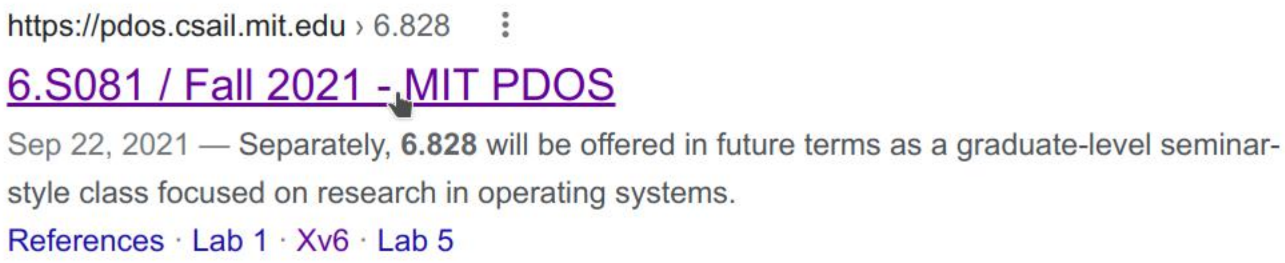
The xv6 Filesystem

Reference

- The xv6 book
    - Chapter 8 “File system”
- https://pdos.csail.mit.edu/6.828/2021/xv6/book-riscv-rev2.pdf
- For latest version, google “mit xv6”



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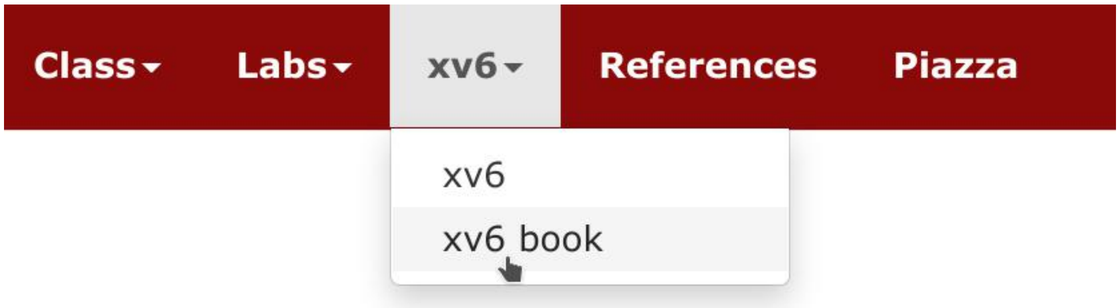
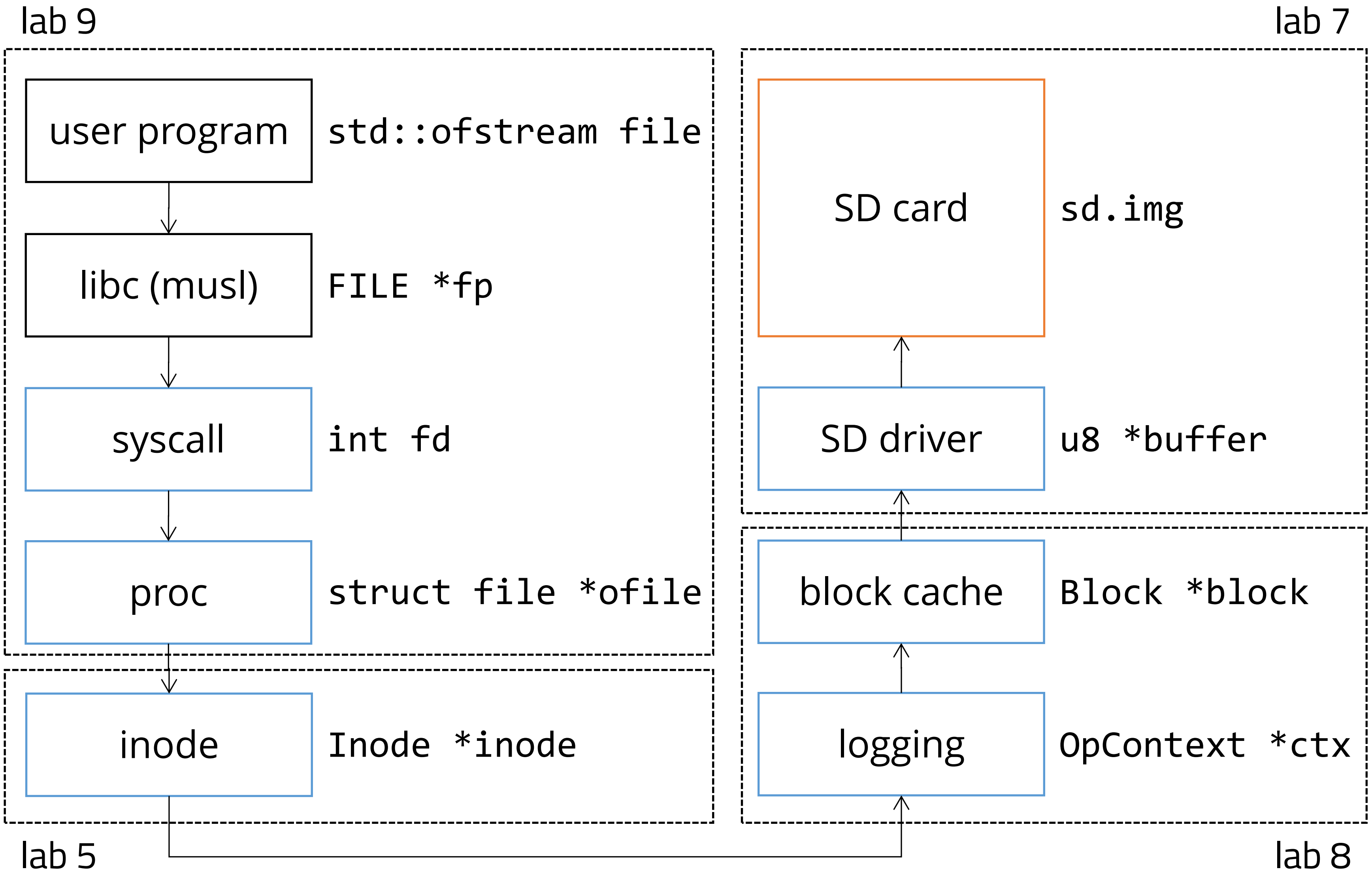
References · Lab 1 · Xv6 · Lab 5



Features

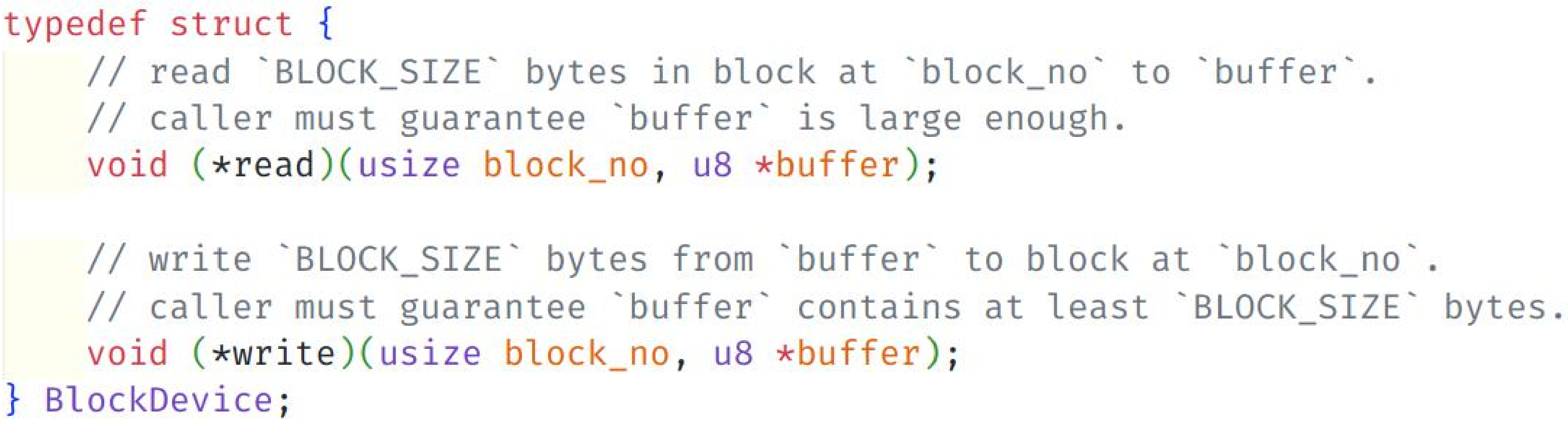
- Unix-like file and directory interface
  - Use inode, dirent, stat, …
- One directory tree
  - No “C:”, “D:”, “E:”, “F:”
- One disk storage
  - No mount points
- Concurrent access
  - Protect every data structure with lock and reference count
  - Fine-grained locks for path name lookup
- Crash consistency
  - With write-ahead logging, or journaling
  - No checksum, no rollback
- Block cache
  - No disk IO scheduler
- Asynchronous EMMC SD read/write

Overview


lab 9
user program
std::ofstream file
libc (musl)
FILE *fp
syscall
int fd
proc
struct file *ofile
inode
Inode *inode
lab 5
lab 7
SD card
sd.img
SD driver
u8 *buffer
block cache
Block *block
logging
OpContext *ctx
lab 8

Synchronous API

- Block process when processing
  - Multiple processes can issue concurrent requests
- Only return when work is done
- The underlying implementation can be asynchronous
  - Submit work and wait for interrupts or notifications
- Ambitious student can develop an asynchronous framework
  - epoll, aio, io_uring, kqueue

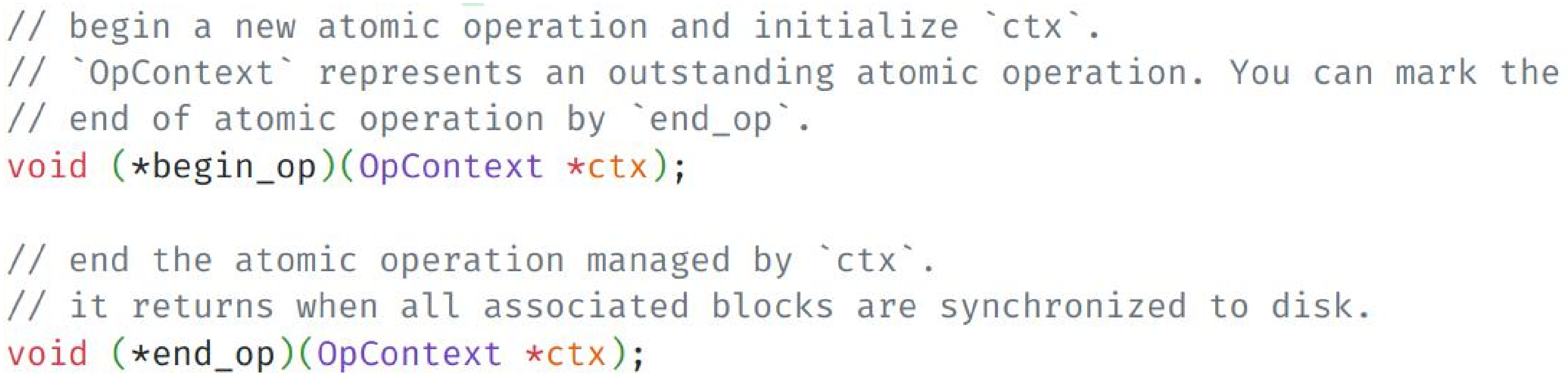


```
typedef struct {
    // read `BLOCK_SIZE` bytes in block at `block_no` to `buffer`.
    // caller must guarantee `buffer` is large enough.
    void (*read)(usize block_no, u8 *buffer);

    // write `BLOCK_SIZE` bytes from `buffer` to block at `block_no`.
    // caller must guarantee `buffer` contains at least `BLOCK_SIZE` bytes.
    void (*write)(usize block_no, u8 *buffer);
} BlockDevice;
```

Atomic Operation

- Writing a word in memory is often atomic
  - 8 bytes on 64-bit platforms
  - Multi-copy atomicity
- Writing a block (512 bytes) on disk is often atomic
  - For historic reasons, they choose this value
- We often manipulate multiple blocks simultaneously
  - `write`: write out new blocks, update inode and bitmap
  - `rename`: OSTEP section 39.8 “Renaming Files”
- Put a series of operations into one “transaction”
  - Cannot be partially done
  - Not database transactions, only atomicity is guaranteed

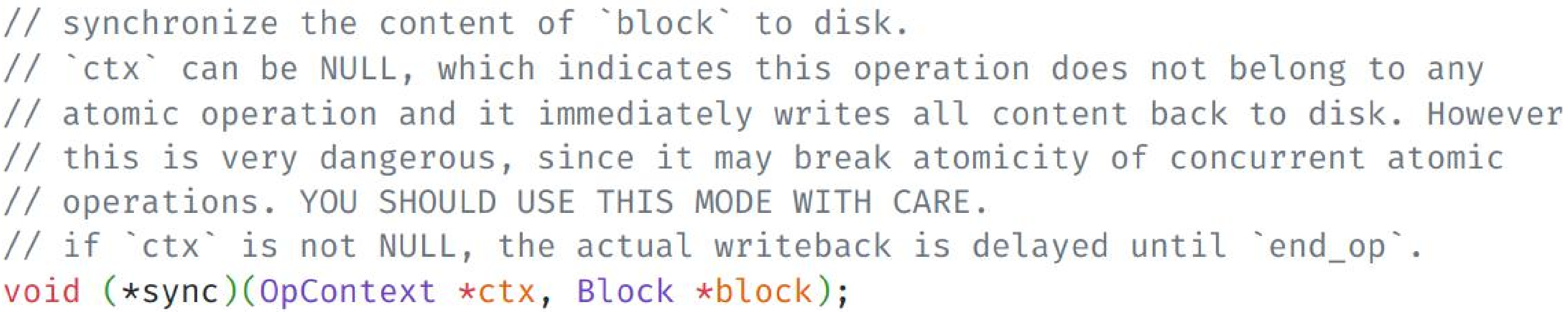


```
// begin a new atomic operation and initialize `ctx`.
// `OpContext` represents an outstanding atomic operation. You can mark the
// end of atomic operation by `end_op`.
void (*begin_op)(OpContext *ctx);

// end the atomic operation managed by `ctx`.
// it returns when all associated blocks are synchronized to disk.
void (*end_op)(OpContext *ctx);
```

Atomic Operation

- `begin_op/end_op` cannot be nested
    - Deadlock
- `begin_op/end_op` is prone to forgetting
    - Maybe you forget to lock last week
- Function that may write must carry `OpContext *ctx`
    - It's a remainder to caller
    - `ctx` can be `NULL`, which means direct write
    - Direct write is dangerous, which may break atomicity



```
// synchronize the content of `block` to disk.
// `ctx` can be NULL, which indicates this operation does not belong to any
// atomic operation and it immediately writes all content back to disk. However
// this is very dangerous, since it may break atomicity of concurrent atomic
// operations. YOU SHOULD USE THIS MODE WITH CARE.
// if `ctx` is not NULL, the actual writeback is delayed until `end_op`.
void (*sync)(OpContext *ctx, Block *block);
```

Fail-Stop Model

- SD card is fail-stop
  - If one operation fails, no subsequent operation can complete
  - No data corruption
- Filesystem module is fail-stop
  - Any unrecoverable fault results in kernel panic
  - Out of memory ⇒ panic
  - Disk full ⇒ panic
  - Invalid memory access ⇒ panic
  - Assertion failure ⇒ panic
  - Invalid parameter ⇒ panic
  - File name not found ⇒ return “NOT FOUND”
  - Summary: DO NOT return error codes, just panic
- Syscall interface should check user input
  - Reject them with return value

Locking

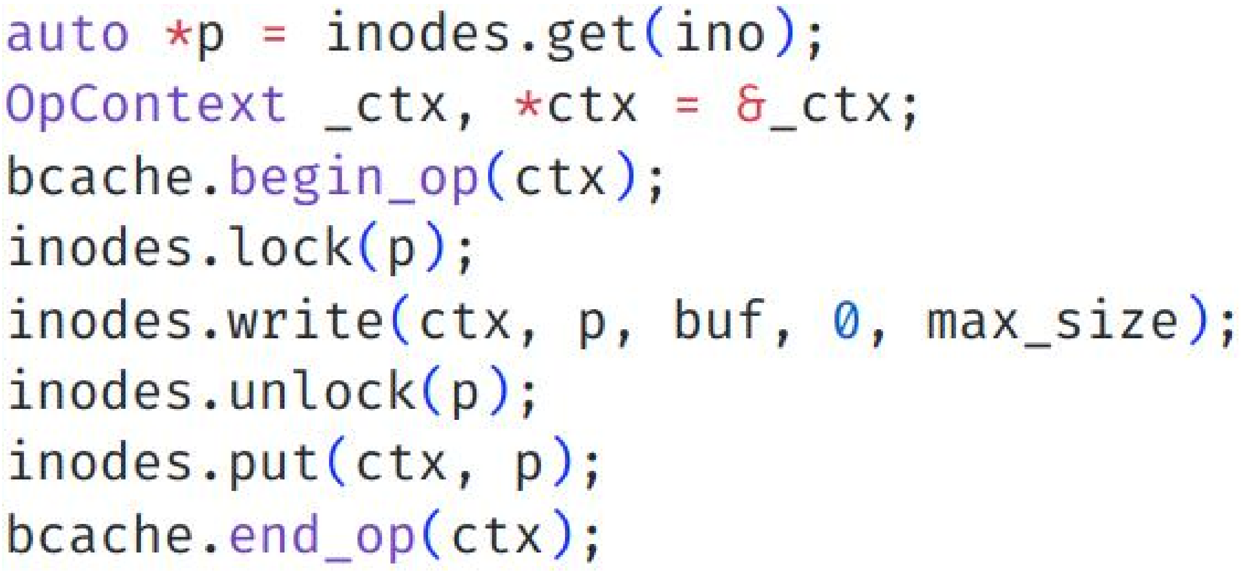
- Hold the lock before doing everything
  - Unless told not to do
  - `inodes.put`
- Use SleepLock
  - Currently no `sleep/wakeup`, we will fix it later

Reference Count

- The number of pointers pointed to an object
    - `increment_rc/decrement_rc`
    - `get/put`
- When reference count goes to zero, the object can be freed
    - `decrement_rc` will return true if this happens
- Hold the lock while modifying reference count
    - Unless you want to design lock-free algorithms
- See `common/rc.h`

Put It Together

- You will do it in lab 9



```
auto *p = inodes.get(ino);
OpContext _ctx, *ctx = &_ctx;
bcache.begin_op(ctx);
inodes.lock(p);
inodes.write(ctx, p, buf, 0, max_size);
inodes.unlock(p);
inodes.put(ctx, p);
bcache.end_op(ctx);
```

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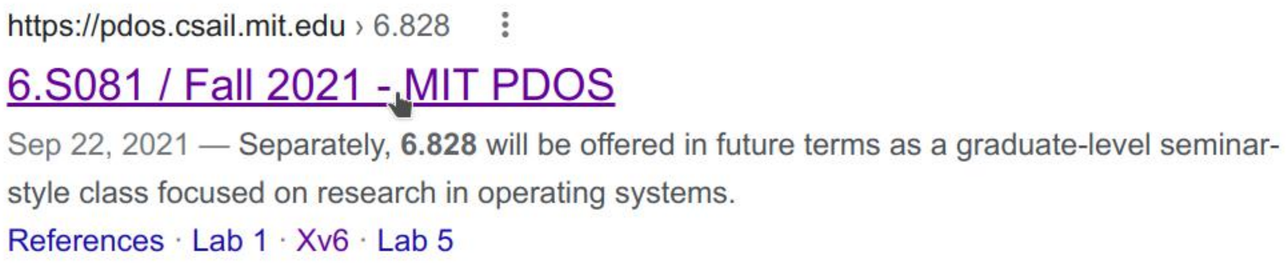

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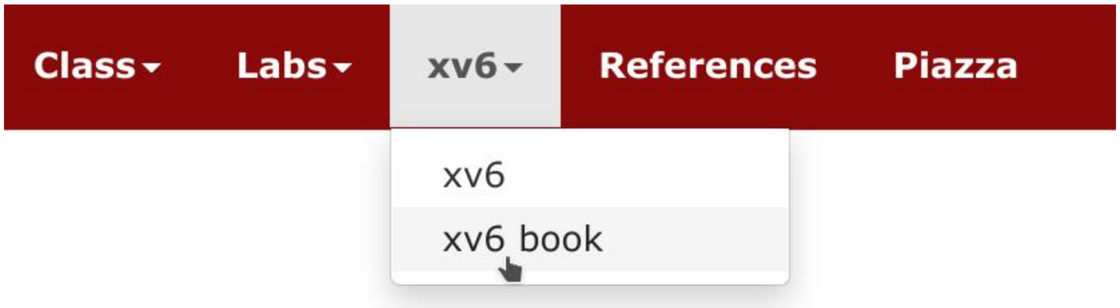
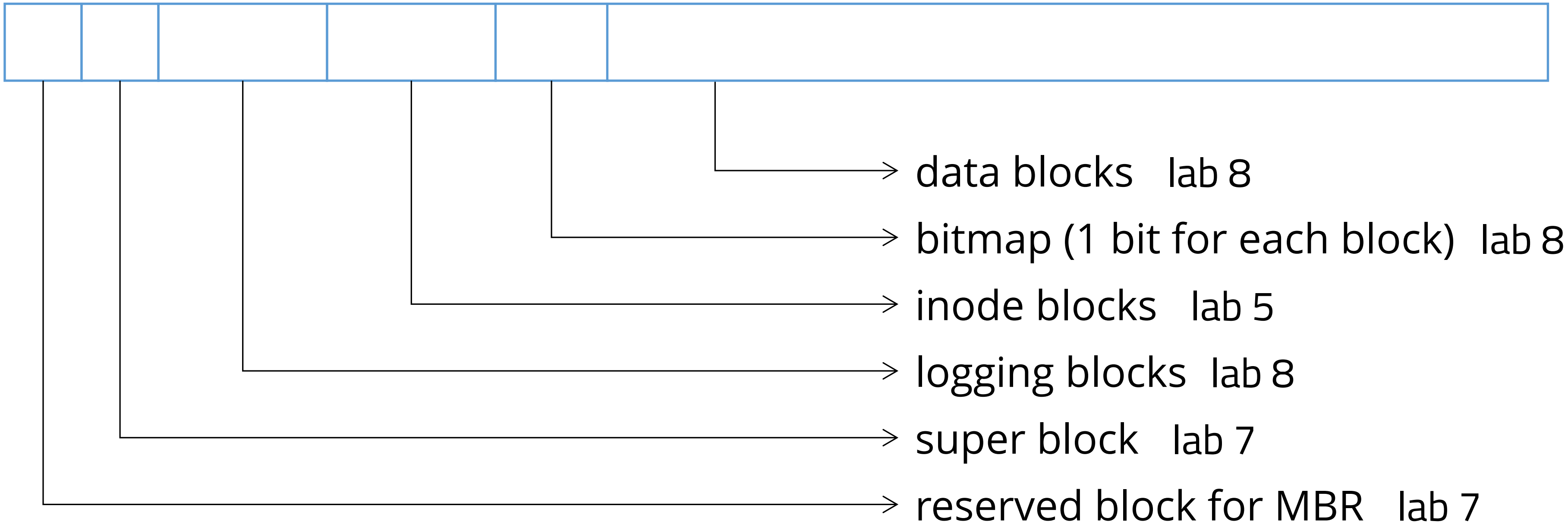


On-Disk Layout

- `fs/defines.h`



data blocks lab 8

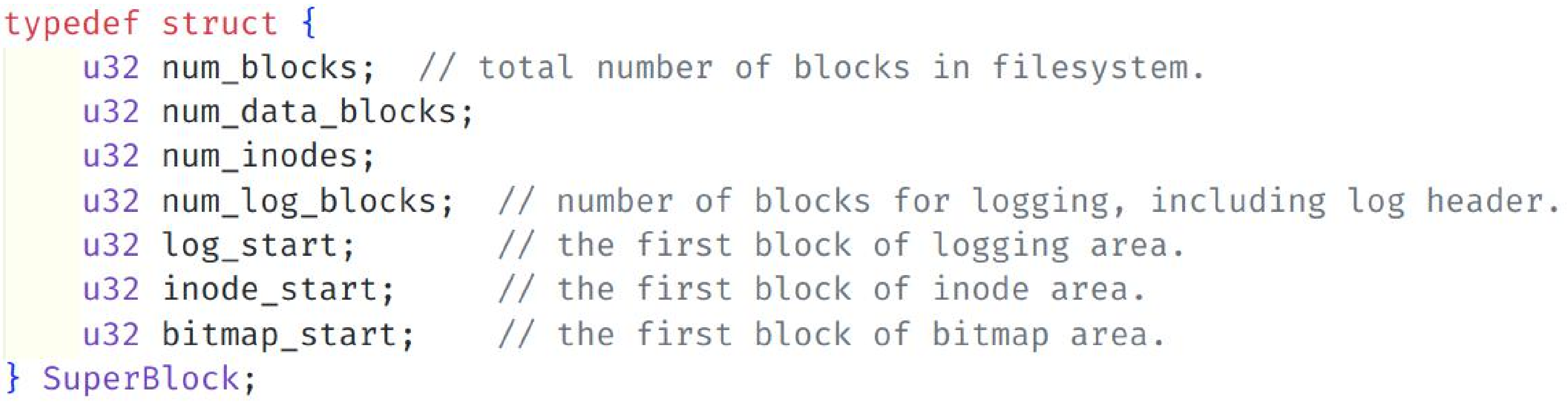
bitmap (1 bit for each block) lab 8

inode blocks lab 5

logging blocks lab 8

super block lab 7

reserved block for MBR lab 7

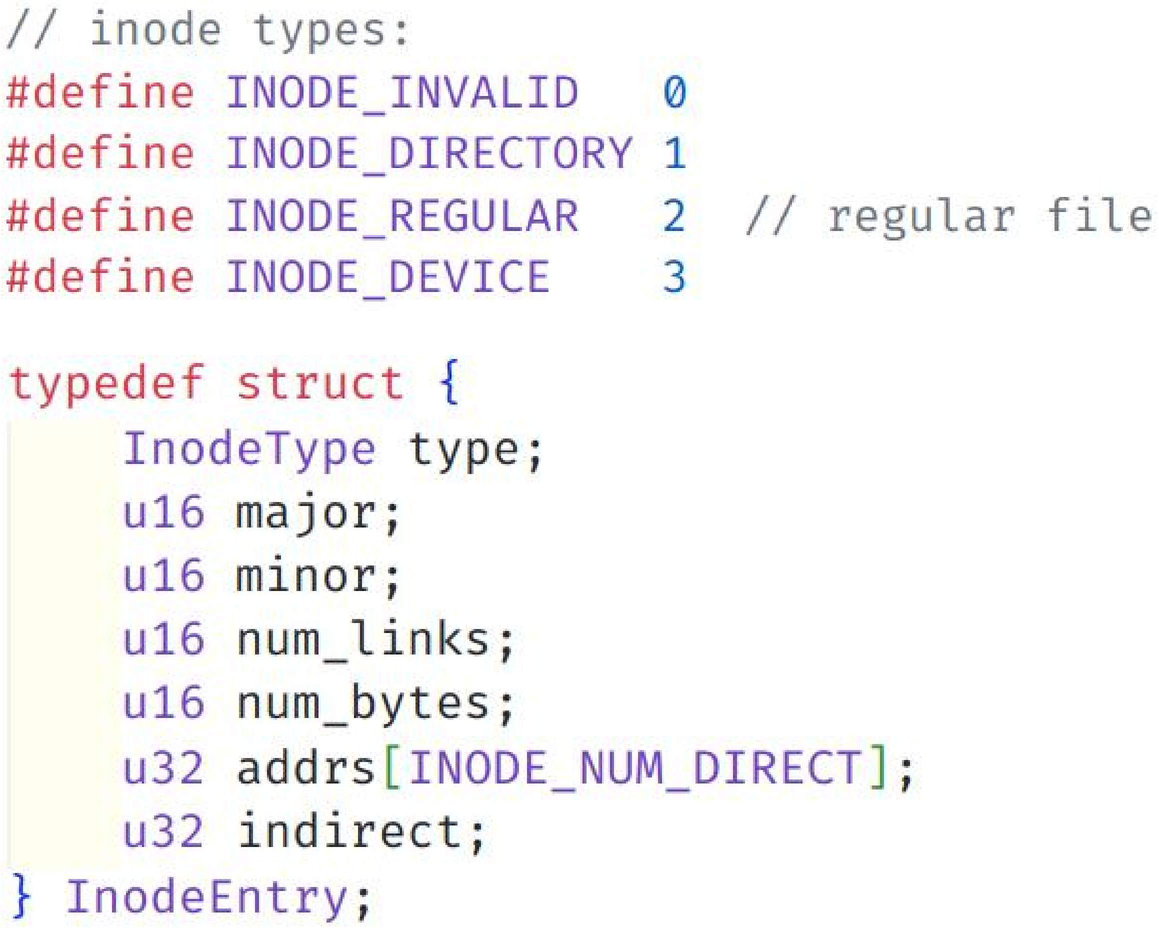


```
typedef struct {
    u32 num_blocks;  // total number of blocks in filesystem.
    u32 num_data_blocks;
    u32 num_inodes;
    u32 num_log_blocks;  // number of blocks for logging, including log header.
    u32 log_start;       // the first block of logging area.
    u32 inode_start;     // the first block of inode area.
    u32 bitmap_start;    // the first block of bitmap area.
} SuperBlock;
```

Inode Tree

- Metadata are stored in inodes
  - Directory
  - Regular file
  - Device file: `/dev/tty`, `/dev/null`
- Inodes are stored consecutively on disk
  - Each one has an inode number (`inode_no`)
  - Each block contains `INODE_PER_BLOCK` inodes
- Usually inodes form a tree
  - Leaves are files
  - Internal nodes are directories
  - It becomes a DAG if OS supports hard link
- Inode contains binary data
  - Directory: directory entries
  - Regular file: file content
  - Device file: ?

Inode



```c
// inode types:
#define INODE_INVALID   0
#define INODE_DIRECTORY 1
#define INODE_REGULAR   2  // regular file
#define INODE_DEVICE    3

typedef struct {
    InodeType type;
    u16 major;
    u16 minor;
    u16 num_links;
    u16 num_bytes;
    u32 addrs[INODE_NUM_DIRECT];
    u32 indirect;
} InodeEntry;
```

Inode Lifetime

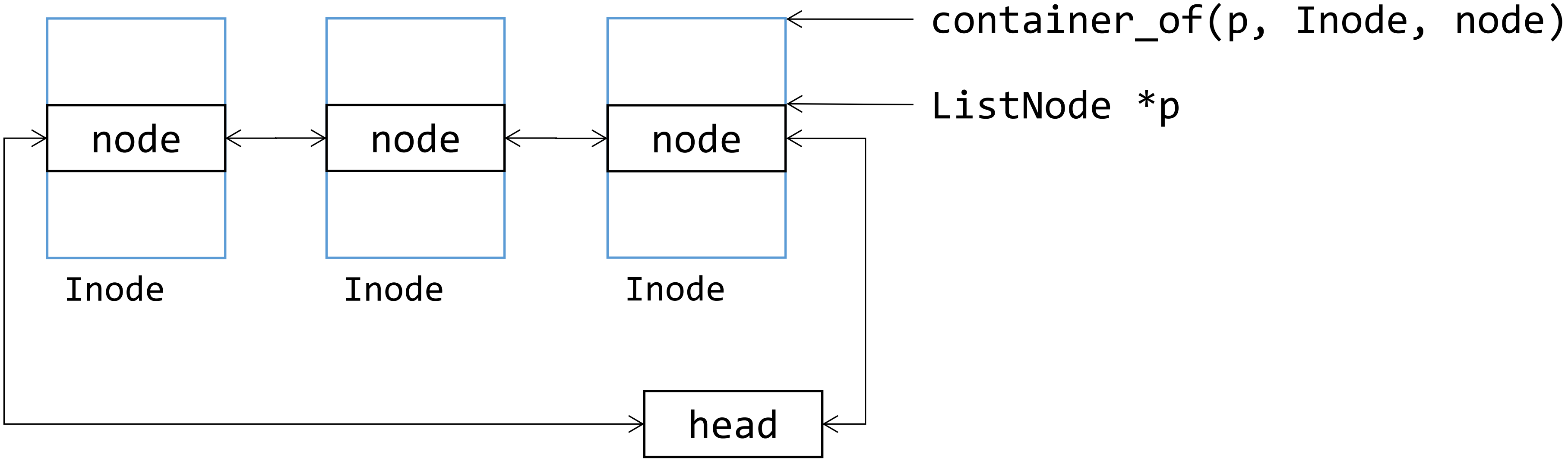
- `alloc`: the birth on disk
- `get`: in-memory pointer to inode
- `lock`/`unlock`: in-memory locking
- `put`: destory in-memory pointer
    - If there’s no pointer and no hard link to it, free it on disk
    - `rc.count == 0 && num_links == 0`
    - ⇒ `put` may write something to disk
- You need to maintain a pool of in-memory inodes
    - Use memory pool to allocate new inode
    - Use linked list to search through
    - Advanced: SLAB, hash map and binary search tree

Arena: Object Memory Pool

- `core/arena.h`
- A simple constant time object allocator
- See `arena_test` for usage

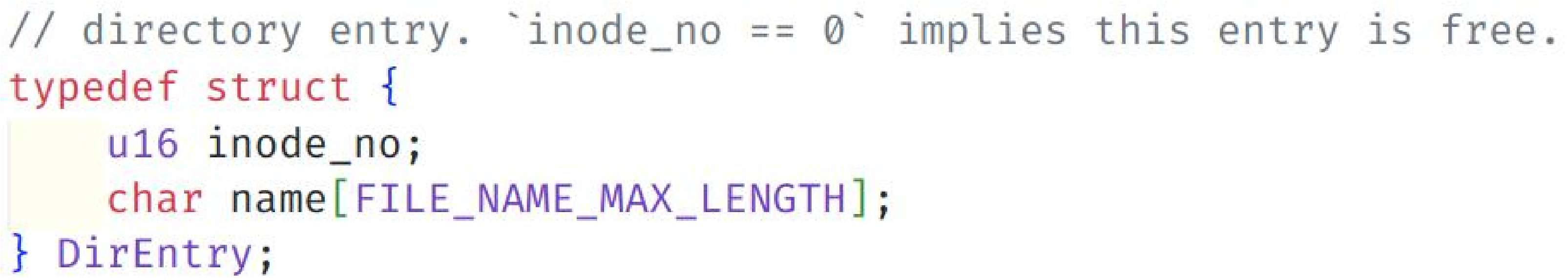
ListNode: Circular Linked List

- common/list.h
- Implement circular doubly linked list
- Minimum list size: 1
  - p->next == p && p->prev == p
- Basic operations: merge and detach
  - merge can implement push_back, push_front, insert, …
- Idiom: put ListNode as a member of inode struct
  - Use macro container_of to get original inode pointer



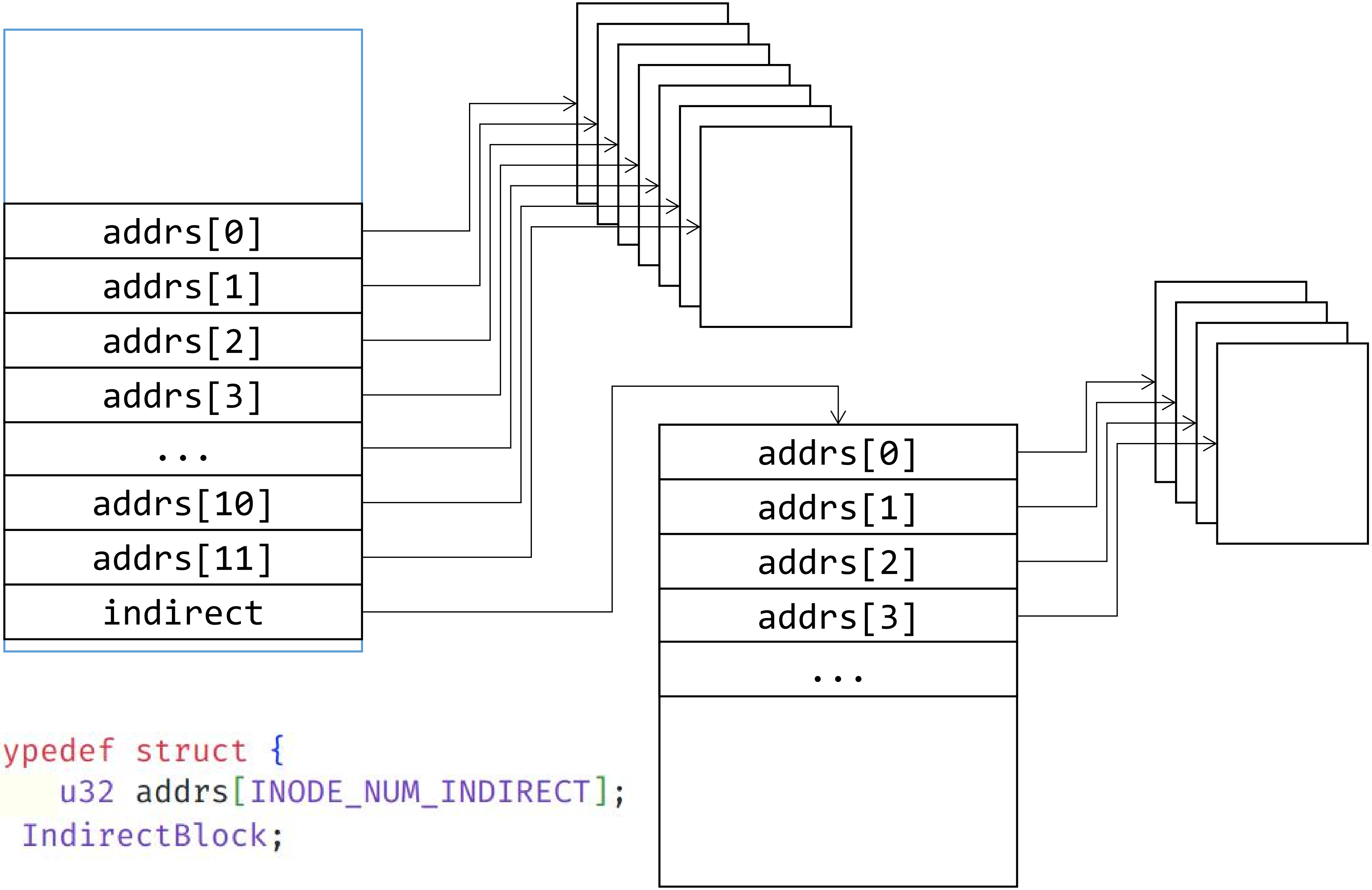
Inode Data Management

- Regular File:
  - `sync`: read data from disk or write dirty data to disk
  - `clear`: discard all binary data
  - `read`: read existing data
  - `write`: overwrite or append data
- Directory:
  - Directory is a special file: an array of entires
  - `lookup`: search for entry with specified name
  - `insert`: add a new entry
  - `remove`: erase entry at specified index
  - Just like `std::vector<DirEntry>`



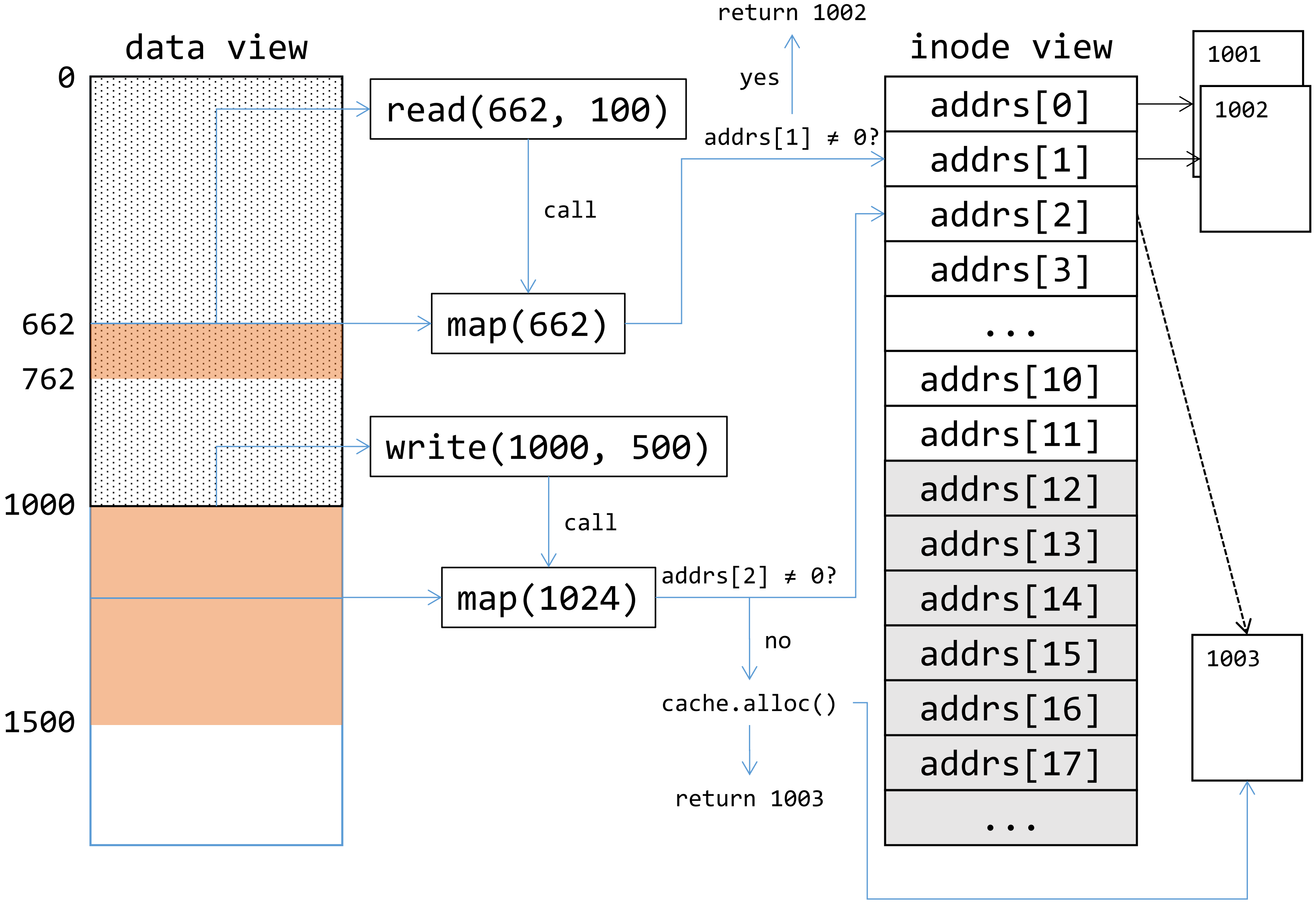
```
// directory entry. `inode_no == 0` implies this entry is free.
typedef struct {
    u16 inode_no;
    char name[FILE_NAME_MAX_LENGTH];
} DirEntry;
```

Direct & Indirect Addresses



```
typedef struct {
    u32 addrs[INODE_NUM_INDIRECT];
} IndirectBlock;
```

inode_{read,write,map}

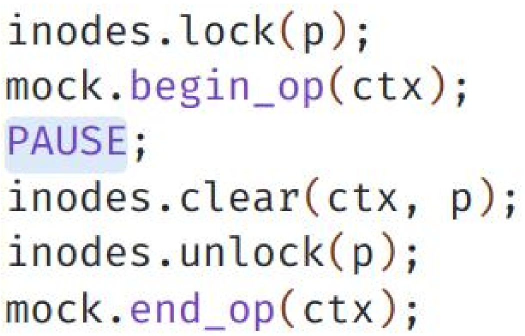


Block Cache Interface

- `fs/cache.h`
- Inodes read/write/allocate/free blocks via block cache
    - Block cache manages on-disk bitmap and in-memory block pool
- Before you operate on a block, you should lock it
    - `cache->acquire`: return a locked block
    - `cache->release`: unlock and return the block back to cache
- Whenever you need atomicity, `begin_op`/`end_op` can help
- Block cache does not have a “`write`” interface
    - It’s `sync`
    - Actual write can be delayed, depending on your context

Inode Unit Testing

- `fs/test`
- Written in C++
  - Each test is running in a forked child: not friendly to debugger
  - Use C++ exceptions to report error
- Underlying block cache is mocked
  - Along with some OS functionalities, e.g. locks
- Run the test:
  - `cd src/fs/test`
  - `mkdir build; cd build`
  - `cmake ..`
  - `make && ./inode_test`
- Debug tools:
  - `coredumpctl gdb`: open coredump after test crashed
  - PAUSE: inject static breakpoint
  - `gdb -p [pid]`: attach to a running test process
  - `kill -CONT [pid]`: continue running after pause



```
inodes.lock(p);
mock.begin_op(ctx);
PAUSE;
inodes.clear(ctx, p);
inodes.unlock(p);
mock.end_op(ctx);
```

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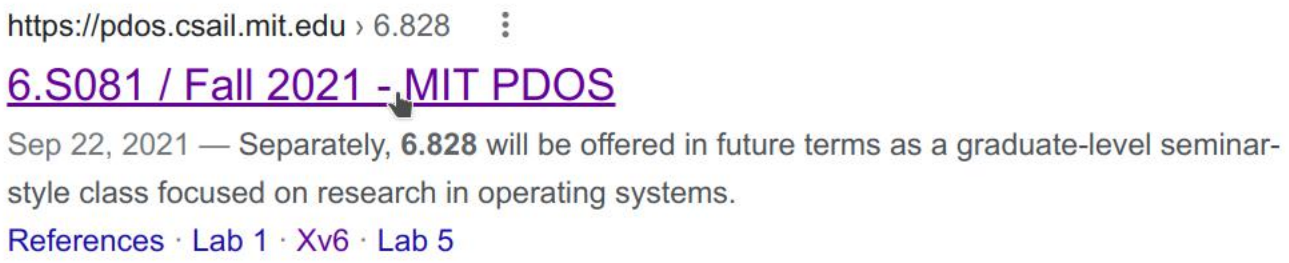

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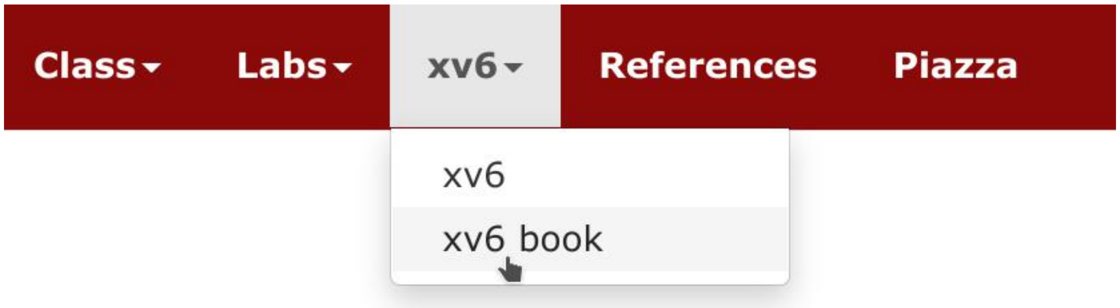


Naïve Block Layer

- `read/write`
- Slow
  - Need interrupts and large data copying
  - Batch?
  - Async?
- Data race
  - Some are false data race: two inodes on the same block
- No atomicity guarantee
  - A database jargon
  - All or nothing
  - In our case, crash consistency
  - We use locks at higher layers to provide isolation & consistency
- Our solution: cache + lock + log

Block Cache

- Cache what you read in memory
- Directly modify in memory
- Delayed write back
  - Explicit write back with `sync(NULL, ...)`
- Try to keep cache small
  - Evict when `#cached` is larger than `EVICTION_THRESHOLD`
  - It's a soft limit, not hard limit
  - LRU policy: move to front at `read`
- `read` returns a pointer to a block inside cache
- Implementation: organize blocks as a list

Per-Block Lock

- Use sleep lock
- `acquire` = `get` + `lock`
- `release` = `put` + `unlock`

Crash Consistency

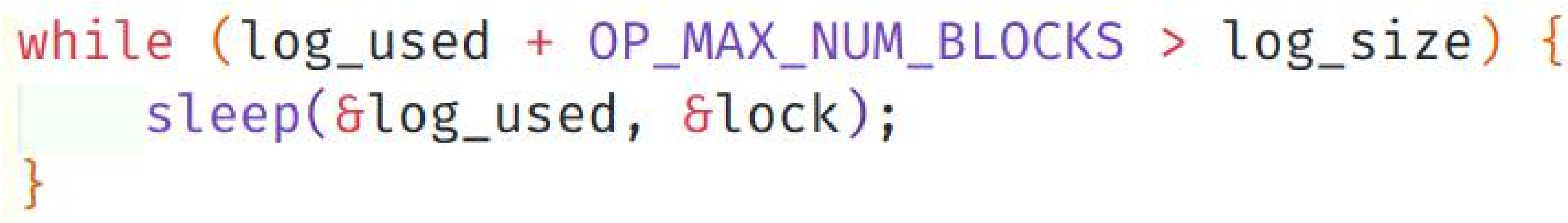
- Writing a single block is safe
- Implement at inode layer: `fsck`
    - Only checks metadata
- General solution: logging = journaling
    - Reserve a space on disk for log entires
    - Group multiple writes in one atomic operation
- Two-phase checkpoint
    - Write the entire operation to log first
    - Then copy to their original locations
- Crash at log write: this operation simply fails
- Crash at copying: contents still in log, replay

Atomic Operation

- New API: `begin_op`, `end_op`
  - `end_op` returns when entire operation is persisted to disk
  - **NOTE**: this is different from xv6!
- Track write set in `OpContext`
  - `sync(ctx, ...)`
- Multiple writes to the same block as a single write
  - We call it *local absorption*
- All writes must be delayed until `end_op`
  - Pinned blocks: you must not evict them in cache
- Concurrent operations?
  - Log entries are not unlimited
  - Different operations may touch the same block
  - Naïve way: one by one
  - Our solution: log reservation + group checkpoint

Log Reservation

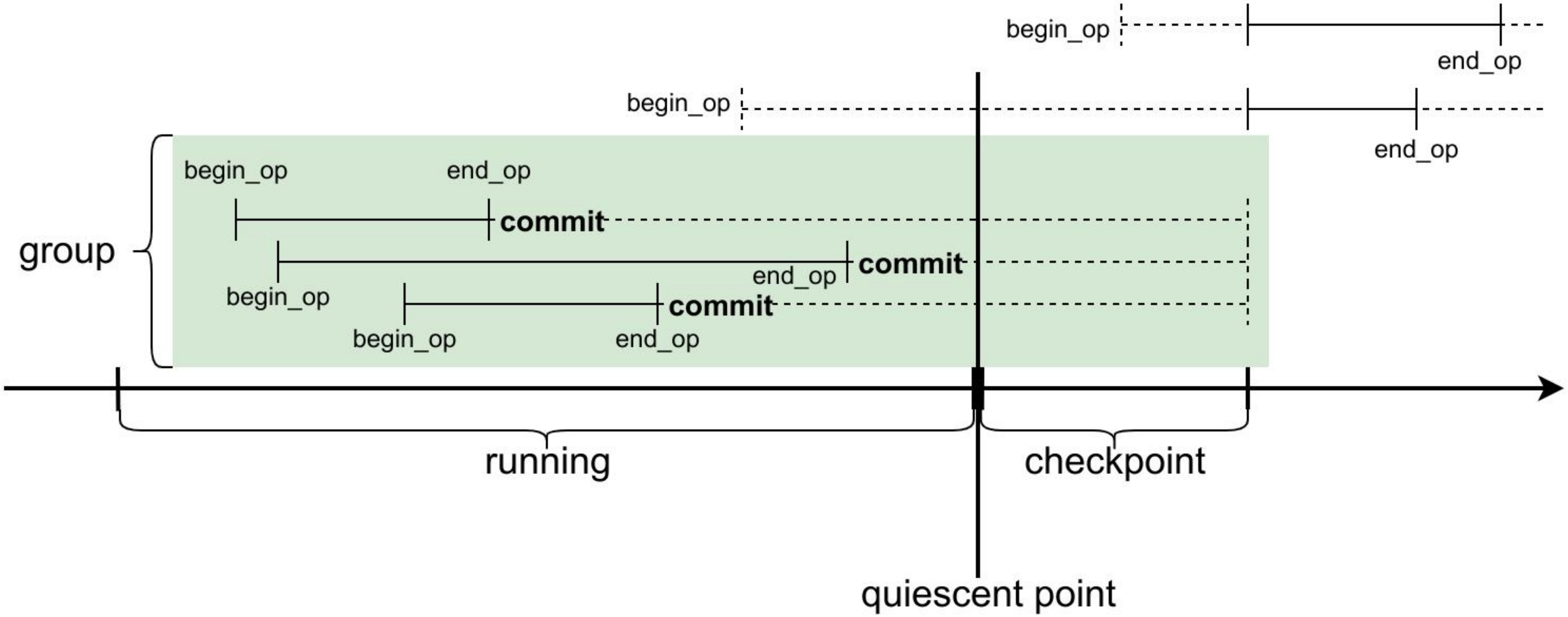
- We assume an atomic operation can track at most n blocks
  - n = `OP_MAX_NUM_BLOCKS`
- So reserve at least n log entries before start
- In `end_op`, release log entires that are not used
- If there's no enough log entries to reserve: `sleep`
  - `wakup` when `log_used` changes



```
while (log_used + OP_MAX_NUM_BLOCKS > log_size) {
    sleep(&log_used, &lock);
}
```

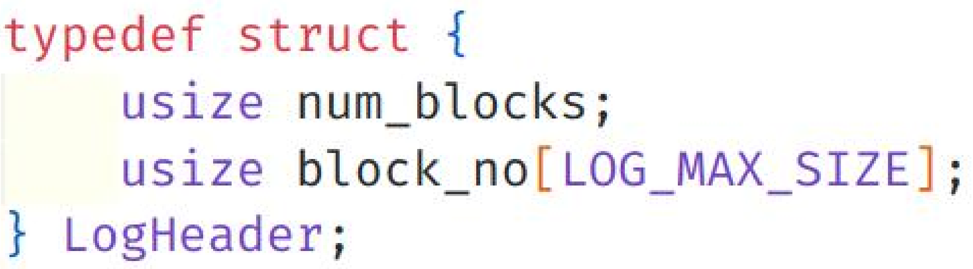
Group Checkpoint

- Different operations may touch the same block
  - Write them together
- When: no outstanding operation
  - At *quiescent point*
- Who: the last one who commits



Lifetime of Atomic Operation

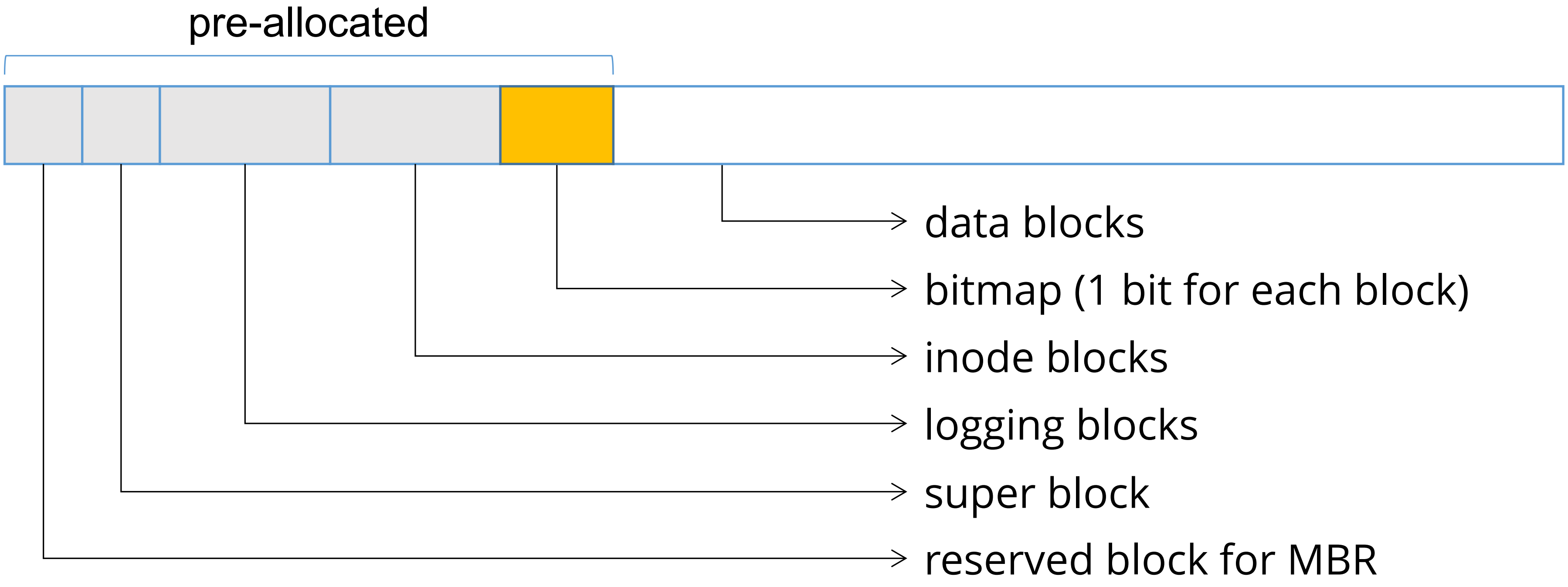
- Running: after `begin_op`, before calling `end_op`
    - You can sync in this state
- Committed: already called `end_op`, but `end_op` still waits
    - Associated blocks have been tracked in global log header
- Checkpointed: all blocks have been persisted
- `begin_op(reserve)[→sync]*→end_op(commit→checkpoint)`
- `commit`: set block numbers in log header
    - Global absorption: multiple same block numbers can be merged
- `checkpoint`: 4 steps
    - Write blocks to log area
    - Write log header
    - Copy blocks to original locations
    - Reset log header



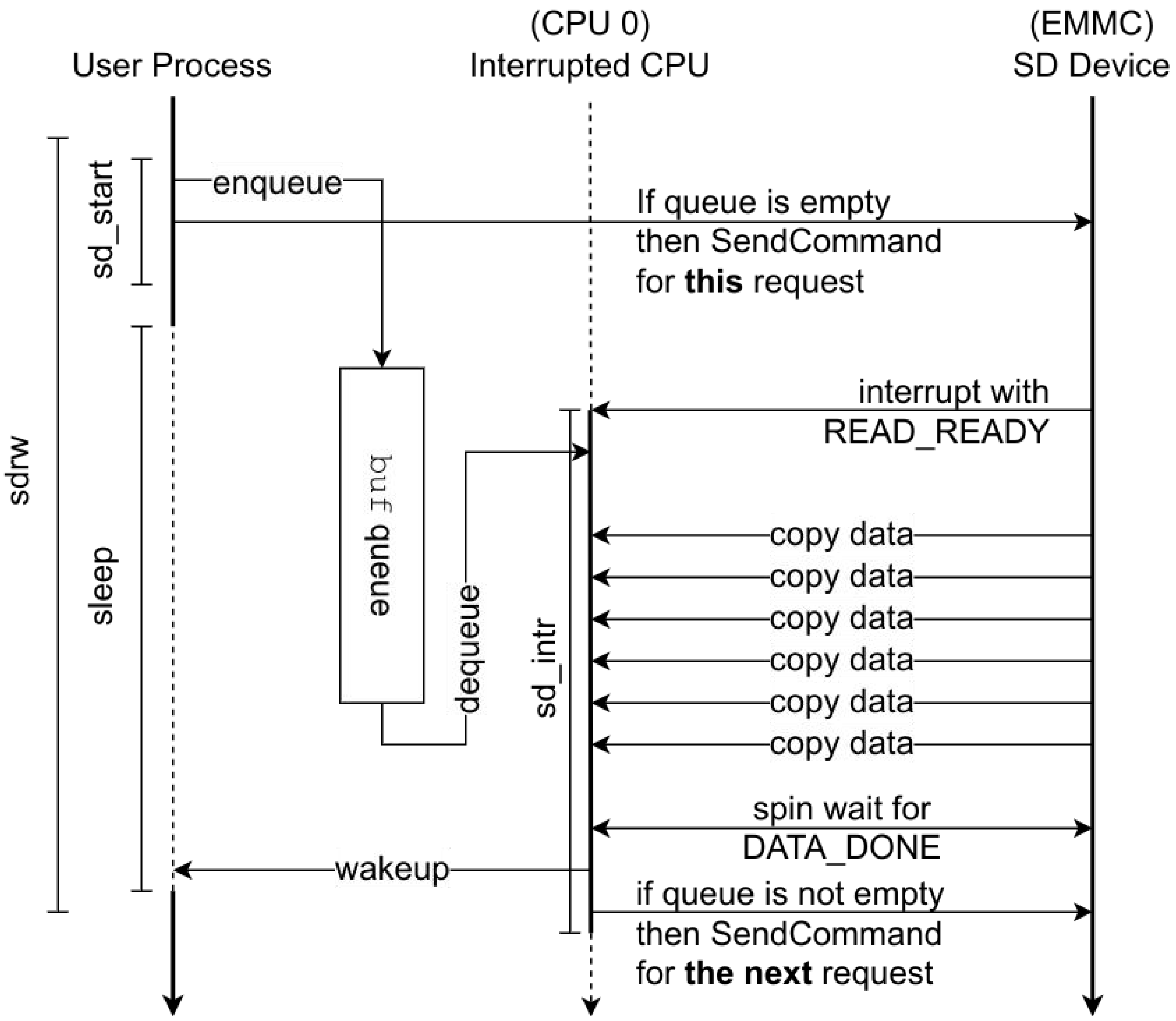
```
typedef struct {
    usize num_blocks;
    usize block_no[LOG_MAX_SIZE];
} LogHeader;
```

Bitmap

- Every block has a bit in bitmap area
  - Even for bitmap itself
- Some blocks are *pre-allocated*
  - `mkfs` will set their bits for us
- We only need to manage data blocks
  - `alloc/free`
  - A good exercise to use block cache interface :)



SD Read


User Process
(CPU 0)
Interrupted CPU
(EMMC)
SD Device
sdrw
sd_start
sleep
enqueue
If queue is empty
then SendCommand
for **this** request
buf queue
interrupt with
READ_READY
dequeue
sd_intr
copy data
copy data
copy data
copy data
copy data
copy data
spin wait for
DATA_DONE
wakeup
if queue is not empty
then SendCommand
for **the next** request