The Page Cache

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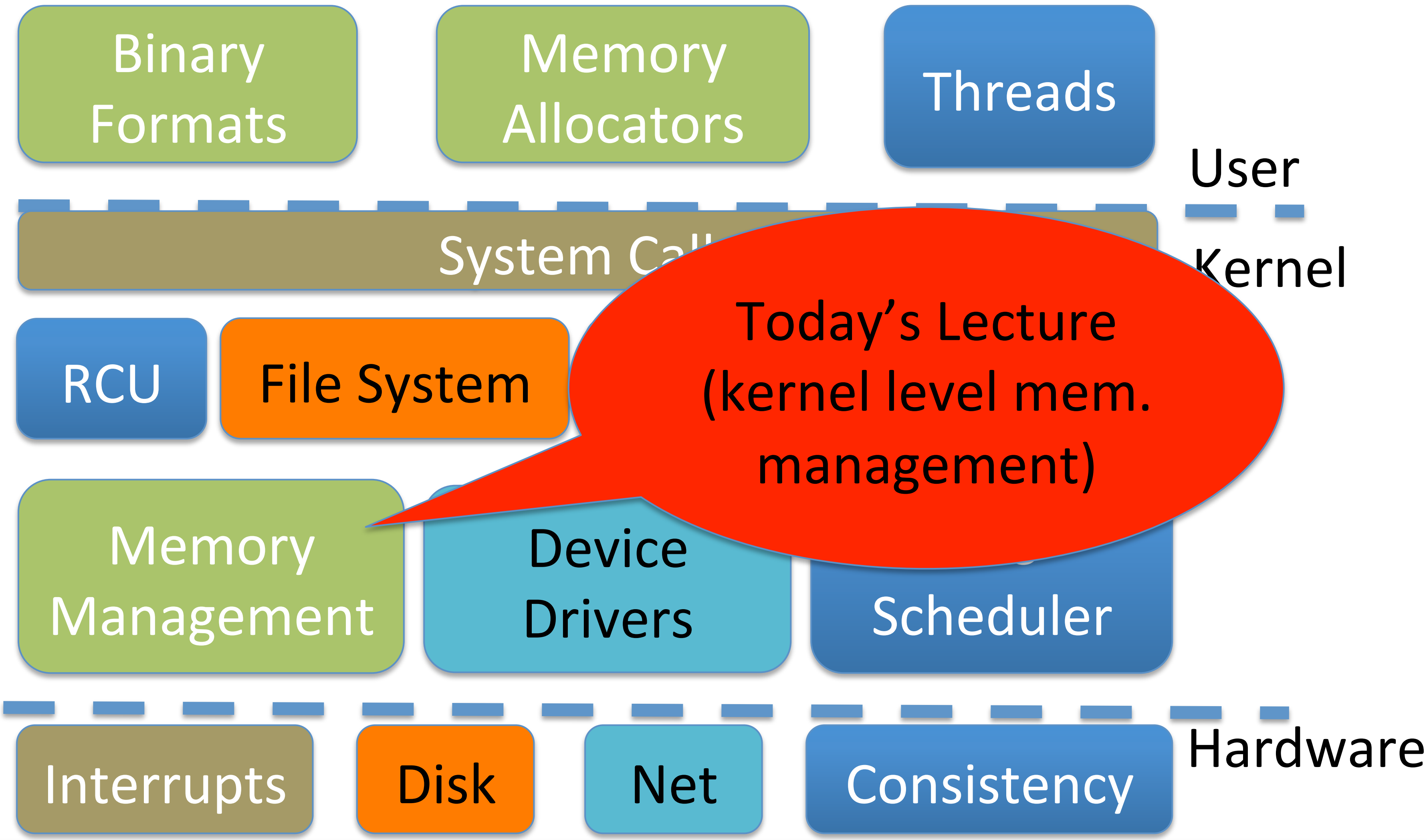
Logical Diagram



Recap of previous lectures

- Page tables: translate virtual addresses to physical addresses
- VM Areas (Linux): track *what* should be mapped at in the virtual address space of a process
- Hoard/Linux slab: Efficient allocation of *objects* from a superblock/slab of pages

Background

- Lab2: Track physical pages with an array of PageInfo structs
  - Contains reference counts
  - Free list layered over this array
- Just like JOS, Linux represents physical memory with an array of page structs
  - Obviously, not the exact same contents, but same idea
- Pages can be allocated to processes, or to cache file data in memory

Today's Problem

- Given a VMA or a file's inode, how do I figure out which physical pages are storing its data?
- Next lecture: We will go the other way, from a physical page back to the VMA or file inode

The address space abstraction

- Unifying abstraction:
  - Each file inode has an address space (0—file size)
  - So do block devices that cache data in RAM (0---dev size)
  - The (anonymous) virtual memory of a process has an address space (0—4GB on x86)
- In other words, all page mappings can be thought of as and (object, offset) tuple
  - Make sense?

Address Spaces for:

- VM Areas (VMAs)
- Files

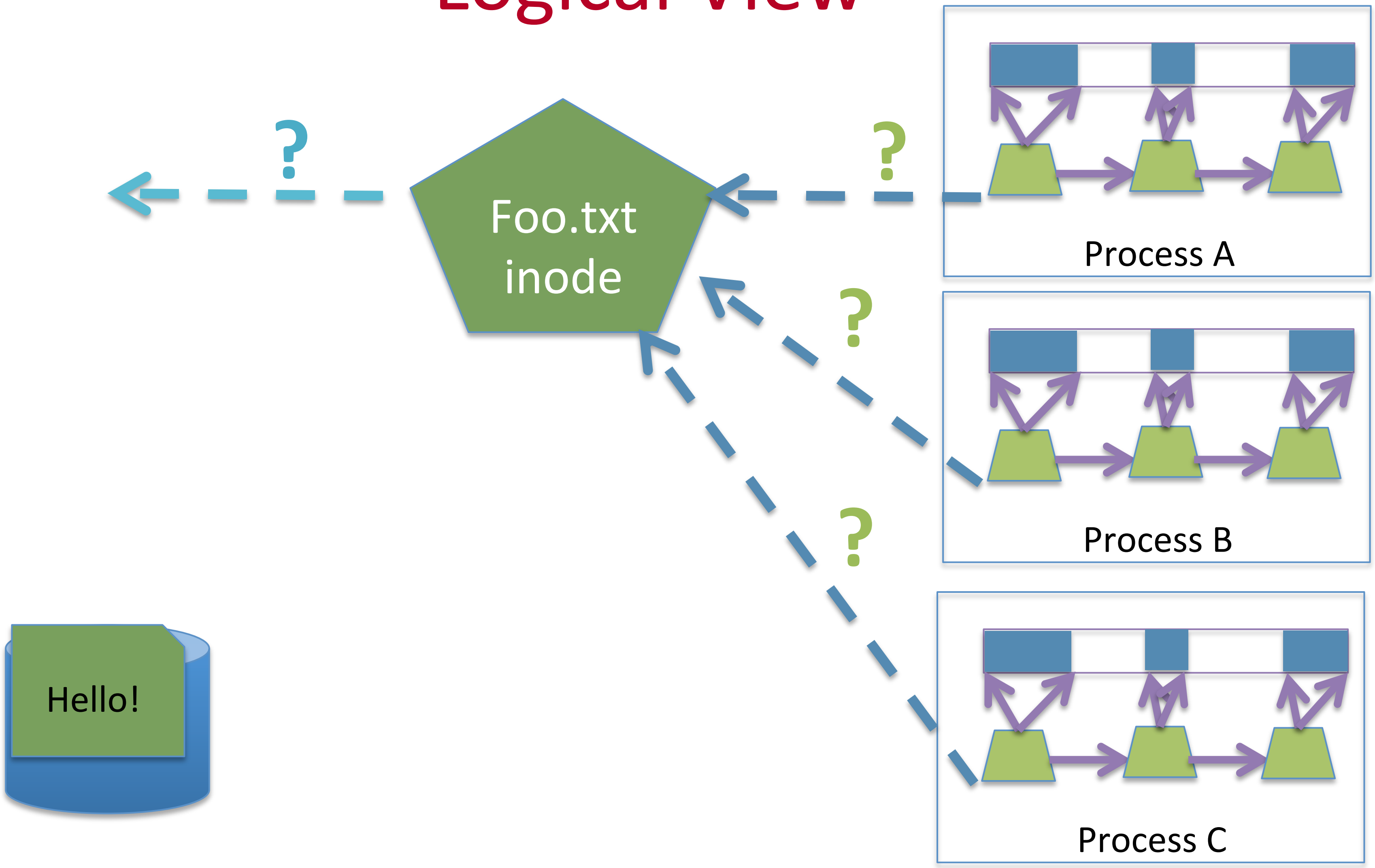
Start Simple

- "Anonymous" memory – no file backing it
  - E.g., the stack for a process
- Not shared between processes
  - Will discuss sharing and swapping later
- How do we figure out virtual to physical mapping?
  - Just walk the page tables!
- Linux doesn't do anything outside of the page tables to track this mapping

File mappings

- A VMA can also represent a memory mapped file
- The kernel can also map file pages to service **`read()`** or **`write()`** system calls
- Goal: We only want to load a file into memory once!

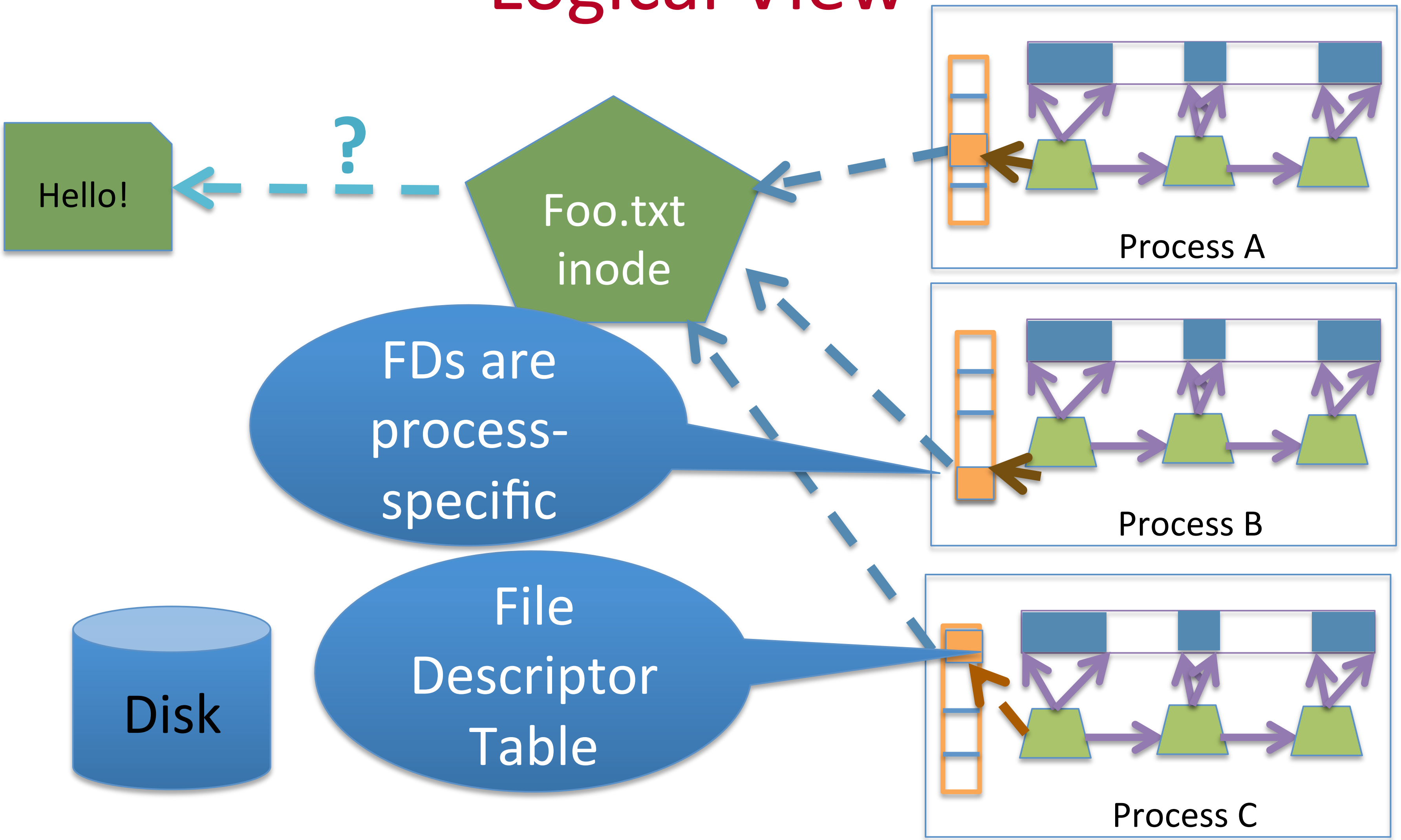
Logical View



VMA to a file

- Also easy: VMA includes a file pointer and an offset into file
  - A VMA may map only part of the file
  - Offset must be at page granularity
  - Anonymous mapping: file pointer is null
- File pointer is an open file descriptor in the process file descriptor table
  - We will discuss file handles later

Logical View



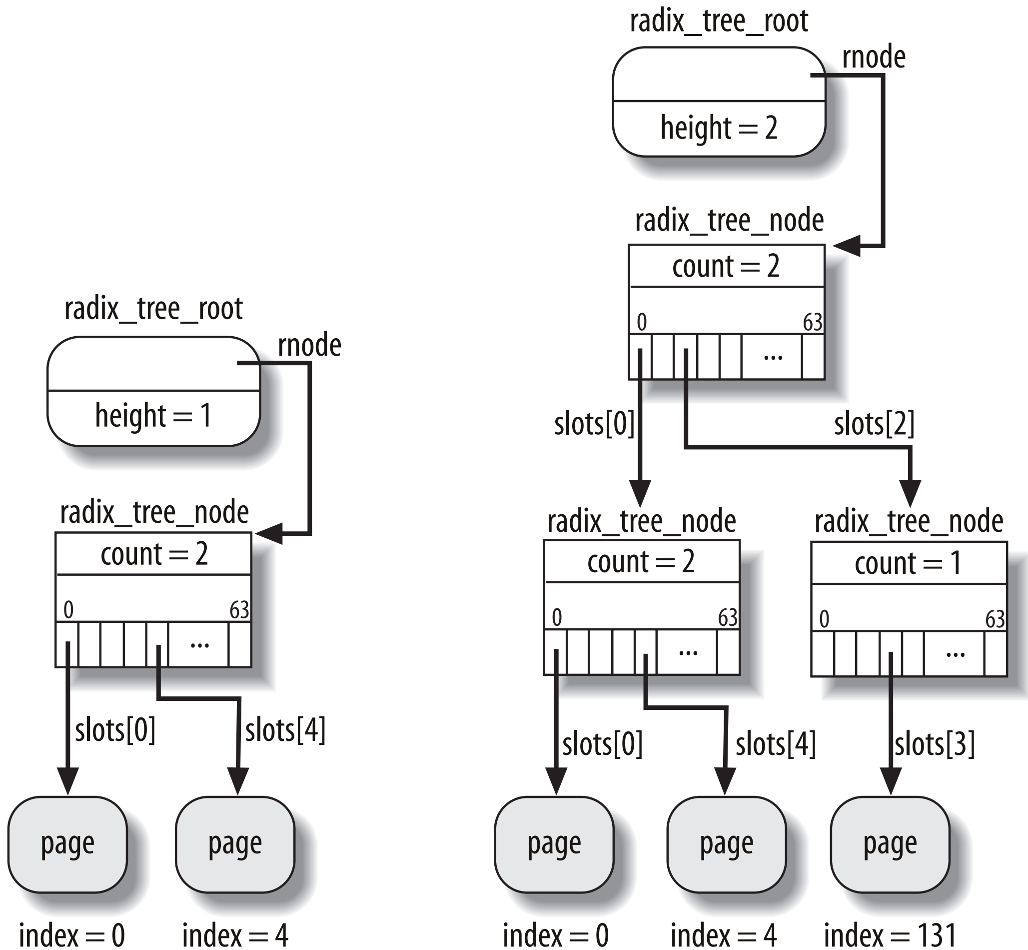
Tracking file pages

- What data structure to use for a file?
  - No page tables for files
- For example: What page stores the first 4k of file "foo"
- What data structure to use?
  - Hint: Files can be small, or very, very large

The Radix Tree

- A space-optimized trie
  - Trie: Rather than store entire key in each node, traversal of parent(s) builds a prefix, node just stores suffix
    - Especially useful for strings
  - Prefix less important for file offsets, but does bound key storage space
- More important: A tree with a branching factor k > 2
  - Faster lookup for large files (esp. with tricks)
- Note: Linux's use of the Radix tree is constrained

From "Understanding the Linux Kernel"



(a) radix tree of height 1 (b) radix tree of height 2

A bit more detail

- Assume an upper bound on file size when building the radix tree
  - Can rebuild later if we are wrong
- Specifically: Max size is 256k, branching factor (k) = 64
- 256k / 4k pages = 64 pages
  - So we need a radix tree of height 1 to represent these pages

Tree of height 1

- Root has 64 slots, can be null, or a pointer to a page
- Lookup address X:
  - Shift off low 12 bits (offset within page)
  - Use next 6 bits as an index into these slots (2^6 = 64)
  - If pointer non-null, go to the child node (page)
  - If null, page doesn't exist

Tree of height n

- Similar story:
  - Shift off low 12 bits
- At each child shift off 6 bits from middle (starting at 6 * (distance to the bottom – 1) bits) to find which of the 64 potential children to go to
  - Use fixed height to figure out where to stop, which bits to use for offset
- Observations:
  - "Key" at each node implicit based on position in tree
  - Lookup time constant in height of tree
    - In a general-purpose radix tree, may have to check all k children, for higher lookup cost

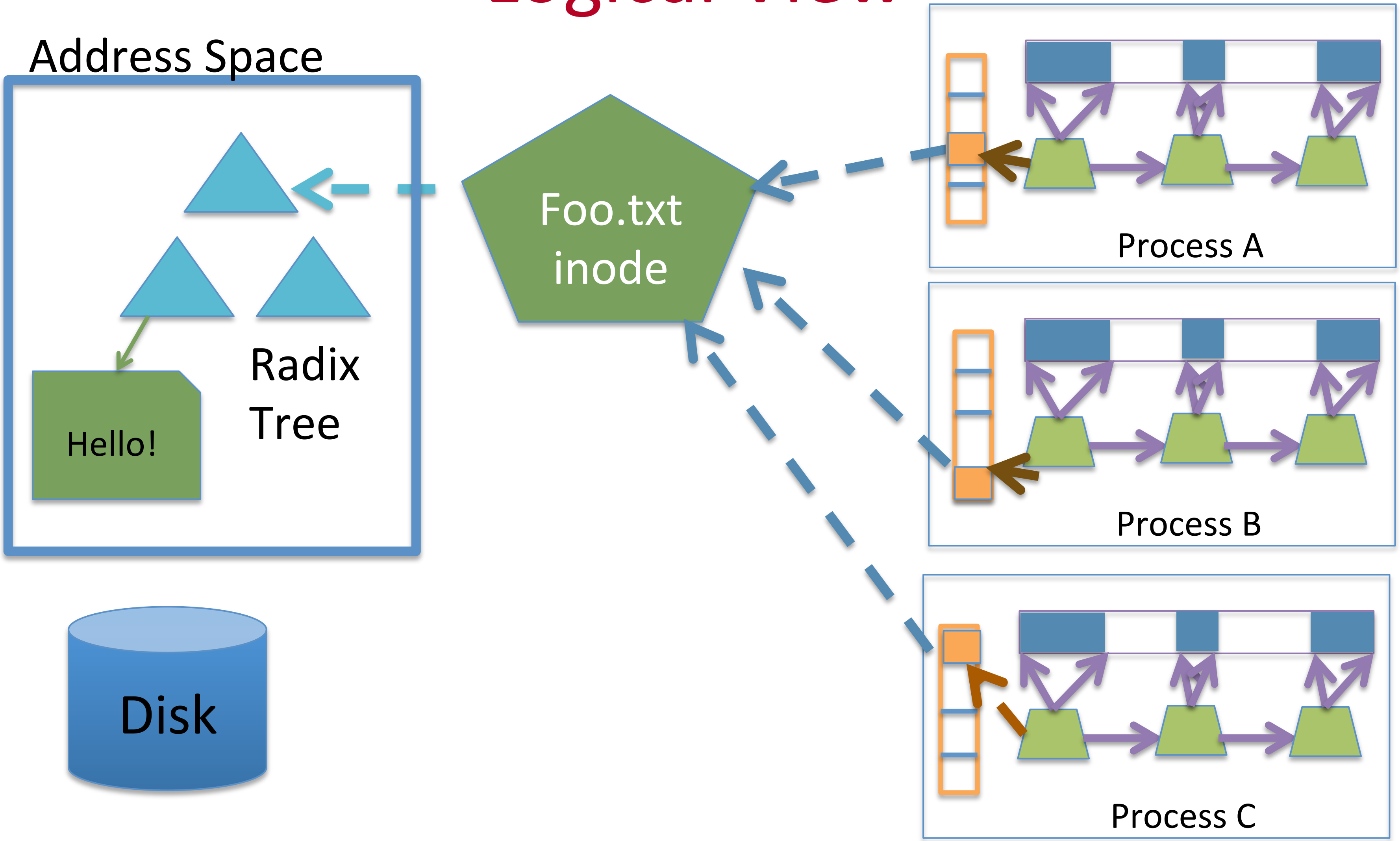
Fixed heights

- If the file size grows beyond max height, must grow the tree
- Relatively simple: Add another root, previous tree becomes first child
- Scaling in height:
  - 1: 2^((6*1) +12) = 256 KB
  - 2: 2^((6*2) + 12) = 16 MB
  - 3: 2^((6*3) + 12) = 1 GB
  - 4: 2^((6*4) + 12) = 64 GB
  - 5: 2^((6*5) + 12) = 4 TB

Back to address spaces

- Each address space for a file cached in memory includes a radix tree
  - Radix tree is sparse: pages not in memory are missing
- Radix tree also supports tags: such as dirty
  - A tree node is tagged if at least one child also has the tag
- Example: I tag a file page dirty
  - Must tag each parent in the radix tree as dirty
  - When I am finished writing page back, I must check all siblings; if none dirty, clear the parent's dirty tag

Logical View



Recap

- Anonymous page: Just use the page tables
- File-backed mapping
  - VMA -> open file descriptor-> inode
  - Inode -> address space (radix tree)-> page

Problem 2: Dirty pages

- Most OSes do not write file updates to disk immediately
  - (Later lecture) OS tries to optimize disk arm movement
- OS instead tracks "dirty" pages
  - Ensures that write back isn't delayed too long
    - Lest data be lost in a crash
- Application can force immediate write back with sync system calls (and some open/mmap options)

Sync system calls

- sync() – Flush all dirty buffers to disk
- fsync(fd) – Flush all dirty buffers associated with this file to disk (including changes to the inode)
- fdatasync(fd) – Flush only dirty data pages for this file to disk
  - Don't bother with the inode

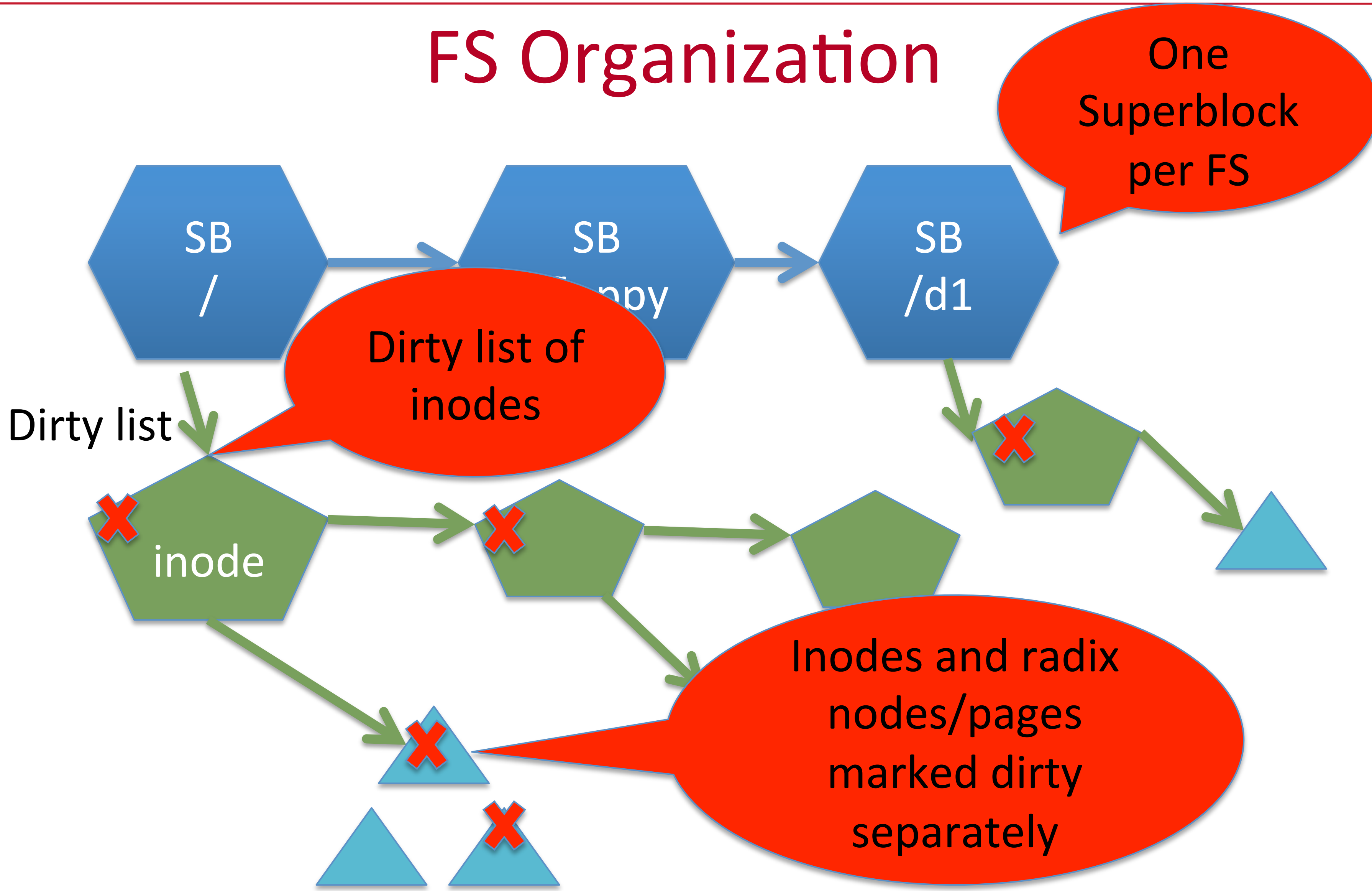
How to implement sync?

- Goal: keep overheads of finding dirty blocks low
  - A naïve scan of all pages would work, but expensive
  - Lots of clean pages
- Idea: keep track of dirty data to minimize overheads
  - A bit of extra work on the write path, of course

How to implement sync?

- Background: Each file system has a super block
  - All super blocks in a list
- Each super block keeps a list of dirty inodes
- Inodes and superblocks both marked dirty upon use

FS Organization



Simple traversal

```
for each s in superblock list:
    if (s->dirty) writeback s
    for i in inode list:
        if (i->dirty) writeback i
        if (i->radix_root->dirty) :
            // Recursively traverse tree writing
            // dirty pages and clearing dirty flag
```

Asynchronous flushing

- Kernel thread(s): pdflush
  - A kernel thread is a task that only runs in the kernel's address space
  - 2-8 threads, depending on how busy/idle threads are
- When pdflush runs, it is given a target number of pages to write back
  - Kernel maintains a total number of dirty pages
  - Administrator configures a target dirty ratio (say 10%)

pdflush

- When pdflush is scheduled, it figures out how many dirty pages are above the target ratio
- Writes back pages until it meets its goal or can't write more back
  - (Some pages may be locked, just skip those)
- Same traversal as sync() + a count of written pages
  - Usually quits earlier

How long dirty?

- Linux has some inode-specific bookkeeping about when things were dirtied
- pdflush also checks for any inodes that have been dirty longer than 30 seconds
  - Writes these back even if quota was met
- Not the strongest guarantee I've ever seen…

But where to write?

- Ok, so I see how to find the dirty pages
- How does the kernel know where on disk to write them?
  - And which disk for that matter?
- Superblock tracks device
- Inode tracks mapping from file offset to sector

Block size mismatch

- Most disks have 512 byte blocks; pages are generally 4K
  - Some new "green" disks have 4K blocks
  - Per page in cache – usually 8 disk blocks
- When blocks don't match, what do we do?
  - Simple answer: Just write all 8!
  - But this is expensive – if only one block changed, we only want to write one block back

Buffer head

- Simple idea: for every page backed by disk, store an extra data structure for each disk block, called a buffer_head
- If a page stores 8 disk blocks, it has 8 buffer heads
- Example: write() system call for first 5 bytes
  - Look up first page in radix tree
  - Modify page, mark dirty
  - Only mark first buffer head dirty

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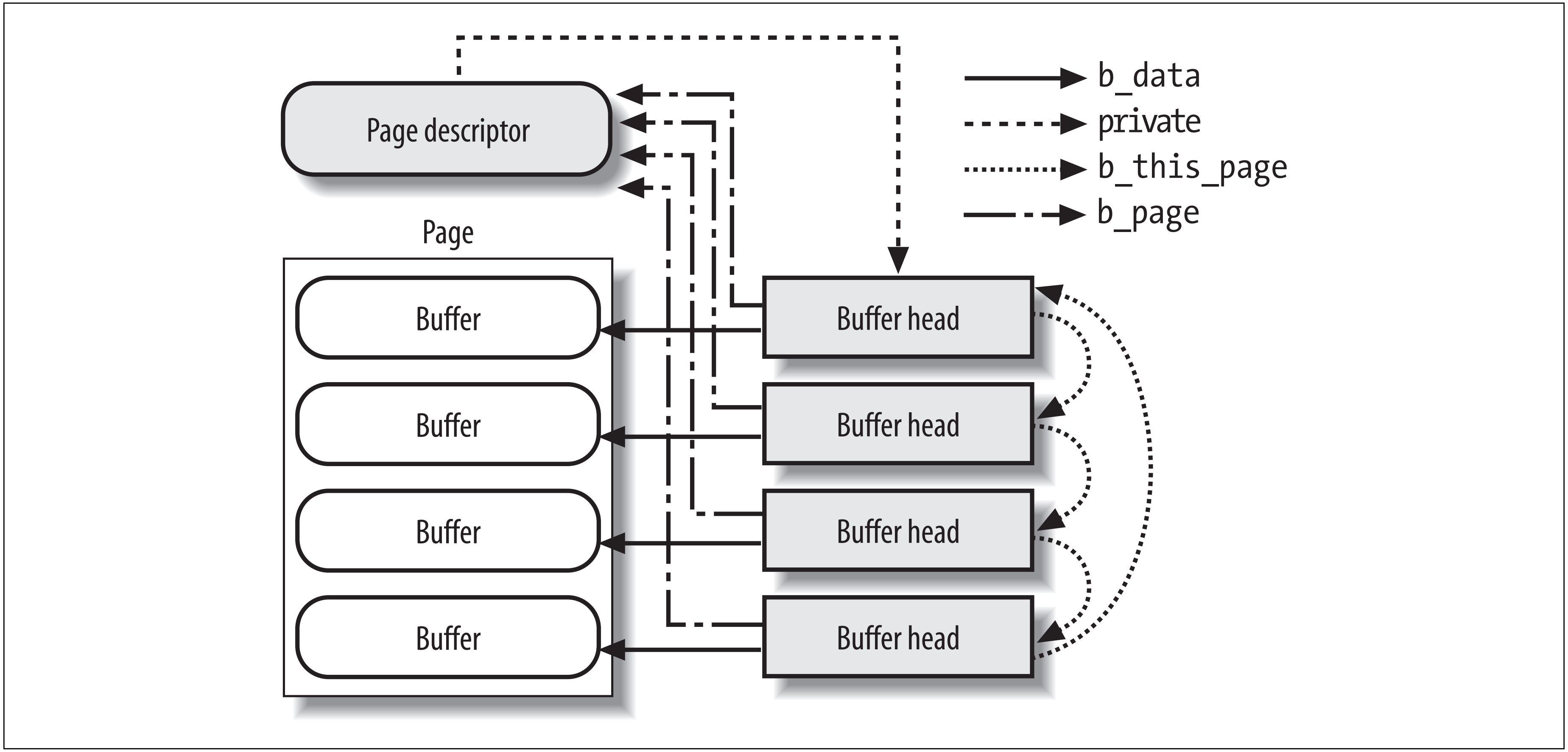

Figure 15-2. A buffer page including four buffers and their buffer heads

More on buffer heads

- On write-back (sync, pdflush, etc), only write dirty buffer heads
- To look up a given disk block for a file, must divide by buffer heads per page
  - Ex: disk block 25 of a file is in page 3 in the radix tree
- Note: memory mapped files mark all 8 buffer_heads dirty. Why?
  - Can only detect write regions via page faults

Summary

- Seen how mappings of files/disks to cache pages are tracked
  - And how dirty pages are tagged
  - Radix tree basics
- When and how dirty data is written back to disk
- How difference between disk sector and page sizes are handled