Lecture 16: File Systems II

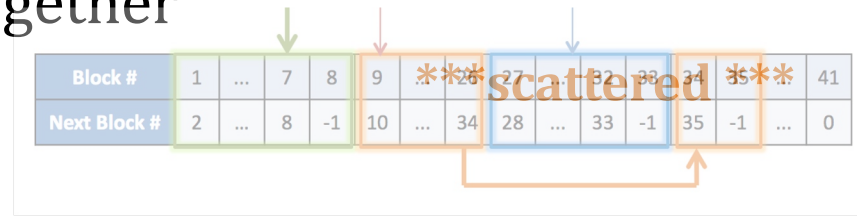
Yinqian Zhang@ 2022, Spring

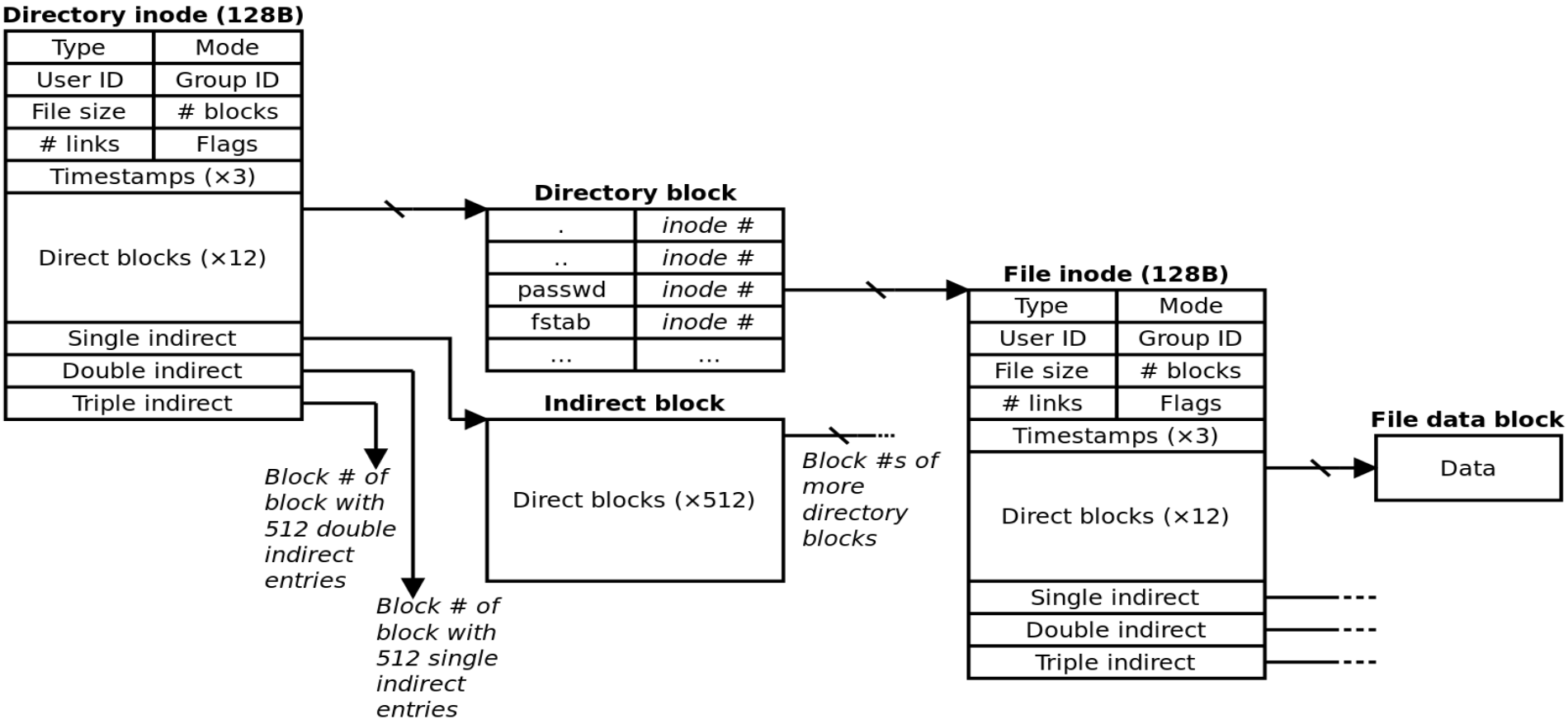
iNode Allocation

- 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

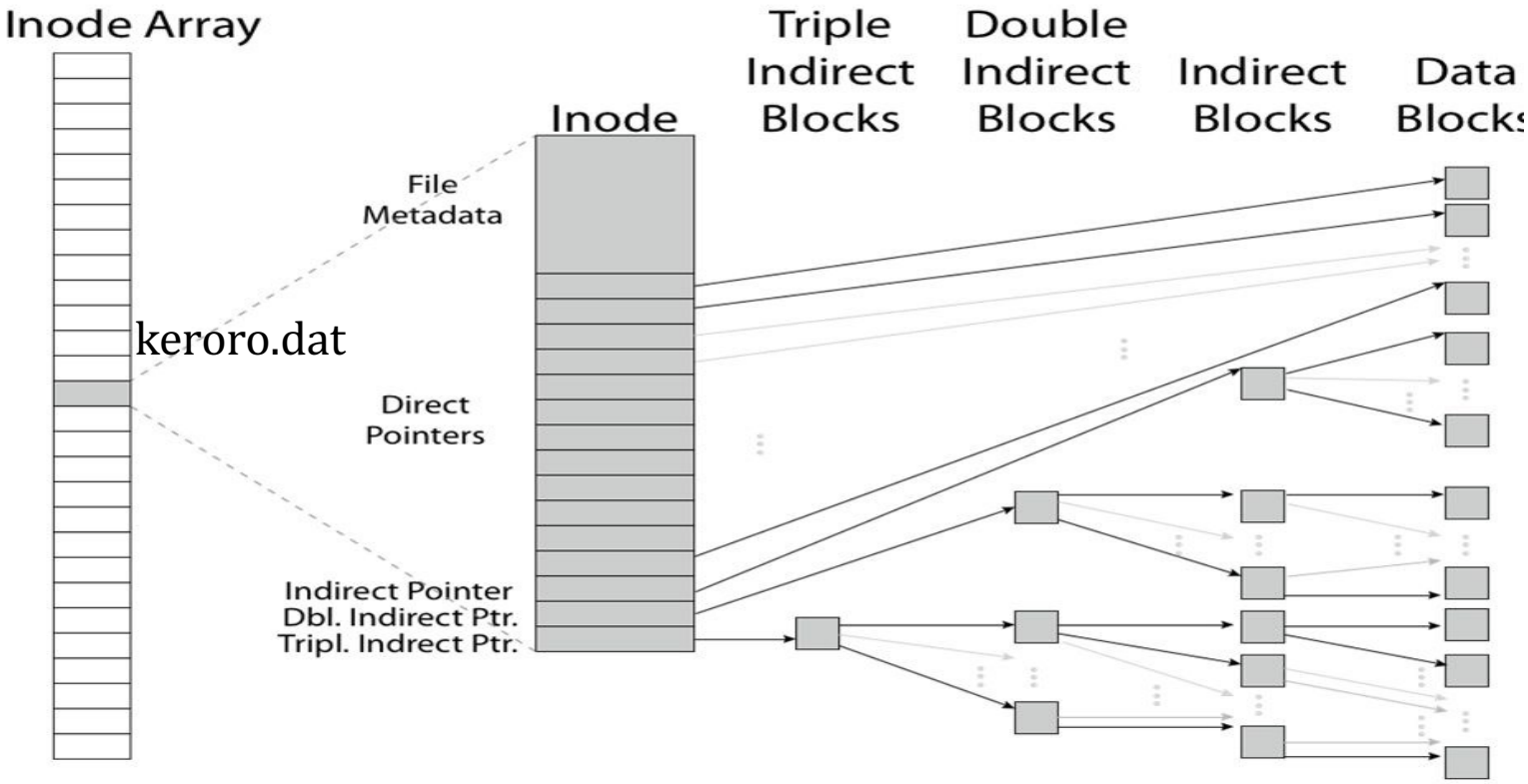
- All pointers of a file are located together
  - **VS. FAT: pointers of a file are**
- One directory/file has one iNode





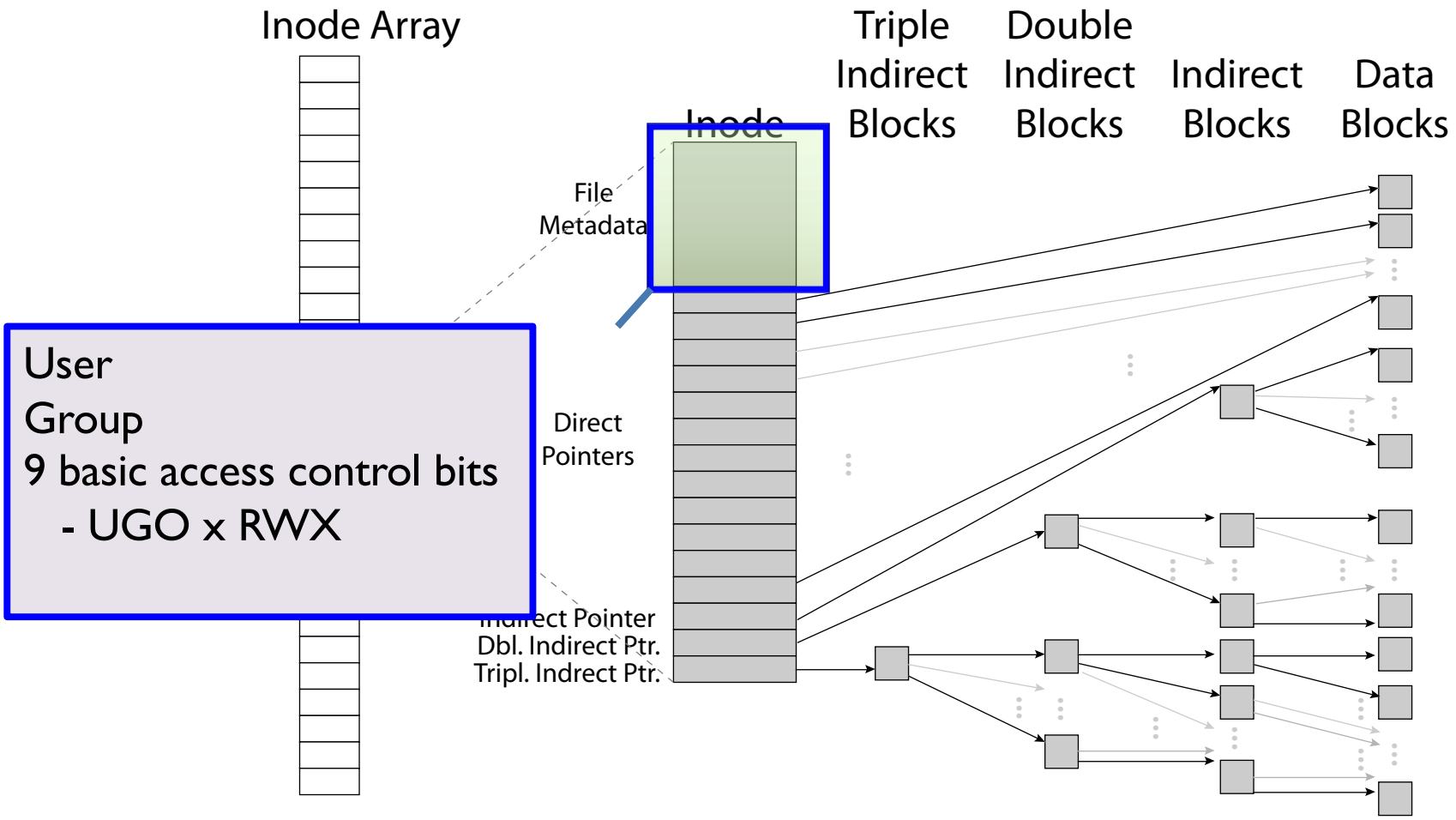
iNode

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



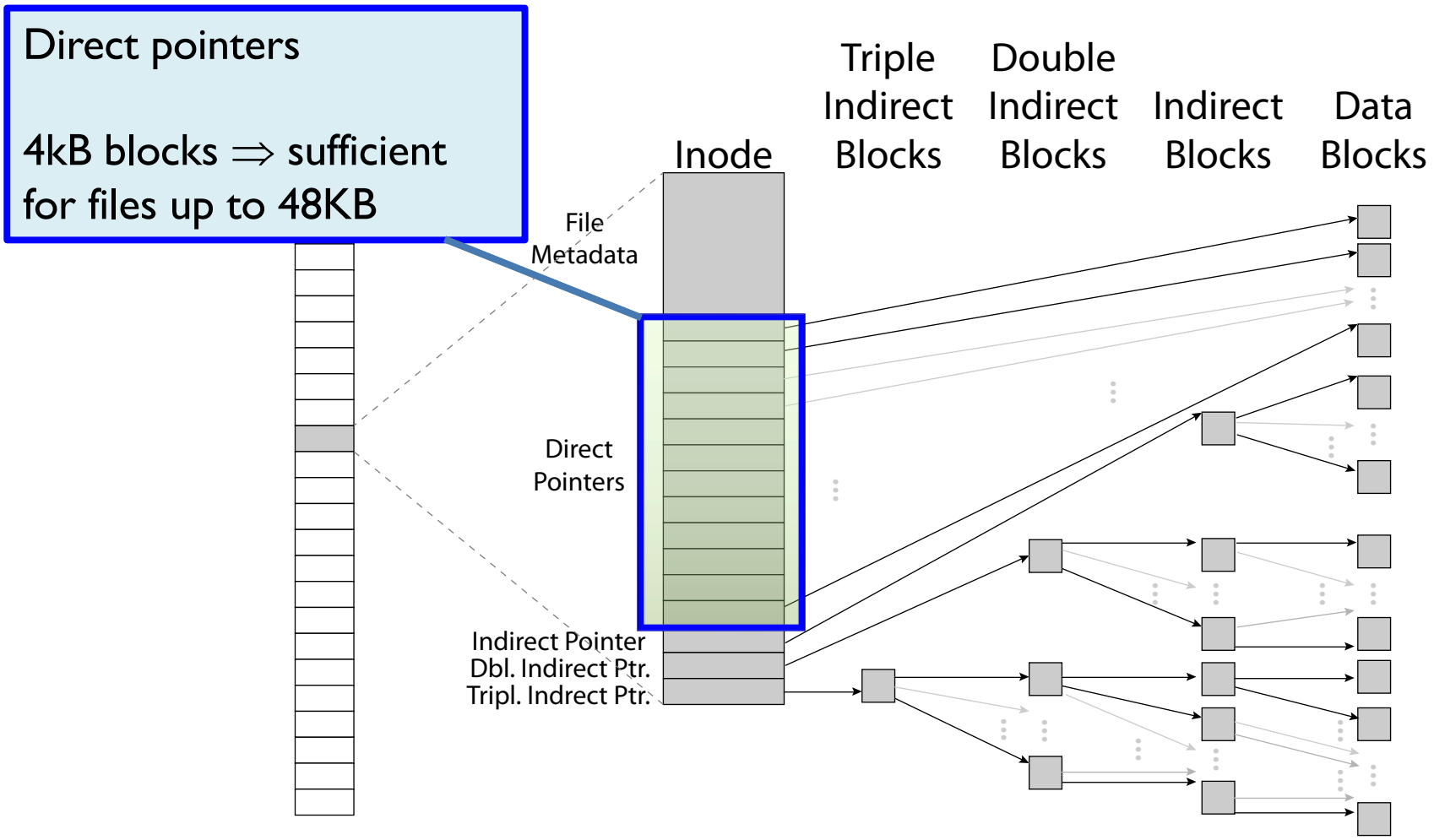
File Attributes

- iNode metadata



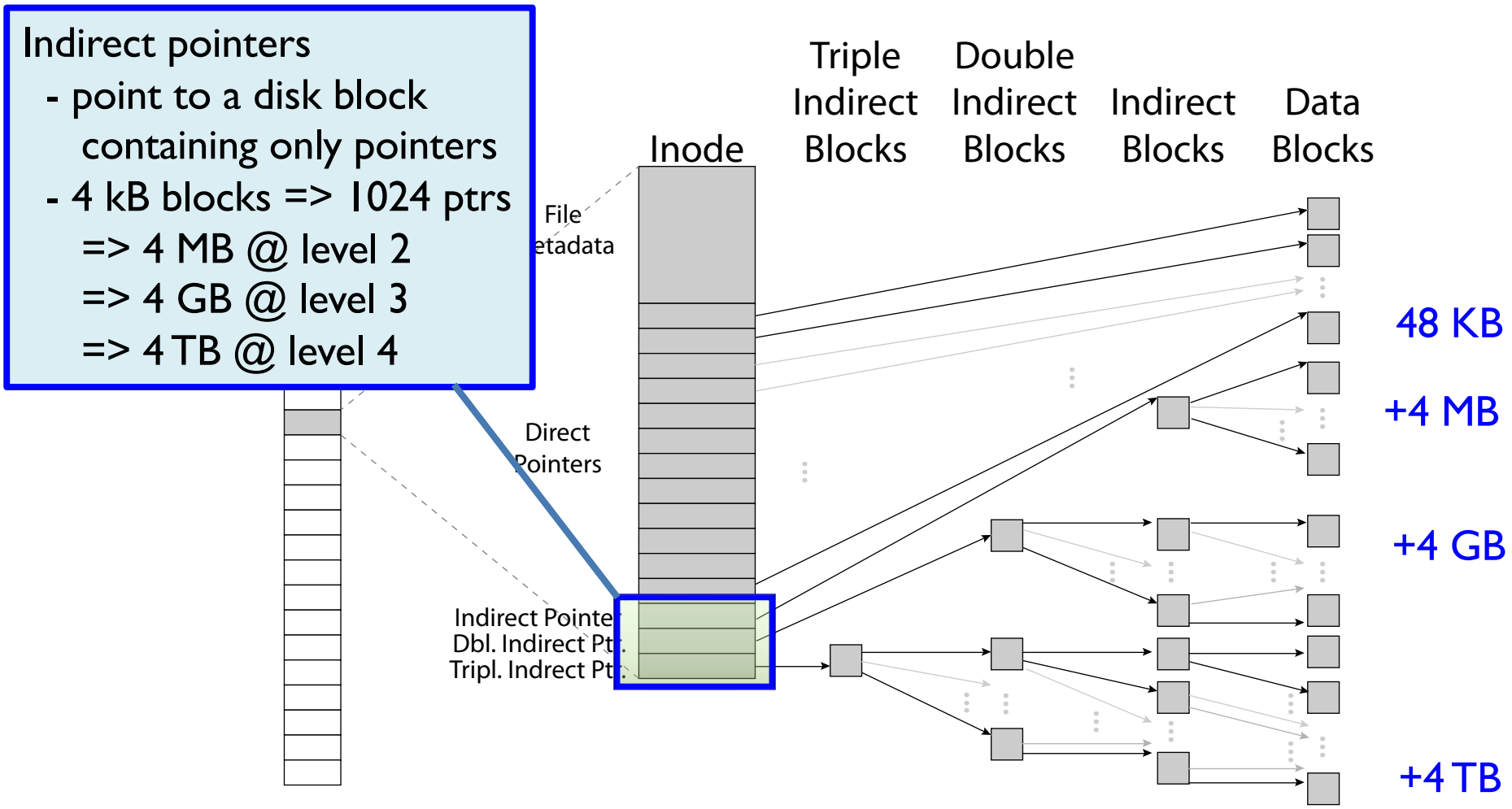
Data Storage

- Small files: 12 pointers direct to data blocks



Data Storage

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



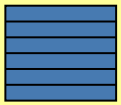
Index-node – file size

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

$$12 \times 2^x + 1 \times 2^x/4 \times 2^x + 1 \times (2^x/4)^2 \times 2^x + 1 \times (2^x/4)^3 \times 2^x$$

File size = number of data blocks * Block size



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

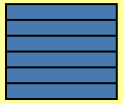
Index-node – file size

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

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

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

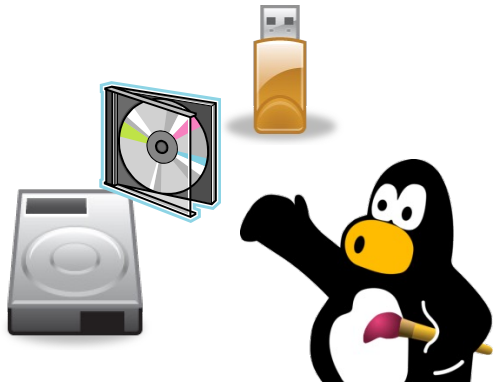
Ext 2/3/4

- Disk layout

- Directory

- Hard and Soft Links

- Consistency



File System Ext

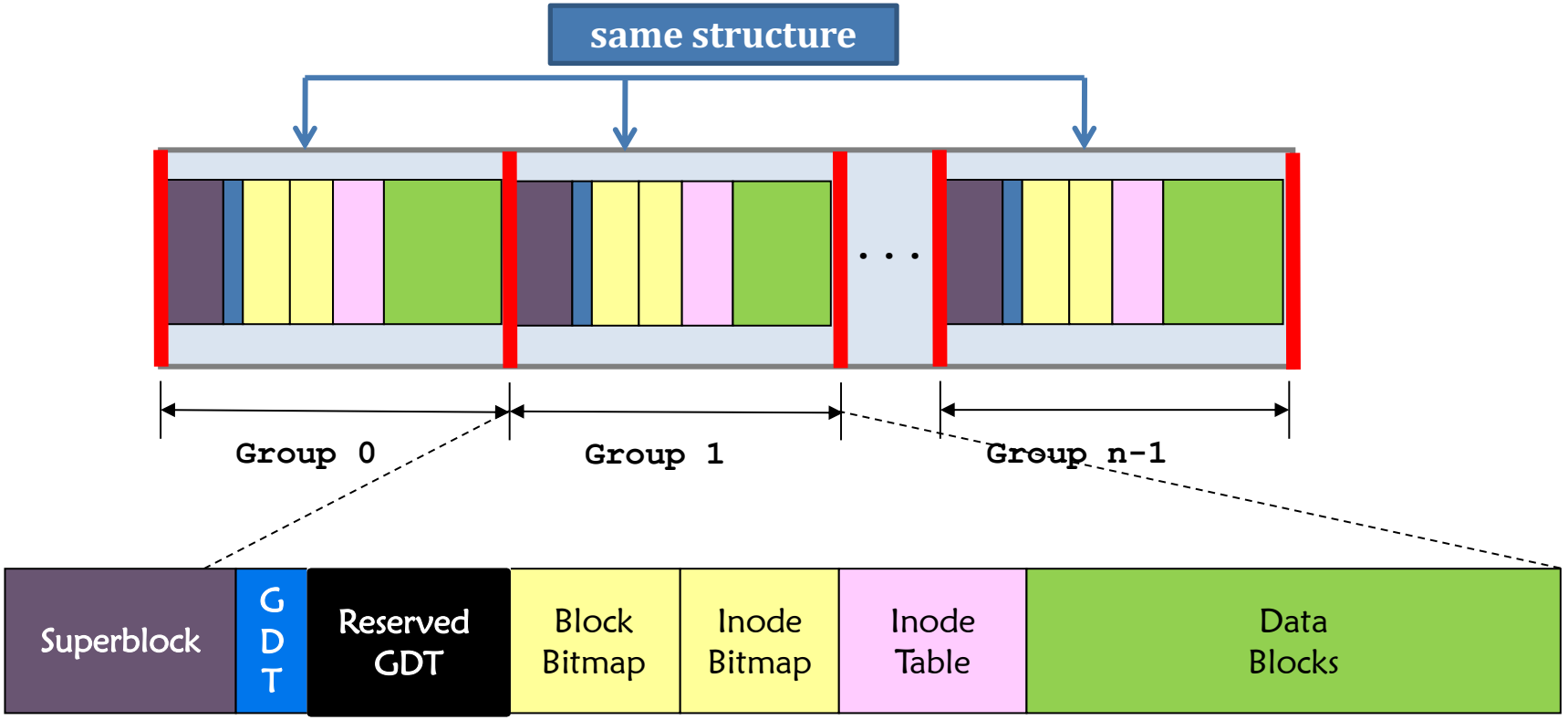
- The latest default FS for Linux distribution is the **Fourth Extended File System**, **Ext4** for short.

- 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

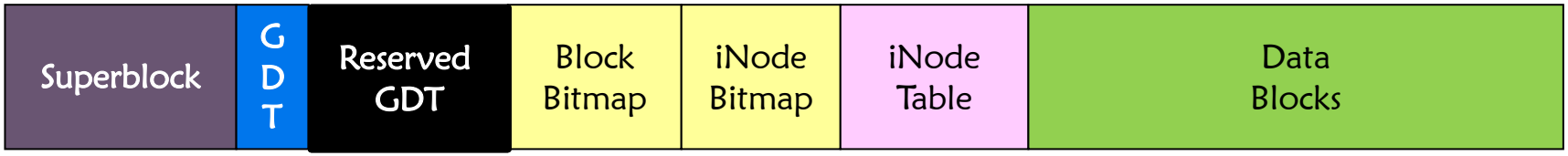
- The file system is divided into **block groups** and every block group has the **same structure**



Ext2/3 – FS layout

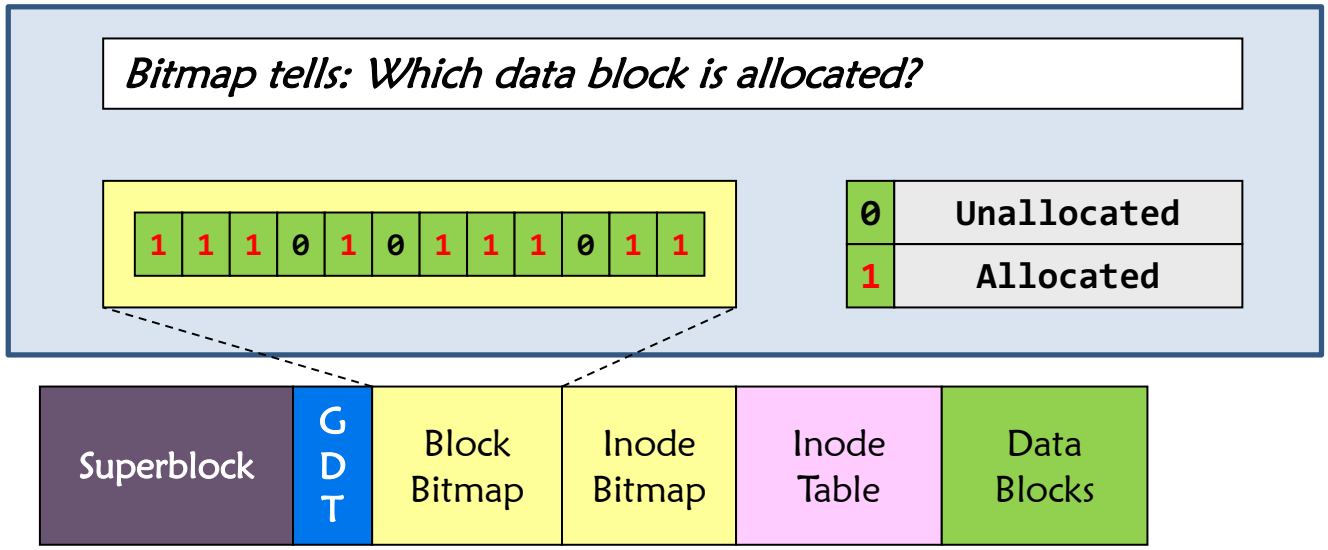
- Layout of one block group is as follows:

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

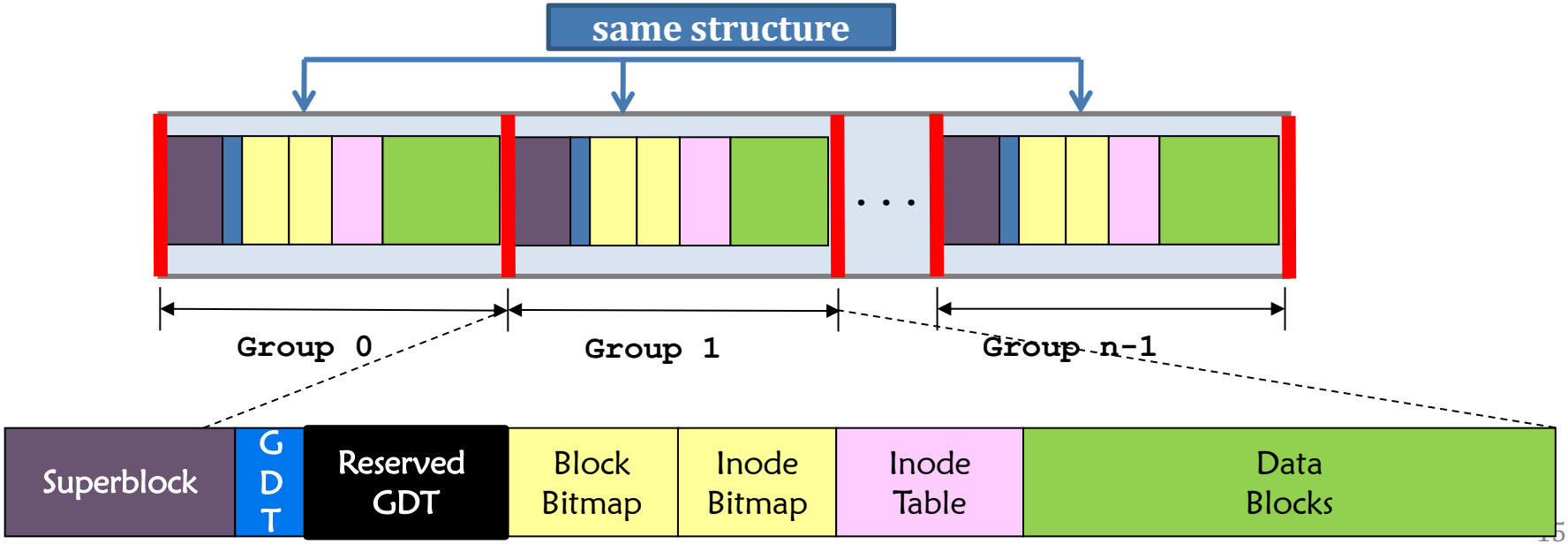


- iNode Bitmap
  - A bit string that represents if an iNode (index-node) is allocated or not

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

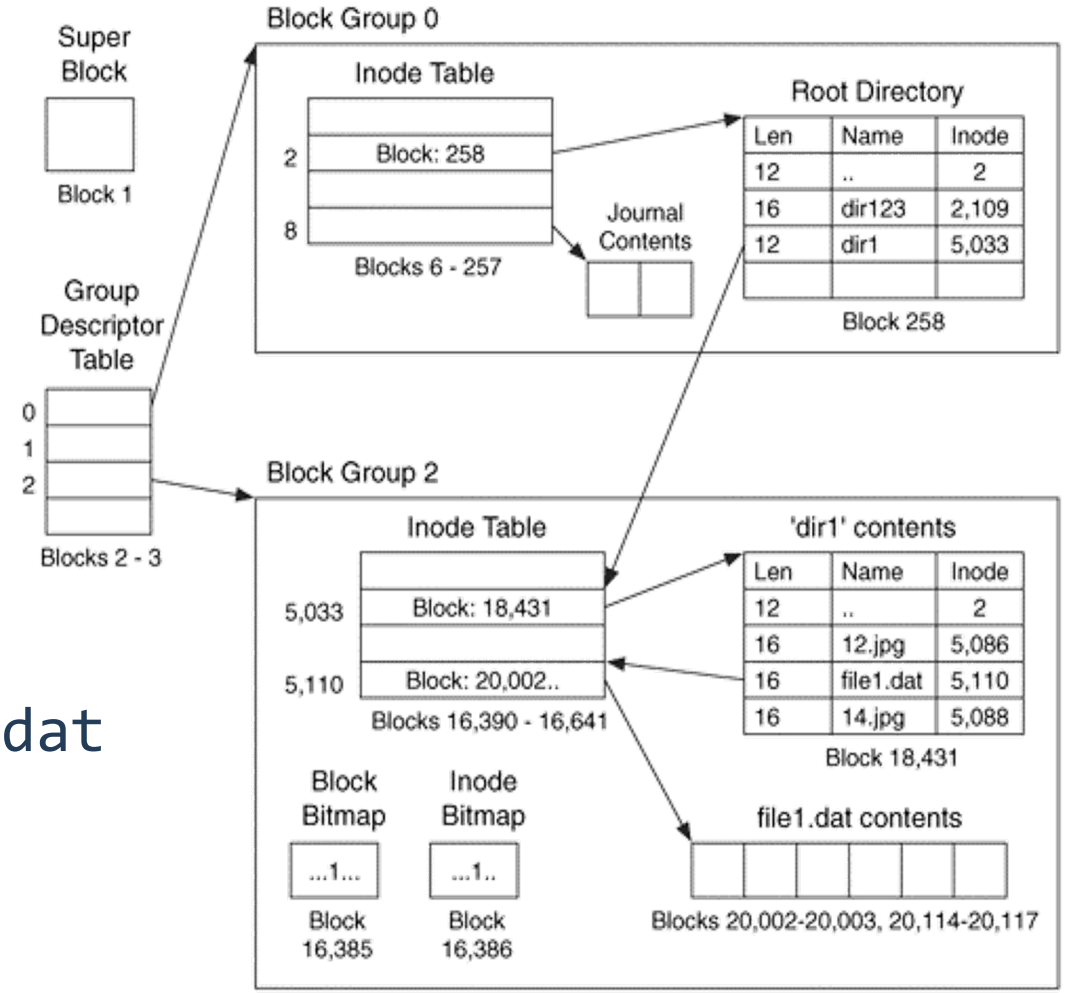
Ext2/3 – Block groups

- 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



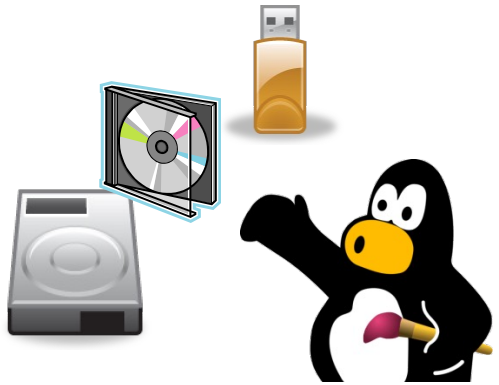
- Example: create a `file1.dat` under `/dir1/` in Ext3

Ext 2/3

- Disk layout;

- Directory;

- Hard and Soft Links.

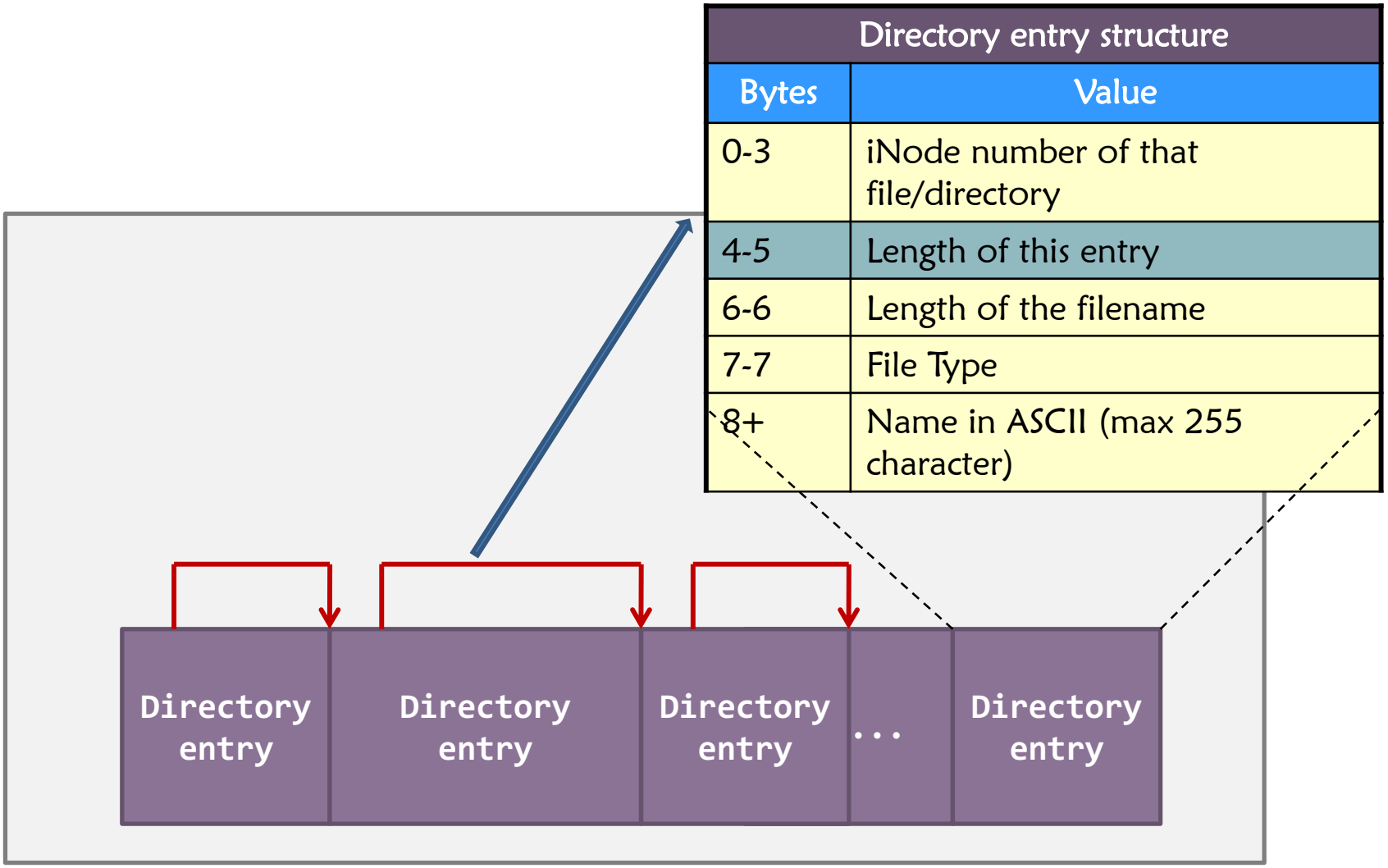


Ext2/3 – iNode structure (for 1 file)

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.

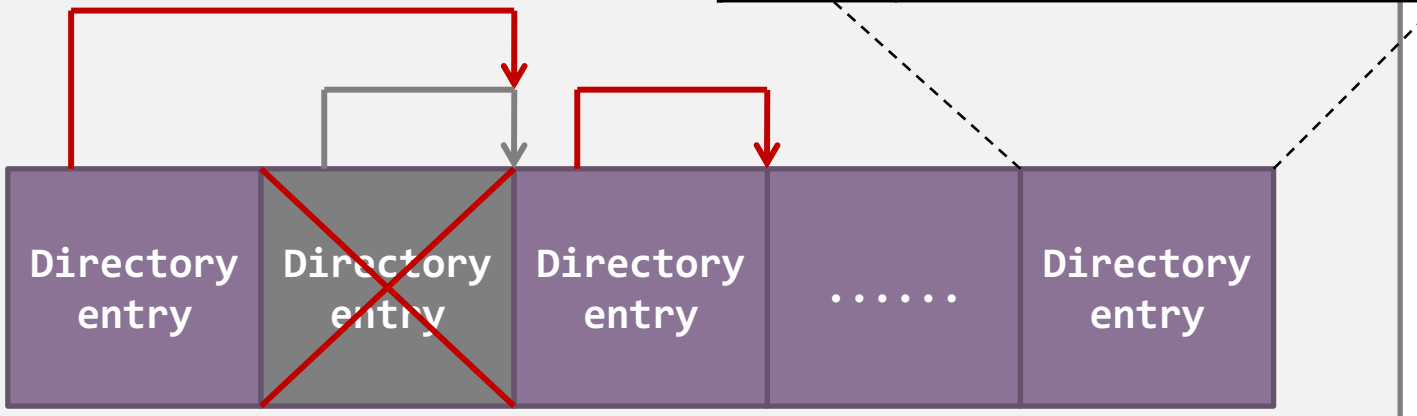
Ext2/3 –directory entry in a directory block



Ext2/3 – File Deletion

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)

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

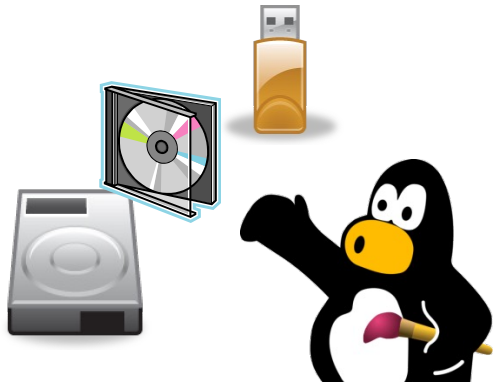


Ext 2/3

- 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.

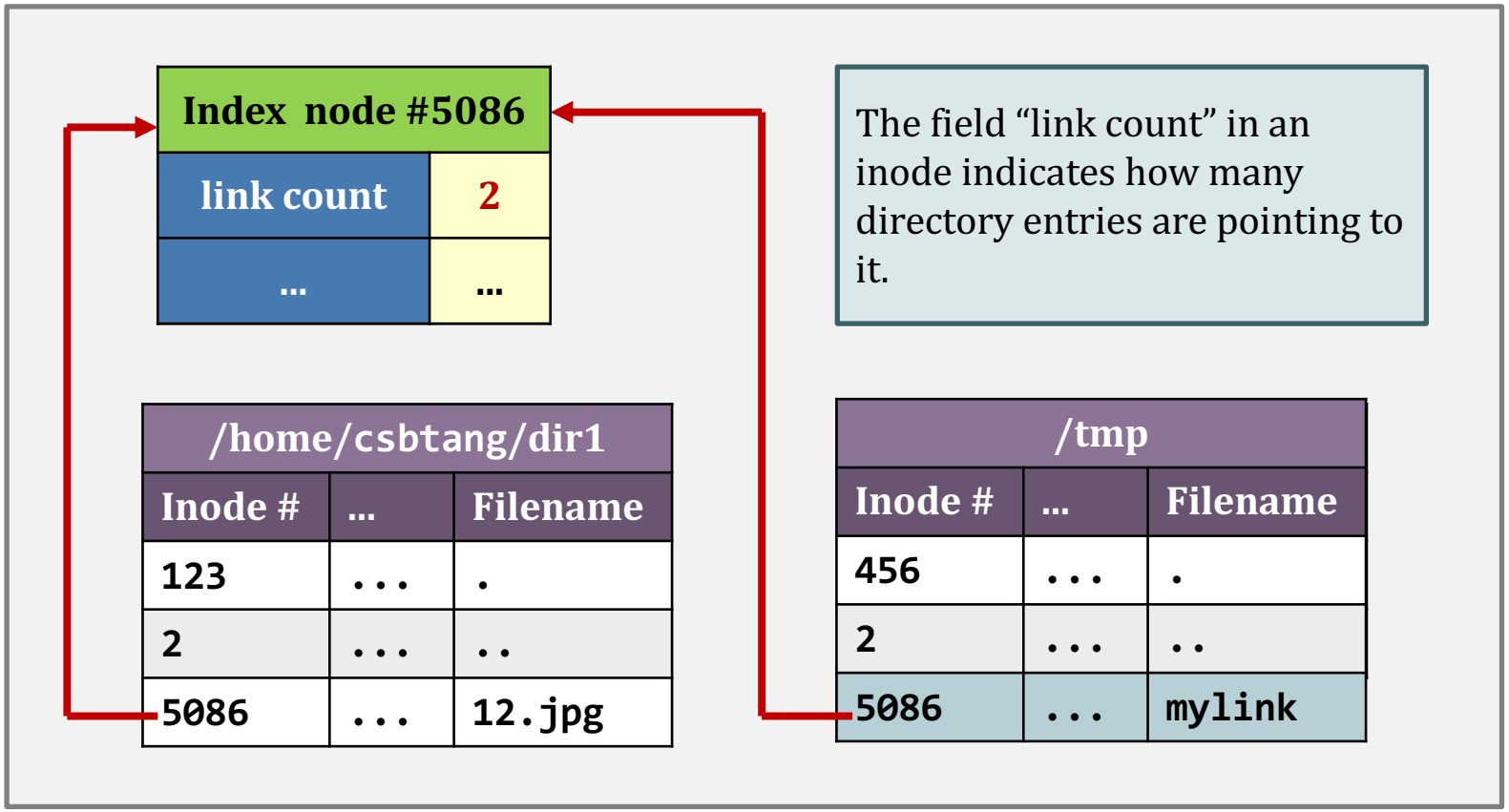
```
# ln /home/csbtang/dir1/12.jpg /tmp/mylink
```

/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**.

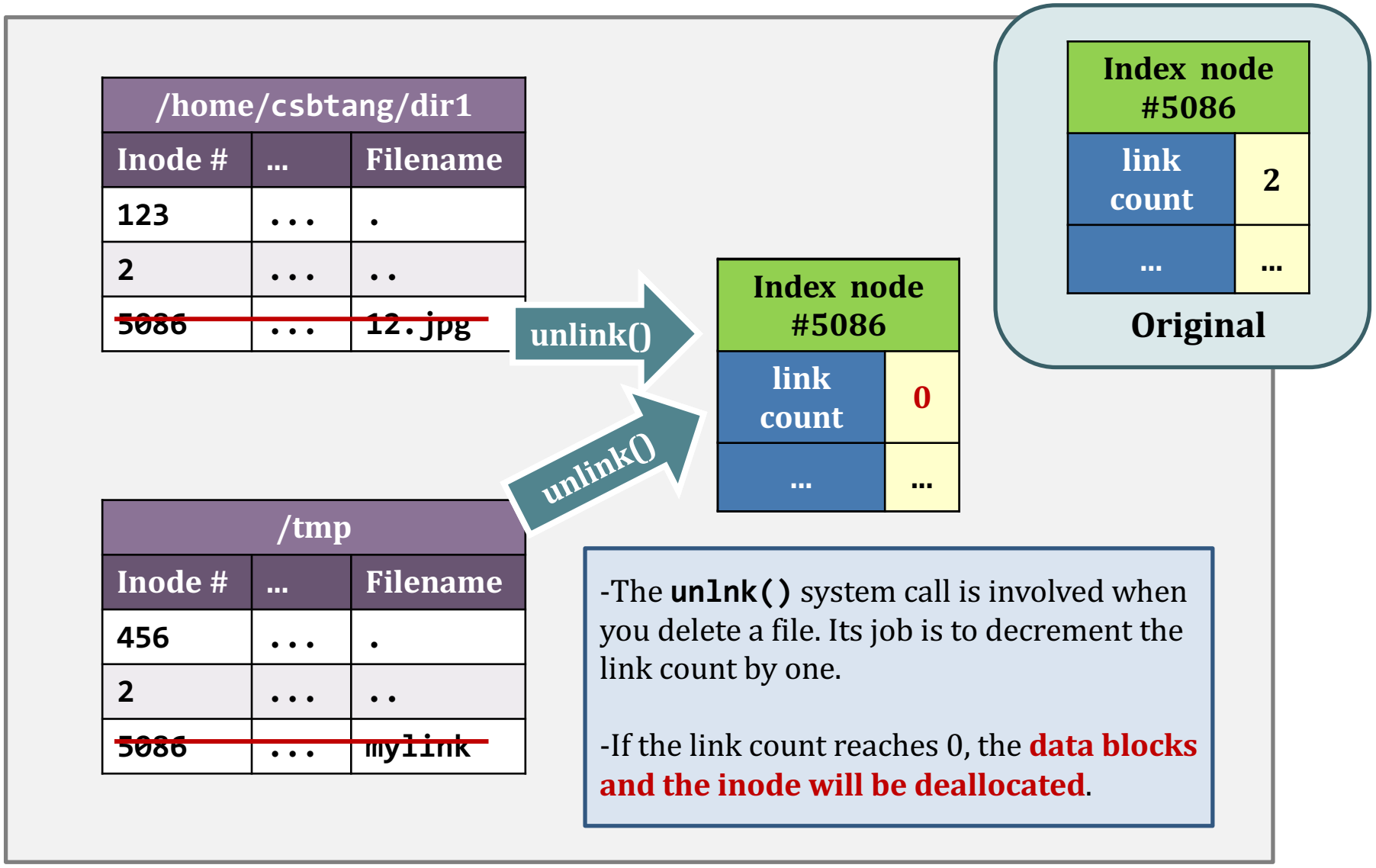


Ext2/3 – link file: examples on hard link

- 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.

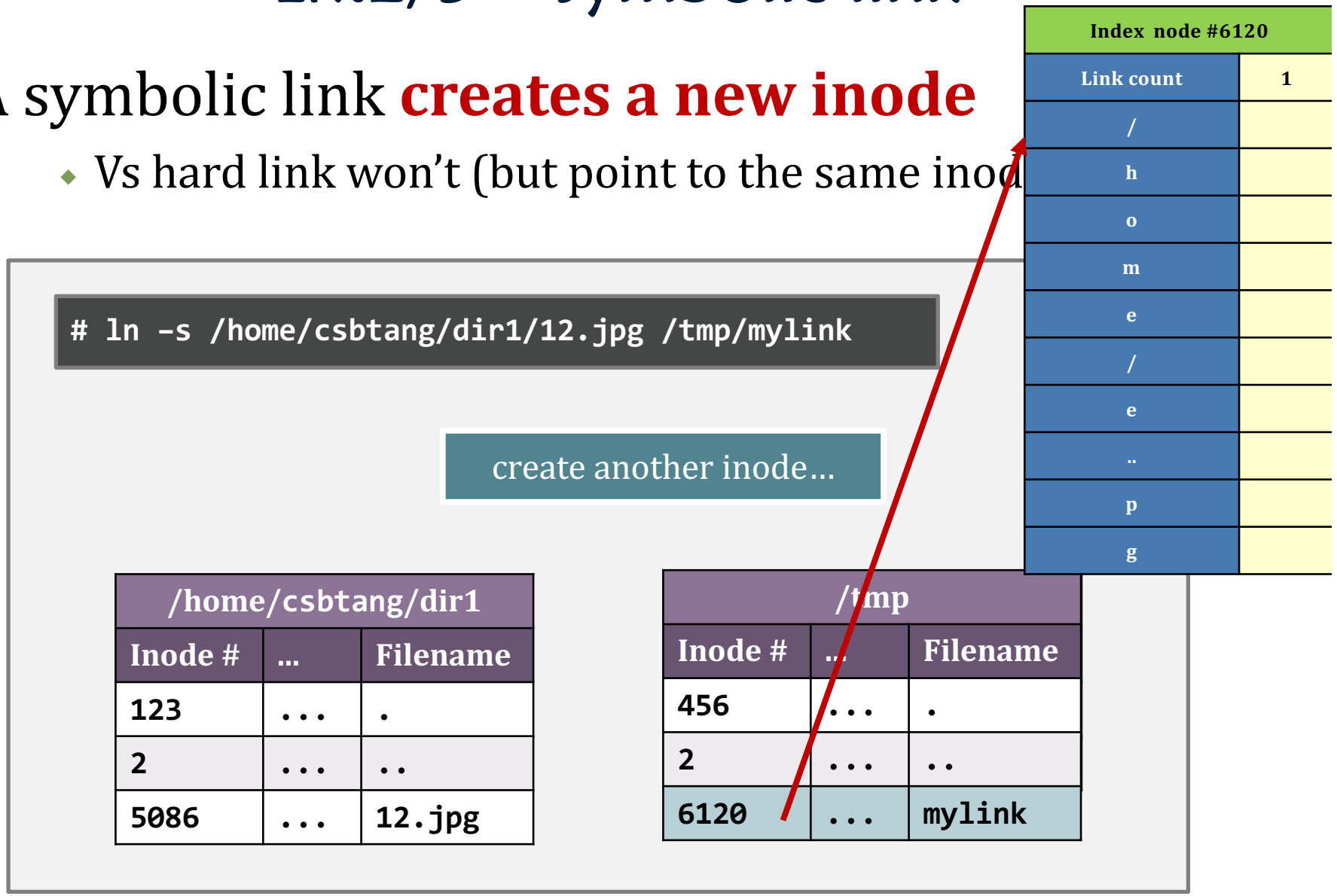
```
# ls -F /
bin/    home/           media/  rules.log  tmp/
boot/   initrd.img@     mnt/    sbin/      usr/
cdrom/  initrd.img.old@ opt/    selinux/   var/
dev/    lib/            proc/   srv/       vmlinuz@
etc/    lost+found/     root/   sys/       vmlinuz.old@
# stat /
  File: `/'
  Size: 4096 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

Ext2/3 – removing file and link count



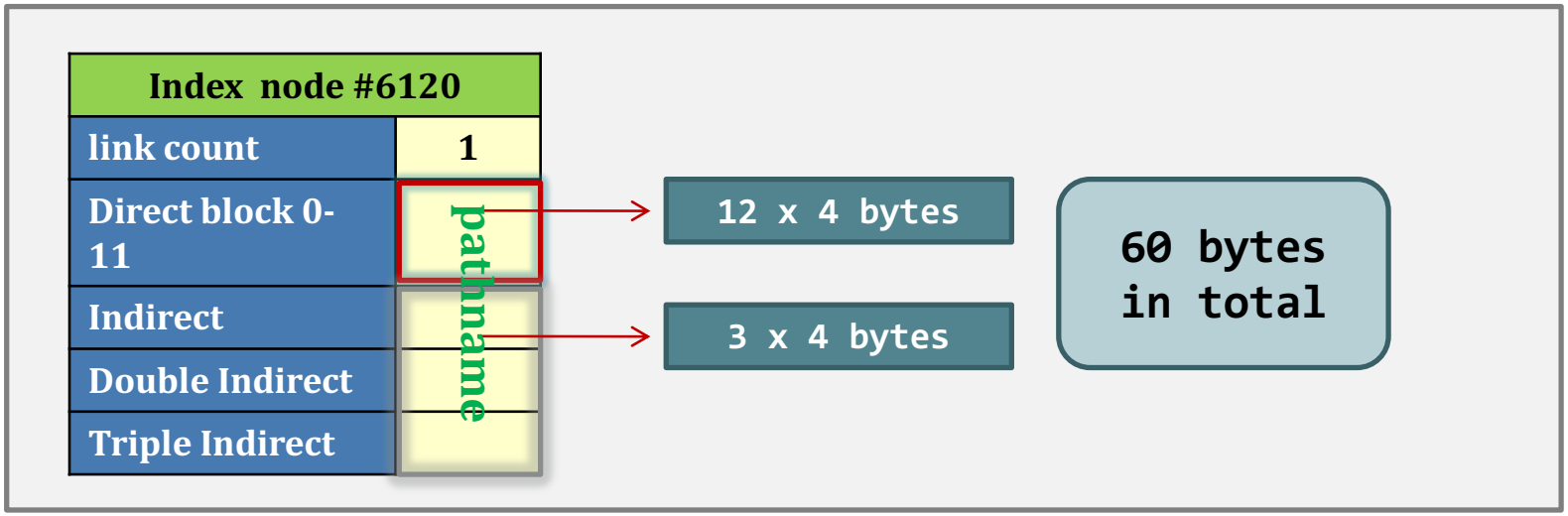
Ext2/3 – symbolic link

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



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



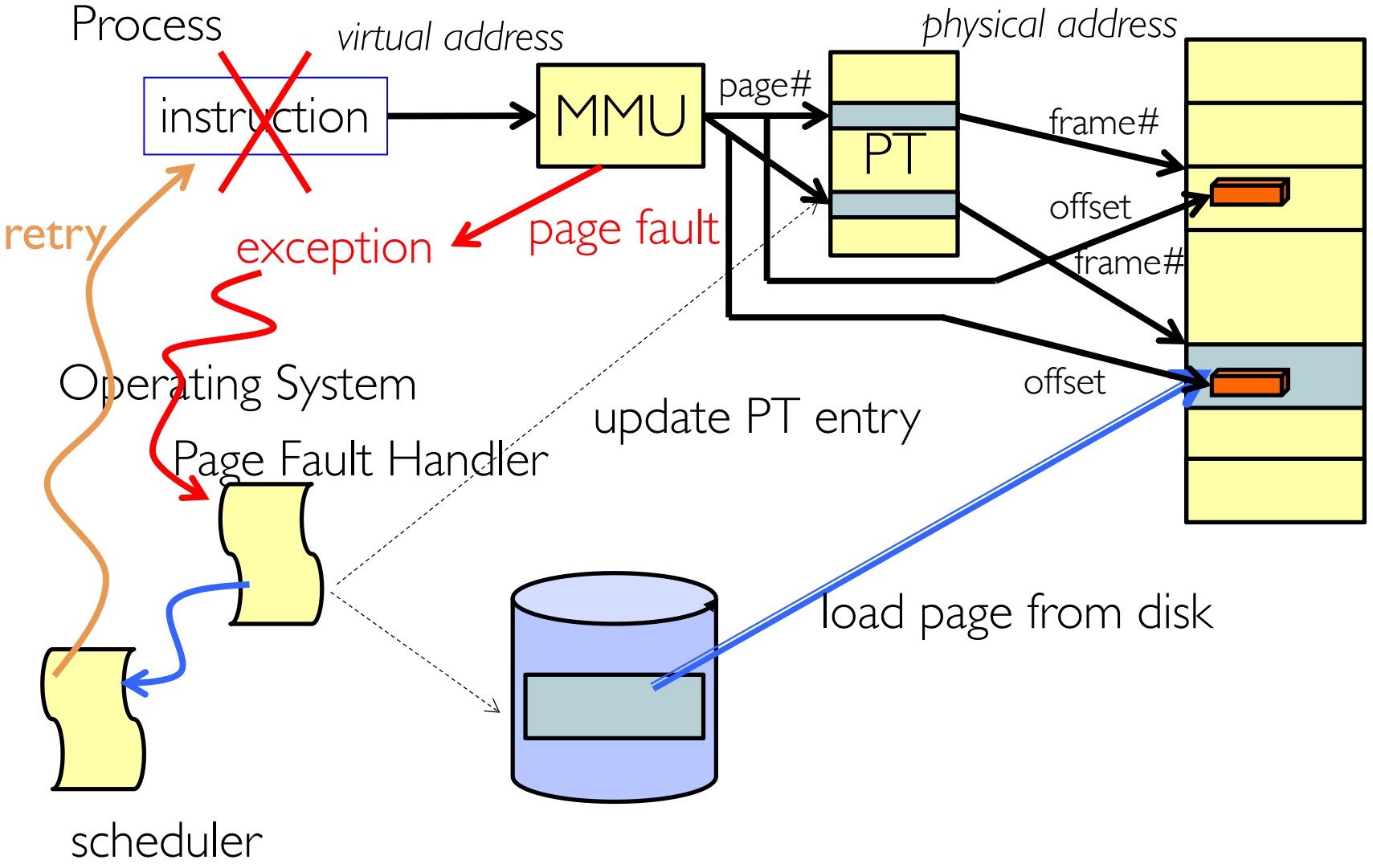
Summary of Links

- 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

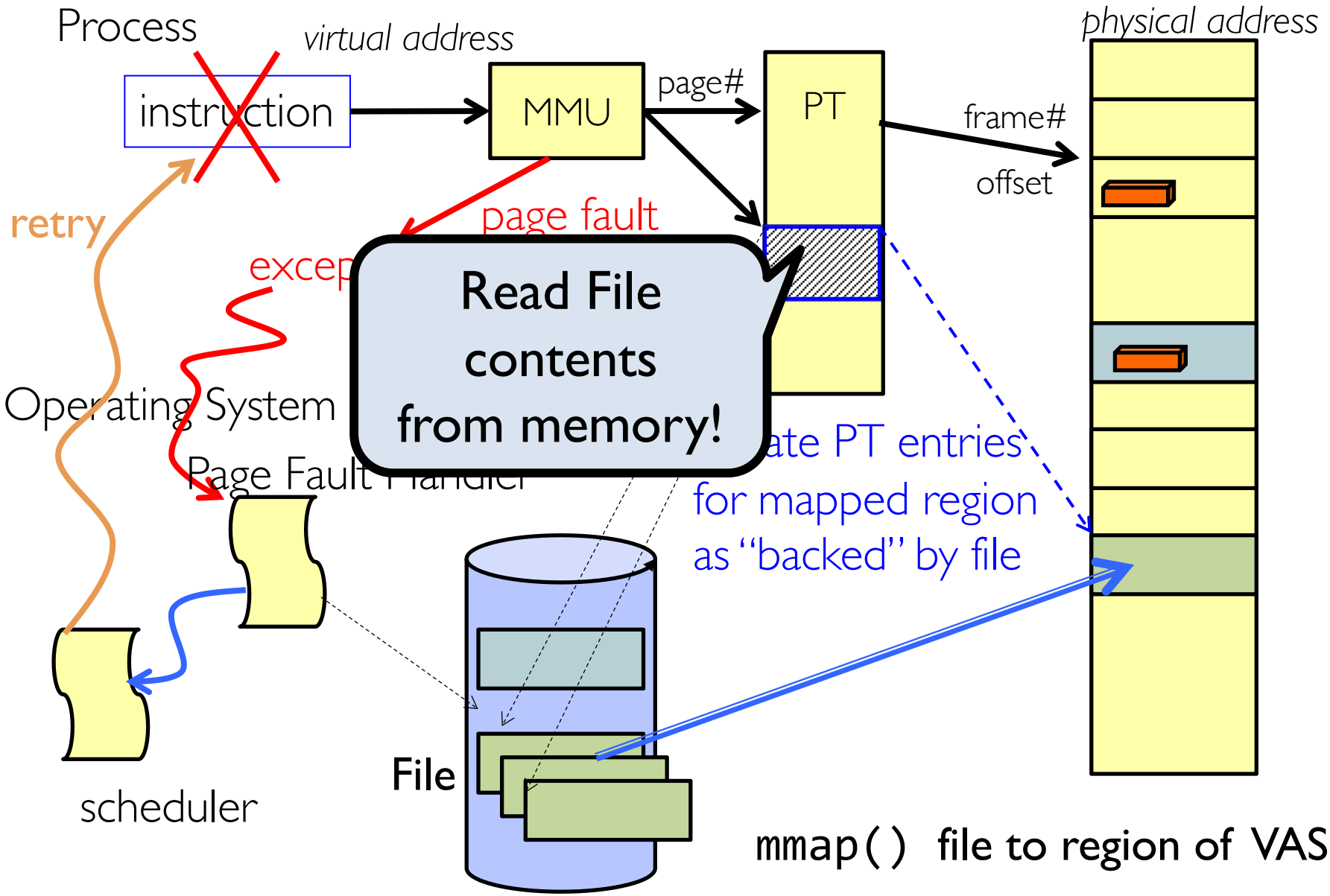
Memory Mapped Files

- 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



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!