FAT, I-nodes

Computer Operating Systems, Spring 2024

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TAs:

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Emily Shen	Julius Snipes	Ryan Boyle	Zhiyan Lu

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- How is milestone 1 looking?

Administrivia

- Penn-shell is out!
  - **Full thing is due at the end of the week** (2/23 @ 11:59 pm)
  - Done in partners
  - Should have everything you need to complete the assignment in this class
  - Please add your partner to the gradescope submission if you can.
  - Autograder for full thing should be up today

Administrivia

- Midterm booked:
  - 5:15 - 7:15 pm in Meyerson B1
  - Thursday 2/29 (the Thursday before break)
  - Let me know if you conflicts

- Final Tentatively Booked
  - Tuesday May 7th, Noon – 2pm in Towne 100
  - Not confirmed yet, but this is likely it

- Travis is still a little sick, but probably be in-person for next lecture

Penn-Shell Compatibility

- From the signal(2) man page

```
Portability
    The only portable use of signal() is to set a signal's disposition to SIG_DFL or SIG_IGN.  The semantics when using signal()
    to establish a signal handler vary across systems (and POSIX.1 explicitly permits this variation); do not use  it  for  this
    purpose.
```

- If you want to have better help from TA's put this at the top of your file before you #include anything
  - This *should* get signals to behave as we expect, so TAs can better help
  - If you got it working another way, that is OK. Auto-grader *should* still accept it

```
#ifndef _POSIX_C_SOURCE
#define _POSIX_C_SOURCE 200809L
#endif

#ifndef _DEFAULT_SOURCE
#define _DEFAULT_SOURCE 1
#endif
```

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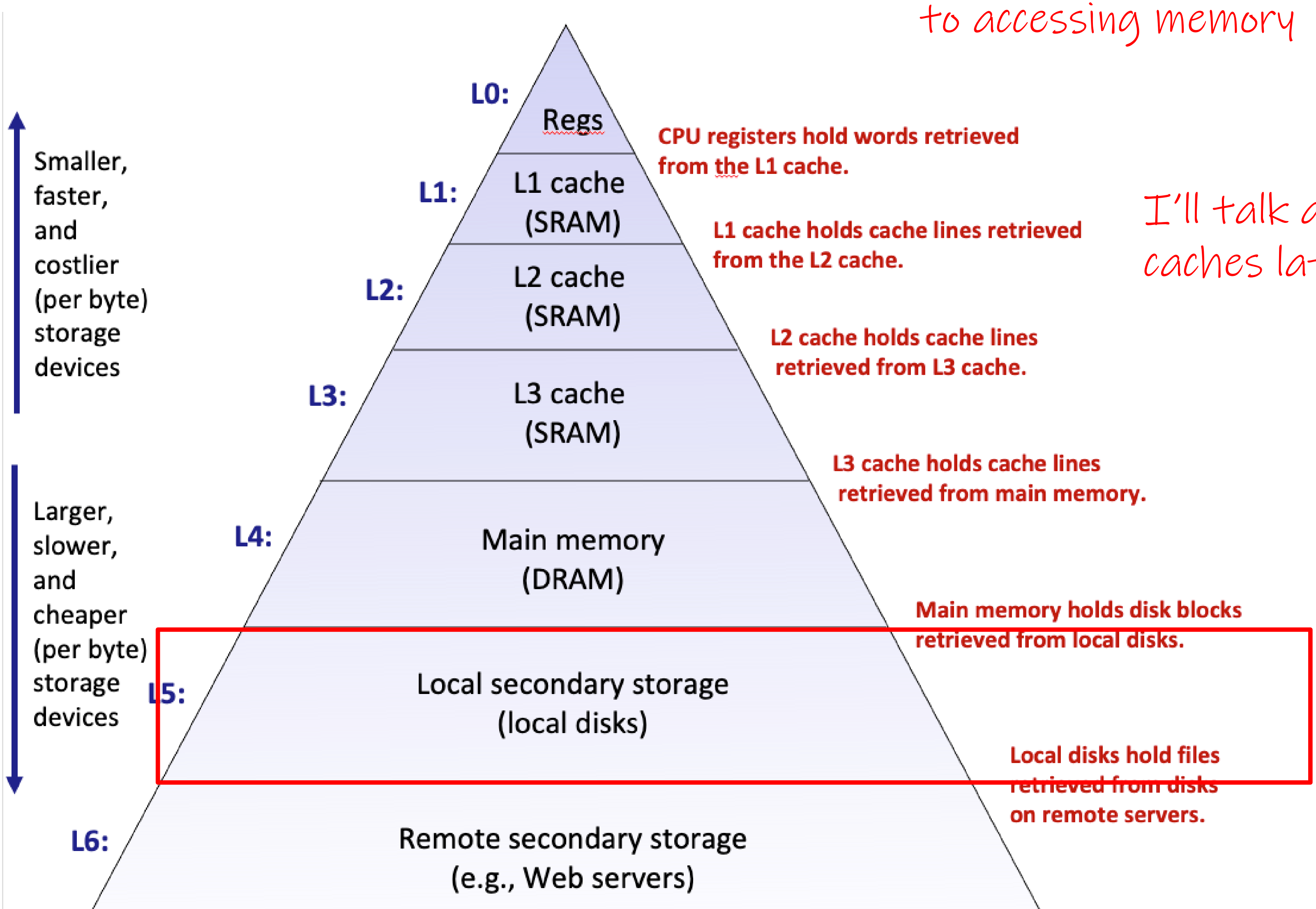
- How are you doing?

Lecture Outline

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

Memory Hierarchy

Files systems are really really really slow compared to accessing memory

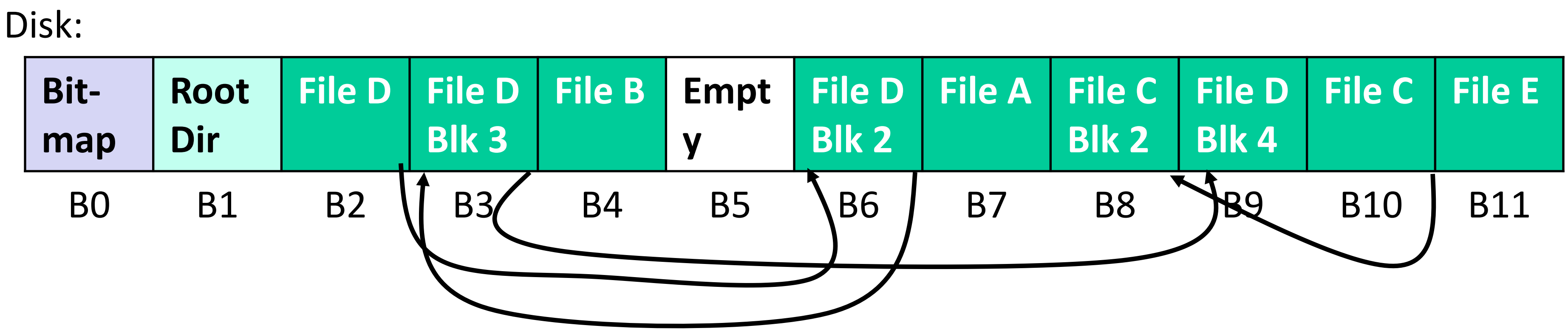


I'll talk about caches later

Bryant and O'Hallaron, Computer Systems: A Programmer's Perspective, Third Edition

FAT (File Allocation Table)

- Instead of this:



- We can instead store the pointers or “links” in a table in memory to get…

Linked List via FAT

- FAT is logically very similar as a linked list, we just store the links somewhere else that can be conveniently stored in memory
- Since the links are in memory, we can find the N^{th} block of a file with much fewer disk accesses
- Disk accesses take a long time, so this is good ☺

FAT (File Allocation Table)

- This table is called the File Allocation Table (FAT)
- This table is in memory when it is running
- Table stored in disk initially, loaded into memory when computer is booted.
- Replaces the bitmap
  - Why can it do that?

Block #	Next
0	BITMAP/SPECIAL
1	END
2	6
3	9
4	END
5	EMPTY / UNUSED
6	3
7	END
8	END
9	END
10	8
11	END

Disk:

FAT	Root Dir	File D	File D Blk 3	File B	Empty	File D Blk 2	File A	File C Blk 2	File D Blk 4	File C	File E
B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11

FAT Walkthrough

- The FAT is the reason why the operating system knows which block is used for which purpose
- If we wanted to read the 4th block from file D:

Block #	Next
0	BITMAP/SPECIAL
1	END
2	6
3	9
4	END
5	EMPTY / UNUSED
6	3
7	END
8	END
9	END
10	8
11	END

Disk:

FAT	Root Dir	???	???	???	???	???	???	???	???	???	???
B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11

FAT Walkthrough

- The FAT is the reason why the operating system knows which block is used for which purpose
- If we wanted to read the 4th block from file D:
  - Read the directory entry for File D to see that it starts at block 2

Block #	Next
0	BITMAP/SPECIAL
1	END
2	6
3	9
4	END
5	EMPTY / UNUSED
6	3
7	END
8	END
9	END
10	8
11	END

Disk:

FAT	Root Dir	File D Blk 0	???	???	???	???	???	???	???	???	???
B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11

FAT Walkthrough

- The FAT is the reason why the operating system knows which block is used for which purpose
- If we wanted to read the 4th block from file D:
  - Lookup next block in the FAT. We go to FAT entry #2 and the "next" says where the next block is (physical block 6)

Block #	Next
0	BITMAP/SPECIAL
1	END
2	6
3	9
4	END
5	EMPTY / UNUSED
6	3
7	END
8	END
9	END
10	8
11	END

Disk:

FAT	Root Dir	File D Blk 0	???	???	???	File D Blk 1	???	???	???	???	???
B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11

FAT Walkthrough

- The FAT is the reason why the operating system knows which block is used for which purpose
- If we wanted to read the 4th block from file D:
  - Lookup next block in the FAT. We go to FAT entry #6 and the "next" says where the next block is (physical block 3)

Block #	Next
0	BITMAP/SPECIAL
1	END
2	6
3	9
4	END
5	EMPTY / UNUSED
6	3
7	END
8	END
9	END
10	8
11	END

Disk:

FAT	Root Dir	File D Blk 0	File D Blk 2	???	???	File D Blk 1	???	???	???	???	???
B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11

FAT Walkthrough

- The FAT is the reason why the operating system knows which block is used for which purpose
- If we wanted to read the 4^{th} block from file D:
  - Lookup next block in the FAT. We go to FAT entry #3 and the "next" says where the next block is (physical block 9)

Block #	Next
0	BITMAP/SPECIAL
1	END
2	6
3	9
4	END
5	EMPTY / UNUSED
6	3
7	END
8	END
9	END
10	8
11	END

Disk:

B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
FAT	Root Dir	File D Blk 0	File D Blk 2	???	???	File D Blk 1	???	???	File D Blk 3	???	???

FAT Walkthrough

- The FAT is the reason why the operating system knows which block is used for which purpose
- If we wanted to read the 4th block from file D:
  - The FAT entry for block 9 has a special value for "next" to indicate it is the last block in the file

Block #	Next
0	BITMAP/SPECIAL
1	END
2	6
3	9
4	END
5	EMPTY / UNUSED
6	3
7	END
8	END
9	END
10	8
11	END

Disk:

FAT	Root Dir	File D Blk 0	File D Blk 2	???	???	File D Blk 1	???	???	File D Blk 3	???	???
B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11

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- What if we want to extend a file in FAT?

- What steps do we need to take?

- Hint: FAT is in memory, what are the big differences between Disk and Memory?

Poll Everywhere

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- What if we want to extend a file in FAT?

- What steps do we need to take?
  - Lookup a free block in the FAT, mark it as a last block
  - Lookup the last block in the file, change its FAT entry to think the newly allocated block is the new "last"
  - …
  - Write the FAT table to disk, memory is volatile storage

- Hint: FAT is in memory, what are the big differences between Disk and Memory?

FAT is great ☺*

- FAT has allowed us to have non-contiguous blocks for a file.
- At the same time, we only need one disk read to access the Nth block of a file

- What could go wrong with this?
  - FAT is really big and is in memory, so memory consumption goes up ☹

FAT size

- A FAT is similar to a bitmap
  - A bitmap needs 1 bit per block
  - A FAT needs ~16-bits per block ☹
- At least we don't need bitmap anymore!

- Grows a lot as the size of disk grows
  - As the disk grows, there are more blocks in the disk. We need more FAT entries, and each entry needs more bits. (To hold the block number. # of bits for block # grows to support more blocks)
  - **A FAT may be bigger than one block**
  - Since we need to keep the FAT in memory, this increases our memory consumption as well
  - FAT got fazed out for I-nodes (next lecture) because of this

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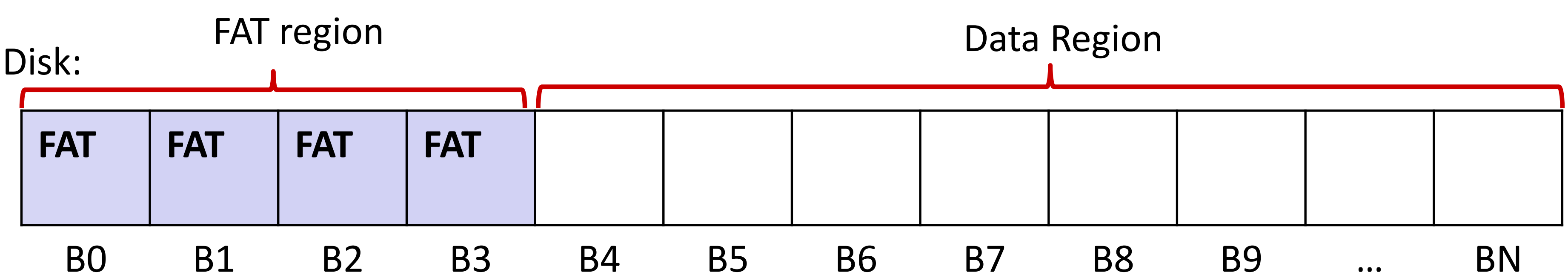
- When you create a file system with PennFAT, you specify the number of blocks the FAT (this is just the table) takes up and the size of a block.

- Let's say I want to create a FAT that spans 4 blocks, a block is 4096 (2^{12}) bytes, and a FAT entry is 2 bytes.
  - How many entries do I have?
  - How many Blocks do we have that can store actual file data?



Poll Everywhere

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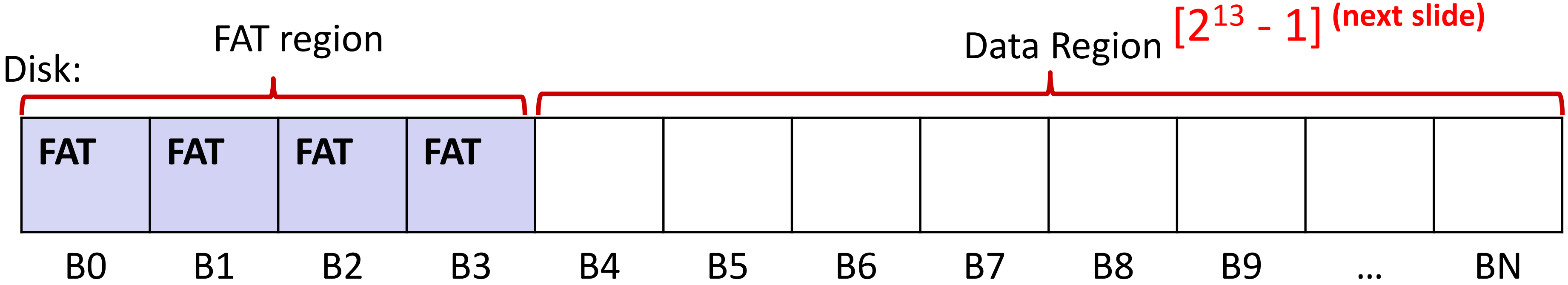
- When you create a file system with PennFAT, you specify the number of blocks the FAT (this is just the table) takes up and the size of a block.

- Let's say I want to create a FAT that spans 4 blocks, a block is 4096 (2^{12}) bytes, and a FAT entry is 2 bytes.
  - How many entries do I have? $4 * 2^{12} / 2 = [2^{13}]$
  - How many Blocks do we have that can store actual file data? $[2^{13} - 1]$ **(next slide)**



PennOS FAT Details

- If we have N entries in the FAT, we only have N – 1 blocks in the FAT

- The first FAT entry `FAT[0]` holds meta data about the FAT, so it doesn't correspond to a "real" block

- An entry is 16-bits, which is 2 bytes.
- Consider the example 2-byte value: 0x2004
  - We can split this into two bytes
  - The MSB (Most Significant Byte) 0x20 -> 32 in decimal
  - The LSB (Least Significant Byte) 0x04 -> 4 in decimal

PennOS FAT[0] MSB

- The first FAT entry **`FAT[0]`** holds meta data about the FAT, so it doesn't correspond to a "real" block
- Consider the example 2-byte value: 0x2004
  - We can split this into two bytes
  - The MSB (Most Significant Byte) 0x20 -> 32 in decimal
  - The LSB (Least Significant Byte) 0x04 -> 4 in decimal
- The MSB is number of blocks in the FAT
  - in this example, the FAT is 32 blocks

PennOS FAT[0] LSB

- The first FAT entry **`FAT[0]`** holds meta data about the FAT, so it doesn't correspond to a "real" block
- Consider the example 2-byte value: 0x2004
  - We can split this into two bytes
  - The MSB (Most Significant Byte) 0x20 -> 32 in decimal
  - The LSB (Least Significant Byte) 0x04 -> 4 in decimal
- The LSB is between 0 and 4, and specifies the size of the blocks for the file system

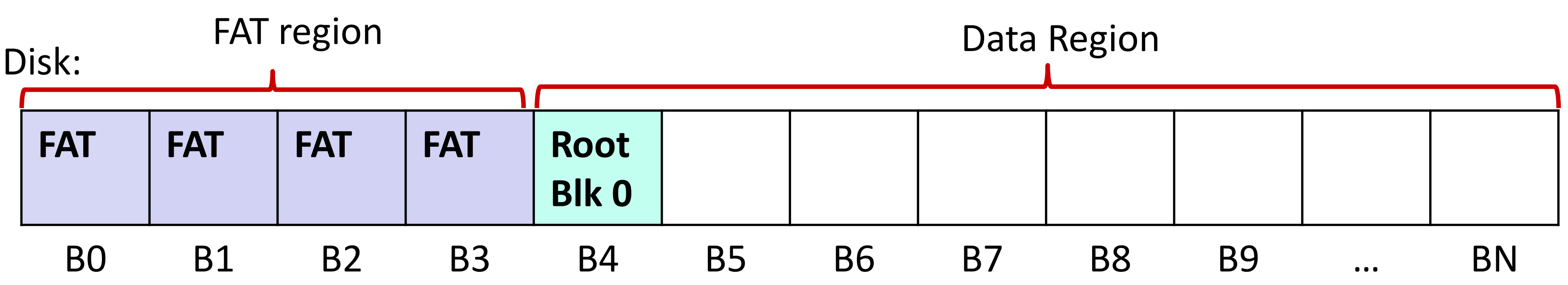
LSB	Block Size
0	256
1	512
2	1,024
3	2,048
4	4,096

PennOS FAT Entry Special Values

- A PennFAT entry is 16-bits and only contains the block number of the next block in the file.
- There are two special values a PennFAT entry can hold
- 0x0000 (0 in decimal)
  - Indicate the block is free.
  - We start indexing into our blocks in the data region starting with index 1 🤢🤢 🤮🤮🤮
- 0xFFFF (65535 as unsigned, -1 as signed)
  - Indicates that there is no block after this logically in the file
  - That this is the last block in the file

PennOS root Directory

- PennFAT has a special value for **`FAT[1]`** as well.
- It still corresponds to a data block, but that data block is the first block of the root directory
- This means we always know where the root directory starts. (at index 1 into the data region)



Lecture Outline

- FAT & PennFAT wrap-up
- **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?

- **Big memory consumption, one entry needed for every block in the file system, and that all needs to be in memory.**
  - **A FAT likely spans multiple blocks**
  - **This size also grows as disk grows :/**

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- Could we instead store FAT blocks on disk and only load into memory the parts that are used for looking up files that are currently open/being used?

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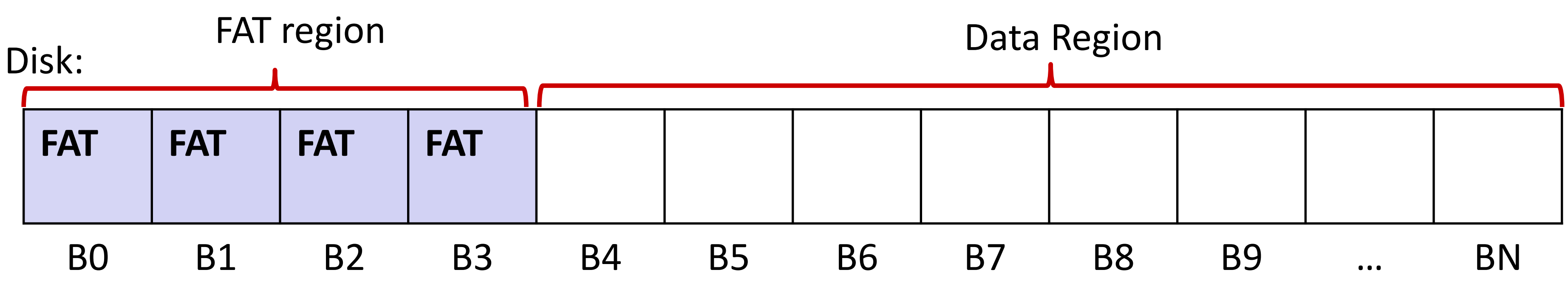
- Could we instead store FAT blocks on disk and only load into memory the parts that are used for looking up files that are currently open/being used?

- **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)**

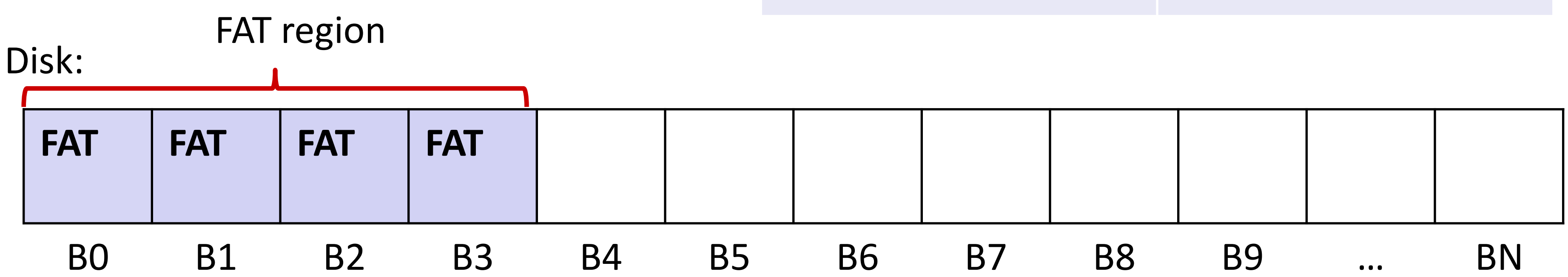


Explanation

Consider we have a file that starts at block 2 into the data region

- 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

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



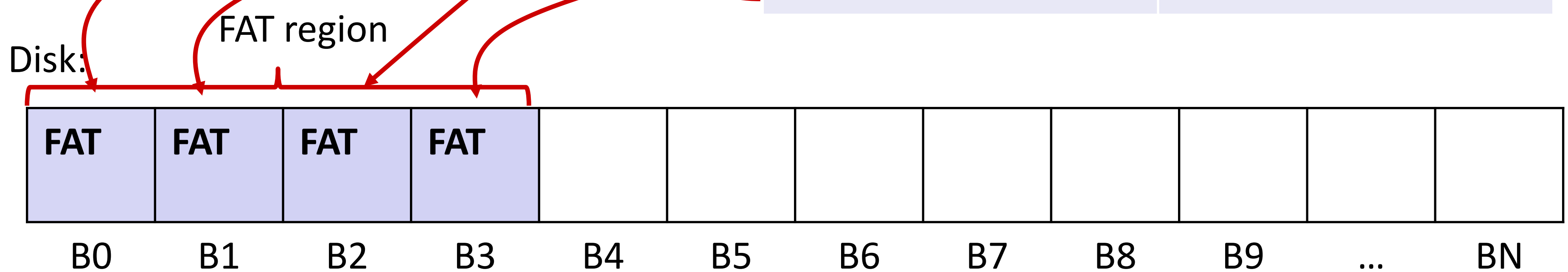
Explanation

Consider we have a file that starts at block 2 into the data region

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

- 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

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



Inode motivation

- Idea: we usually don't care about ALL blocks in the file system, just the blocks for the currently open files

- 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

meta data
0^{th} phys block #
1^{st} phys block #
2^{nd} phys block #
3^{rd} phys block #
4^{th} phys block #
…
12^{th} phys block #

Inode layout

- Inodes contain:
  - some metadata about the file
    - Owner of the file
    - Access permissions
    - Size of the file
    - Time of last change
  - 12 physical block numbers corresponding to the first 12 logical blocks of a file
- In C struct format:

```
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:

Bit-map	**Inodes**	**…**	**…**	**…**	**…**	**…**	**…**	**…**
B0	B1	B2	B3	B4	B5	B6	B7	B8

Inodes Disk Layout

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

Bit-map	Inodes	…	…	…	…	…	…	…
B0	B1	B2	B3	B4	B5	B6	B7	B8

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

Bit-map	Inode 0	Inode 1	Inode 2	Inode 3	…	Inode n	…	…	…	…	…	…	…
B0	B1						B2	B3	B4	B5	B6	B7	B8

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)

Bit-map	**Inode 0**	**Inode 1**	**Inode 2**	**Inode 3**	**…**	**Inode n**	**…**	**…**	**…**	**…**	**…**	**…**	**…**
B0			B1				B2	B3	B4	B5	B6	B7	B8

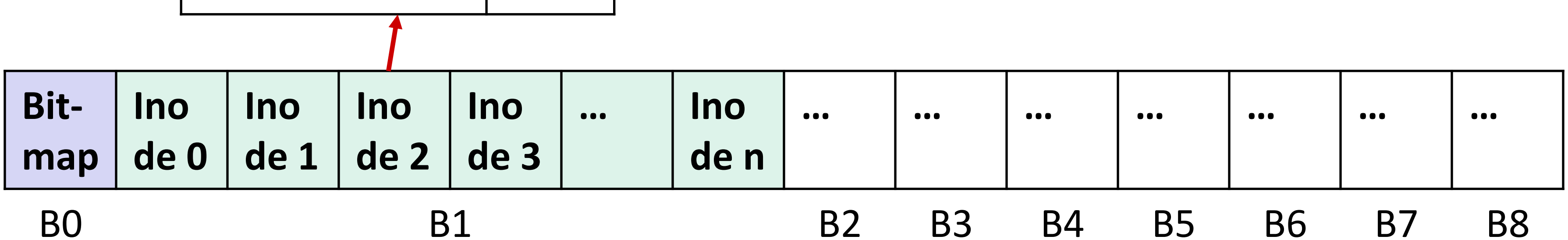
Example File Block Lookup

- 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)
  - We can read the Inode to see which blocks makeup the file

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



Example File Block Lookup

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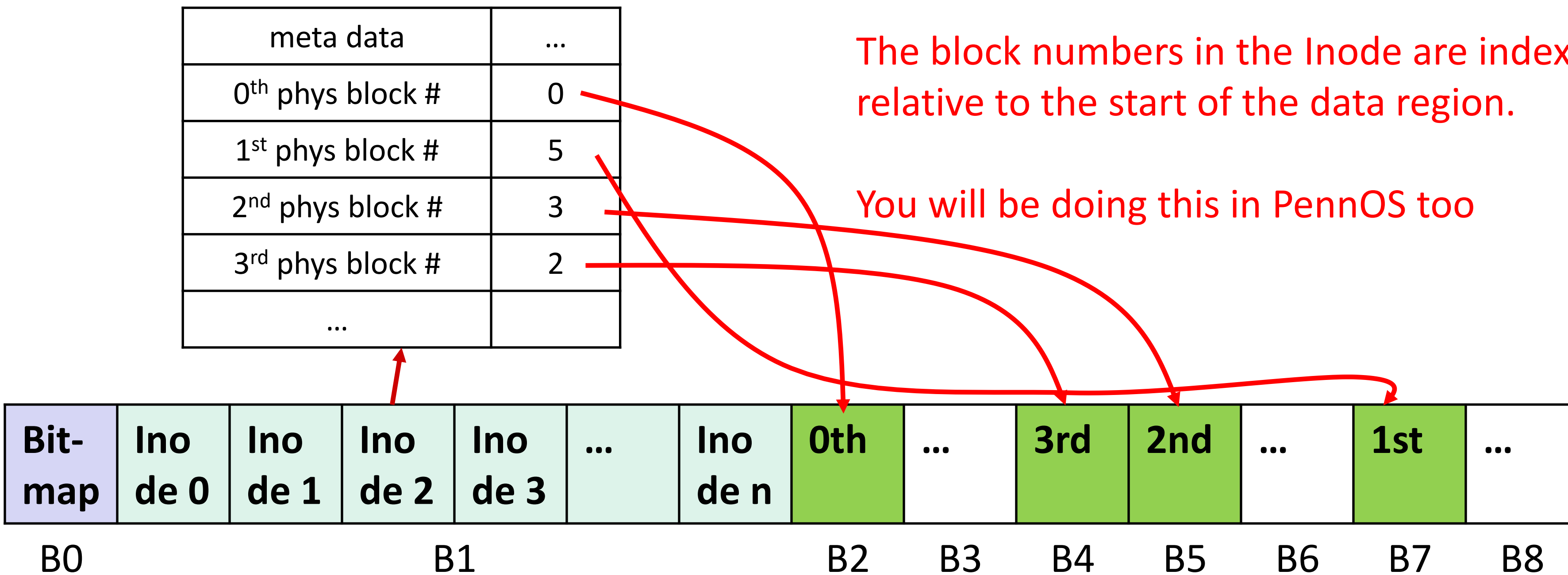


The block numbers in the Inode are indexes relative to the start of the data region.

You will be doing this in PennOS too

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
  - This block can hold 128 block numbners

meta data	…
0^{th} phys block #	0
1^{st} phys block #	5
…	…
11^{th} phys block #	2
Block of ptrs	
…	

12^{th} phys block #	--
13^{st} phys block #	--
…	…
139^{th} phys block #	--

File Sizes with Inode

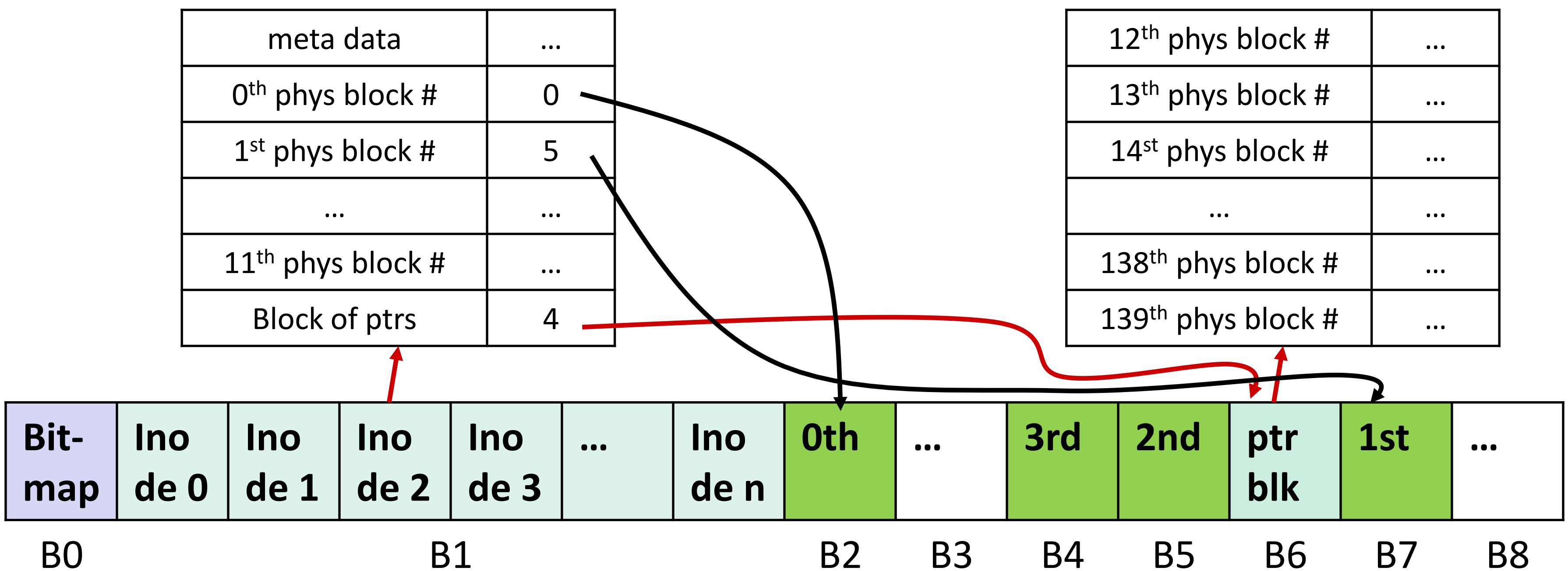
- So with Inodes, how many blocks can we have per file?
  - So far: 12 blocks per file (this is not enough, way too small!
- We can allocate a block to hold more block numbers

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

File Sizes with Inode

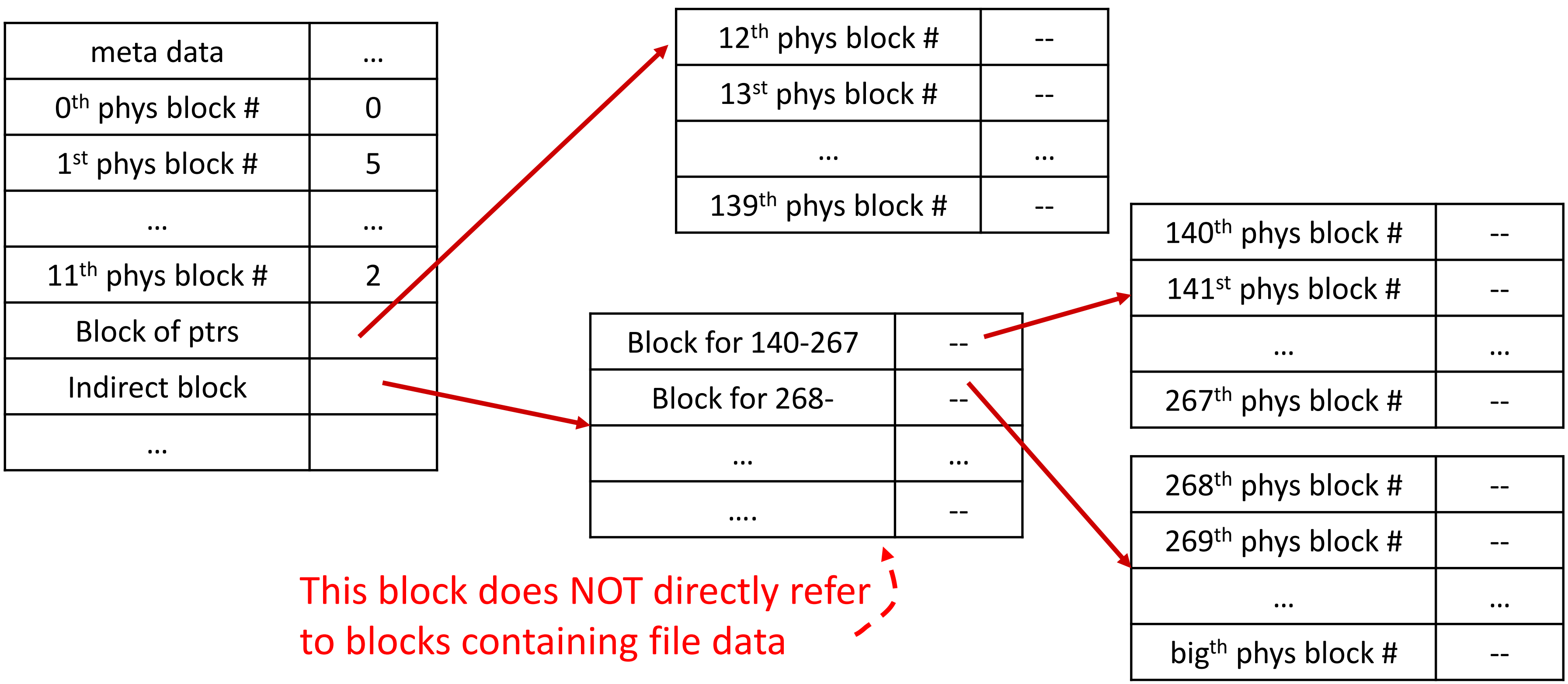
- So with Inodes, how many blocks can we have per file?
  - So far: 12 blocks per file (this is not enough, way too small!

- We can allocate a block to hold more block numbers



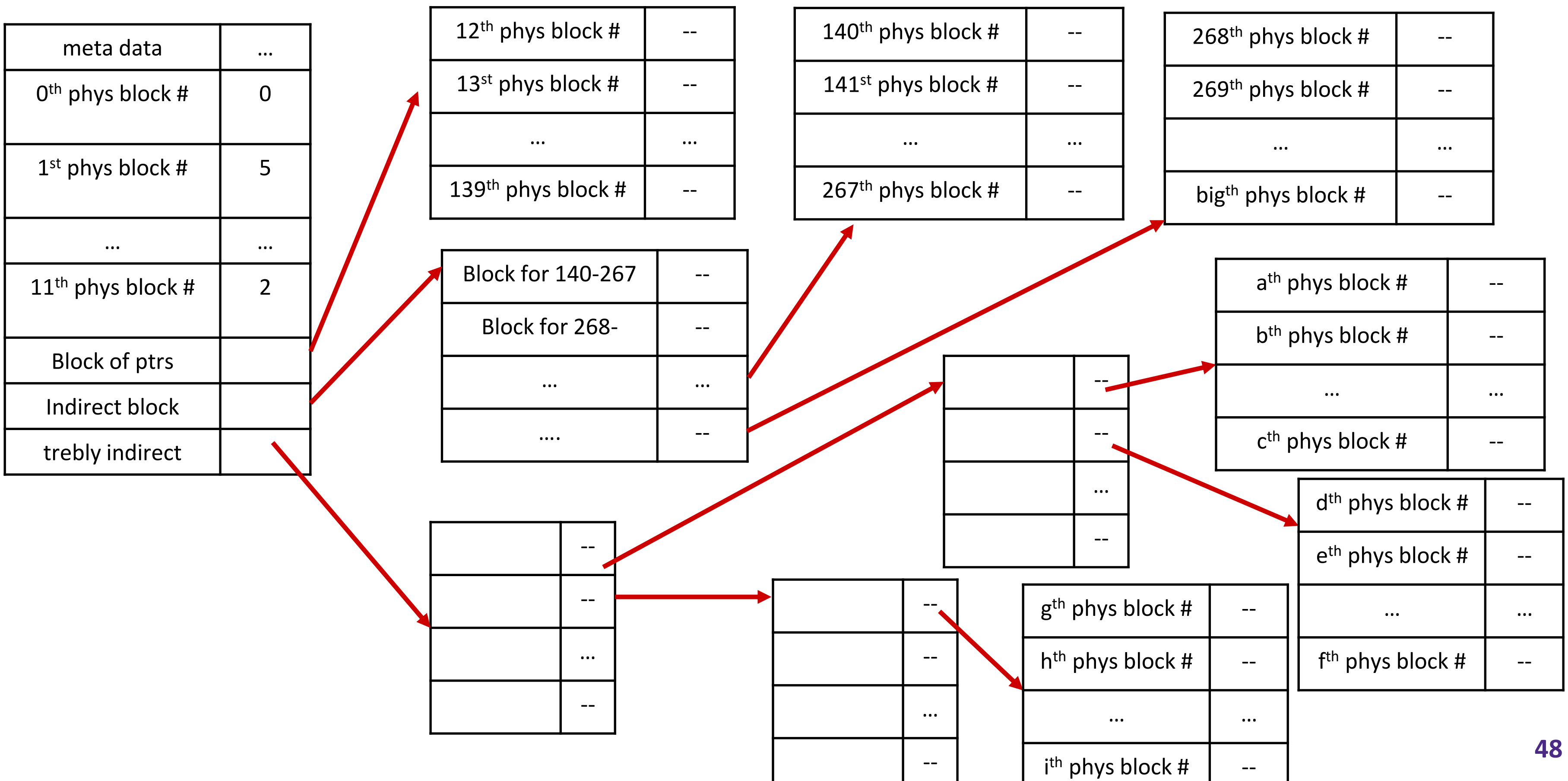
We need moreeeeee

- 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



MORE MORE MORE MORE MORE MORE MOR

- 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 ext2)
- If you need more space than this, the operating system will tell you no
- Boon did the math on this: this is already enough for a file that is

$$(128 \times 512) + 10 \times 512\ \textit{Bytes}$$
$$\left(128^2 \times 512\right) + (128 \times 512) + (10 \times 512)\ \textit{Bytes}$$
$$\left(128^3 \times 512\right) + \left(128^2 \times 512\right) + (128 \times 512) + (10 \times 512)\ \textit{Bytes}$$

- Big enough

Poll Everywhere

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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

- FAT & PennFAT wrap-up
- 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

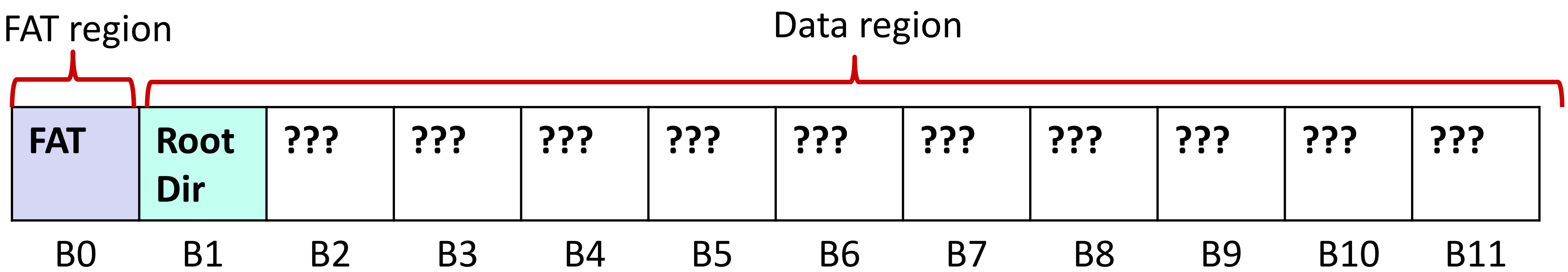
- A directory is essentially like a file
  - We will store its data on disk inside of blocks (like a file)

- 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

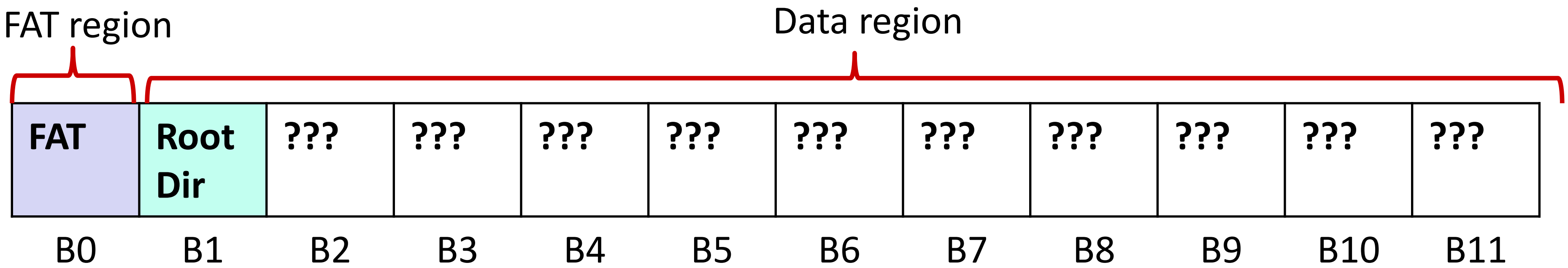


- And the root Directory contains a list of directory entries

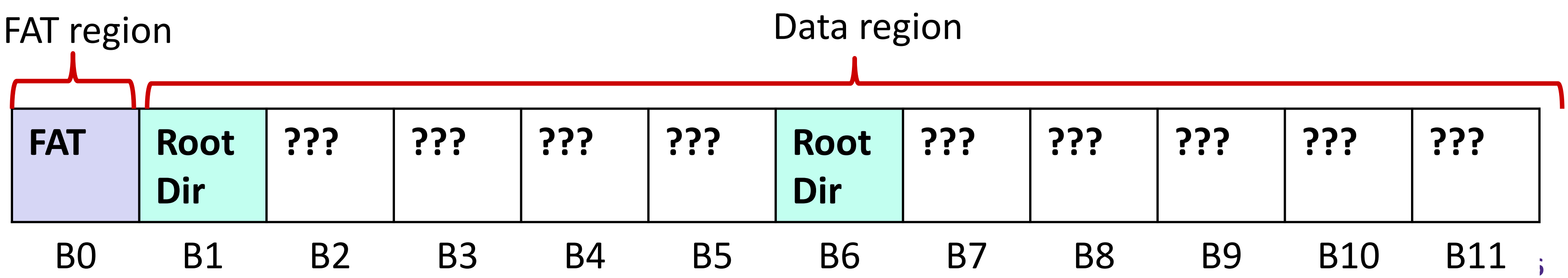
File Name	Block Number
A	7
B	4
C	9
D	2
E	10

Growing a Directory

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



- 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
…	…

Question is not good format for pollev ☹

Discuss

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

Root DIR

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B	2
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FAT

Block # (FAT Index)	Next (FAT value)
0	METADATA
1	4
2	8
3	END
4	END
5	EMPTY
6	END
7	END
8	3
…	…

FAT region (B0–B3) | Data region (B4–B11)

FAT	FAT	FAT	FAT	Root Dir	???	???	???	???	???	???	???
B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11

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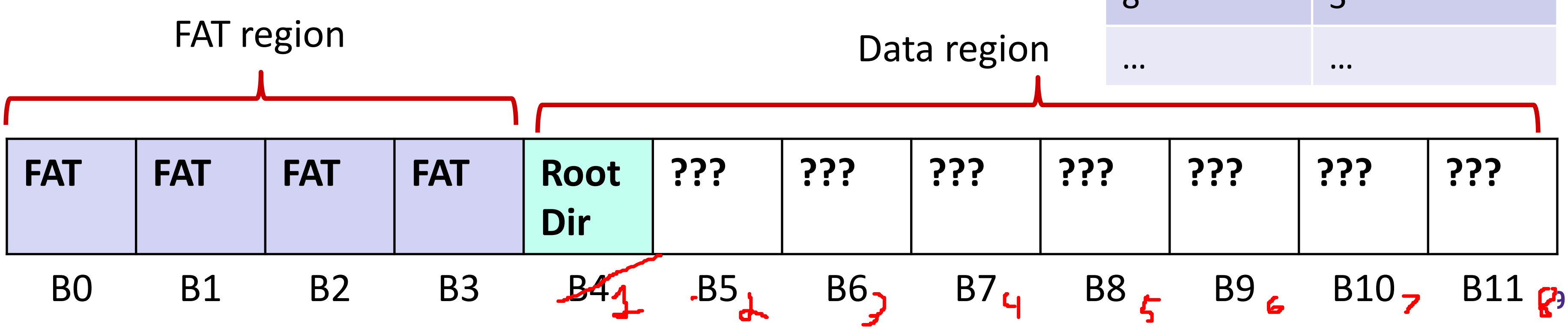

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FAT	FAT	FAT	FAT	Root Dir	File B	???	???	???	???	???	???

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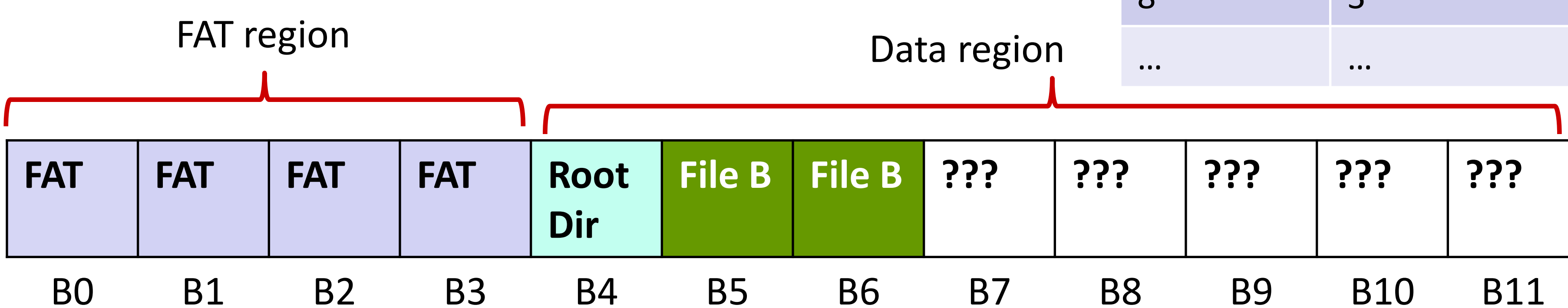

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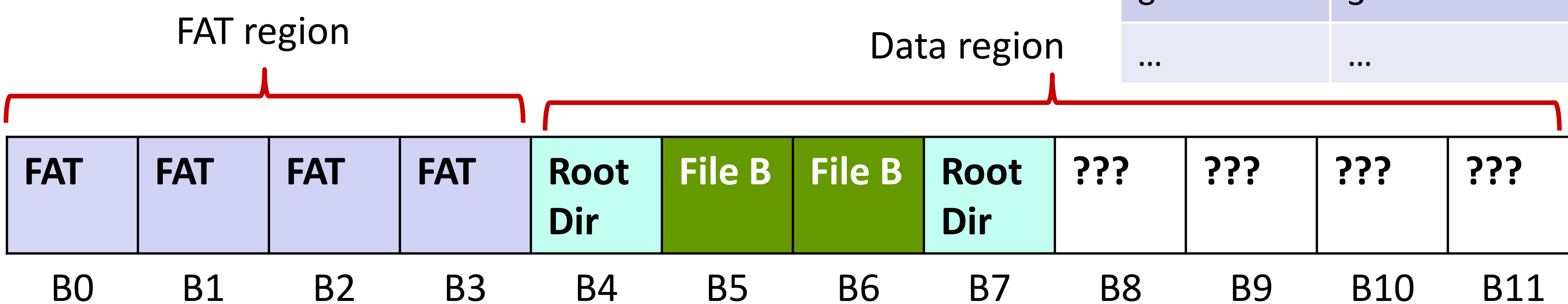

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FAT region: B0–B3; Data region: B4–B11

B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
FAT	FAT	FAT	FAT	Root Dir	File B	File B	Root Dir	EMP TY	???	???	???

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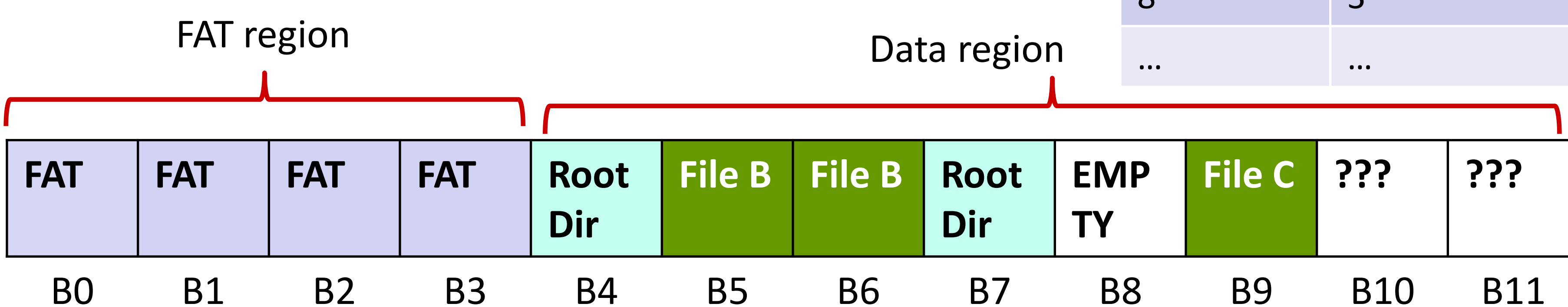

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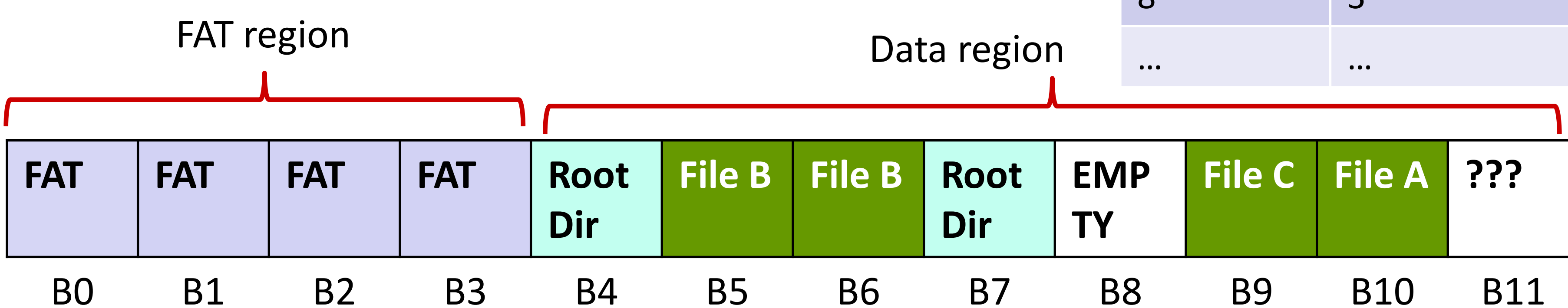

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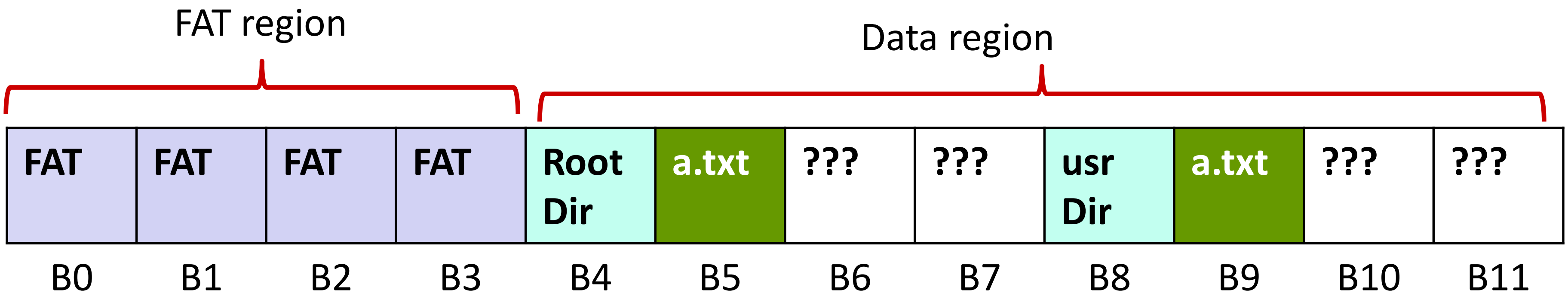
FAT region (B0–B3) | Data region (B4–B11)

B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
FAT	FAT	FAT	FAT	Root Dir	File B	File B	Root Dir	EMPTY	File C	File A	File B

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

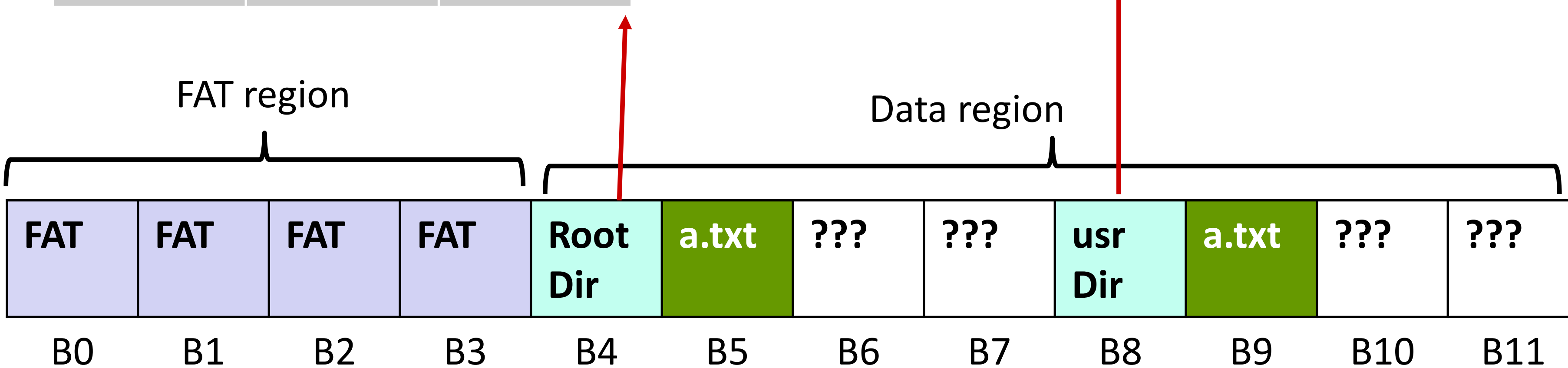
- We would also have some information in a directory entry to specify what kind of file it is

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

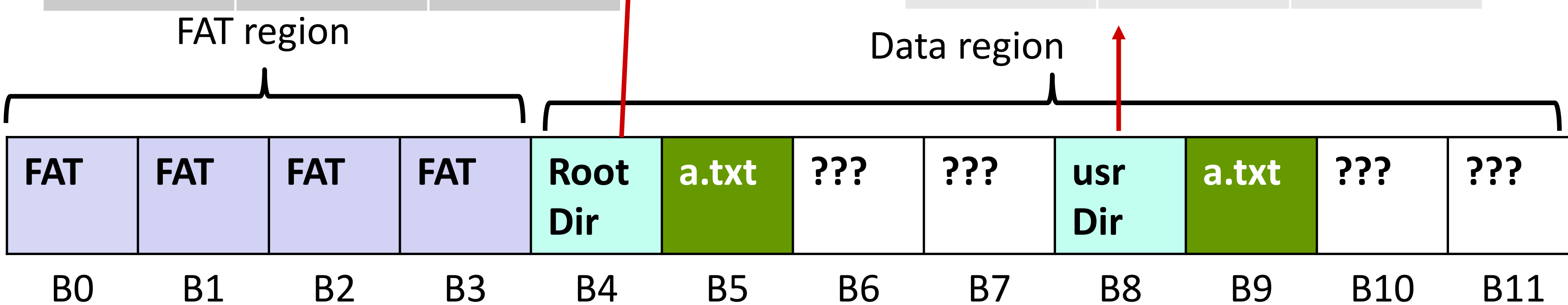
root DIR

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

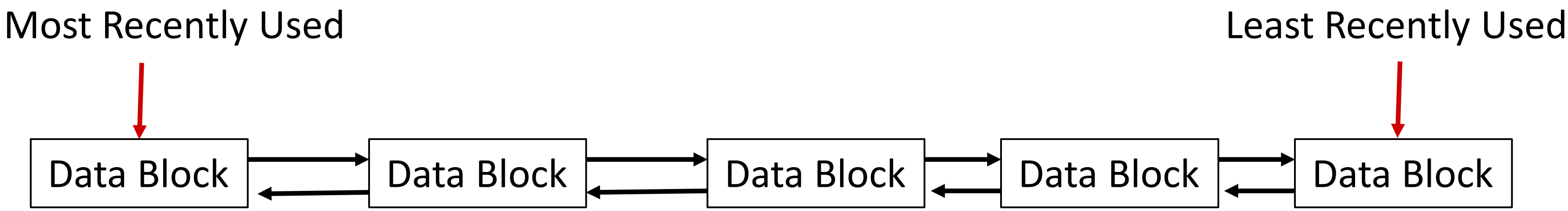
- Disk I/O is really slow (relative to accessing memory)

- 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

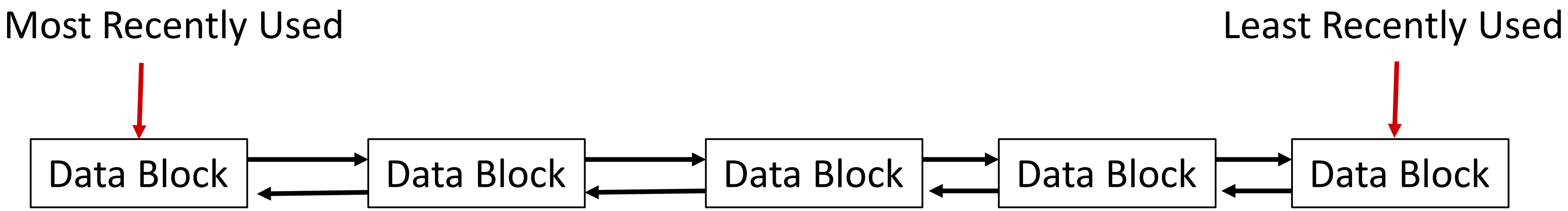
- We can use a linked list to store blocks in LRU



- What is the algorithmic runtime analysis to: **Discuss**
  - lookup a specific block?
  - Removal time?
  - Time to move a block to the front or back?

Block Caching Data Structure

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



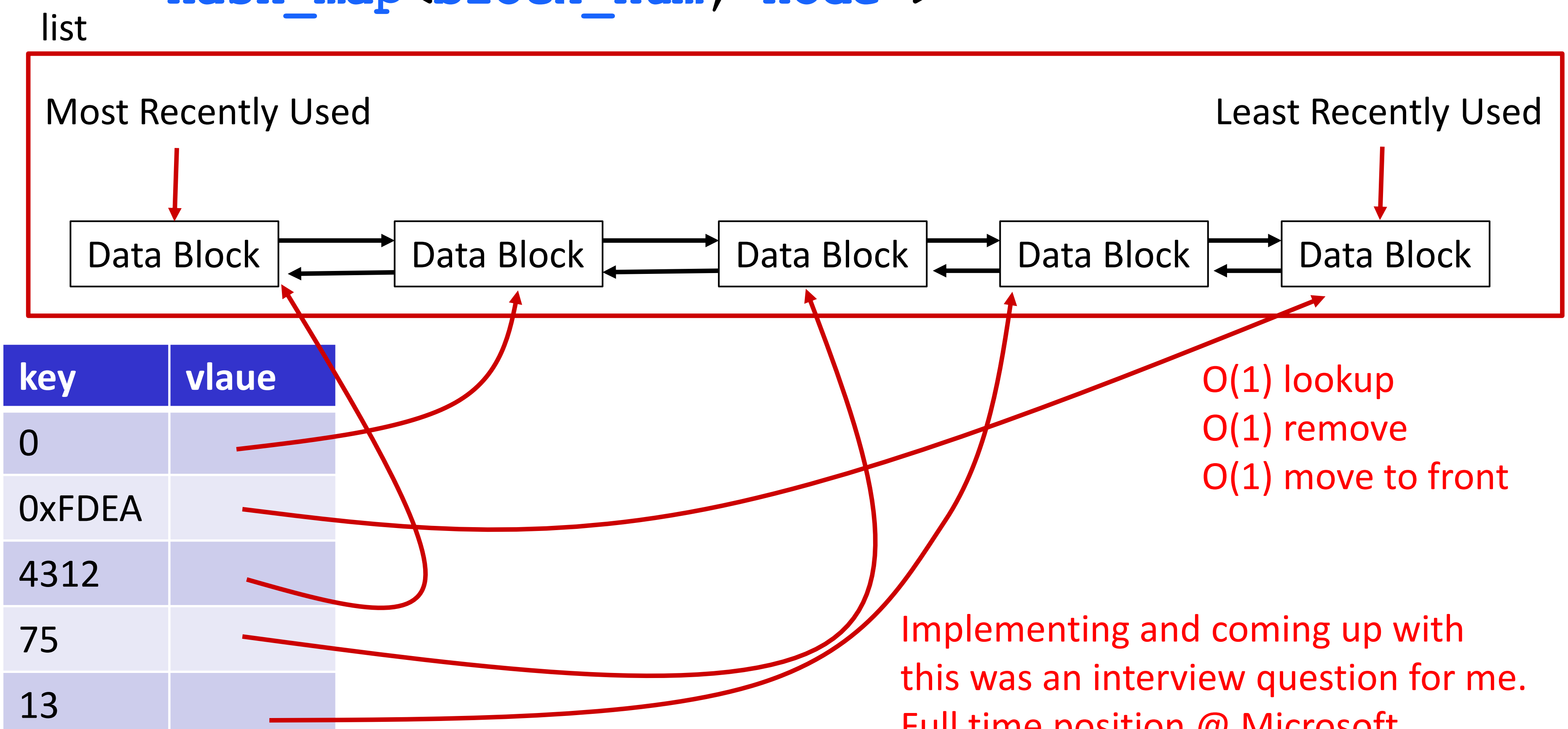
- What is the algorithmic runtime analysis to:
  - lookup a specific block? O(n)
  - Removal time? O(1)
  - Time to move a block to the front or back? O(1)

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*>`



key	vlaue
0	
0xFDEA	
4312	
75	
13	

O(1) lookup
O(1) remove
O(1) move to front

Implementing and coming up with this was an interview question for me. Full time position @ Microsoft