FAT, I-nodes

Computer Operating Systems, Spring 2024

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Alicia Sun	Haoyun Qin	Rafael Sakamoto	Yousef AlRabiah	
August Fu	Jonathan Hong	Sarah Zhang	Yu Cao	

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- How is milestone 1 looking? And How are you?

Administrivia

- Milestone 1 is due this Friday at Midnight!
- Recitation is tonight!
  - On Thursdays in Towne 217 from 7PM - 8PM

Lecture Outline

- **Inodes**
- Directories
- Block Caching

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- What was the big downside of using FAT?

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- What was the big downside of using FAT?

- **Huge memory consumption!**
  - **We need an entry in the FAT for every single block in the FS!**
    - **Remember, we map block #s (indices in the table) to other blocks.**
  - **A FAT likely spans multiple blocks**
  - **This size also grows as disk grows :/ (bc more blocks!)**

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- Instead, could we store ***most*** FAT blocks ***on disk*** and only load into memory the FAT blocks that are used for looking up files that are currently open used (aka have entries in the file table, etc)?

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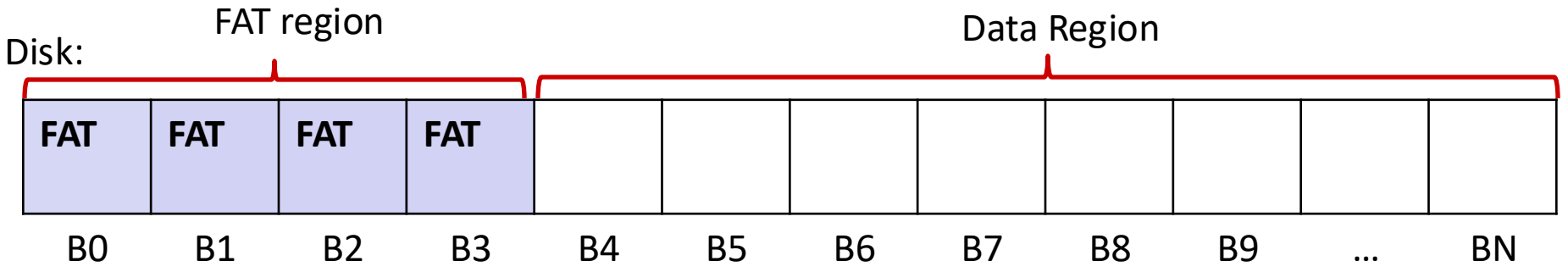
- **Yes, but the blocks of a file could be spread out across disk. We may have to load all FAT blocks to lookup a file anyways**

Explanation

- Blocks of a file could be spread out across disk. We may have to load all FAT blocks to lookup a file anyways
- Small example:
  - Consider block size 256,
  - FAT entry 2 bytes, so 128 entries per FAT block
  - FAT takes up 4 blocks
- **Reminder: FAT region is separate from the data region (blocks it manages)**



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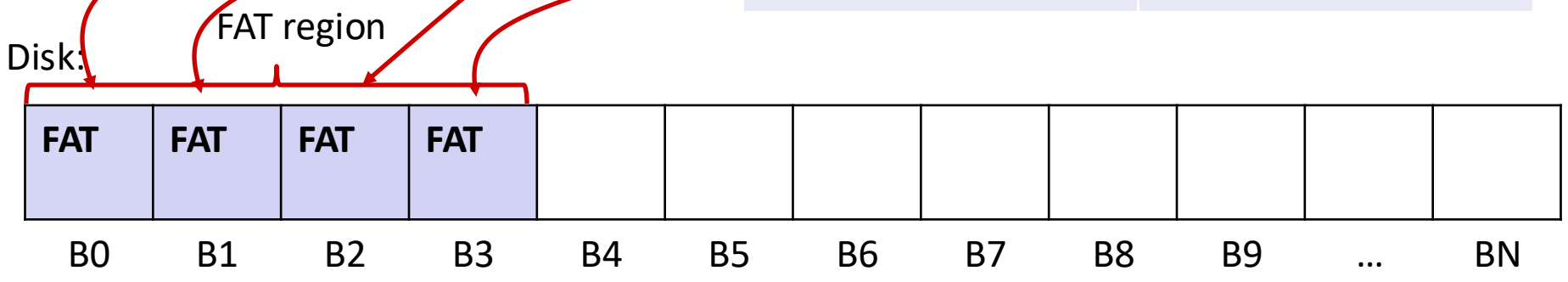
Block #	Next
…	
2	128
…	
128	256
…	
256	500
…	
500	



Consider we have a file that starts at the second block of the Data Region

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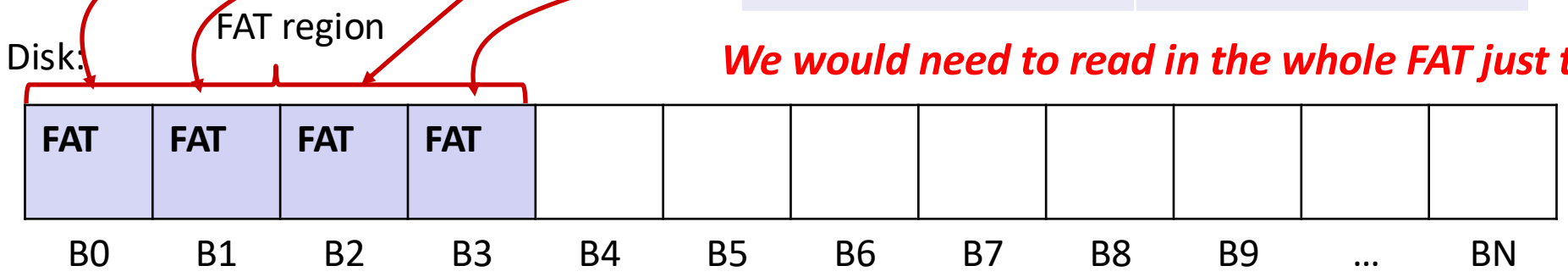
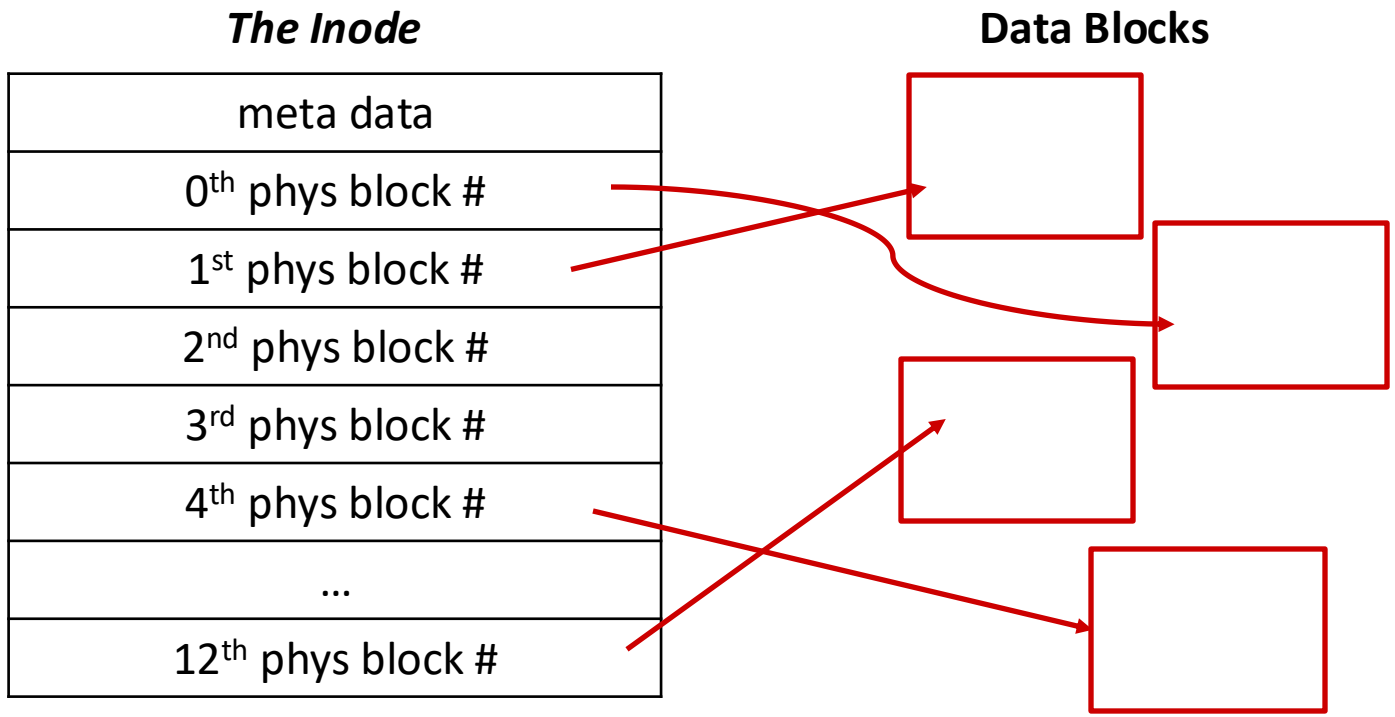


We would need to read in the whole FAT just to look up this file

Inode motivation

- Idea: we usually don't care about ALL blocks in the file system, just the blocks for the currently open files
- Instead of spreading out the block numbers in a table, can we group the block numbers of a file together?

- ***Yes: we call these inodes***:
  - Contains some metadata about the file and 12 physical block numbers corresponding to the first 12 logical blocks of a file



*not all data blocks shown.

Inode layout

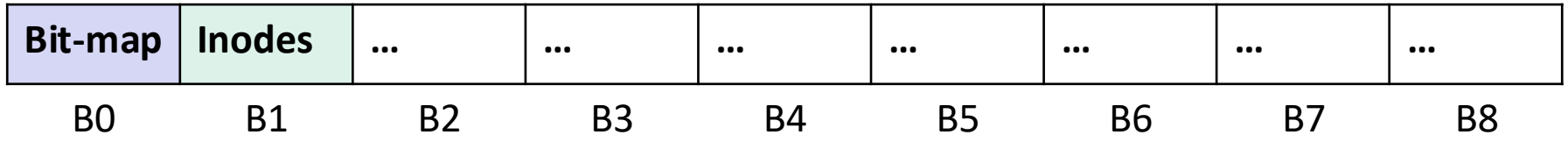
- Inodes contain:
  - some metadata about the file
    - Owner of the file
    - Access permissions
    - Size of the file
    - Time of
      - last change of file, last access to file, last change to INODE of file.
  - 12 physical block numbers corresponding to the first 12 logical blocks of a file

```
typedef block_no_t int

struct inode_st {
  attributes_t metadata;
  block_no_t blocks[12];
  // more fields to be shown
  // on later slides
};
```

Inodes Disk Layout

- When we use Inodes instead of FAT, we get something like this instead:



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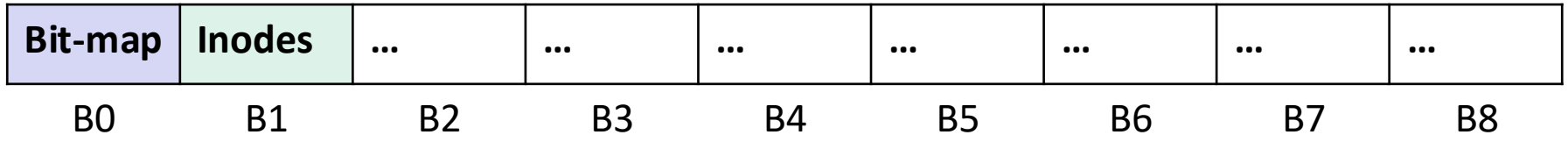

Wait, why do we need a Bit-Map for this filesystem implementation?
How many blocks could we track if a block size is 512 bytes?

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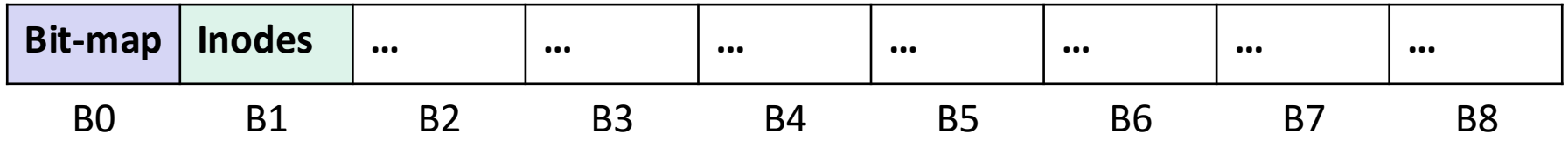

Wait, why do we need a Bit-Map for this filesystem implementation?
How many blocks could we track if a block size is 512 bytes?

Inodes don't track which blocks are free so we need a separate structure to track which blocks are free.

512 bytes is 4096 blocks! (One bit for each block)

Inodes Disk Layout

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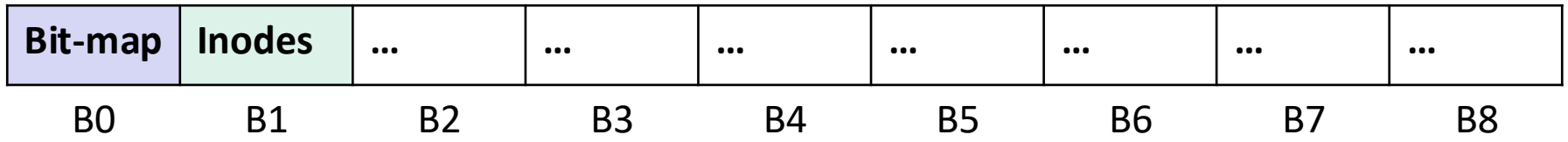
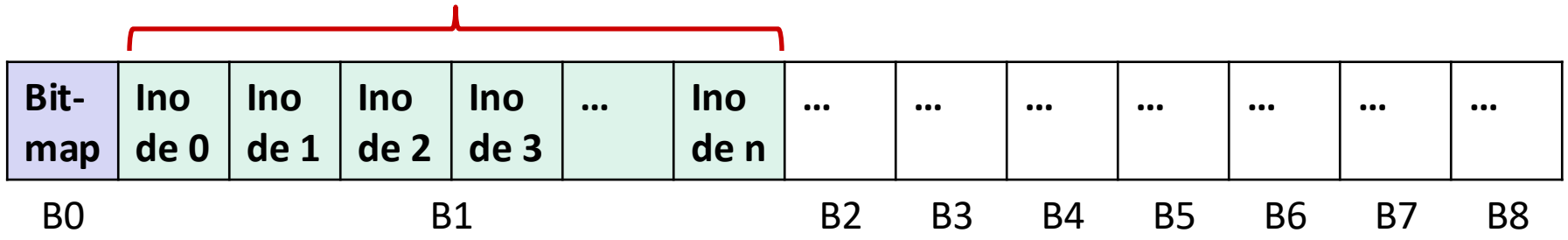
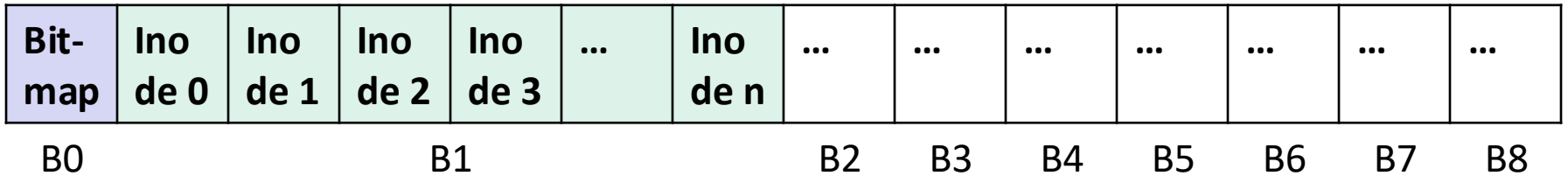


- Inodes are smaller than a block, can fit multiple inodes in a single block
- Each Inode is numbered



Example File Block Lookup

- Each File will have an Inode number
- Suppose that we wanted to look up a file that is made of 4 blocks.
  - First, we need the Inode number for the file (lets assume it is 2)



Example File Block Lookup

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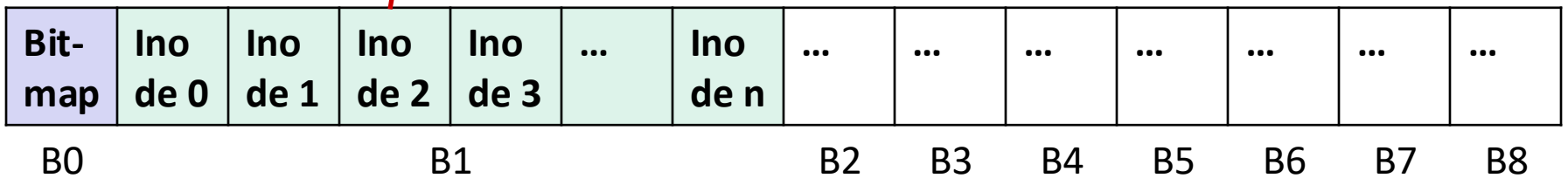
- Suppose that we wanted to look up a file that is made of 4 blocks.
  - First, we need the Inode number for the file (lets assume it is 2)
  - We can read the Inode to see which blocks makeup the file

meta data	…
0th phys block #	0
1st phys block #	5
2nd phys block #	3
3rd phys block #	2
…	

The block numbers in the Inode are indexes relative to the start of the data region.

You will be doing this in PennOS too



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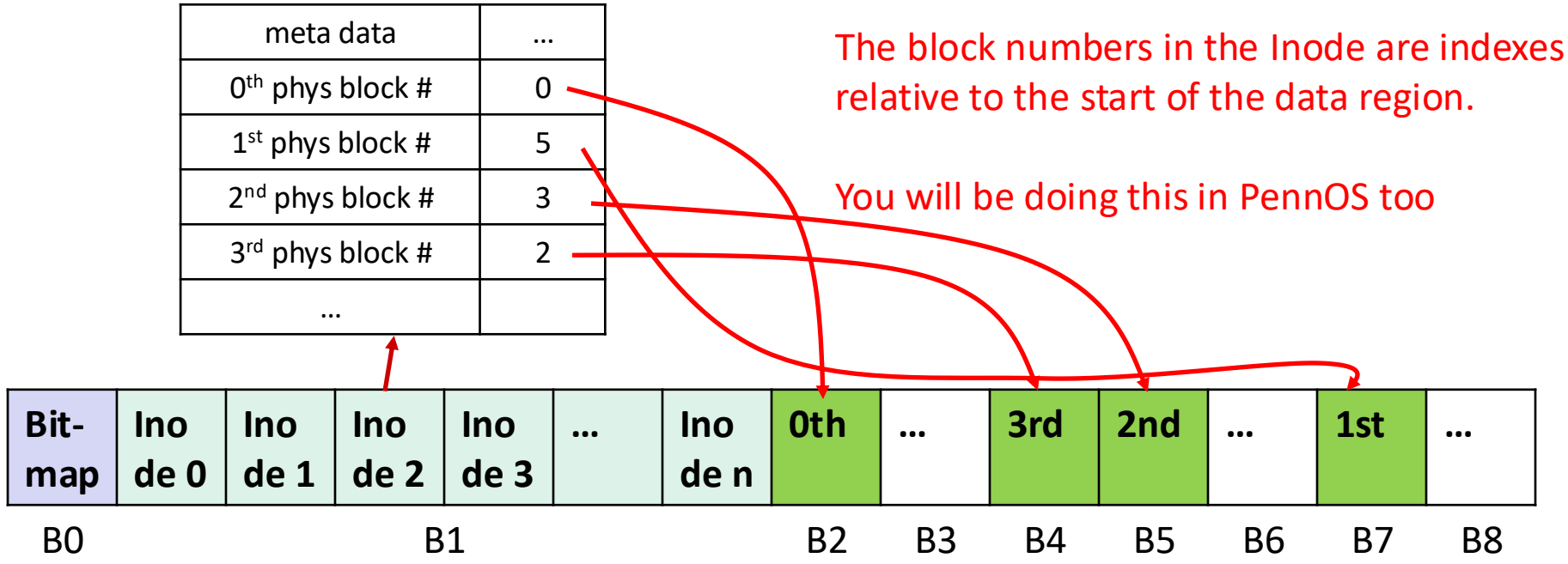
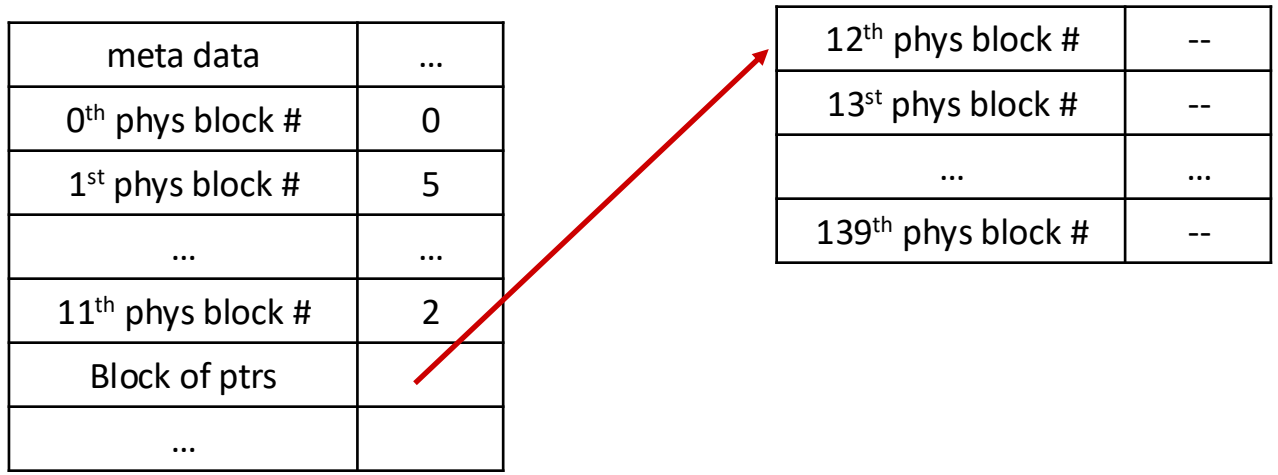


File Sizes with Inode

- So with Inodes, how many blocks can we have per file?
  - So far: 12 blocks per file (this is not enough, way too small!)
    - About 6,000 bytes.
    - An average MP4 song would at least 3,000,000 bytes.
- We can allocate a ***block*** to hold more block numbers
  - This block can hold 128 block numbers



This is a singly indirect pointer;
it points to a block of pointers (or block numbers)

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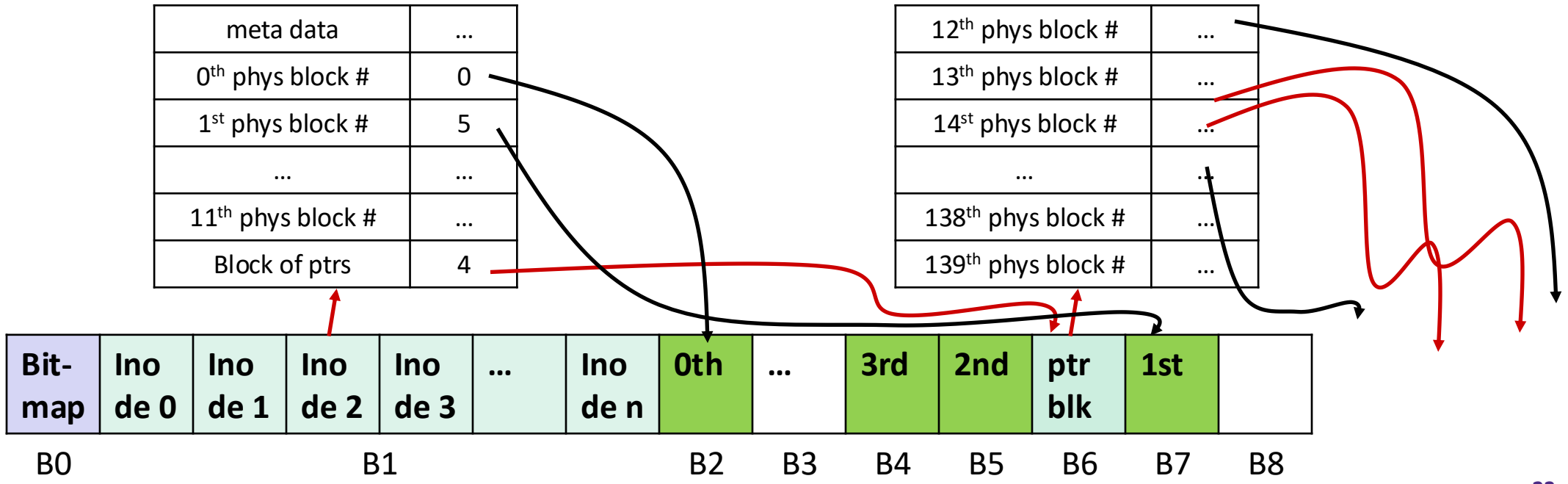
File Sizes with Inode

- So with Inodes, how many blocks can we have per file?
  - So far: 12 blocks per file (this is not enough, way too small!)

- We can allocate a block to hold more block numbers

If each block is 512 bytes, we can hold 128 block #s in a single block.



We need moreeeeee

- What if a file needs more than 140 blocks?
- Add another field to the inode that refers to a block that refers to other blocks that refer to data blocks

meta data	…
0th phys block #	0
1st phys block #	5
…	…
11th phys block #	2
Single Indirect Ptr	
Double Indirect Ptr	
…	

12th phys block #	--
13st phys block #	--
…	…
139th phys block #	--

Block for 140-267	--
Block for 268-	--
…	…
….	--

140th phys block #	--
141st phys block #	--
…	…
267th phys block #	--

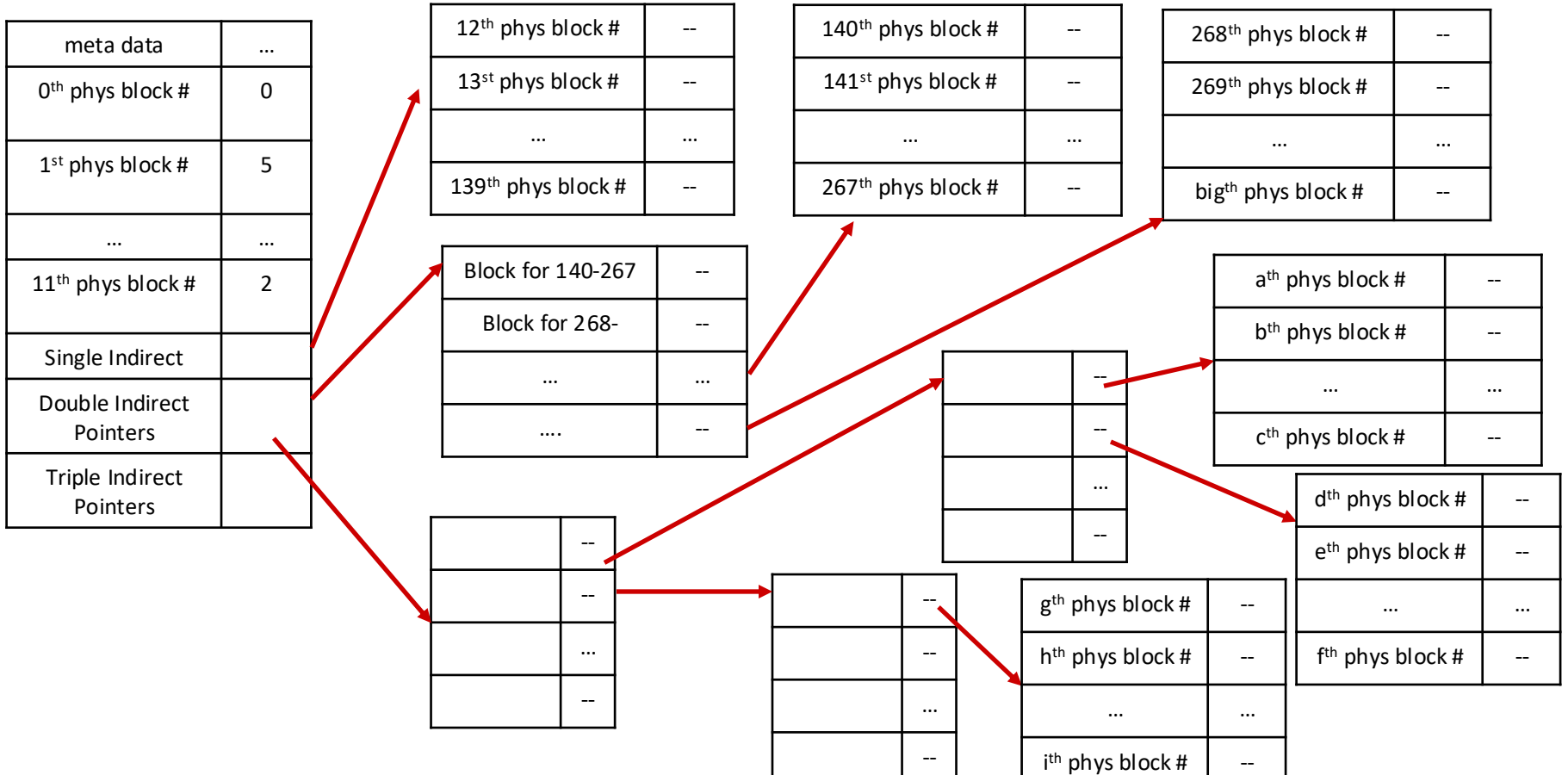
268th phys block #	--
269th phys block #	--
…	…
bigth phys block #	--

These blocks refer to real data blocks.

This block refers to blocks that are composed of 128 blocks numbers.

MORE MORE MORE MORE MORE MORE

- What if our file needs more than that?
  - We can add another field to our Inode that refers to a pointer block that refers to pointer blocks that refer to data blocks…



More?

- No more (at least on Linux ext2)
- If you need more space than this, the operating system will tell you **no**

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  block_no_t *single_ind;
  block_no_t **double_ind;
  block_no_t ***triple_ind;
};
```

What is the *largest file possible if each block is 512 bytes and each block_n_t is 4 bytes?*

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```

What is the *largest file possible if each block is 512 bytes and each block_n_t is 4 bytes?*

12 * 512 bytes

(128 * 512) bytes

(128 * 128 * 512) bytes

(128 * 128 * 128 * 512) bytes

In total, around ***1082202112 bytes***.

Really, Linux ext2 supports 1024 bytes, 2048, and 4096 byte blocks sizes. For 4086 byte blocks, the max size is ~ 4TB.

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- How is this better than FAT?

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- How is this better than FAT?

- Inodes keep all the information of a file near each other
- if we wanted to store in memory only the information of open files, we could do that with les memory consumption

- In other words: only need to store in memory the inodes of the open files instead of the whole FAT

Lecture Outline

- Inodes
- **Directories**
- Block Caching

Directory Entries with Inodes

- With FAT we said a directory entry had:
  - The file name
  - The number of the first block of the file

- With Inodes, we instead store the inode number for the file in the directory entry

Reminder: Directories

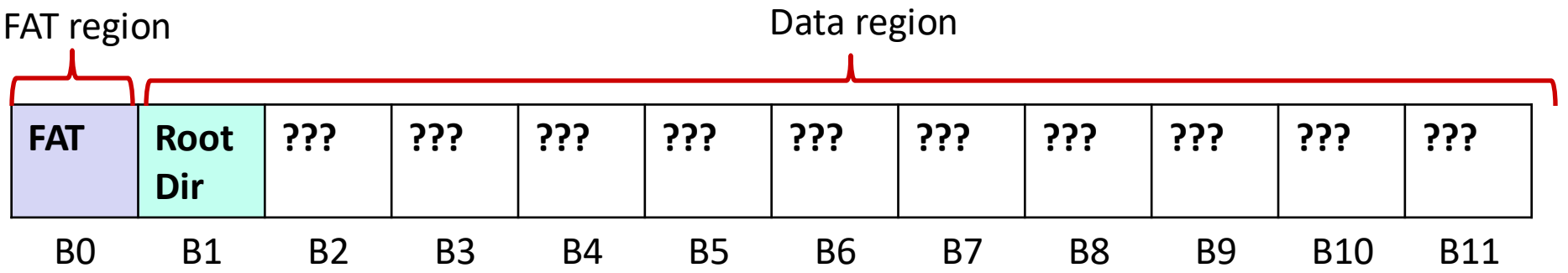
- A directory is essentially like a file
  - We will store its data on disk inside of blocks (like a file)

- The directory content format is known to the file system.
  - Contains a list of directory entries
  - Each directory entry contains the name of the file, some metadata and…
    - If using Inodes, the inode for the file
    - If using FAT, the first block number of the file

  - I know we just said Inodes are better and more modern, but PennOS uses FAT (:/) so my examples will follow that, it is not much different for Inodes though

Review: Directories

- In FAT our file system looked something like this:
  - 2 regions, and assuming FAT is just 1 block



- And the root Directory contains a list of directory entries

File Name	Block Number
A	7
B	4
C	9
D	2
E	10

Growing a Directory

- In FAT our file system looked something like this:
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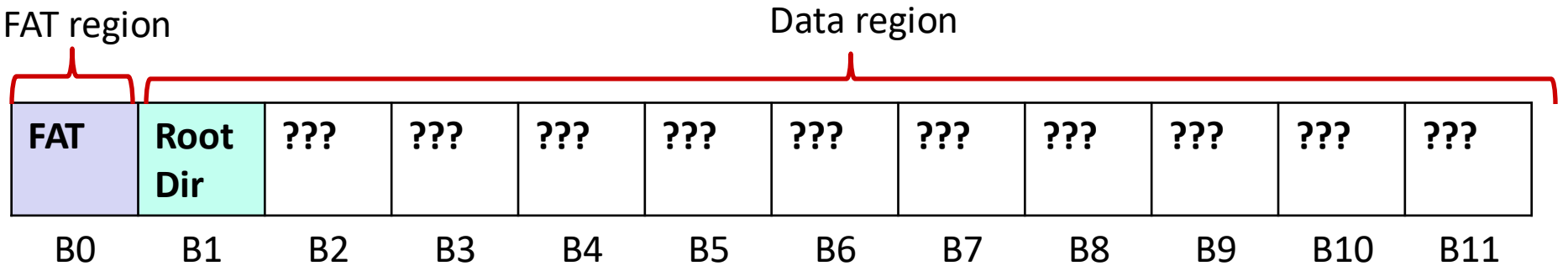
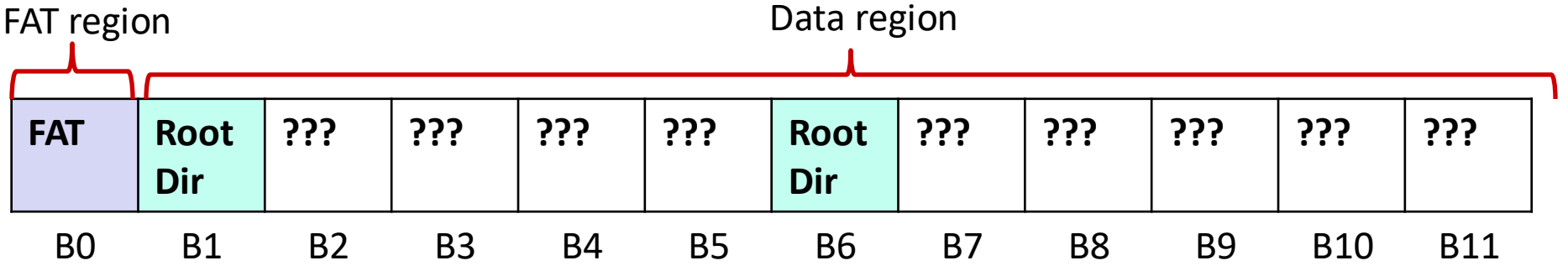


- What happens if the root directory starts filling up?
  - The root directory is itself a file, it can expand to another block



Growing a Directory

- We would also need to update the FAT to account for this change.
  - Root directory in PennFAT starts at index 1 into the data region
  - Index 1 into the data region is the first block in the data region 

Block # (FAT Index)	Next (FAT value)
0	METADATA
1	END
…	…
….	…
…	…
6	EMPTY
7	EMPTY
…	…

Block # (FAT Index)	Next (FAT value)
0	METADATA
1	6
…	…
….	…
…	…
6	END
7	EMPTY
…	…

Poll Yourself

Discussss

- Let's say PennFAT is 4 blocks
- What are value of the remaining blocks in the diagram?

Root DIR

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FAT

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2	8
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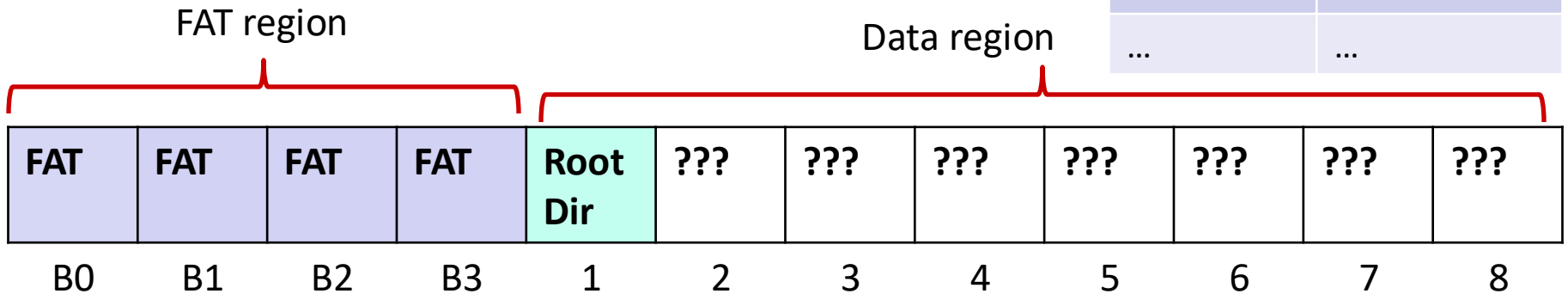
8	3
…	…



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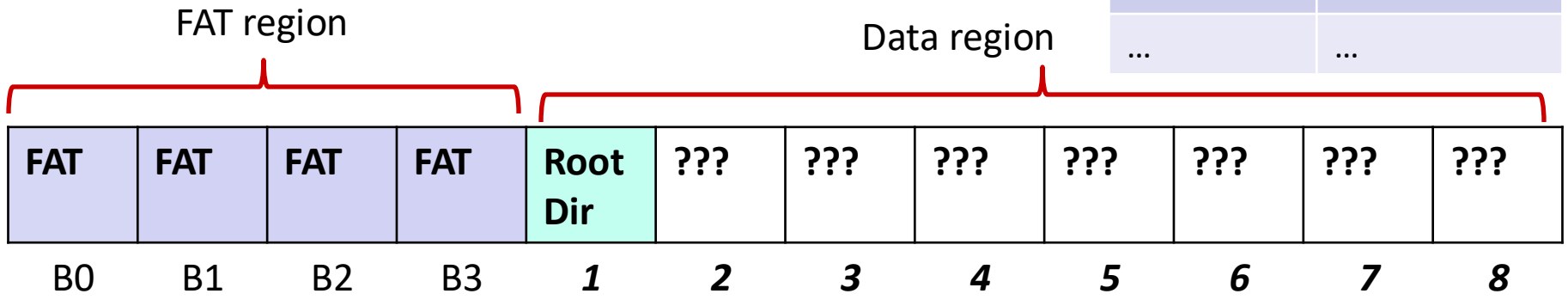
Hint: Index into data region starting at index 1



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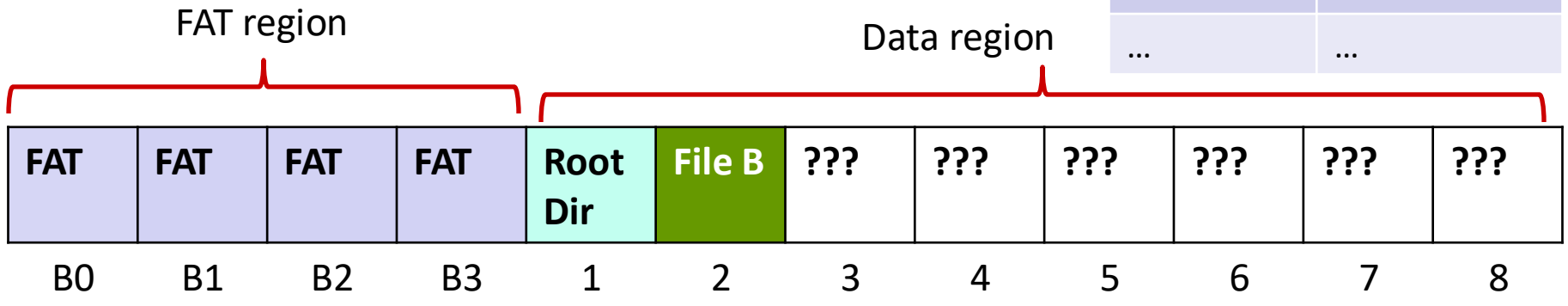

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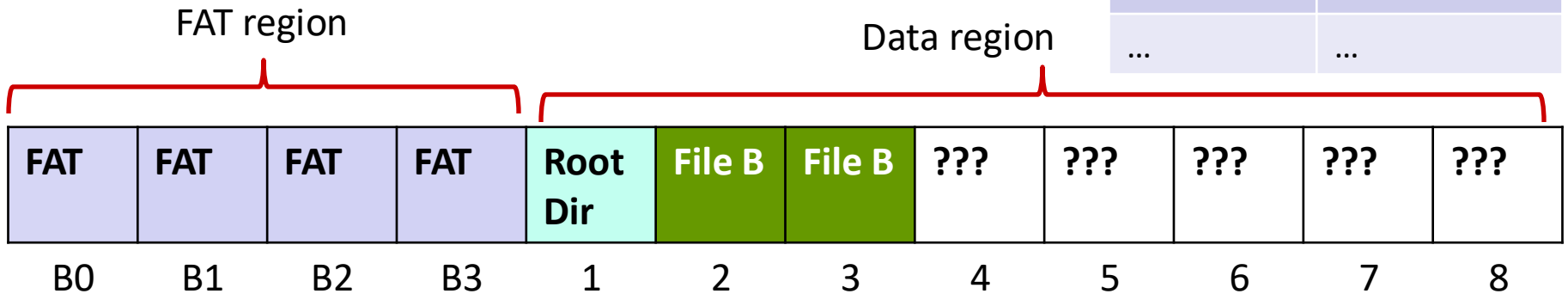

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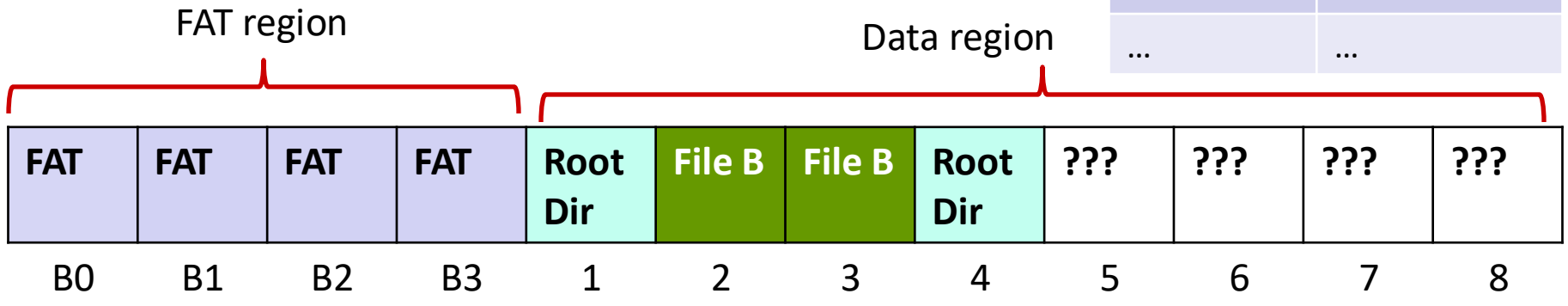

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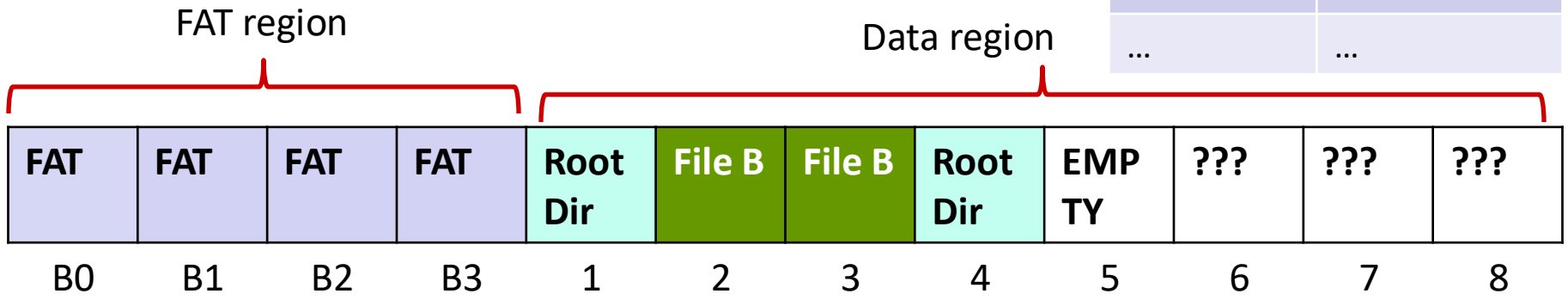

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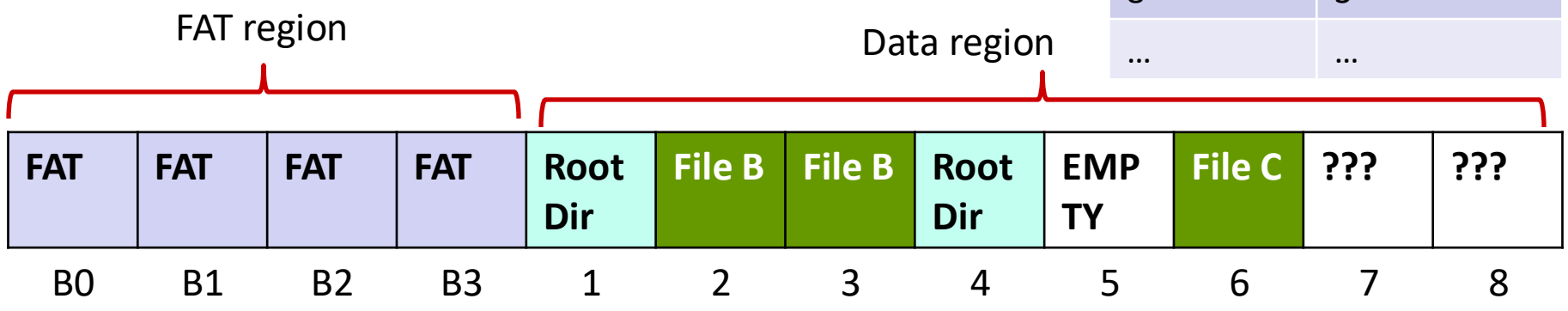

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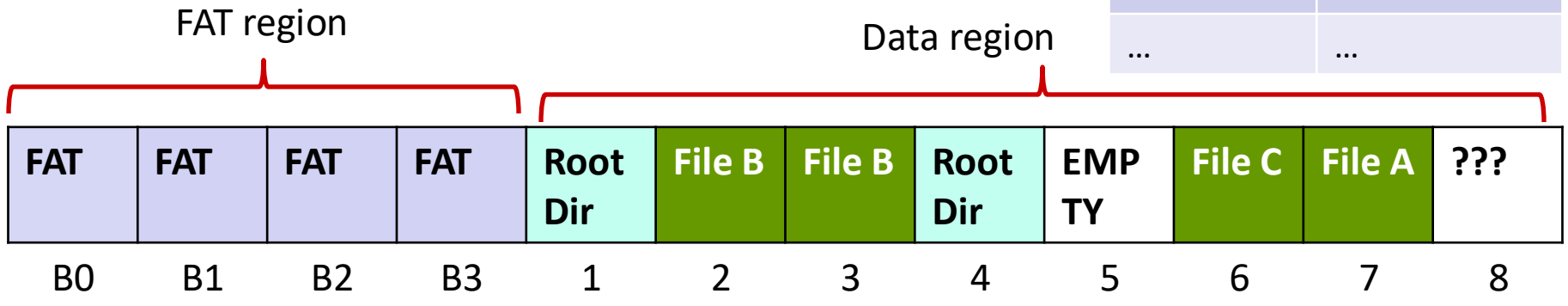

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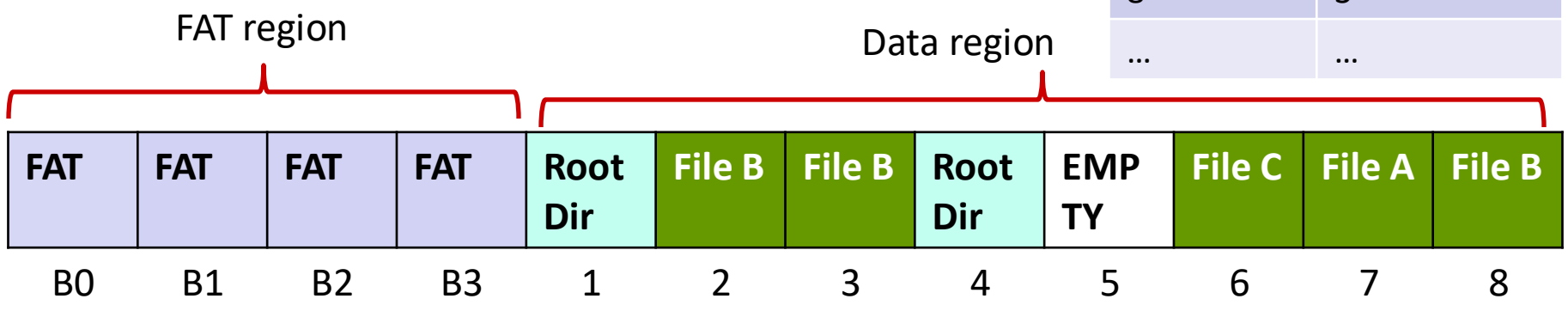
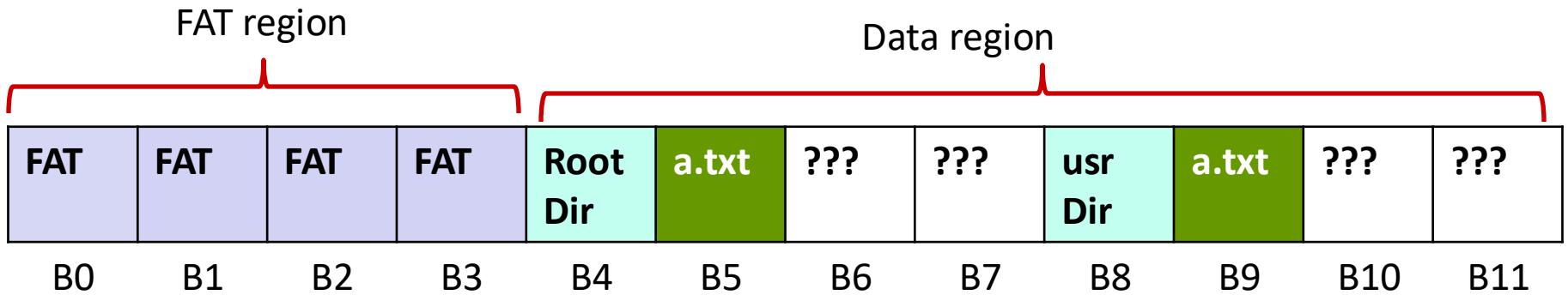
8	3
…	…



Sub Directories

- In PennOS, we are only required to deal with 1 directory, but you can implement sub-directories.
  - Sub directories are just other (special) files
- Consider we have the following two directories and files
  - /a.txt
  - /usr/a.txt
  - Above are two separate files!



Sub Directories

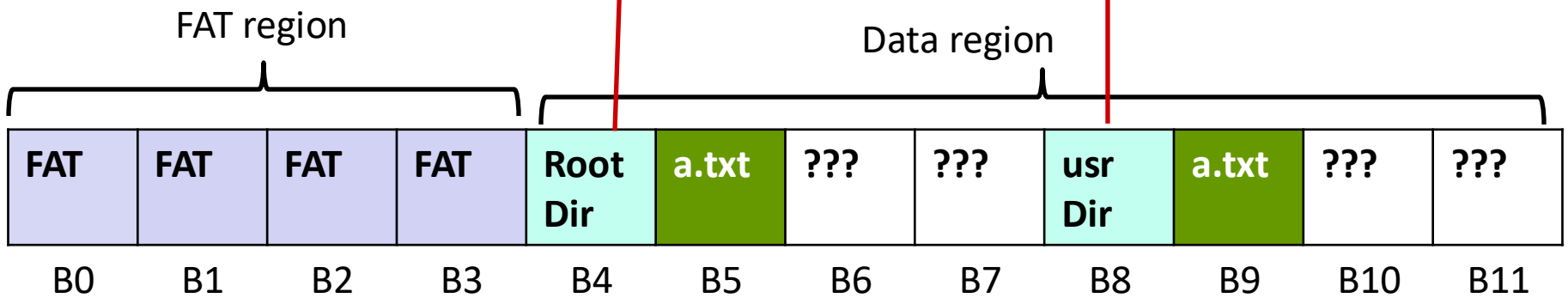
- We would also have some information in a directory entry to specify what kind of file it is

Root DIR

File Name	Block Number	File Type
a.txt	2	Regular
usr/	5	directory
…	..	

usr DIR

File Name	Block Number	File Type
a.txt	6	Regular
…	..	



. and ..

- It would be useful to support . and . .
  - . Refers to the current directory, . . refers to parent directory

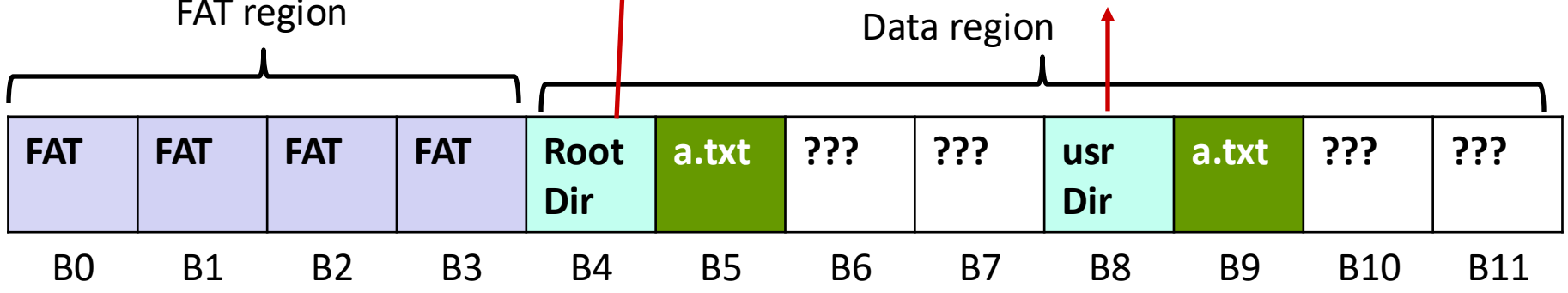
root DIR

File Name	Block Number	File Type
.	1	directory
..	1	directory
a.txt	2	Regular
usr/	5	directory
…	..	

Has no parent, refers to self

usr DIR

File Name	Block Number	File Type
.	5	directory
..	1	directory
a.txt	6	Regular
…	..	



Lecture Outline

- FAT & PennFAT wrap-up
- Inodes
- Directories
- **Block Caching**

Block Caching

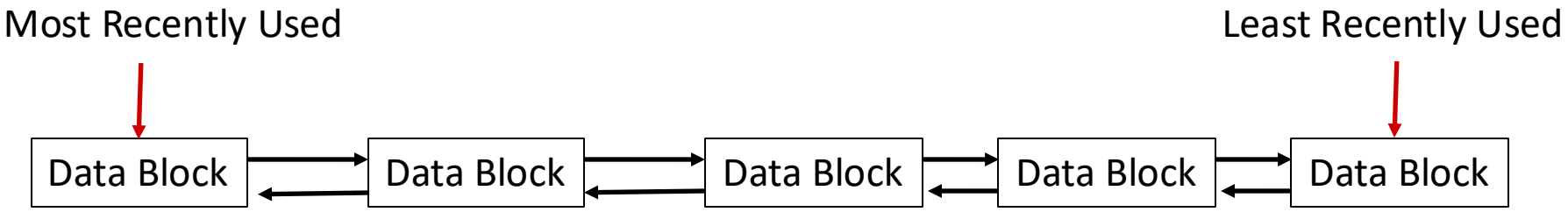
- Disk I/O is really slow (relative to accessing memory)

- What can we do instead to make it faster?
  - Keep data that we want to access in memory ☺
  - We already did this with FAT and Inodes for open files

- We can do the same for data blocks we think we may use again in the future

Block Caching Data Structure

- We can use a linked list to store blocks in LRU

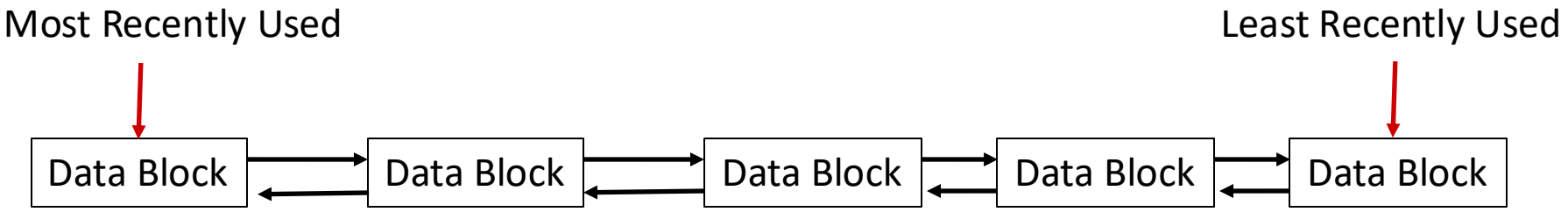


- What is the algorithmic runtime analysis to:
  - lookup a specific block?
  - Removal time of LRU?
  - Time to move a block to the front or back?
    - Consider search time

Discuss

Block Caching Data Structure

- We can use a linked list to store blocks in LRU



- What is the algorithmic runtime analysis to:
  - lookup a specific block? O(n)
  - Removal time of LRU? O(1)
  - Time to move a block to the front or back? O(n)
    - Consider search time

Discuss

Is there a structure we know of that has O(1) lookup time?

Chaining Hash Cache

- We can use a combination of two data structures:
  - `linked_list<block>`
  - `hash_map<block_num, node*>`