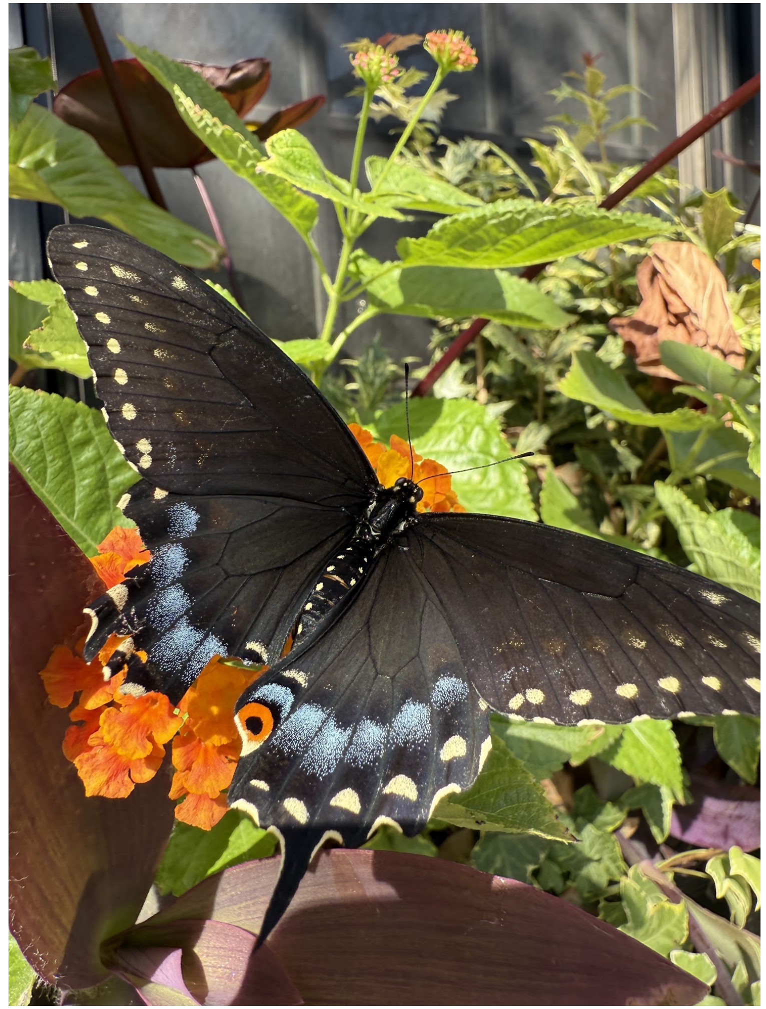
FAT & I-nodes

Computer Operating Systems, Fall 2025



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Lecture Outline

- **Inodes**
- Directories
- Block Caching

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- What was the big downside of using FAT?

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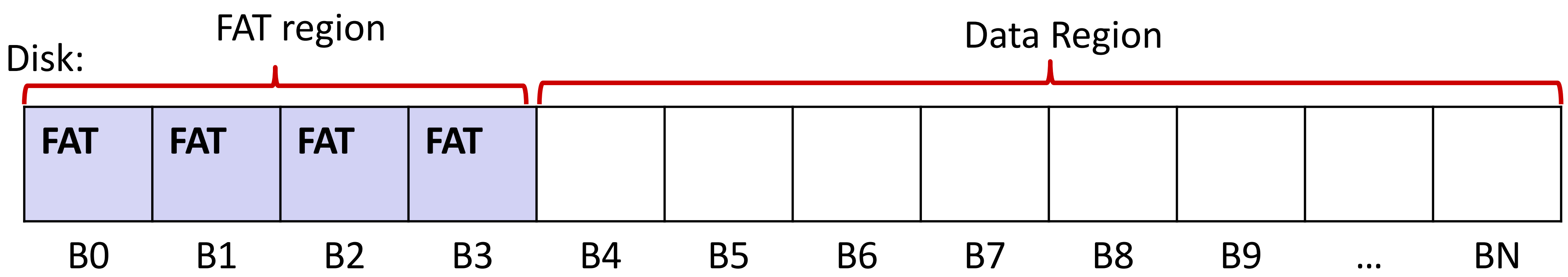
- Instead, could we store ***most*** FAT blocks ***on disk*** and only load into memory the FAT blocks that are used for looking up files that are currently open used (aka have entries in the file table, etc)?

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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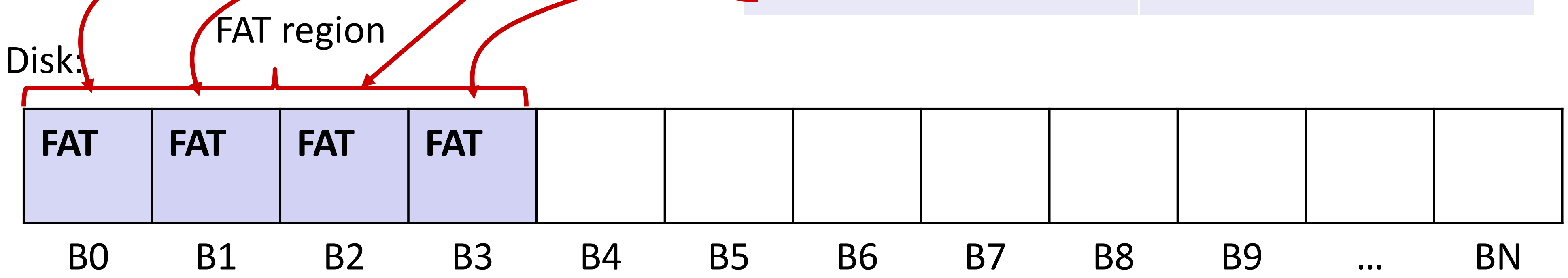
- Small example:
  - Consider block size 256,
  - FAT entry 2 bytes, so 128 entries per FAT block
  - FAT takes up 4 blocks

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

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



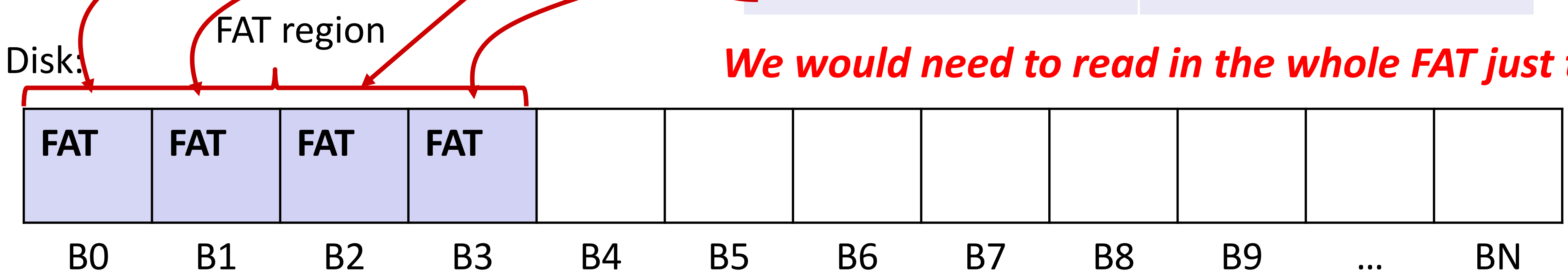
Explanation

- 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

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

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

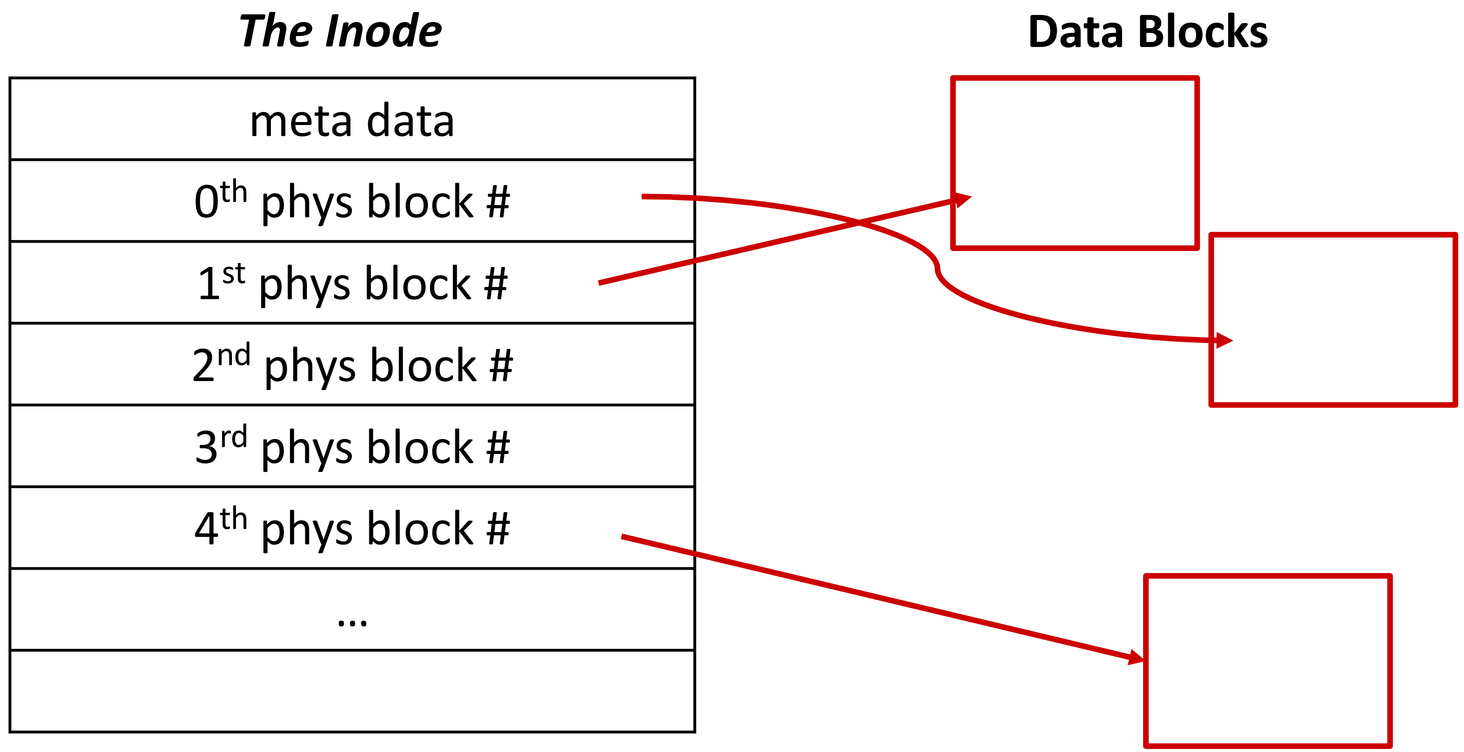
We would need to read in the whole FAT just to look up this file



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 13 physical block numbers corresponding to the first 13 logical blocks of a file



*not all data blocks shown.

General Inode layout

- Inodes contain:
  - some metadata about the file
    - Owner of the file
    - Access permissions
    - **Size of the file**
    - **File Type**
    - Time of
      - last change of file, last access to file, last change to INODE of file.
  - `blocks[13];`
    - 13 physical block numbers corresponding to the first 13 logical blocks of a file

```
typedef block_no_t int

struct inode_st {
  attributes_t metadata;
  block_no_t blocks[13];
  // 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

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- 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

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 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

- I-nodes are smaller than a block so we can fit multiple inodes in a single block
- Each i-node is numbered via a corresponding i-number (it's offset within the list)

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 with a corresponding i-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

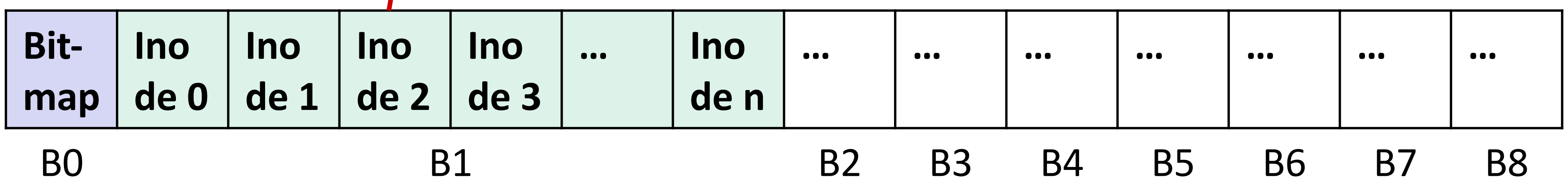
Example File Block Lookup

- Each File will have an Inode with a corresponding i-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
…	

In this example, the block numbers in the Inode are indexes relative to the start of the data region. (Although they don't have to be…)

You will be doing this in PennOS too



Example File Block Lookup

- Each File will have an Inode with a corresponding i-number
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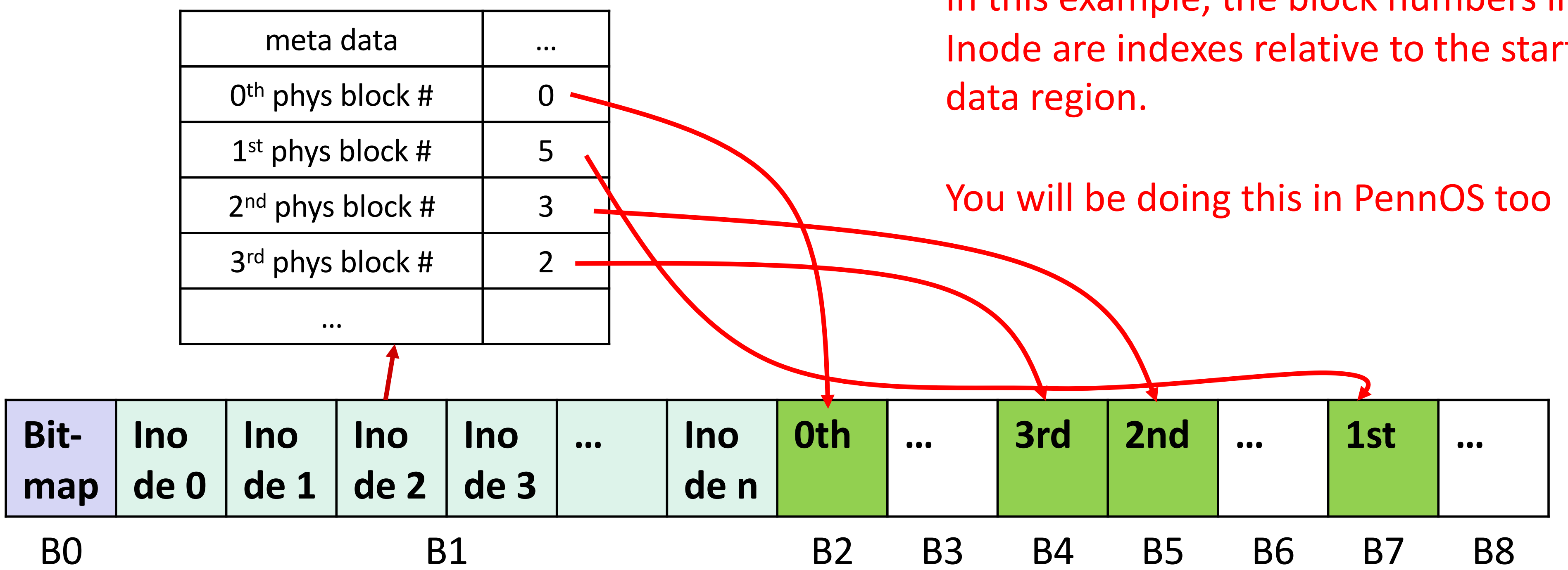


In this example, the block numbers in the Inode are indexes relative to the start of the data region.

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: 13 blocks per file (this is not enough, way too small!)
    - About 7,680 bytes with 512 size blocks.
    - 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 (each block num is an int)

meta data	…
0 phys block #	0
1 phys block #	5
…	…
9 phys block #	2
Block of ptrs	
…	

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

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

Note: please do not imagine these structures like tables.
They are not.
They are purely arrays of integers.

File Sizes with Inode

- So with Inodes, how many blocks can we have per file?
  - So far: 13 blocks per file (this is not enough, way too small!)
    - About 7,680 bytes with 512 size blocks.
    - An average MP4 song would at least 3,000,000 bytes
- We can allocate a ***block*** to hold more block numbers

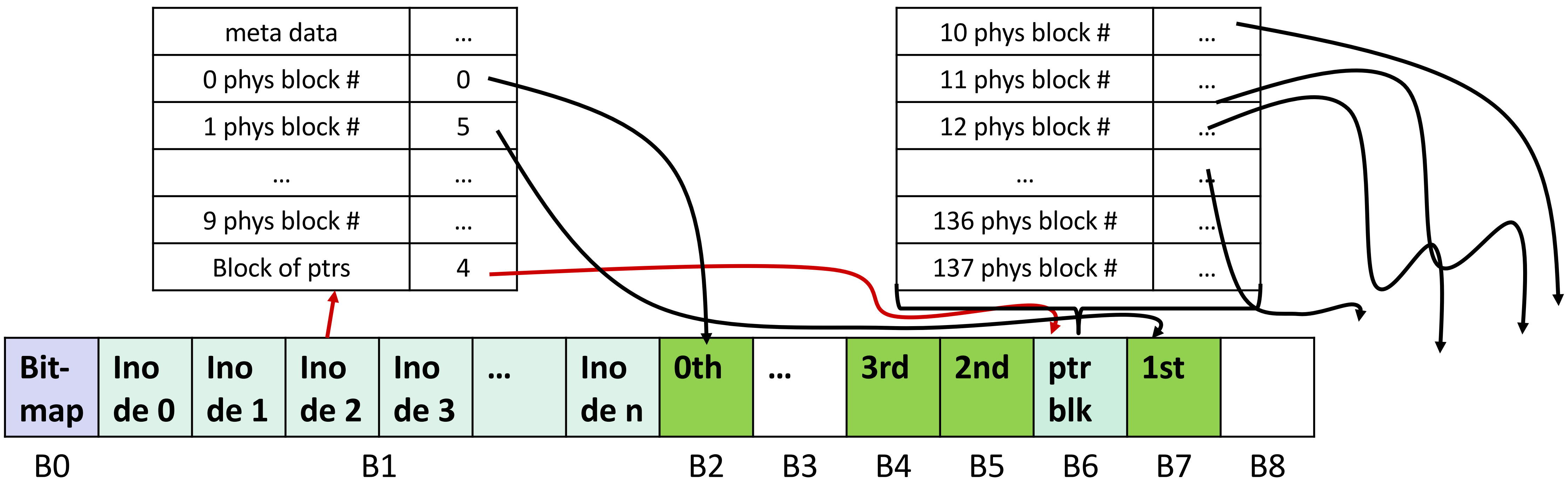
```
struct inode_st {
  attributes_t metadata;
  // the block number at index 10
  // will point to a block of
  // block numbers
  block_no_t blocks[13];
};
```

File Sizes with Inode

- So with Inodes, how many blocks can we have per file?
  - So far: 13 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 137 blocks?
- We can make 11th block number refer to a block that refers to other blocks that refer to data blocks

meta data	…
0 phys block #	0
1 phys block #	5
…	…
9 phys block #	2
Single Indirect Ptr	
Double Indirect Ptr	
…	

10th phys block #	--
13st phys block #	--
…	…
137th phys block #	--

Block for 138-265	--
Block for 266-	--
…	…
….	--

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

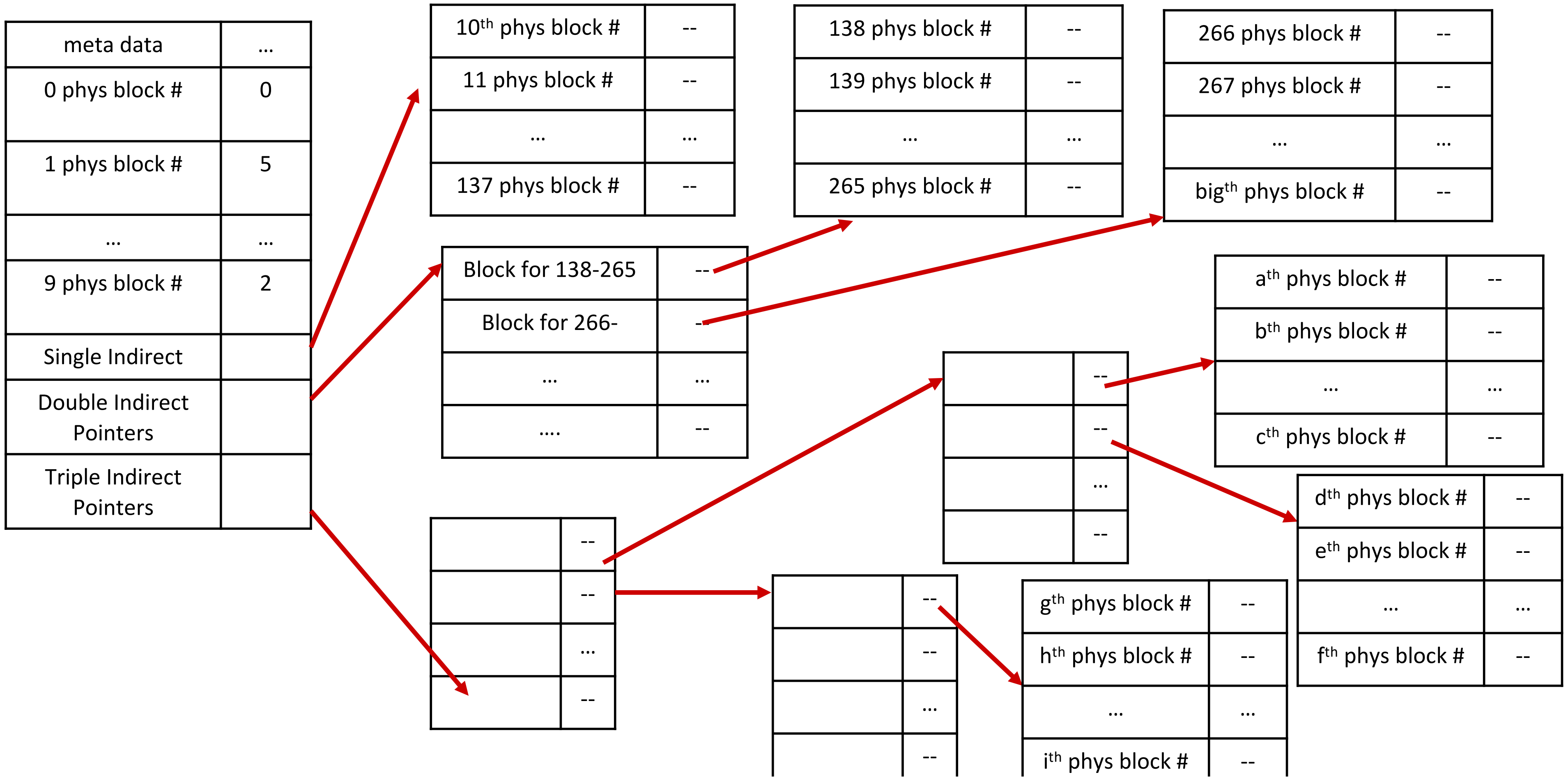
138 phys block #	--
139 phys block #	--
…	…
265 phys block #	--

266 phys block #	--
267 phys block #	--
…	…
n phys block #	--

These blocks refer to real data blocks.

MORE MORE MORE MORE MORE MORE MORE

- What if our file needs more than that?
  - We can make the 13th block number in our Inode refer to a pointer block that refers to pointer blocks that refer to data blocks…



More?

- No more (at least on the Version 7 Unix File System Implementation)
- If you need more space than this, the operating system will tell you **no**

Version 6 Unix File System

```
struct inode_st {
  attributes_t metadata;
  block_no_t blocks[8];
};
```

Metadata will contain a bit telling us if the file is “large”.

If it is, all 8 blocks are singly indirect blocks.

Version 7 Unix File System

```
struct inode_st {
  attributes_t metadata;
  block_no_t blocks[13];
};
```

This is the example we just went through!
Helps support much larger files.

If the file is large, then block_numbers at indexies 10, 11, and 12 are singly doubly, and triply indirect block pointers.

Linux ext2 (Extended 2)

- In the linux ext2 filesystem, it is very similar to Version 7 as it is a descendant of this file system.

```
struct inode_st {
  attributes_t metadata;
  block_no_t blocks[12];
  block_no_t *single_ind;
  block_no_t **double_ind;
  block_no_t ***triple_ind;
};
```

The Linux EXT2 is based on the Unix File System which is a direct descendant of the BSD FFS which is based on the Version 7 Unix File System. Feel free to research this on your own. Too much lore.

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

```
struct inode_st {
  attributes_t metadata;
  block_no_t blocks[12];
  block_no_t *single_ind;
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};
```

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- How is this better than 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 i-nodes, we instead store the inode number for the file in the directory entry

Reminder: Directories

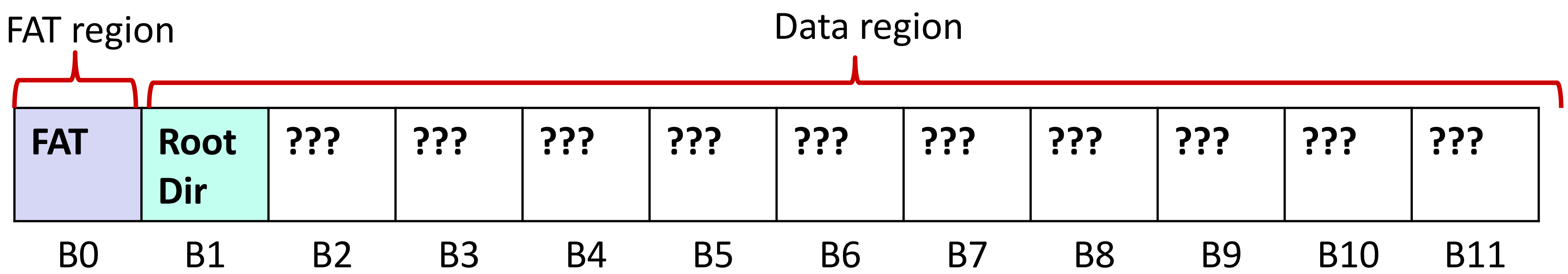
- A directory is essentially like a file
  - We will store its data on disk inside of blocks (like a file)

- 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

FAT region (B0) | Data region (B1–B11)

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

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

FAT region (B0) | Data region (B1–B11)

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

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

File Name	Block Number
A	7
B	2
C	6

FAT

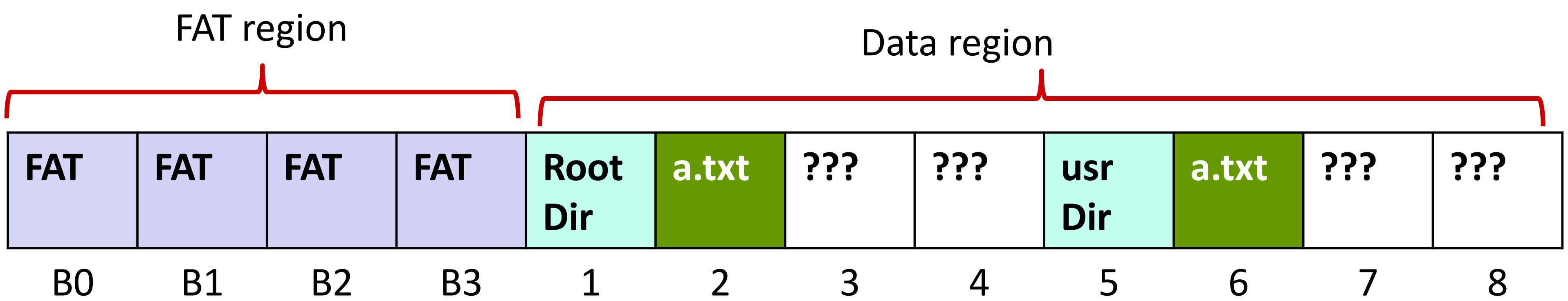
Block # (FAT Index)	Next (FAT value)
0	METADATA
1	4
2	8
3	END
4	END
5	EMPTY
6	END
7	END
8	3
…	…

FAT region / Data region

FAT	FAT	FAT	FAT	Root Dir	???	???	???	???	???	???	???
B0	B1	B2	B3	1	2	3	4	5	6	7	8

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

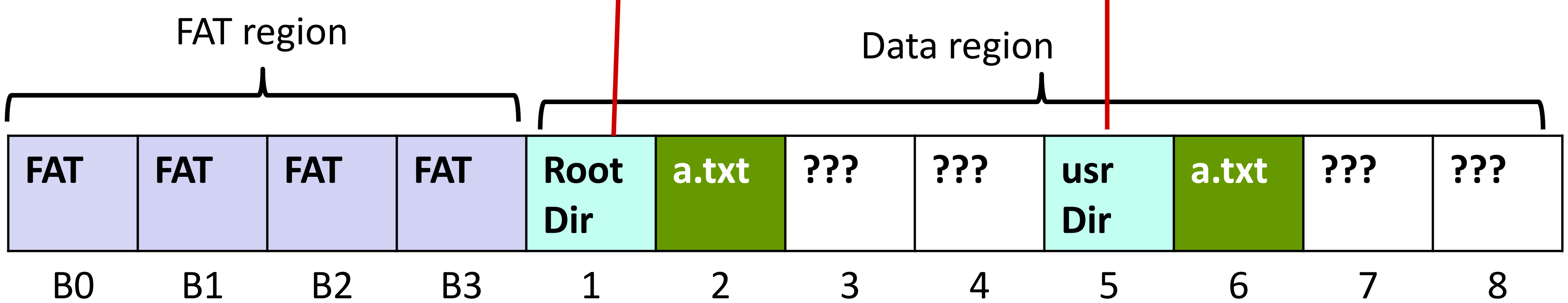
- We would also have some information in a directory entry to specify what kind of file it is

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

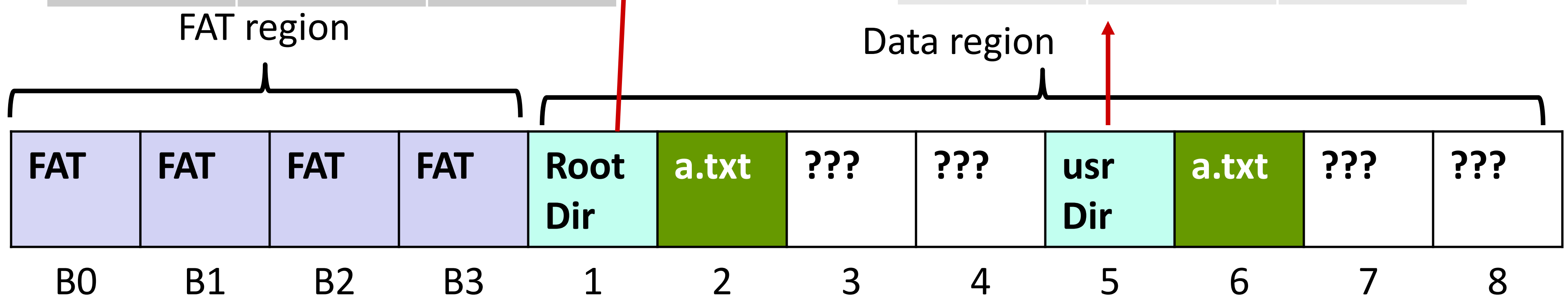
root DIR

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 (A quick optimization)**

Block Caching

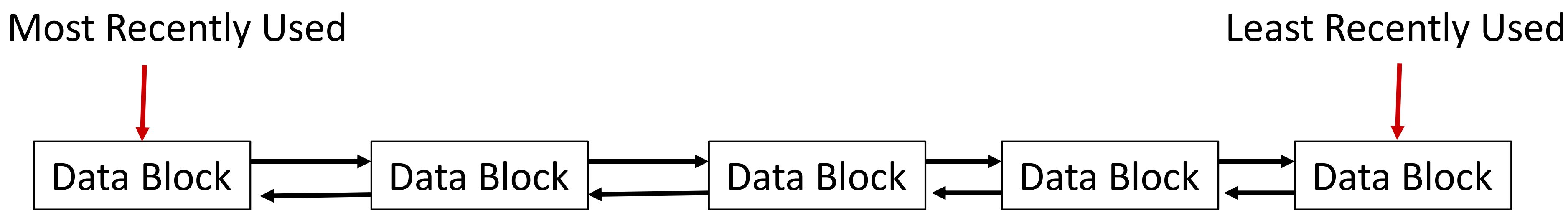
- Disk I/O is really slow (relative to accessing memory)

- 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 and allow them to reside in kernel memory.
- No need to request blocks from disk!

Block Caching Data Structure

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

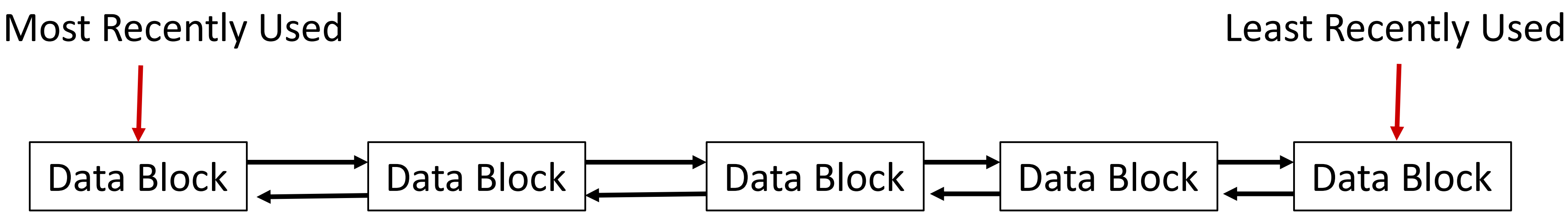


- What is the algorithmic runtime analysis to:
  - lookup a specific block?
  - Removal time of LRU?
  - Time to move a block to the front or back?
    - Consider search time

Discuss

Block Caching Data Structure

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



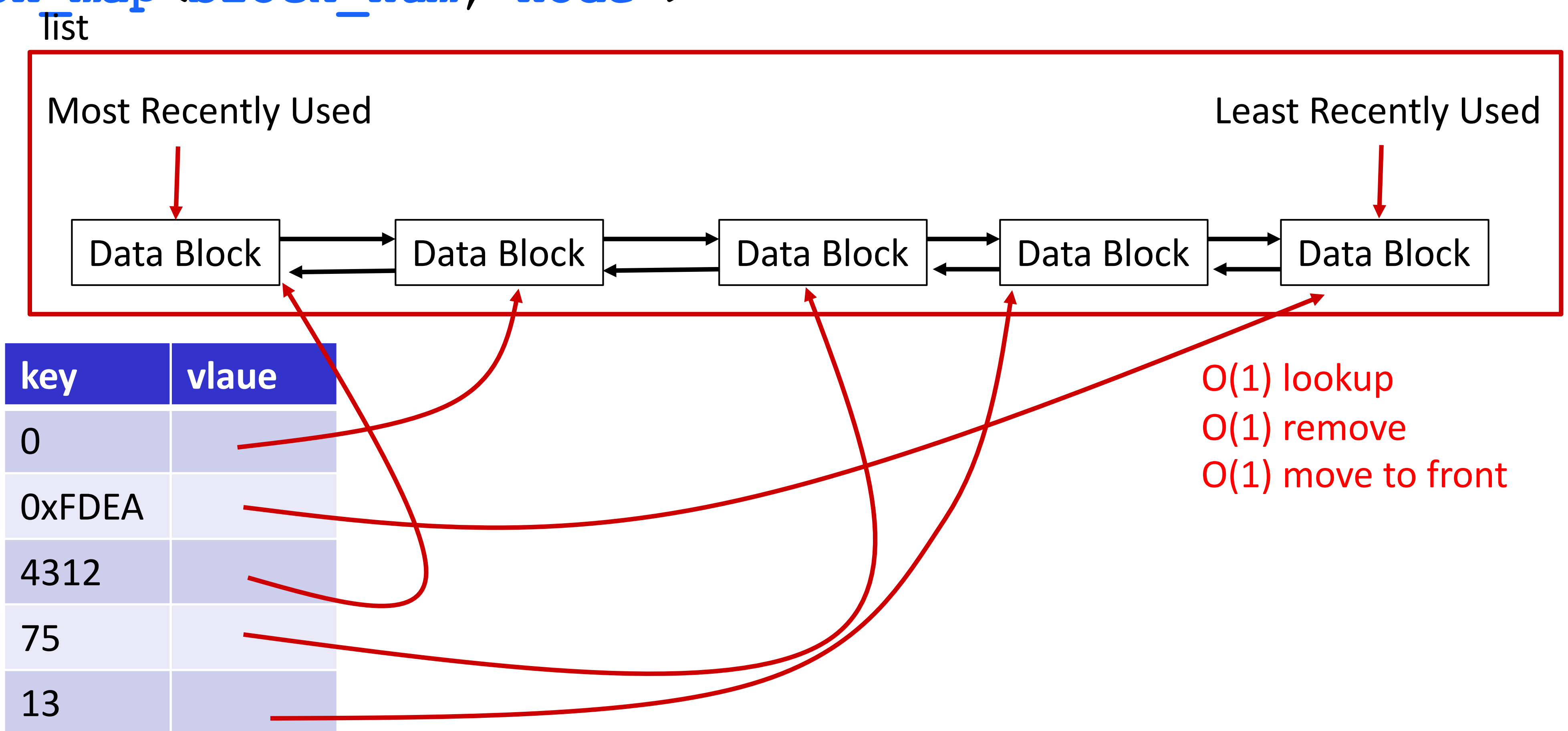
- What is the algorithmic runtime analysis to:
  - lookup a specific block? O(n)
  - Removal time of LRU? O(1)
  - Time to move a block to the front or back? O(n)
    - Consider search time

Discuss

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

Chaining Hash Cache

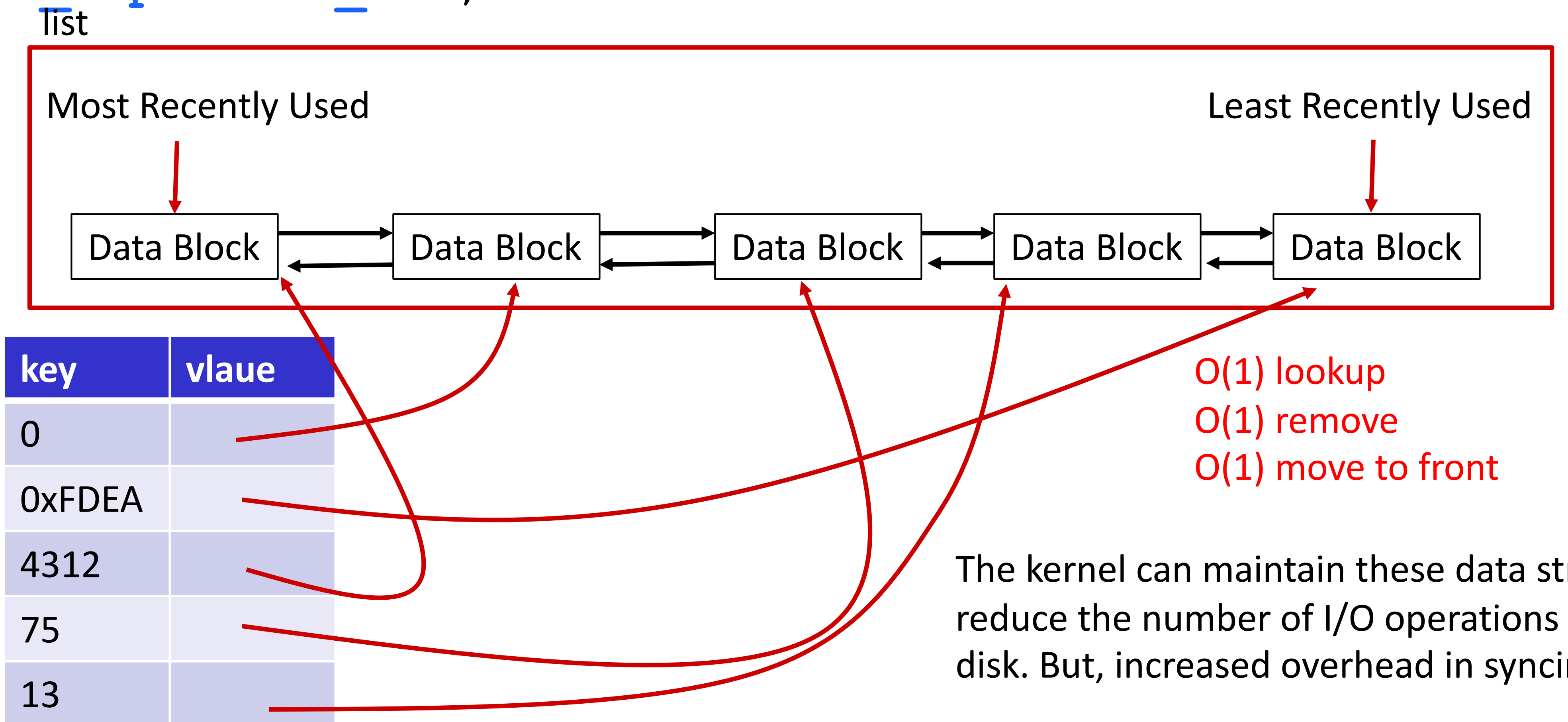
- We can use a combination of two data structures:
  - `linked_list<block>`
  - `hash_map<block_num, node*>`



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

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	

The kernel can maintain these data structures to reduce the number of I/O operations that truly go to disk. But, increased overhead in syncing with FS.

That’s all! See y’all on Thursday!

Poll Everywhere

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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 will more than likely span multiple blocks**
  - **This size also grows as disk grows :/ (bc more blocks!)**

Poll Everywhere

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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)?

- **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**

Poll Everywhere

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- 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

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)

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

```
struct inode_st {
  attributes_t metadata;
  block_no_t blocks[12];
  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?*

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?

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

Poll Yourself

Discussss

- Let's say PennFAT is 4 blocks

- What are value of the remaining blocks in the diagram?

Hint: Index into data region starting at index 1

Root DIR

File Name	Block Number
A	7
B	2
C	6

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

Data region

FAT	FAT	FAT	FAT	Root Dir	File B	File B	Root Dir	EMPTY	File C	File A	File B
B0	B1	B2	B3	1	2	3	4	5	6	7	8