:\windows\gamedata.dat".

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

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

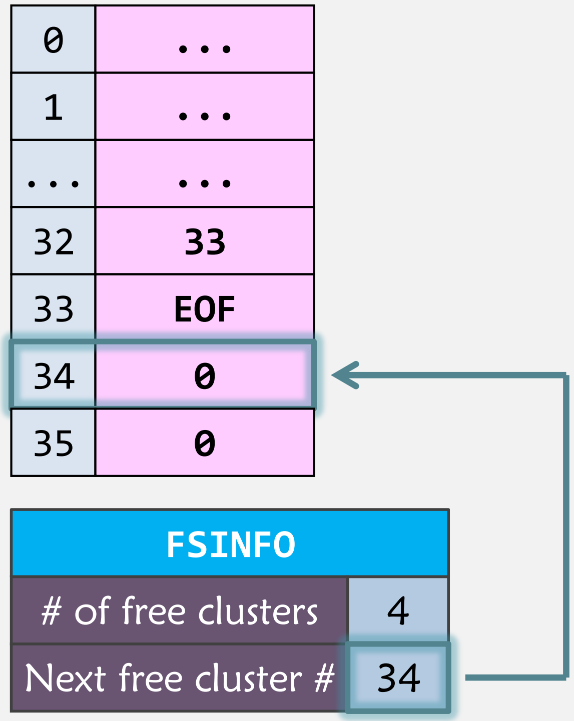
Step 1. Locate the last cluster.

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



FAT series – appending a file

Task: append data to “C:\windows\gamedata.dat”.

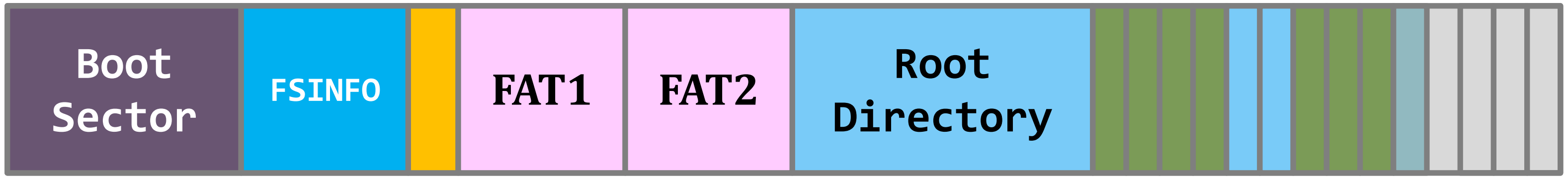


0	...
1	...
...	...
32	**33**
33	**EOF**
34	**0**
35	**0**

FSINFO	
# of free clusters	4
Next free cluster #	34

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

Step 3. Allocate the next cluster through FSINFO.



FAT series – appending a file

Task: append data to “C:\windows\gamedata.dat”.

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

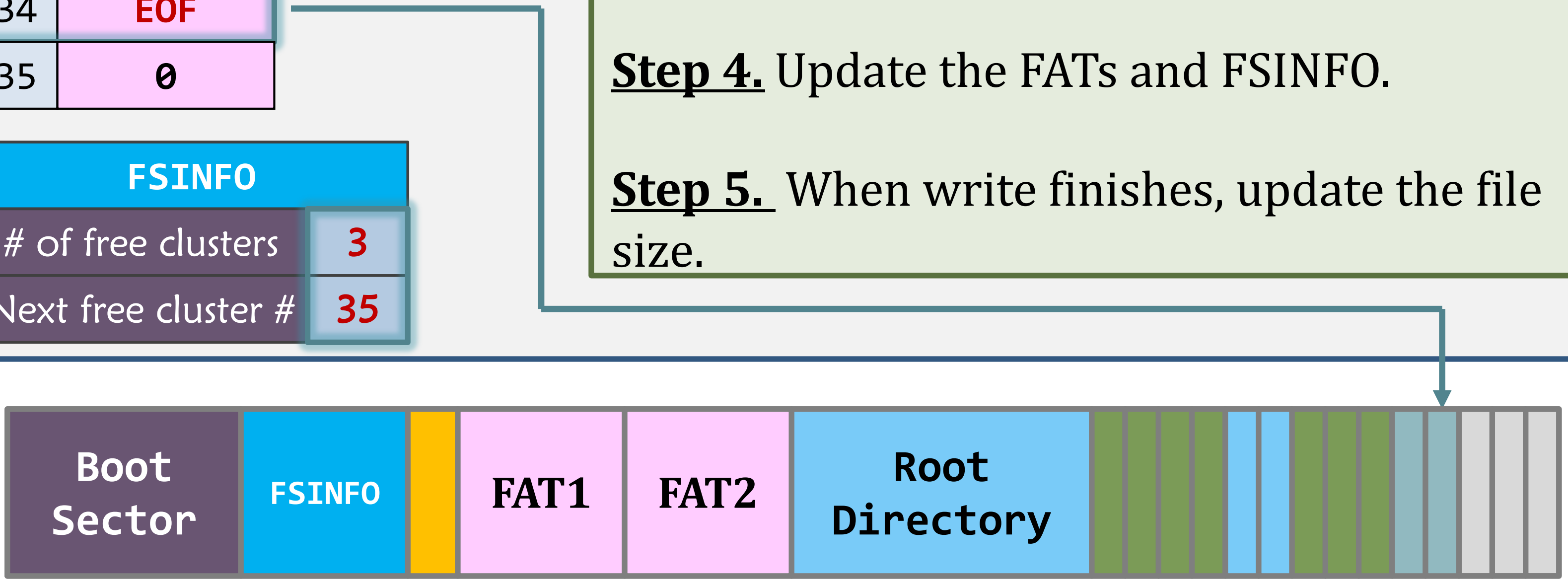
Filename	Attributes	Cluster #
gamedata.dat	......	32

FSINFO	
# of free clusters	3
Next free cluster #	35

Step 3. Allocate the next cluster through FSINFO.

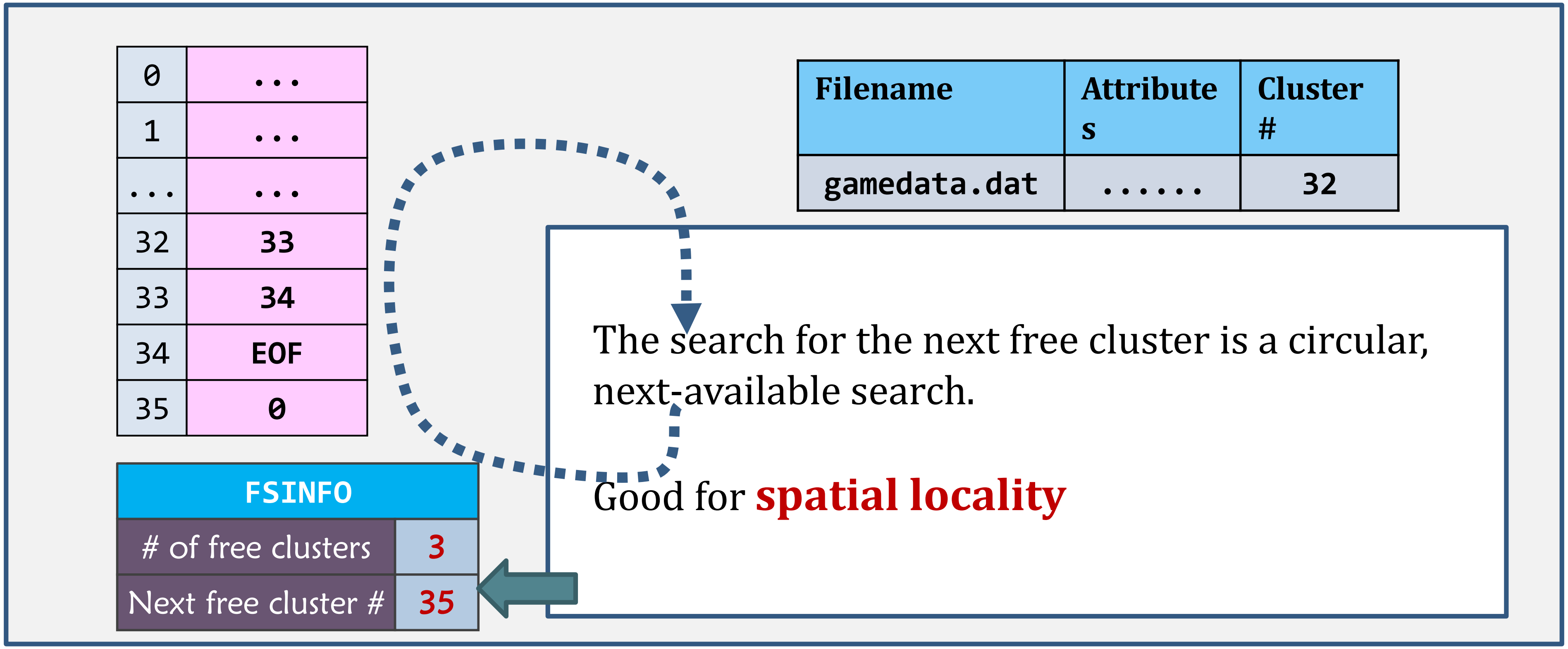
Step 4. Update the FATs and FSINFO.

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



FAT series – appending a file

Task: append data to “C:\windows\gamedata.dat”.



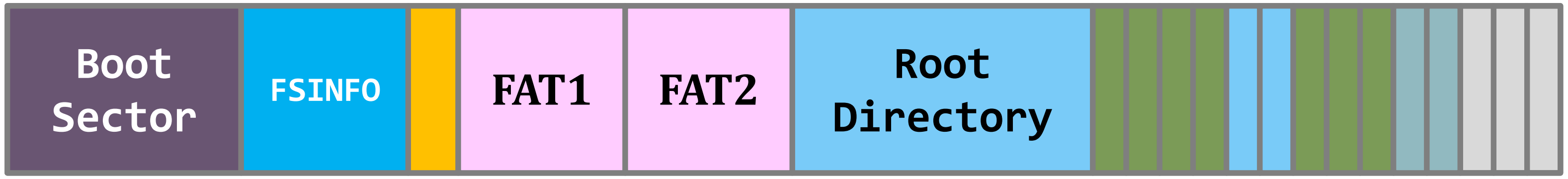
0	...
1	...
...	...
32	33
33	34
34	EOF
35	0

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

FSINFO	
# of free clusters	3
Next free cluster #	35

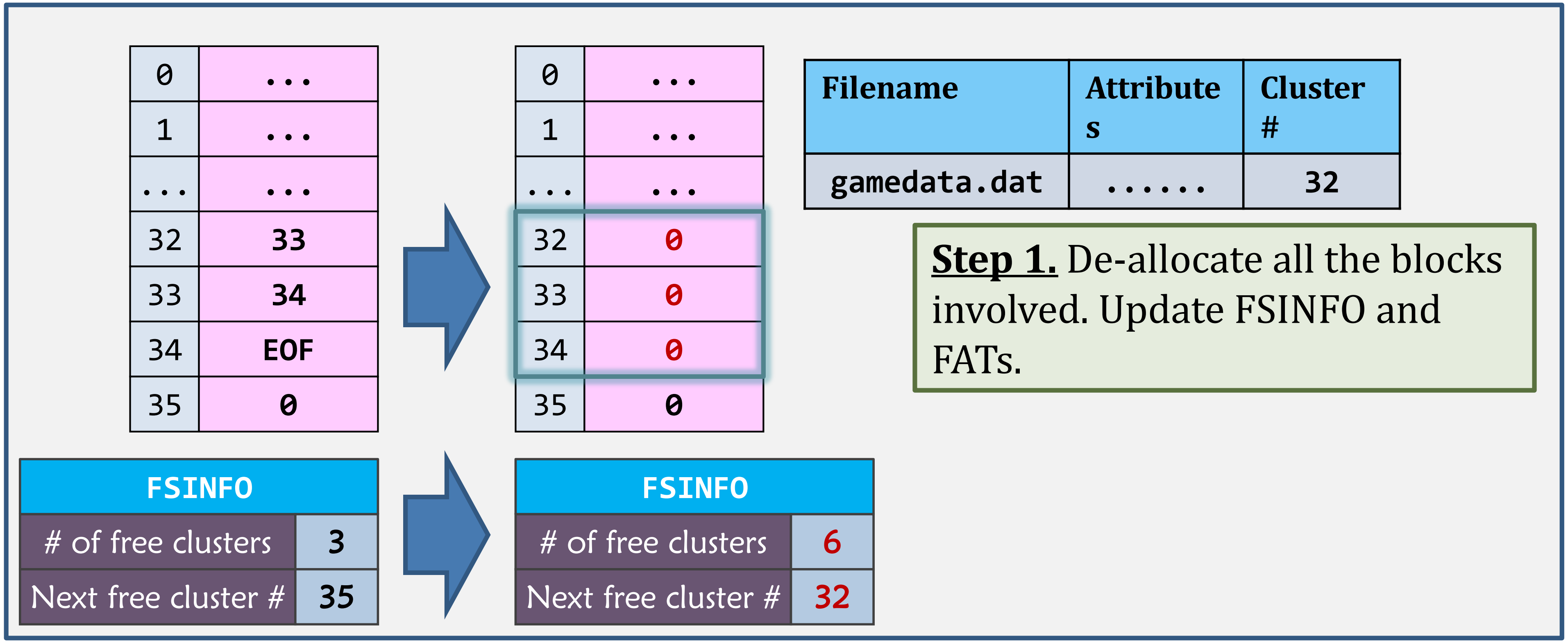
The search for the next free cluster is a circular, next-available search.

Good for **spatial locality**



FAT series – delete a file

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



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

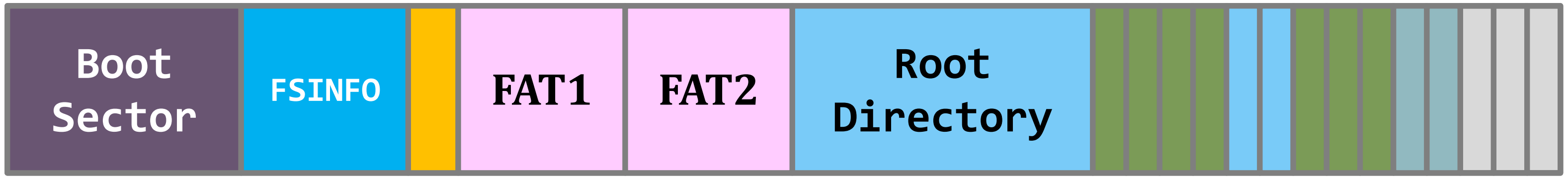
0	...
1	...
...	...
32	0
33	0
34	0
35	0

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

<u>Step 1.</u> De-allocate all the blocks involved. Update FSINFO and FATs.

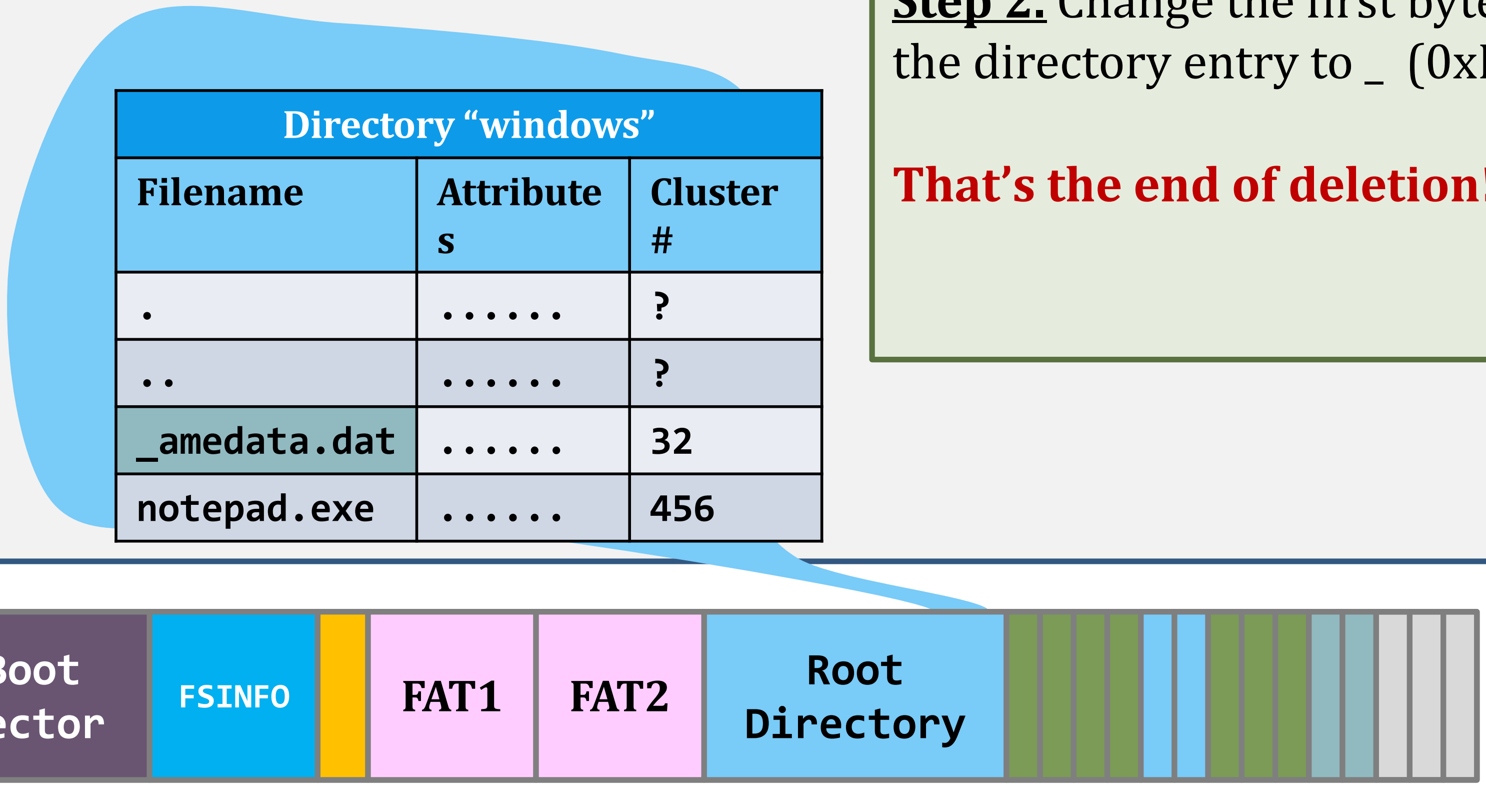
FSINFO	
# of free clusters	3
Next free cluster #	35

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

<u>Step 2.</u> 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 – how to recover a deleted file?

- If you 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 directory entry 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.

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

Summary

- File System:
  - Transforms blocks into Files and Directories
  - Optimize for access and usage patterns
  - Maximize sequential access, allow efficient random access

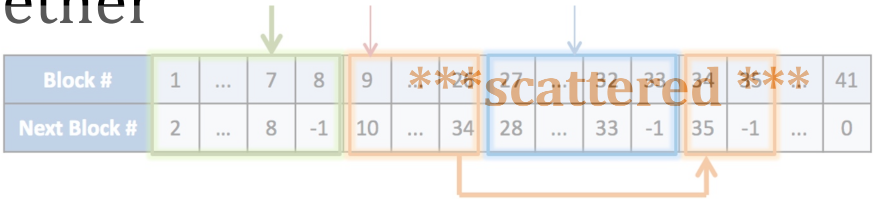
- File Allocation Table (FAT) Scheme
  - Linked-list approach
  - Very widely used: Cameras, USB drives, SD cards
  - Simple to implement, but poor performance and no security

Unix File System

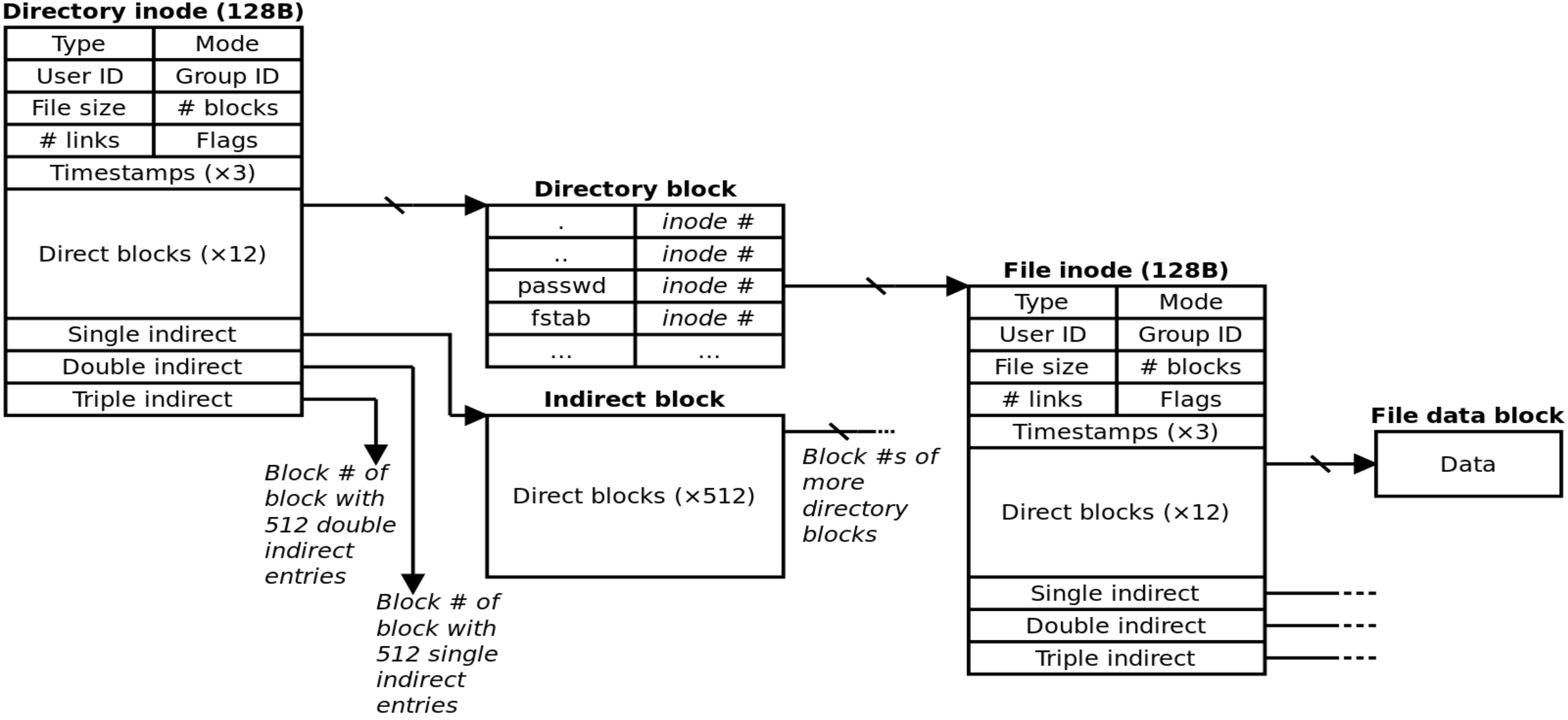
- Original iNode format appeared in BSD 4.1
  - Berkeley Standard Distribution Unix
  - Similar structure for Linux Ext2/3
- File Number is index of iNode arrays
- Multi-level index structure
  - Great for little and large files
  - Unbalanced tree with fixed sized blocks
- Metadata associated with the file
  - Rather than in the directory that points to it
- Scalable directory structure

iNode

- All pointers of a file are located together
  - **VS. FAT: pointers of a file are ***scattered*****
- One directory/file has one iNode



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



Directory inode (128B)

Type	Mode
User ID	Group ID
File size	# blocks
# links	Flags
Timestamps (×3)	
Direct blocks (×12)	
Single indirect	
Double indirect	
Triple indirect	

Directory block

.	*inode #*
..	*inode #*
passwd	*inode #*
fstab	*inode #*
…	…

Indirect block

Direct blocks (×512)

Block #s of more directory blocks

Block # of block with 512 double indirect entries

Block # of block with 512 single indirect entries

File inode (128B)

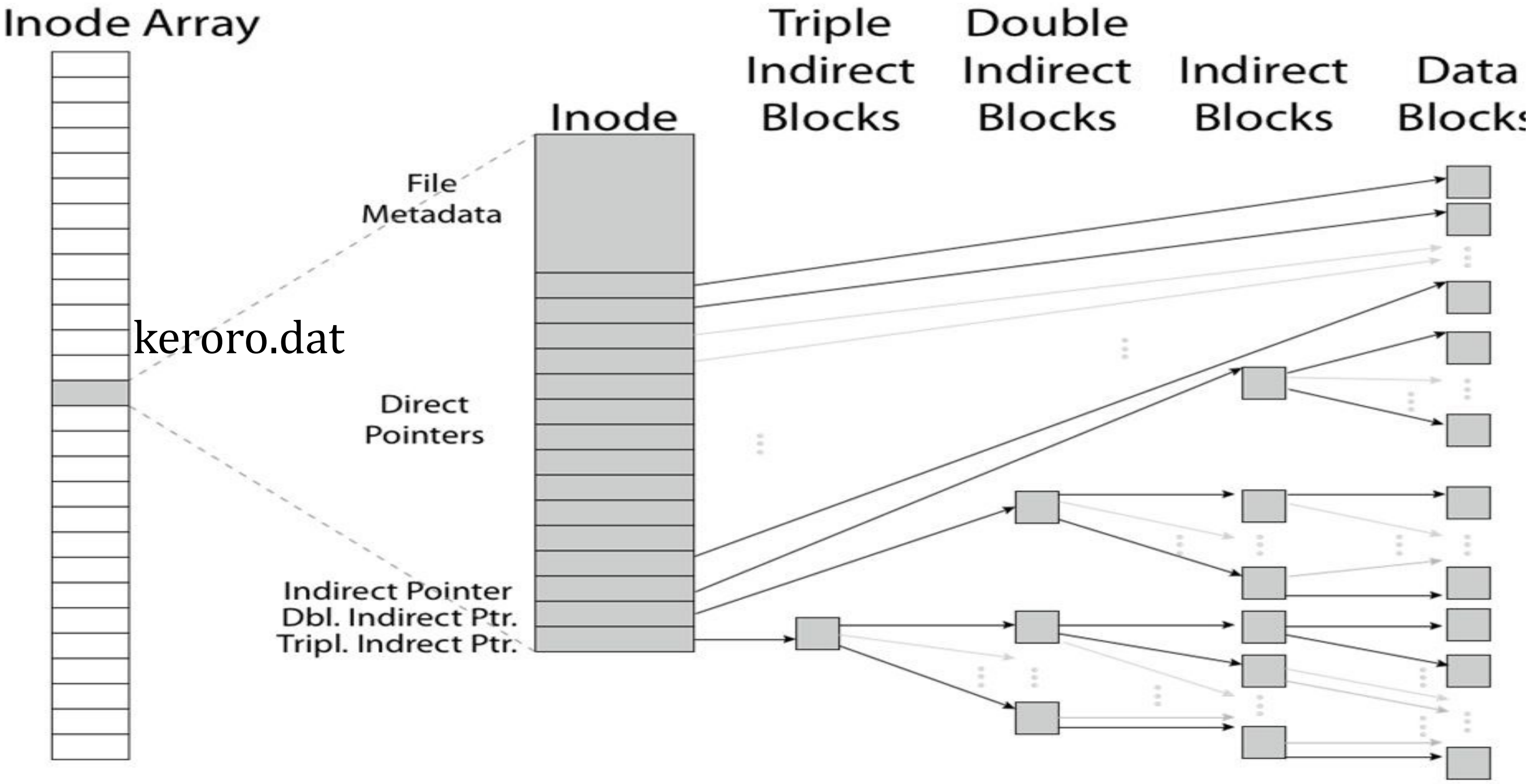
Type	Mode
User ID	Group ID
File size	# blocks
# links	Flags
Timestamps (×3)	
Direct blocks (×12)	
Single indirect	
Double indirect	
Triple indirect	

File data block

Data

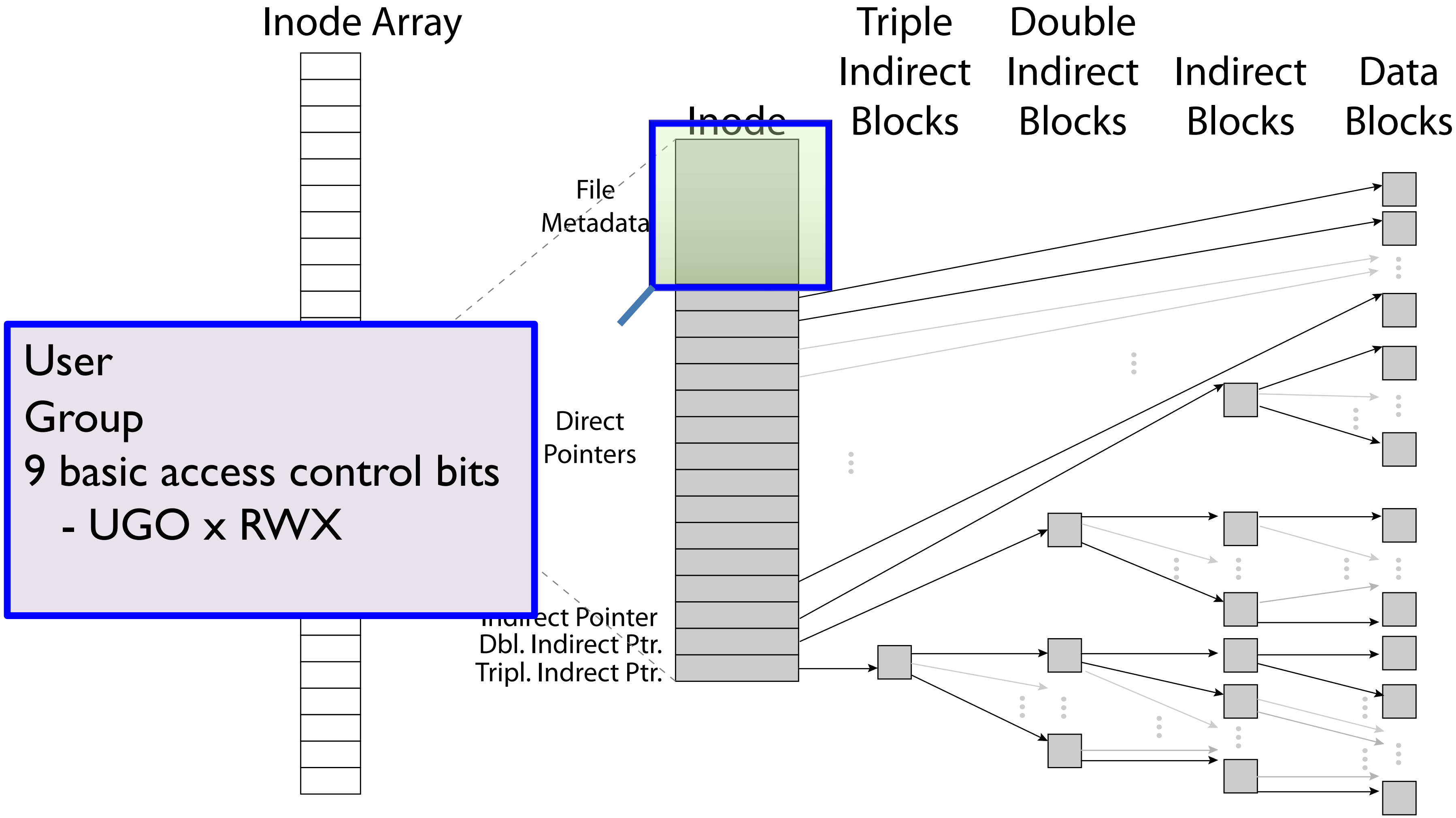
iNode

- iNode Table is an array of iNodes
- Pointers are unbalanced tree-based data structures



File Attributes

- iNode metadata



User

Group

9 basic access control bits

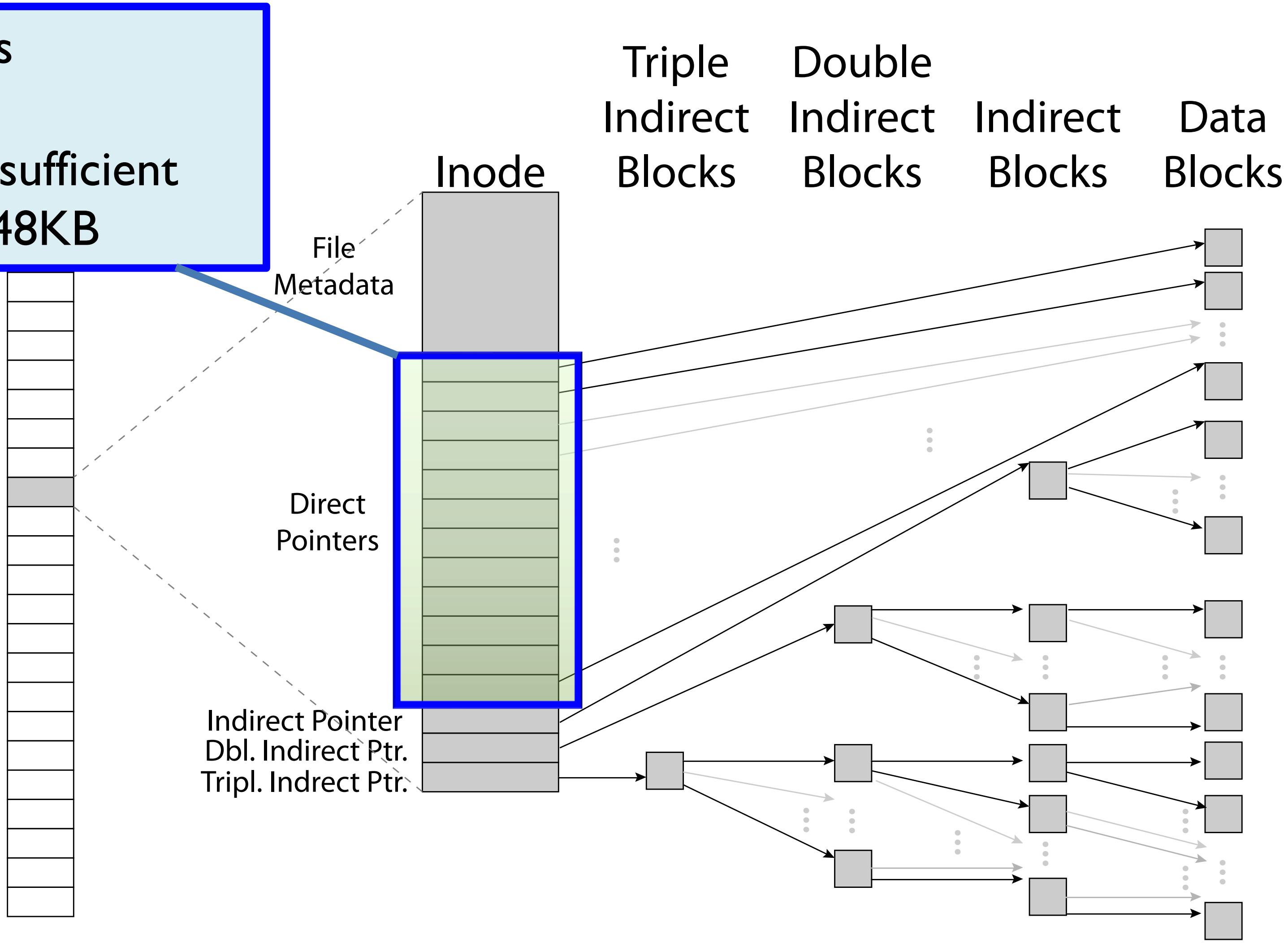
- UGO x RWX

Data Storage

- Small files: 12 pointers direct to data blocks

Direct pointers

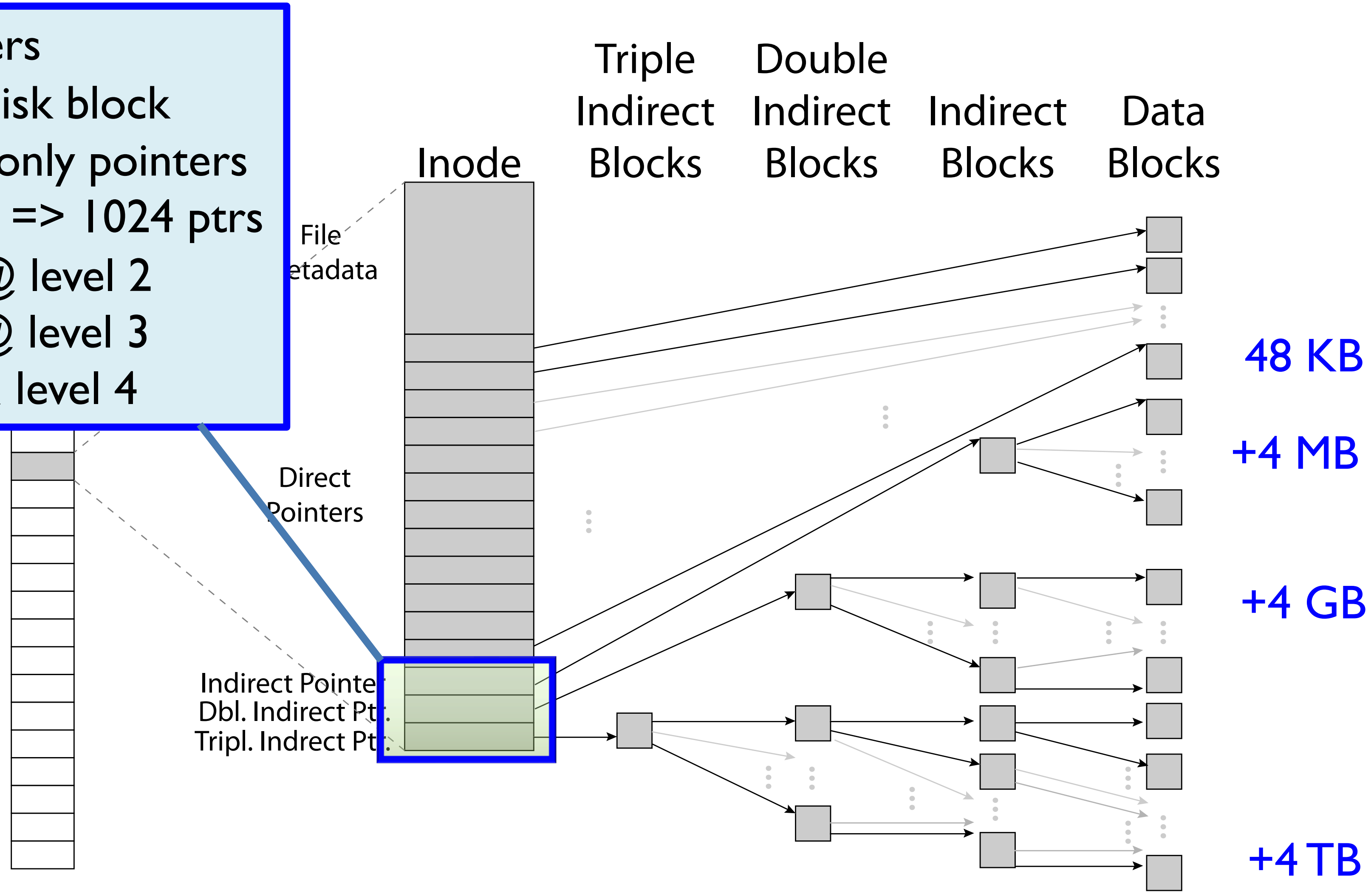
4kB blocks ⇒ sufficient for files up to 48KB



Data Storage

- Large files: 1,2,3 level indirect pointers

Indirect pointers
- point to a disk block containing only pointers
- 4 kB blocks => 1024 ptrs
  => 4 MB @ level 2
  => 4 GB @ level 3
  => 4 TB @ level 4



Index-node – file size

Reminder: Max file size != FS size

Number of direct blocks	12
Number of indirect blocks	1
Number of double indirect blocks	1
Number of triple indirect blocks	1
Block size	2^x bytes
Address length	4 bytes

$$\begin{aligned} &12 \times 2^x && + \\ &1 \times 2^x/4 \times 2^x && + \\ &1 \times (2^x/4)^2 \times 2^x && + \\ &1 \times (2^x/4)^3 \times 2^x && \end{aligned}$$

contains “2^x / 4” addresses

File size = number of data blocks * Block size

Block size 2^x	Max size
1024 bytes = 2^{10}	approx. 16 GB
4096 bytes = 2^{12}	approx. 4 TB

Index-node – file size

File size = number of data blocks x 2^x

Number of direct blocks	12
Number of indirect blocks	1
Number of double indirect blocks	1
Number of triple indirect blocks	1
Block size	2^x bytes
Address length	4 bytes

$$12 \times 2^x + 2^{2x-2} + 2^{3x-4} + \boxed{2^{4x-6}}$$

The dominating factor.

▤ contains "2^x / 4" addresses

Block size 2^x	Max size
1024 bytes = 2^{10}	approx. 16 GB
4096 bytes = 2^{12}	approx. 4 TB

Reminder: Max file size != FS size

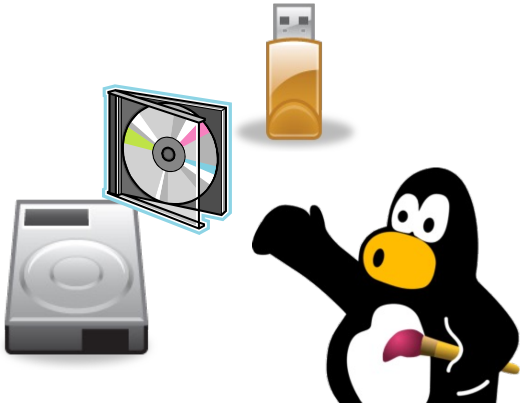
Ext 2/3/4

- Disk layout

- Directory

- Hard and Soft Links

- Consistency



File System Ext

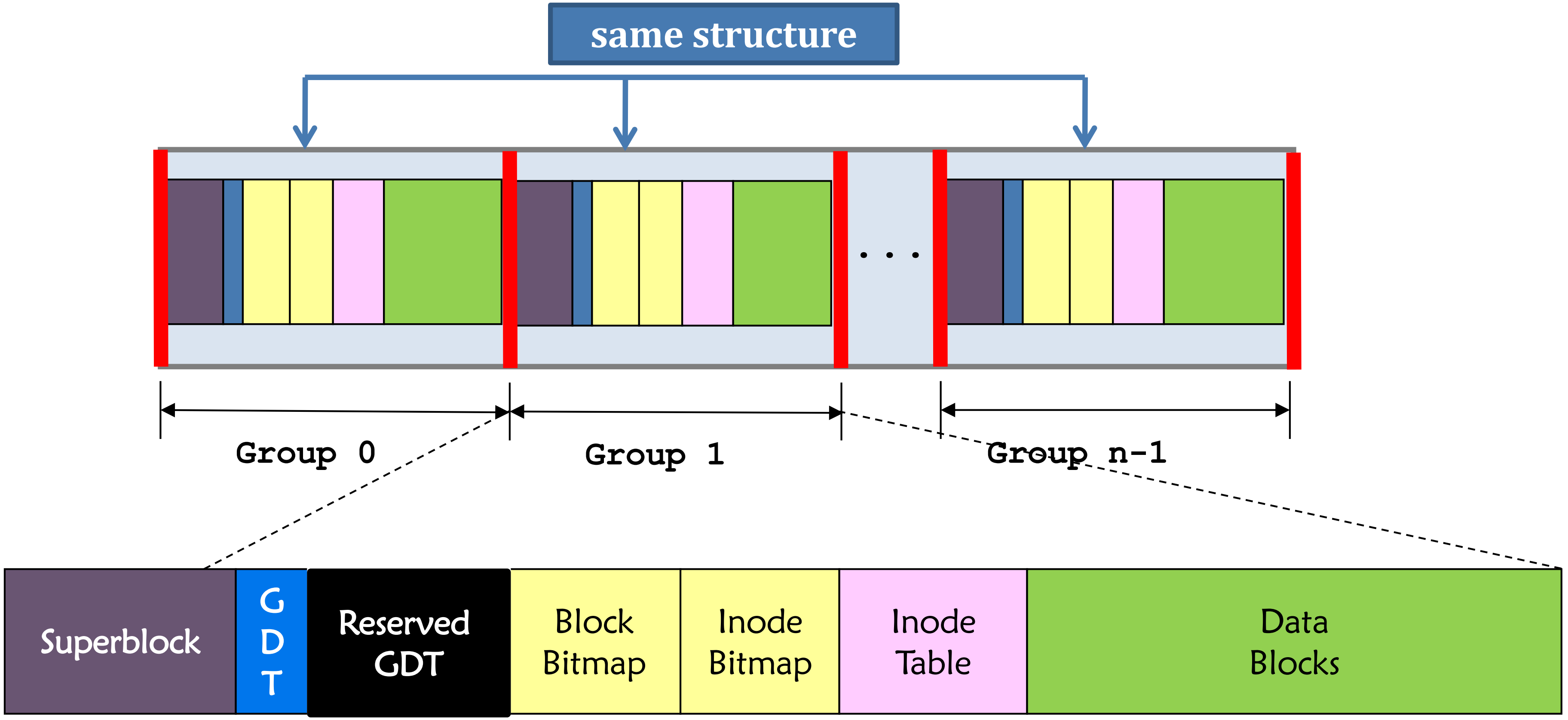
- The latest default FS for Linux distribution is the **Fourth Extended File System**, **Ext4** for short.

- For Ext2 & Ext3:
  - Block size: 1,024, 2,048, or 4,096 bytes.
  - Block address size: 4 bytes => # of block addresses = 2^{32}

$2^x \times 2^{32} = 2^{32+x}$			
Block size	$2^x = 1024$	$2^x = 2048$	$2^x = 4096$
File System size	4 TB	8 TB	16 TB

Ext2/3 – Block groups

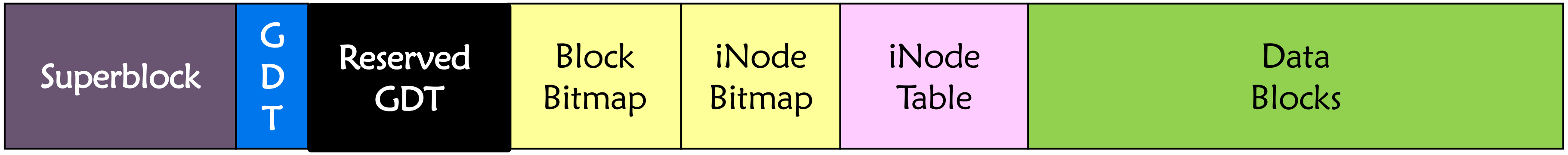
- The file system is divided into **block groups** and every block group has the **same structure**



Ext2/3 – FS layout

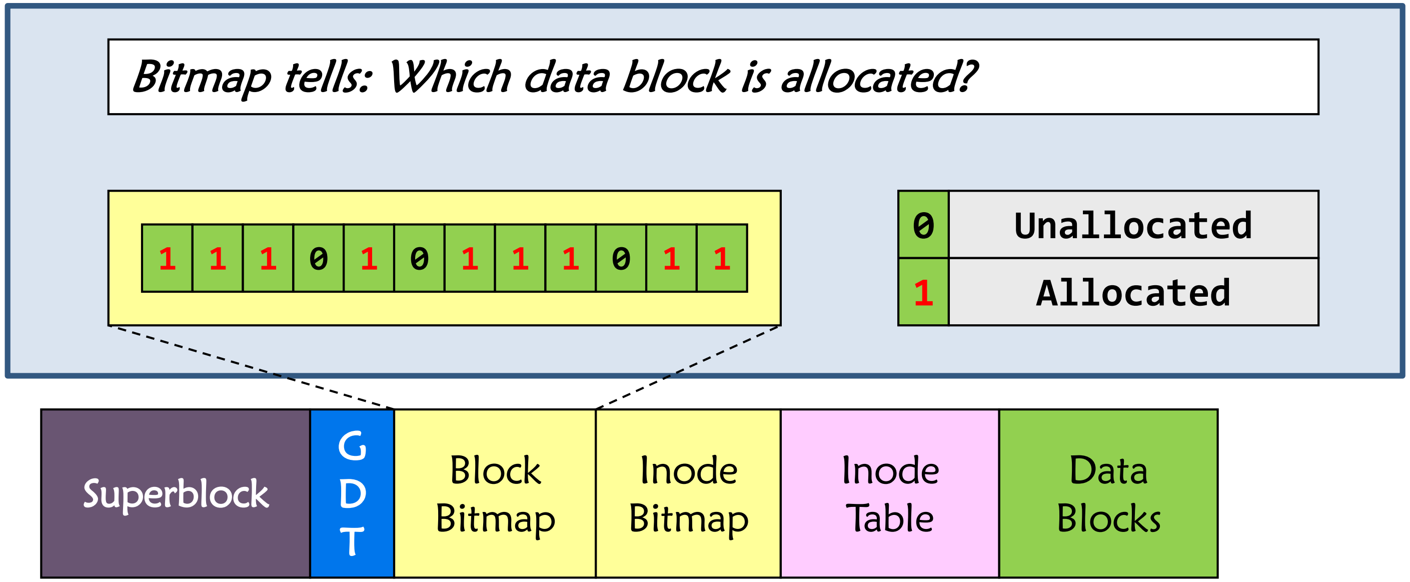
- Layout of one block group is as follows:

Superblock	Stores FS specific data. E.g., the total number of blocks, etc.
GDT – Group Descriptor Table	It stores: - The locations of the **block bitmap**, the **iNode bitmap**, and the **iNode table**. - Free block count, free iNode count, etc…
Block Bitmap	A bit string that represents if a block is allocated or not.
iNode Bitmap	A bit string that represents if an inode (index-node) is allocated or not.
iNode Table	An array of inodes ordered by the inode #.
Data Blocks	An array of blocks that stored files.



https://www.ibm.com/developerworks/cn/linux/l-cn-filesrc5/

Ext2/3 – Block Bitmap & iNode Bitmap

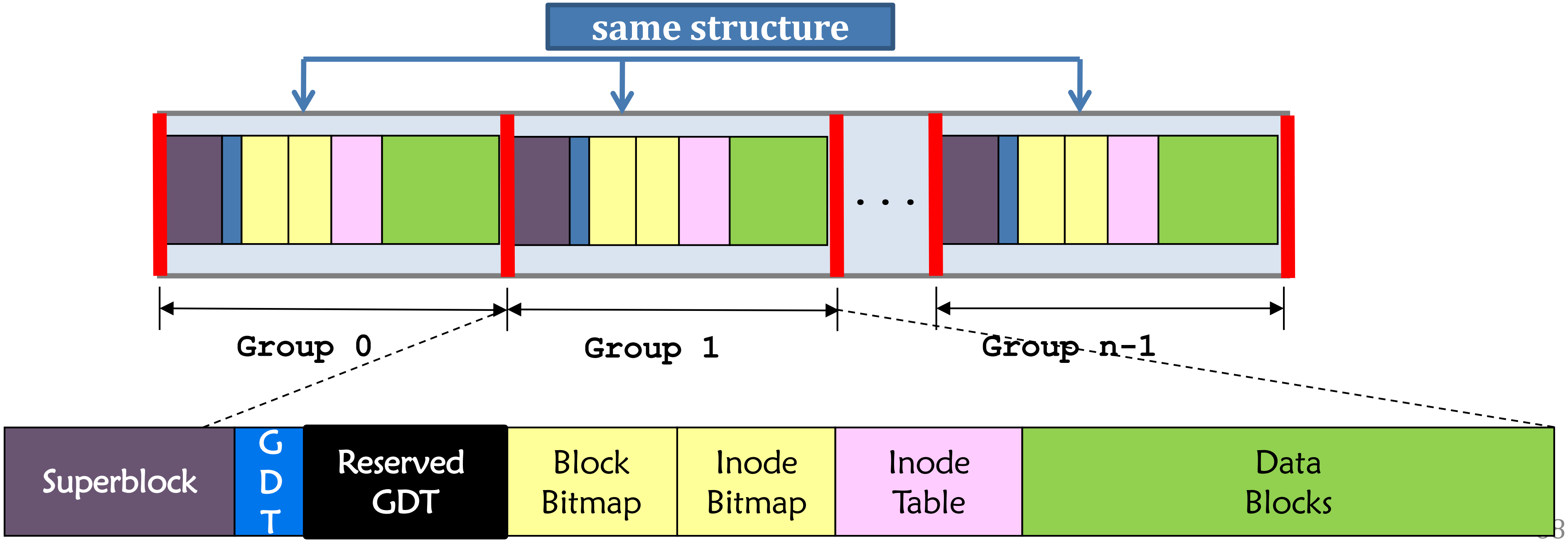


- iNode Bitmap
  - A bit string that represents if an iNode (index-node) is allocated or not

➔ implies that the **number of files in the file system is fixed**!

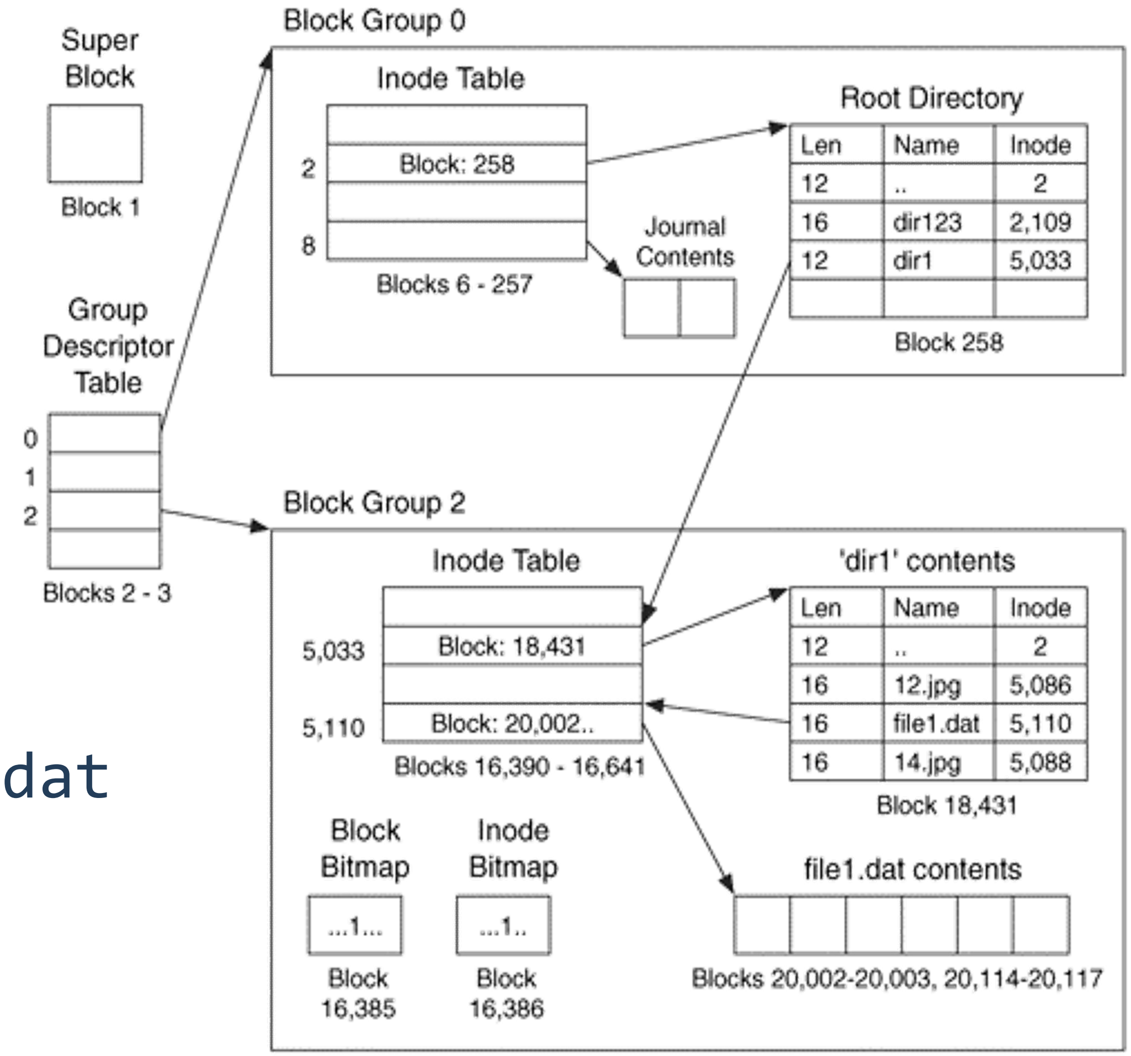
Ext2/3 – Block groups

- Why having groups?
- For **(1) performance** and **(2) reliability**
  - (1) Performance: spatial locality.
    - Group iNodes and data blocks of related files together
  - (2) Reliability: superblock and GDT are **replicated** in each block group (yes, very reliable!)



Linux Example: Ext2/3 Disk Layout

- Disk divided into block groups
  - Each group has two block-sized bitmaps (free blocks/inodes)
  - Block sizes settable at format time: 1K, 2K, 4K, 8K…
  - Provides locality



Root Directory

Len	Name	Inode
12	..	2
16	dir123	2,109
12	dir1	5,033

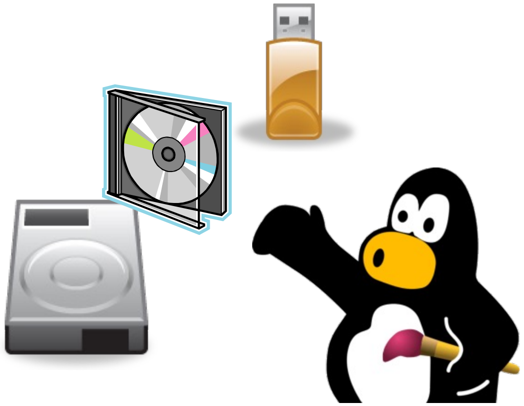
'dir1' contents

Len	Name	Inode
12	..	2
16	12.jpg	5,086
16	file1.dat	5,110
16	14.jpg	5,088

- Example: create a `file1.dat` under `/dir1/` in Ext3

Ext 2/3

- Disk layout;
- Directory;
- Hard and Soft Links.

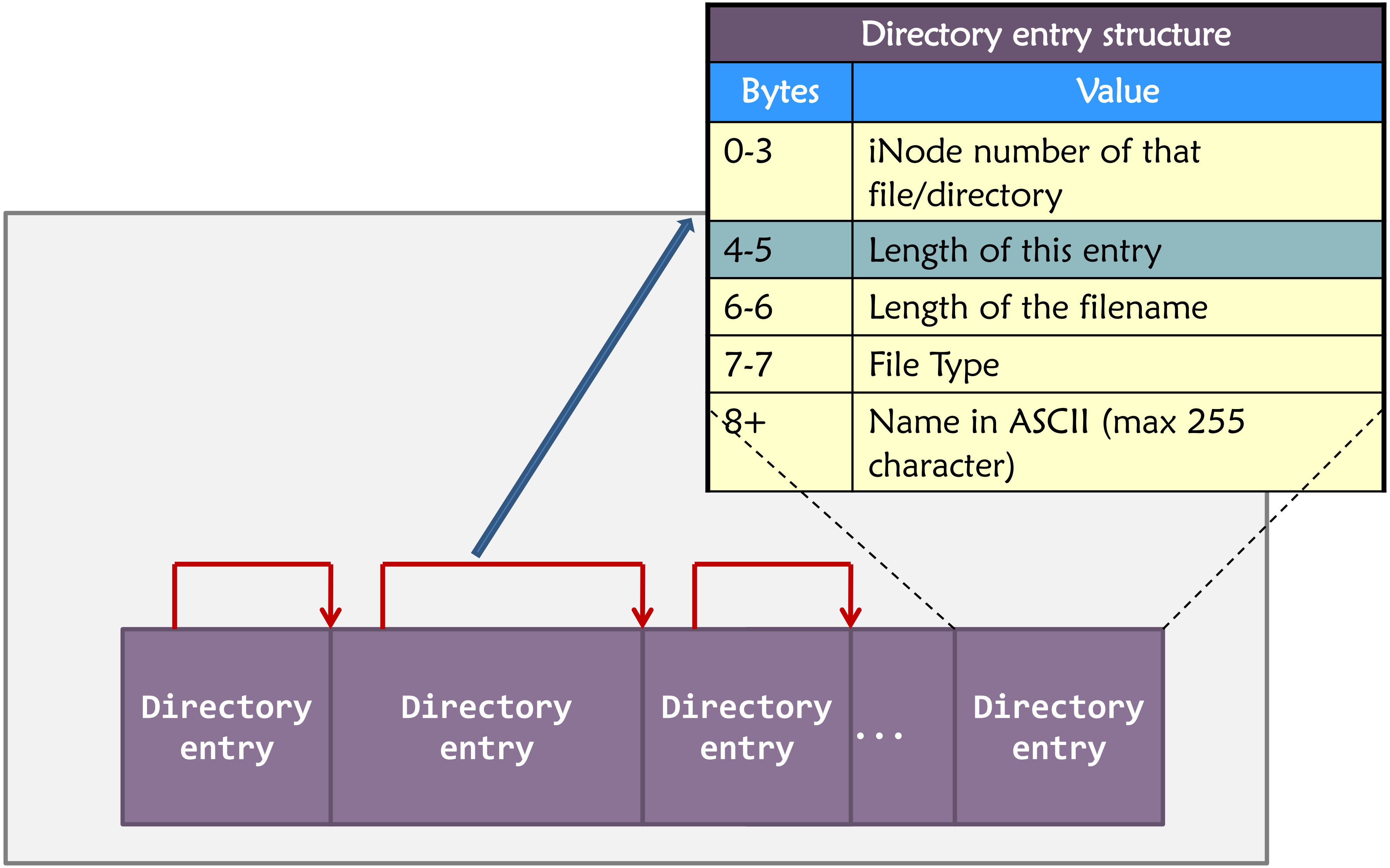


Ext2/3 – iNode structure (for 1 file)

iNode Structure (128 bytes long)	
Bytes	Value
0-1	File type and permission
2-3	User ID
4-7	Lower 32 bits of file sizes in bytes
8-23	Time information
24-25	Group ID
26-27	Link count (will discuss later)
…	…
40-87	12 direct data block pointers
88-91	Single indirect block pointer
92-95	Double indirect block pointer
96-99	Triple Indirect block pointer
…	…
108-111	Upper 32 bits of file sizes in bytes

The locations of the data blocks are stored in the inode.

Ext2/3 –directory entry in a directory block

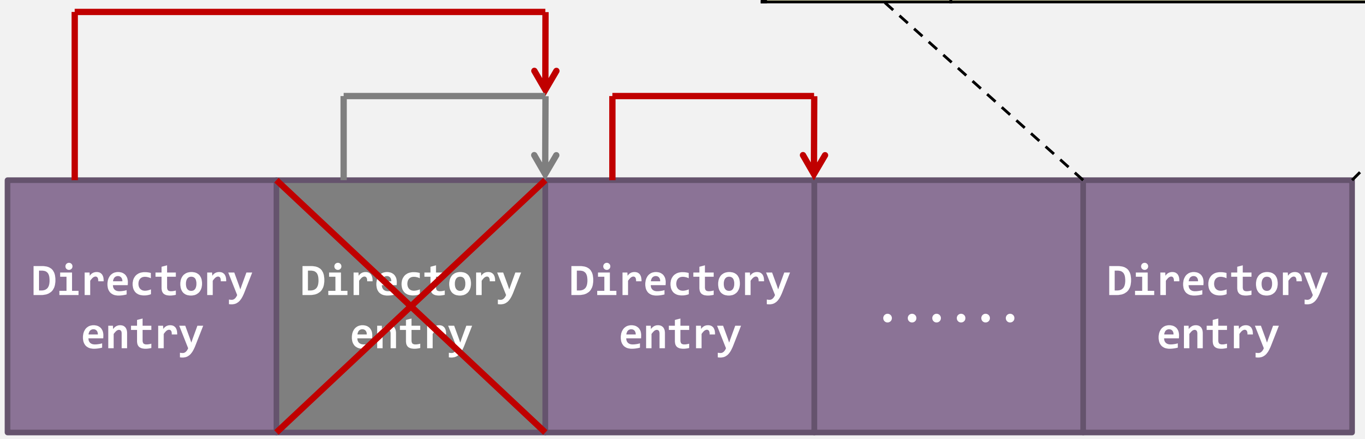


Directory entry structure	
Bytes	**Value**
0-3	iNode number of that file/directory
4-5	Length of this entry
6-6	Length of the filename
7-7	File Type
8+	Name in ASCII (max 255 character)

Ext2/3 – File Deletion

File deletion is just an update of the "entry length" of the previous entry.

Directory entry structure	
Bytes	**Value**
0-3	INode number of that file/directory
4-5	Length of this entry
6-6	Length of the filename
7-7	File Type
8+	Name in ASCII (max 255 character)

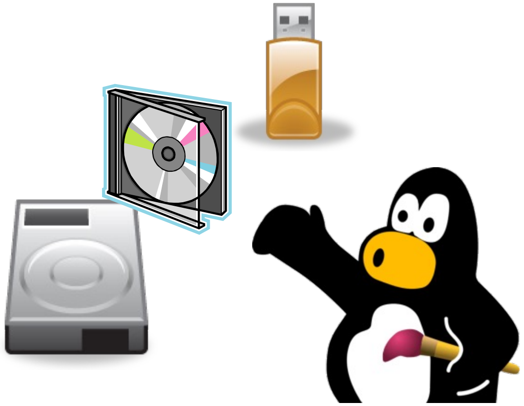


Ext 2/3

- Disk layout;

- Directory;

- **Hard and Soft Links.**



Ext2/3 – link file: what is a hard link

- A hard link is a **directory entry** pointing to the iNode of an existing file.

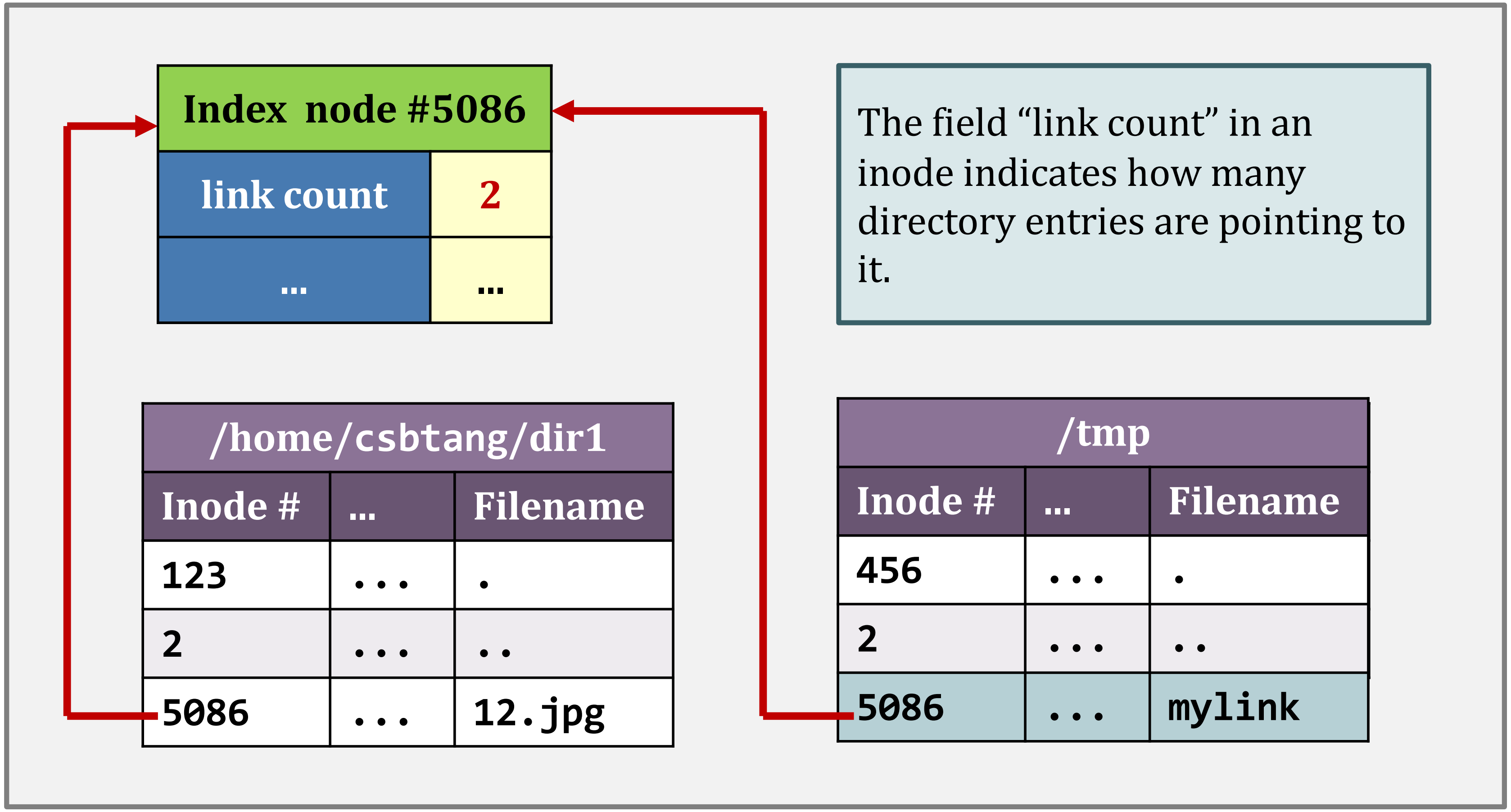
```
# ln /home/csbtang/dir1/12.jpg /tmp/mylink
```

/home/csbtang/dir1		
Inode #	**…**	**Filename**
123	...	.
2	...	..
5086	...	12.jpg

/tmp		
Inode #	**…**	**Filename**
456	...	.
2	...	..
5086	...	mylink

Ext2/3 – link file: what is a hard link

- That **file can be accessed through two different pathnames**.



Index node #5086	
link count	2
...	...

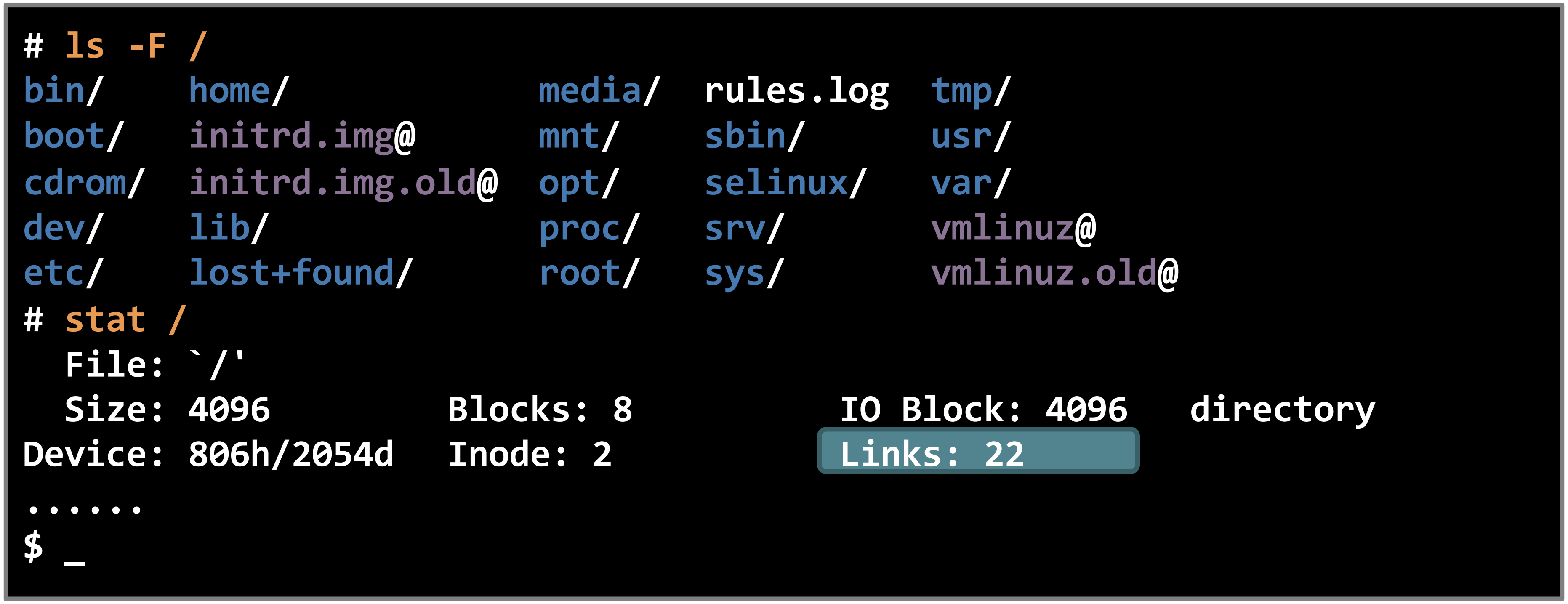
The field “link count” in an inode indicates how many directory entries are pointing to it.

/home/csbtang/dir1		
Inode #	...	Filename
123	...	.
2	...	..
5086	...	12.jpg

/tmp		
Inode #	...	Filename
456	...	.
2	...	..
5086	...	mylink

Ext2/3 – link file: examples on hard link

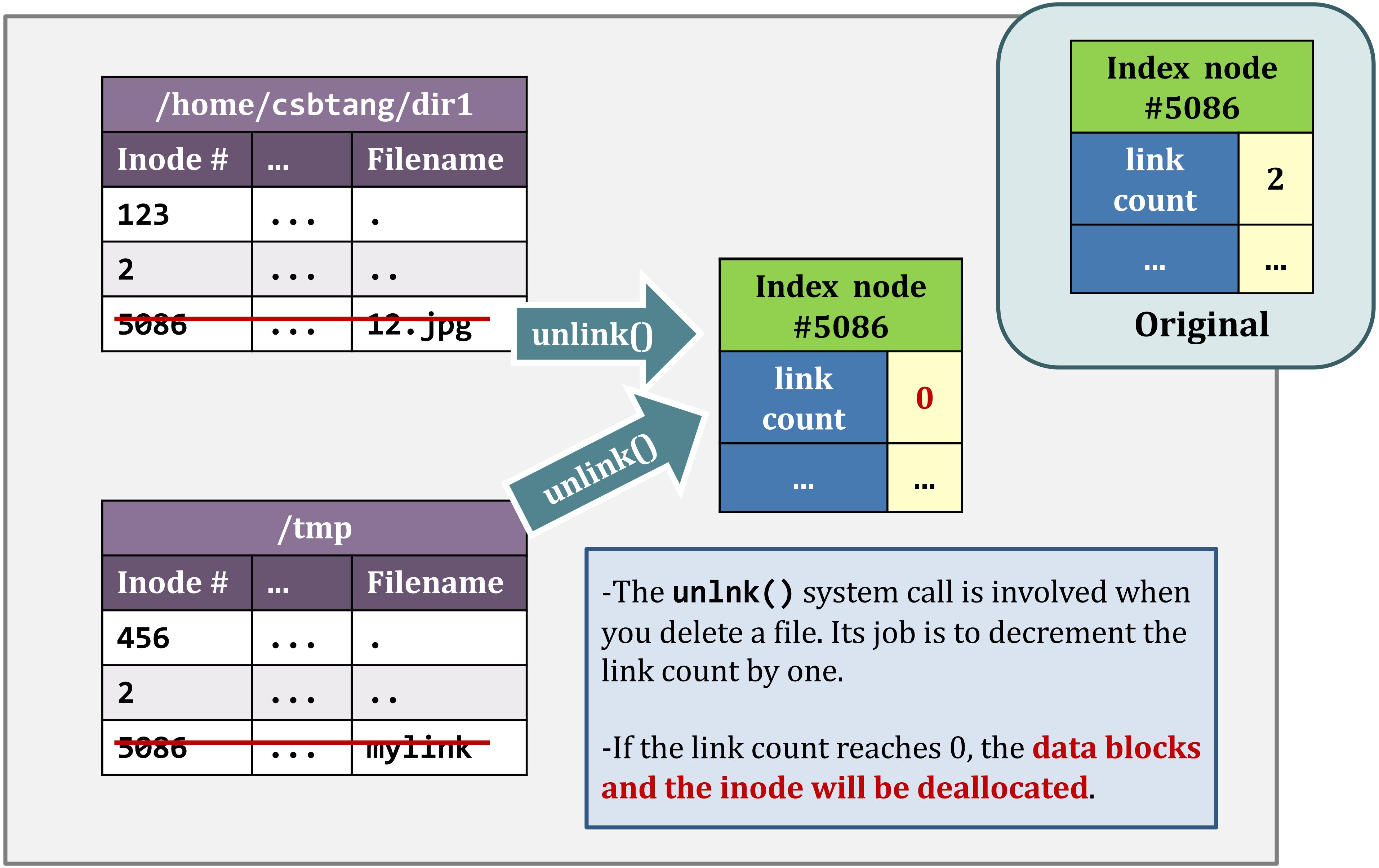
- Let’s look at the link count of the root directory.
  - **20 sub-directories**: have a link “..”;
  - **Root directory**: “.” and “..” pointing to itself;
  - 20 + 2 = 22.



```
# ls -F /
bin/    home/             media/  rules.log  tmp/
boot/   initrd.img@       mnt/    sbin/      usr/
cdrom/  initrd.img.old@   opt/    selinux/   var/
dev/    lib/              proc/   srv/       vmlinuz@
etc/    lost+found/       root/   sys/       vmlinuz.old@
# stat /
  File: `/'
  Size: 4096         Blocks: 8          IO Block: 4096   directory
Device: 806h/2054d   Inode: 2           Links: 22

......
$ _
```

Ext2/3 – removing file and link count



/home/csbtang/dir1		
Inode #	**…**	**Filename**
123	...	.
2	...	..
~~5086~~	~~...~~	~~12.jpg~~

/tmp		
Inode #	**…**	**Filename**
456	...	.
2	...	..
~~5086~~	~~...~~	~~mylink~~

Index node #5086	
link count	0
…	…

Index node #5086	
link count	2
…	…

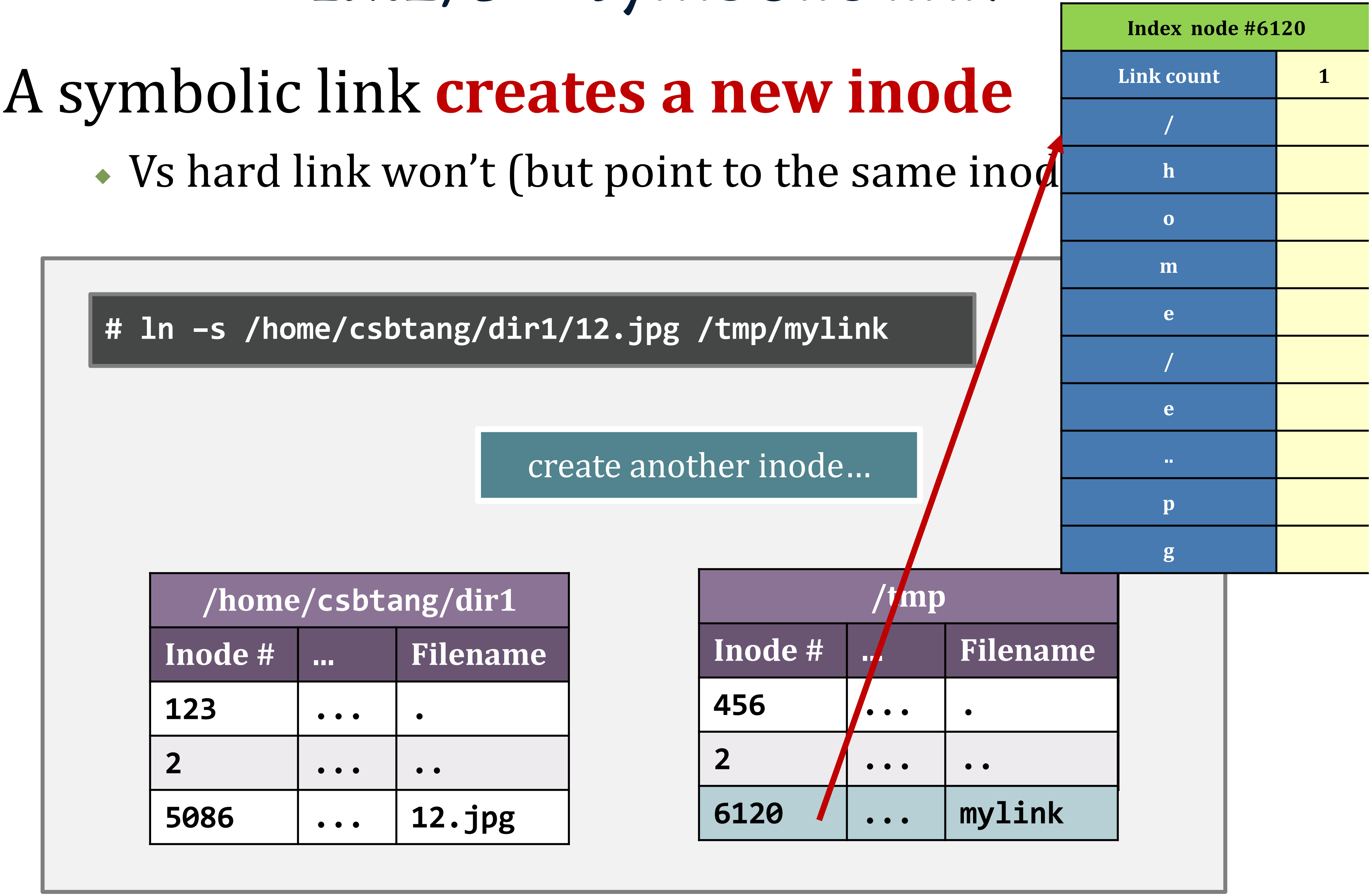
Original

-The **`unlnk()`** system call is involved when you delete a file. Its job is to decrement the link count by one.

-If the link count reaches 0, the **data blocks and the inode will be deallocated**.

Ext2/3 – symbolic link

- A symbolic link **creates a new inode**
  - Vs hard link won’t (but point to the same inod



```
# ln -s /home/csbtang/dir1/12.jpg /tmp/mylink
```

create another inode...

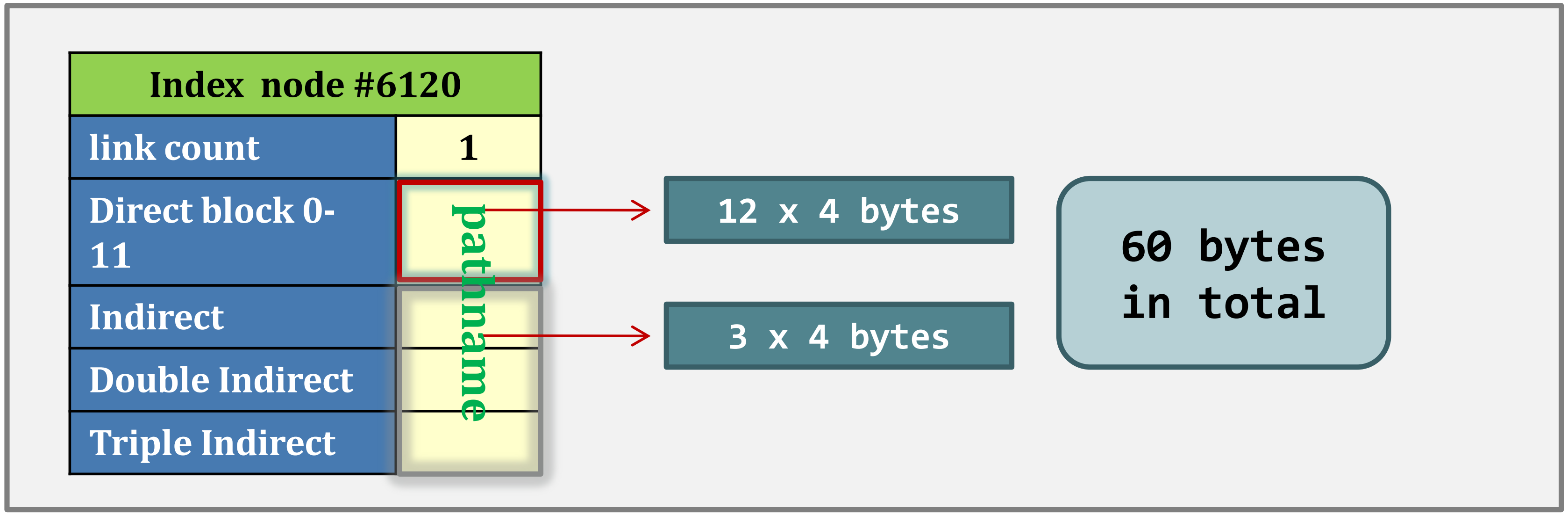
/home/csbtang/dir1		
Inode #	**...**	**Filename**
123	...	.
2	...	..
5086	...	12.jpg

/tmp		
Inode #	**...**	**Filename**
456	...	.
2	...	..
6120	...	mylink

Index node #6120	
Link count	1
/	
h	
o	
m	
e	
/	
e	
..	
p	
g	

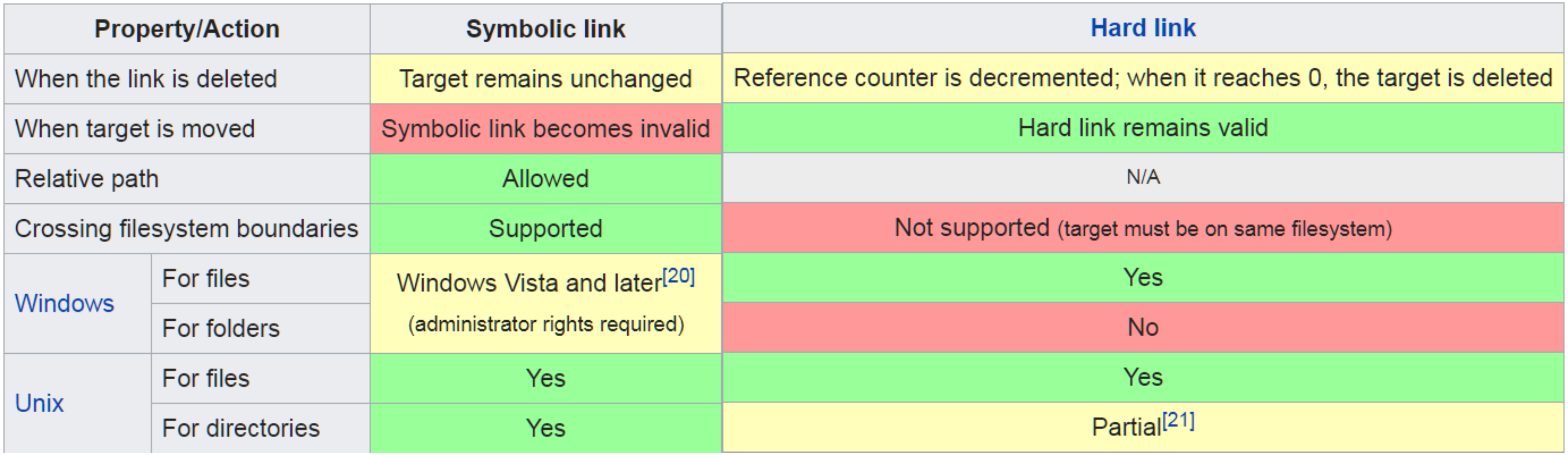
Ext2/3 – symbolic link

- Symbolic link is pointing to a new iNode whose target's **pathname** are stored using the space originally designed for **12 direct block and the 3 indirect block pointers** if the pathname is shorter than 60 characters.
    - Use back a normal inode + **one direct data block** to hold the long pathname otherwise



Summary of Links

- Hard link
  - Sets another directory entry to contain the file number for the file
  - Creates another name (path) for the file
  - Each is “first class”
- Soft link or Symbolic Link
  - Directory entry contains the path and name of the file
  - Map one name to another name



Property/Action		Symbolic link	Hard link
When the link is deleted		Target remains unchanged	Reference counter is decremented; when it reaches 0, the target is deleted
When target is moved		Symbolic link becomes invalid	Hard link remains valid
Relative path		Allowed	N/A
Crossing filesystem boundaries		Supported	Not supported (target must be on same filesystem)
Windows	For files	Windows Vista and later[20] (administrator rights required)	Yes
	For folders		No
Unix	For files	Yes	Yes
	For directories	Yes	Partial[21]

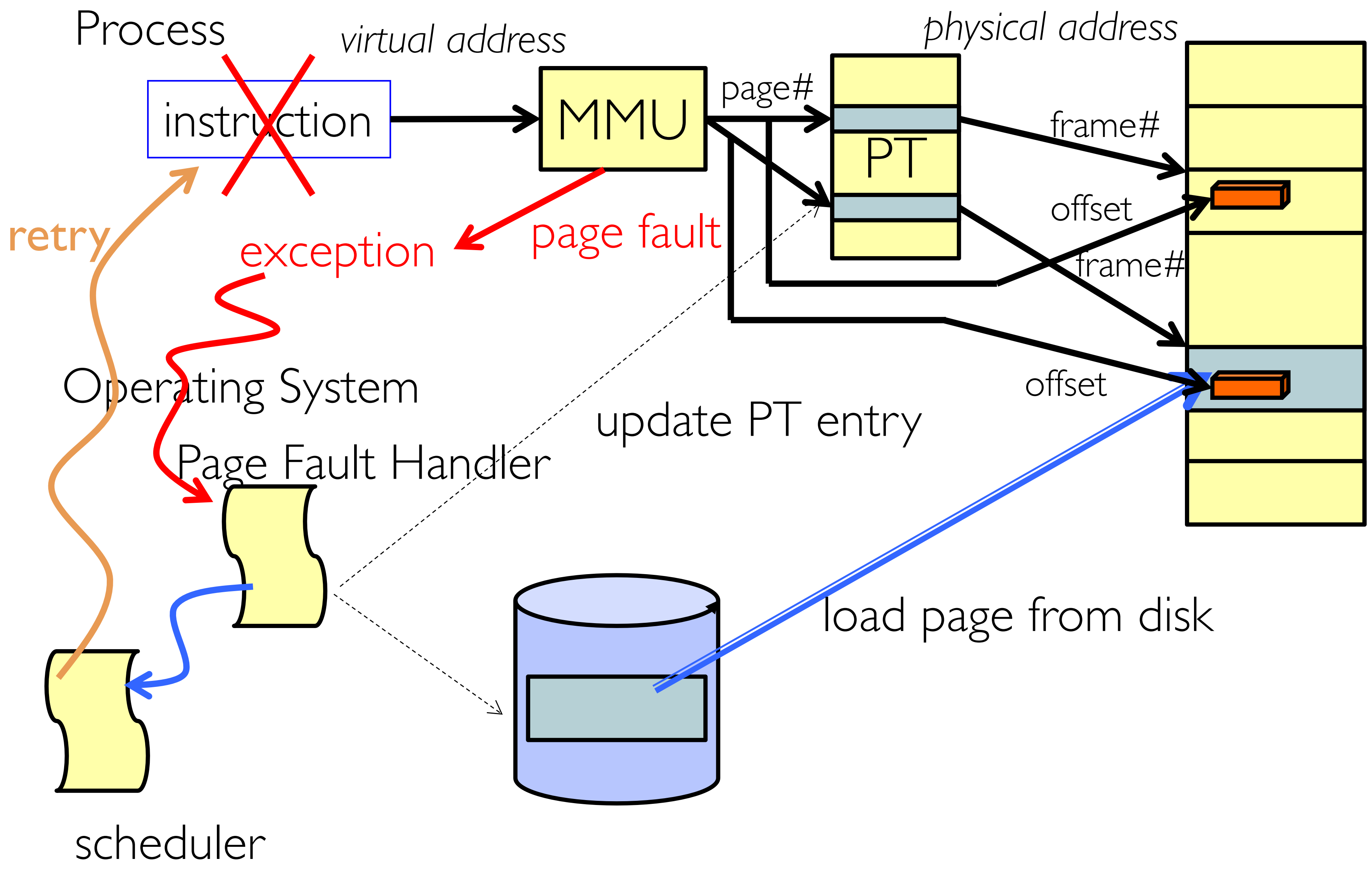
Memory Mapped Files

- Traditional I/O involves explicit transfers between buffers in process address space to/from regions of a file
    - This involves multiple copies into caches in memory, plus system calls

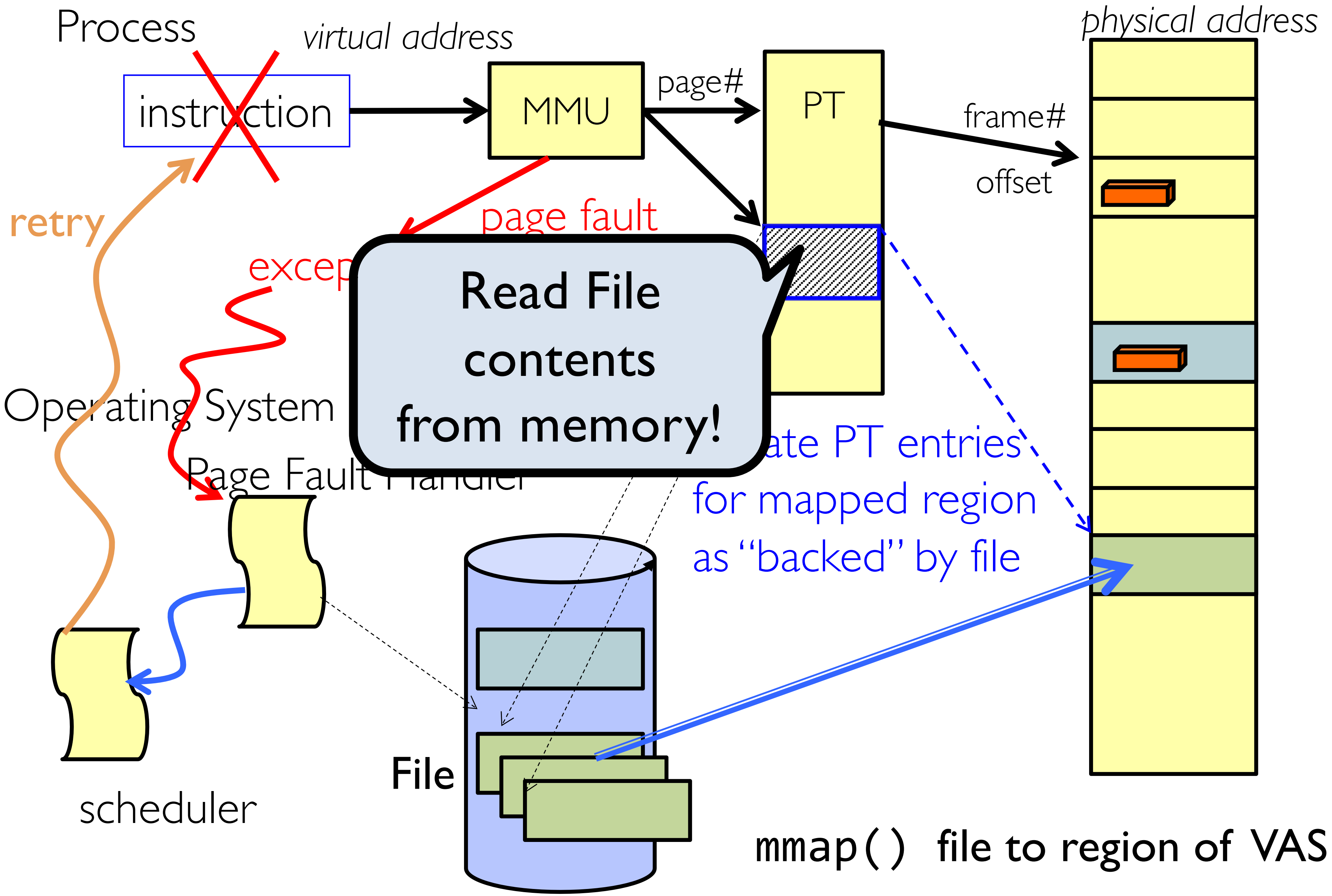
- What if we could “map” the file directly into an empty region of our address space
    - Implicitly “page it in” when we read it
    - Write it and “eventually” page it out

- Executable files are treated this way when we `exec` the process!!

Recall: Who Does What, When?



Using Paging to `mmap()` Files



`mmap()` file to region of VAS

File System Summary (1/2)

- File System:
  - Transforms blocks into Files and Directories
  - Optimize for size, access and usage patterns
  - Maximize sequential access, allow efficient random access
- File defined by header, called “iNode”
- Naming: translating from user-visible names to actual sys resources
  - Directories used for naming for local file systems
  - Linked or tree structure stored in files
- Multilevel Indexed Scheme
  - iNode contains file info, direct pointers to blocks, indirect blocks, doubly indirect, etc..
  - NTFS: variable extents not fixed blocks, tiny files data is in header

File System Summary (2/2)

- 4.2 BSD Multilevel index files
  - iNode contains pointers to actual blocks, indirect blocks, double indirect blocks, etc.
  - Optimizations for sequential access: start new files in open ranges of free blocks, rotational optimization
- File layout driven by freespace management
  - Integrate freespace, iNode table, file blocks and dirs into block group
- Deep interactions between memory management, file system, sharing
  - `mmap()`: map file or anonymous segment to memory

Thank You!