# File System Code

**open,read, write, close, pipe,  fstat, chdir, dup, mknod, link, unlink, mkdir,**

**Files, Inodes, Buffers**

# What we already know

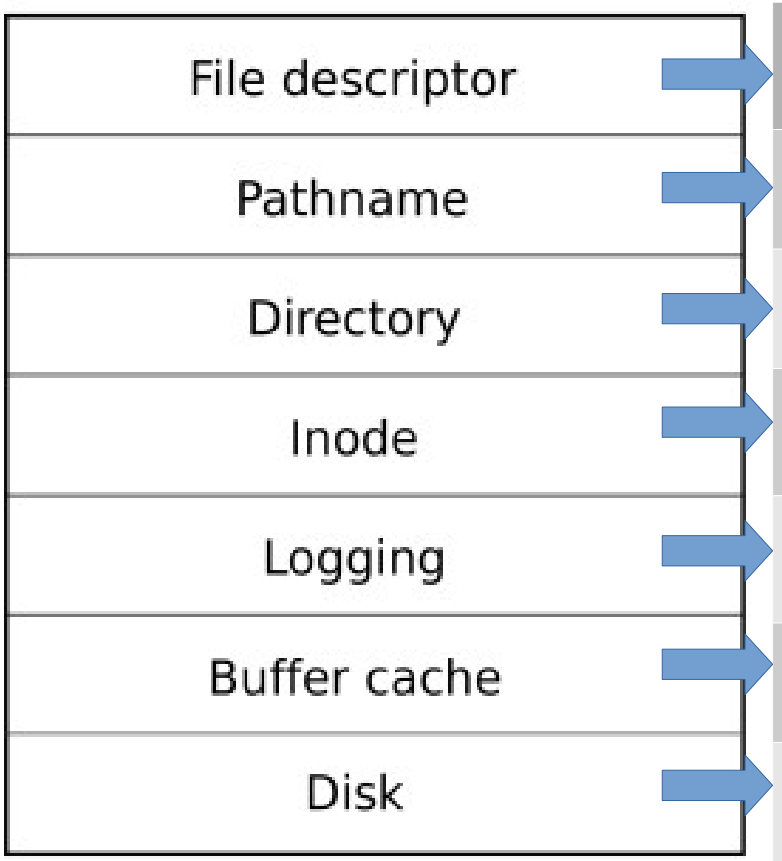
- **File system related system calls**
  - deal with ‘fd’ arrays (ofile in xv6). open() returns first empty index. open should ideallly locate the inode on disk and initialize some data structures
  - maintain ‘offsets’ within a ‘file’ to support sequential read/write
  - dup() like system calls duplicate pointers in fd-array
  - read/write like system calls, going through ‘ofile’ array, should locate data of file on disk
  - We need functions to read/write from disk – that is disk driver
  - cache data of files in OS data structures for performance : buffering
  - Need to handle on disk data structures as well
- **Faster recovery (like journaling in ext3) is desired**

# xv6 file handling code

- Is a very good example in ‘design’ of a layered and modular architecture
- Splits the entire work into different modules, and modules into functions properly
- The task of each function is neatly defined and compartamentalized

# Layers of xv6 file system code

| | |
|---|---|
| System Calls | open, read, write, close, link, pipe, mknod, unlink, fstat, mkdir, chdir, dup, |

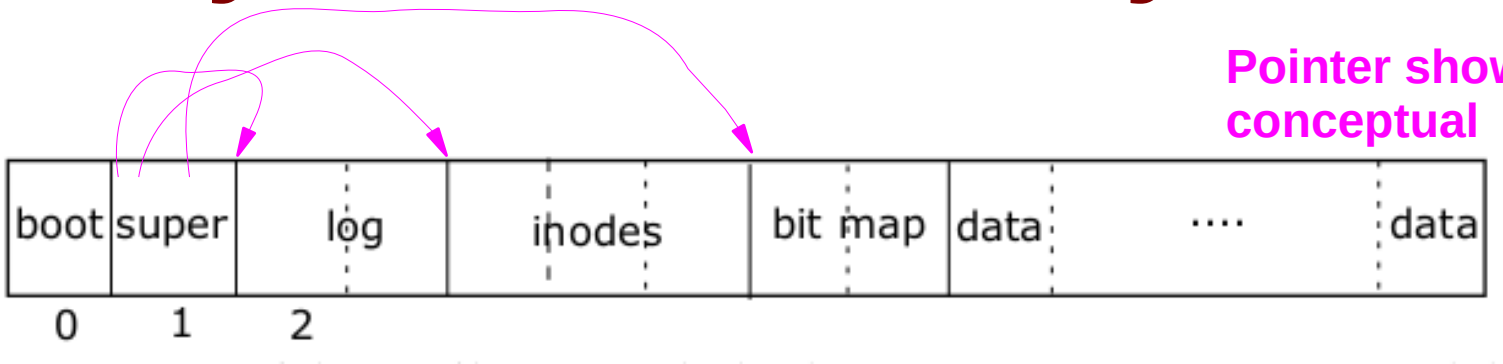



| | |
|---|---|
| **file.c** fileinit, fileallloc, filedup, fileclose, filestat, fileread, filewrite, | |
| **fs.c** namex, namei, nameiparent, skipelem | |
| **fs.c** dirlookup, dirlink | |
| **fs.c** iiinit, ialloc, iupdate,iget, idup, ilock, iunlock, iput, iunlockput, itrunc, stati, readi, writei, bmap, | |
| Block allocation on disk: balloc, bfree<br>**log.c :** begin_op, end_op, initlog, commit, | |
| **bio.c** binit, bget, bread, bwrite, brelse | |
| **ide.c:** idewait, ideinit, idestart, ideintr, iderw | |

Normally, any upper layer can call any lower layer below

**Abhijit: Block allocator should be considered as another Layer!**

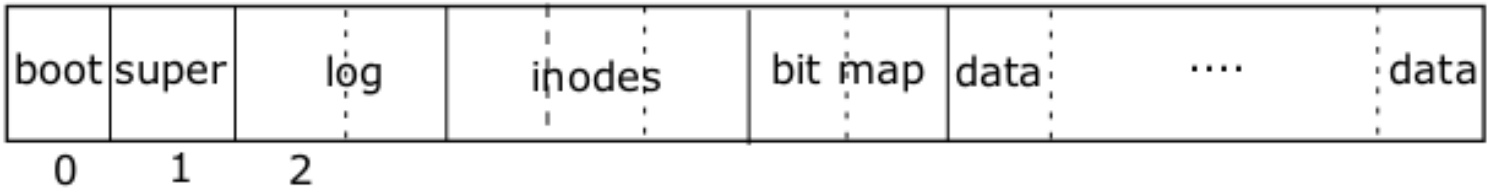
# Layout of xv6 file system




**May see the code of mkfs.c to get insight into the layout**

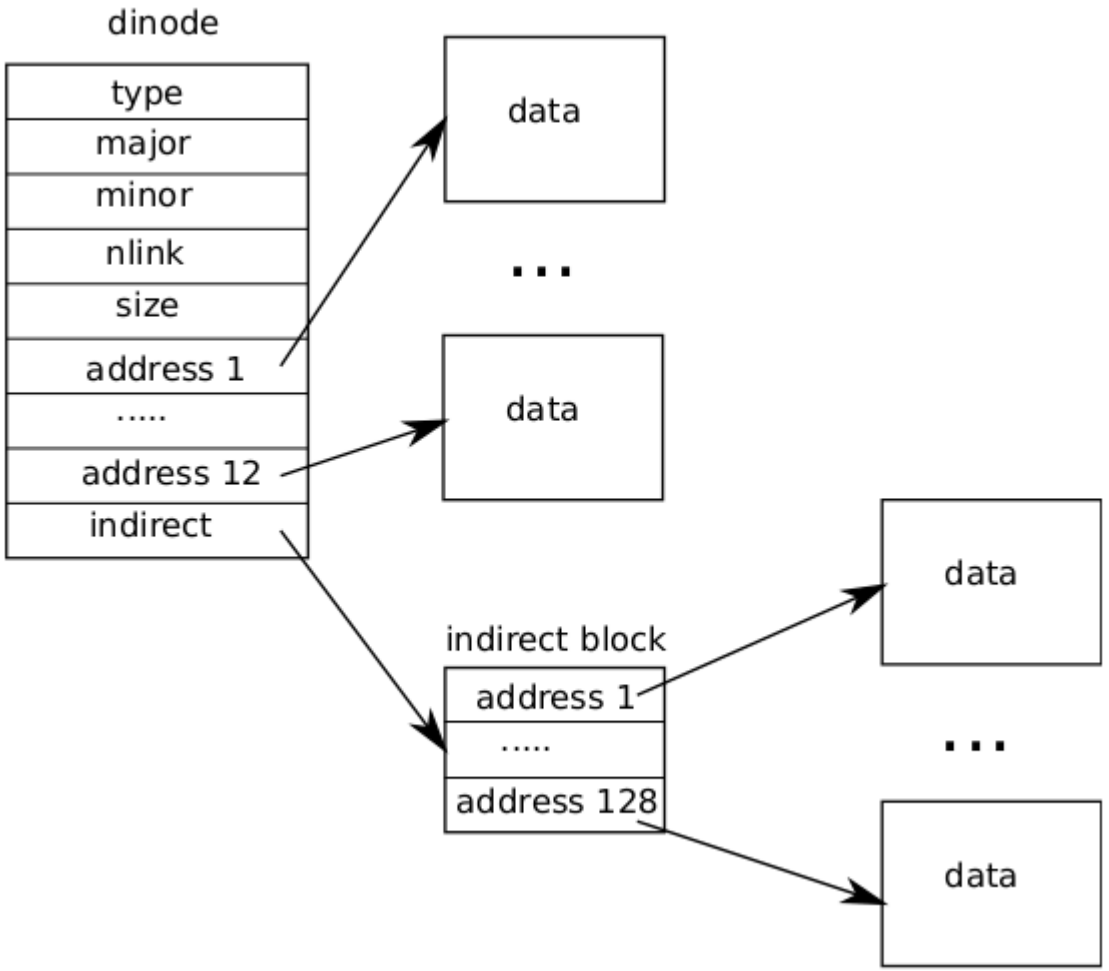
```
struct superblock {
  uint size;         // Size of file system image (blocks)
  uint nblocks;      // Number of data blocks
  uint ninodes;      // Number of inodes.
  uint nlog;         // Number of log blocks
  uint logstart;     // Block number of first log block
  uint inodestart;   // Block number of first inode block
  uint bmapstart;    // Block number of first free map block
};
#define ROOTINO 1  // root i-number
#define BSIZE 512  // block size
```

# Layout of xv6 file system



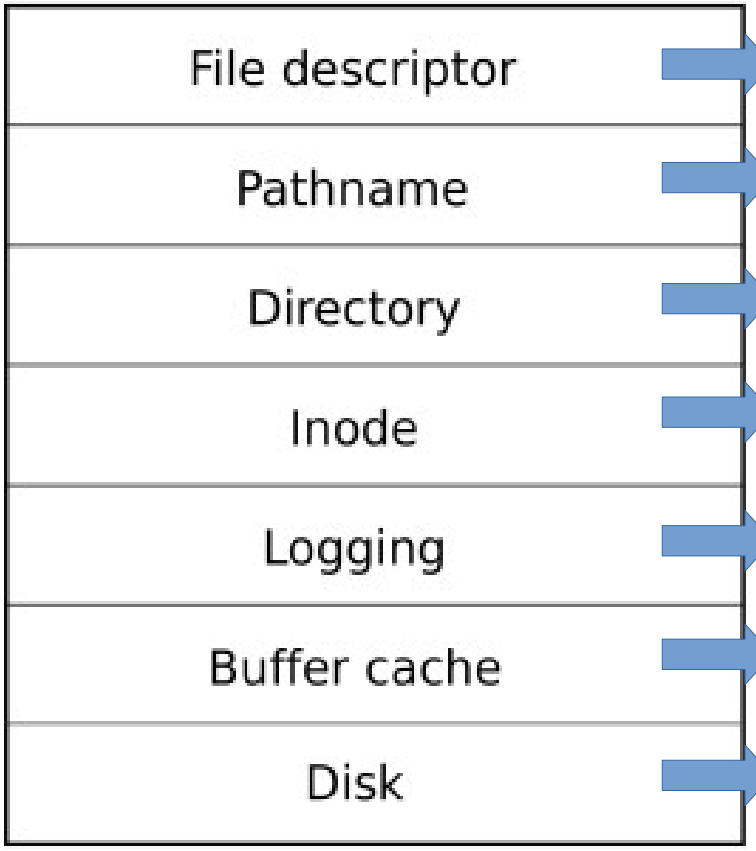

```
#define NDIRECT 12
#define NINDIRECT (BSIZE / sizeof(uint))
#define MAXFILE (NDIRECT + NINDIRECT)
// On-disk inode structure
struct dinode {
  short type;           // File type
  short major;          // Major device number (T_DEV only)
  short minor;          // Minor device number (T_DEV only)
  short nlink;          // Number of links to inode in file system
  uint size;            // Size of file (bytes)
  uint addrs[NDIRECT+1];   // Data block addresses
};

#define DIRSIZ 14

struct dirent {
  ushort inum;
  char name[DIRSIZ];
};
```

# File on disk


dinode
type
major
minor
nlink
size
address 1
.....
address 12
indirect
data
...
data
indirect block
address 1
.....
address 128
data
...
data

# Let’s discuss lowest layer first

| System Calls | open, read, write, close, link, pipe, mknod, unlink, fstat, mkdir, chdir, dup, |
|---|---|




| | |
|---|---|
| File descriptor | **file.c** fileinit, filealloc, filedup, fileclose, filestat, fileread, filewrite, |
| Pathname | **fs.c** namex, namei, nameiparent, skipelem |
| Directory | **fs.c** dirlookup, dirlink |
| Inode | **fs.c** iiinit, ialloc, iupdate,iget, idup, ilock, iunlock, iput, iunlockput, itrunc, stati, readi, writei, bmap, |
| Logging | Block allocation on disk: balloc, bfree<br>**log.c :** begin_op, end_op, initlog, commit, |
| Buffer cache | **bio.c** binit, bget, bread, bwrite, brelse |
| Disk | **ide.c:** idewait, ideinit, idestart, ideintr, iderw |

Normally, any upper layer can call any lower layer below

# ide.c: idewait, ideinit, idestart, ideintr, iderw

```
static struct spinlock idelock;
static struct buf *idequeue;
static int havedisk1;
```

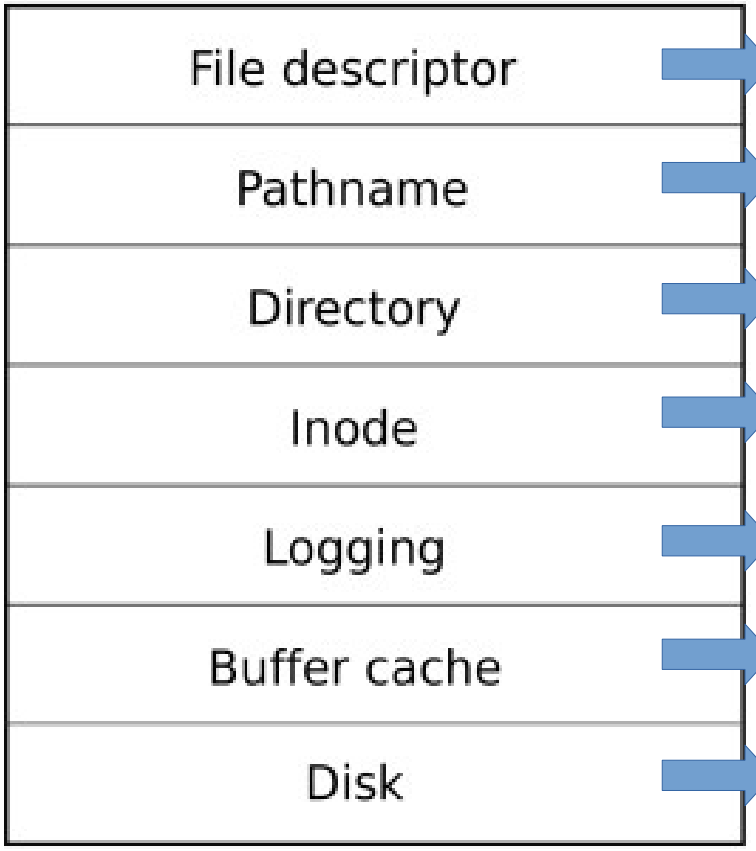
- ideinit
  - was called from main.c: main()
  - Initialized IDE controller by writing to certain ports
  - havedisk=1 setup
  - Initialize idelock
- idewait
  - BUSY loop waiting for IDE to be ready

# ide.c: idewait, ideinit, idestart, ideintr, iderw

- void idestart(buf *b)
  - static void idestart(struct buf *b)
  - Calculate sector number on disk using b->blockno
  - Issue a read/write command to IDE controller.
  - (This is the first buf on idequeue)
- ideintr
  - Take idelock. Called on IDE interrupt (through alltraps()->trap())
  - Wakeup the process waiting on first buffer in buffer *idequeue;
  - call idestart(). Release idelock.
- iderw(buf *b)
  - Move buf b to end of idequeue
  - Call idestart() if not running, sleep on idelock

# Let's see buffer cache layer

| System Calls | open, read, write, close, link, pipe, mknod, unlink, fstat, mkdir, chdir, dup, |
|---|---|

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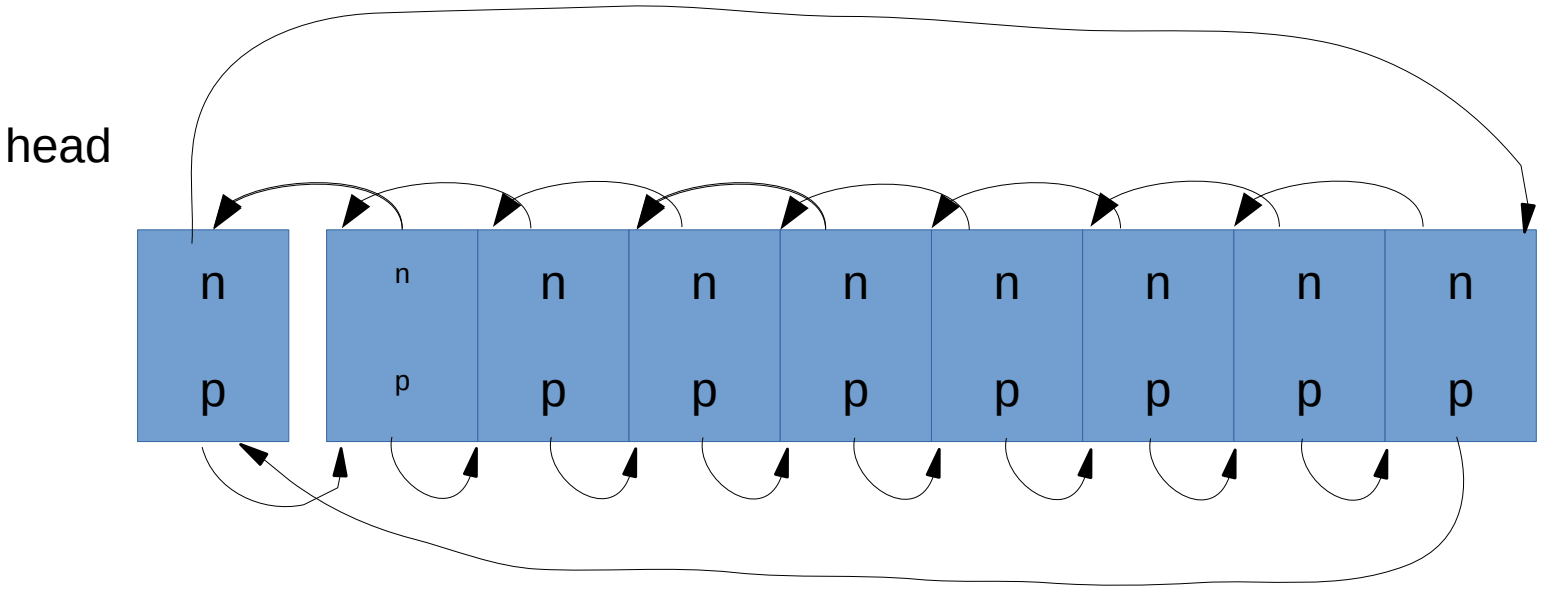
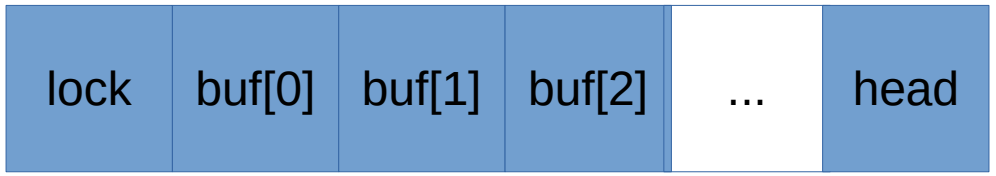
# Reminder: After main()->binit()




Conceptually Linked liks this

Buffers keep moving on list, as LRU




**struct bcache**

# struct buf

```
struct buf {
  int flags;  // 0 or B_VALID or B_DIRTY
  uint dev;   // device number
  uint blockno; // seq block number on device
  struct sleeplock lock; // Lock to be held by process using it
  uint refcnt; // Number of live accesses to the buf
  struct buf *prev; //  cache list
  struct buf *next; // cache list
  struct buf *qnext; // disk queue
  uchar data[BSIZE];  // data 512 bytes
};
#define B_VALID 0x2  // buffer has been read from disk
#define B_DIRTY 0x4  // buffer needs to be written to disk
```

# buffer cache:
# static struct buf* bget(uint dev, uint blockno)

- The bcache.head list is maintained on Most Recently Used (MRU) basis
  - head.next is the Most Recently Used (MRU) buffer
  - hence head.prev is the Least Recently Used (LRU)
- Look for a buffer with b->blockno = blockno and b->dev = dev
  - Search the head.next list for existing buffer (MRU order)
  - Else search the head.prev list for empty buffer
  - panic() if found in-use or empty buffer
- Increment b->refcnt ; Returns buffer locked
- Does not change the list structure, just returns a buf in use

# buffer cache:
# struct buf* bread(uint dev, uint blockno)

```
struct buf*
bread(uint dev, uint blockno)
{
  struct buf *b;
  b = bget(dev, blockno);
  if((b->flags & B_VALID) == 0) {
    iderw(b);
  }
  return b; // locked buffer
}
```

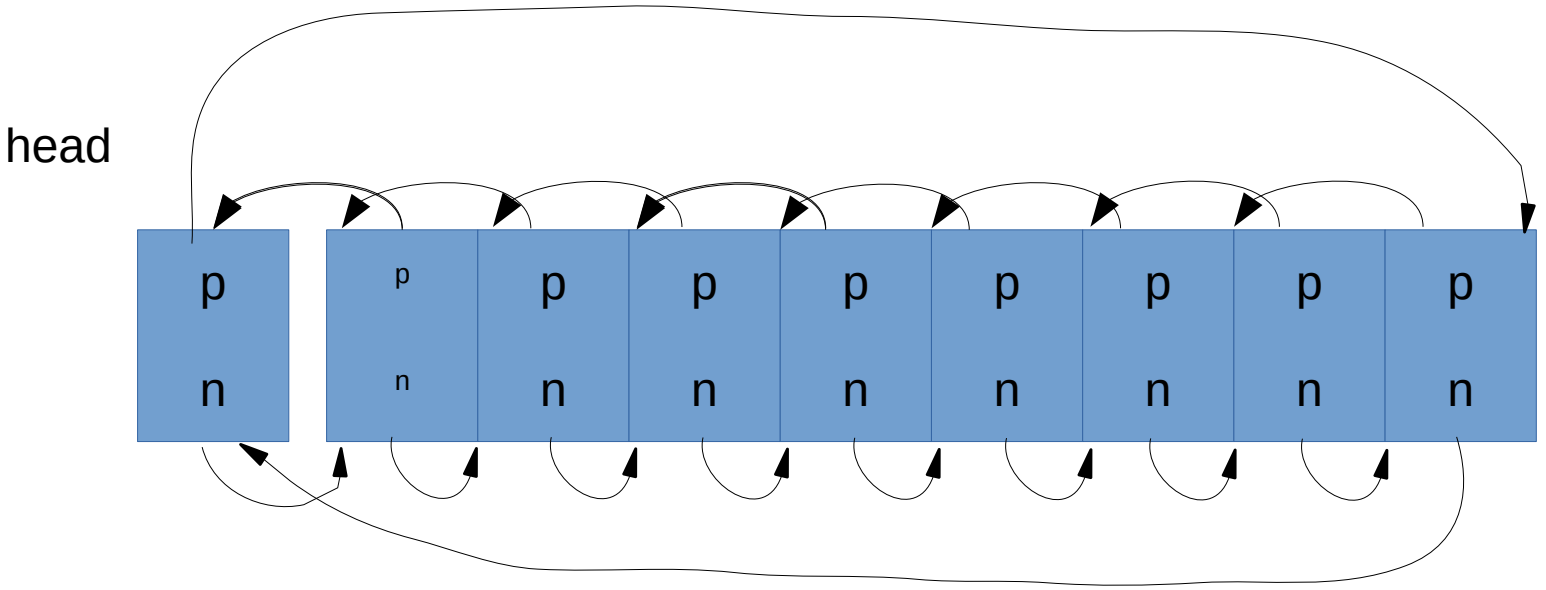
```
void
bwrite(struct buf *b)
{
  if(!holdingsleep(&b->lock))
    panic("bwrite");
  b->flags |= B_DIRTY;
  iderw(b);
}
```

Recollect: iderw moves buf to tail of idequeue, calls idestart() and sleep()

# buffer cache:
# void brelse(struct buf *b)

- release lock on buffer
- b->refcnt = 0
- If b->refcnt = 0
  - Means buffer will no longer be used
  - Move it to front of the front of bcache.head

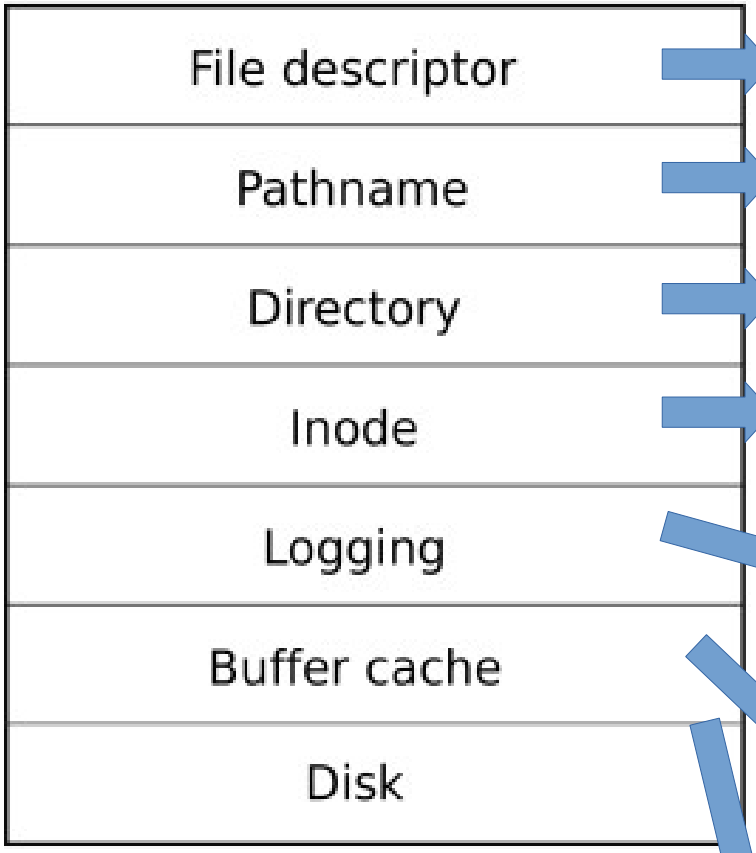
# Overall in this diagram




Buffers keep moving to the front of the list and around
The list always contains NBUF=30 buffers
head.next is always the MRU and head.prev is always LRU buffer

# Let's see logging layer

| System Calls | open, read, write, close, link, pipe, mknod, unlink, fstat, mkdir, chdir, dup, |
|---|---|

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Normally, any upper layer can call any lower layer below

# log in xv6

- a mechanism of recovery from disk
- Concept: multiple write operations needed for system calls (e.g. ‘open’ system call to create a file in a directory)
  - some writes succed and some don’t
  - leading to inconsistencies on disk
- In the log, all changes for a ‘transaction’ (an operation) are either written completely or not at all
- During recovery, completed operations can be “rerun” and incomplete operations neglected

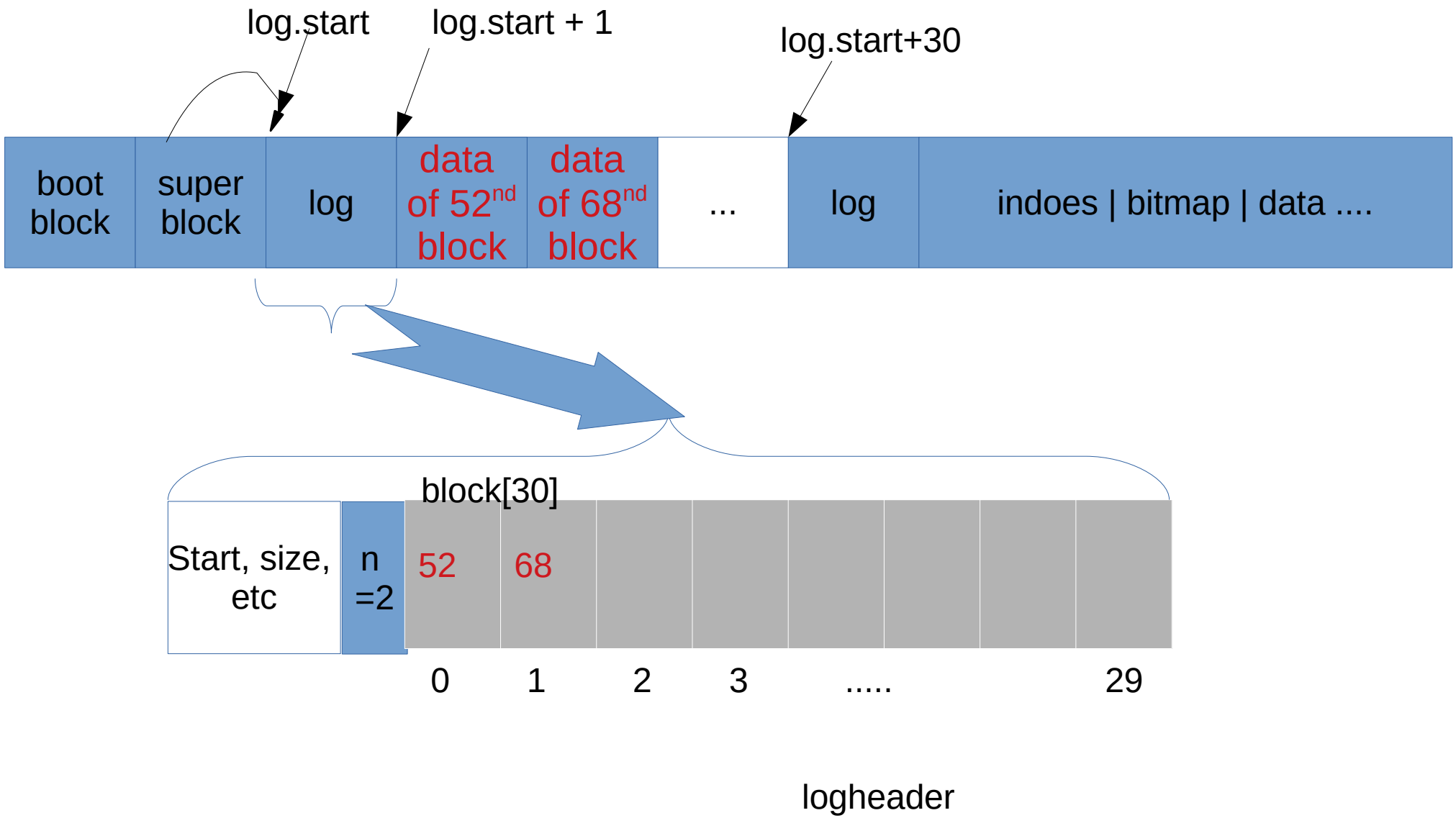
# log in xv6

- xv6 system call does not directly write the on-disk file system data structures.
- A system call calls begin_op() at begining and end_op() at end
  - begin_op() increments log.outstanding
  - end_op() decrements log.outstanding, and if it's 0, then calls commit()
- During the code of system call, whenever a buffer is modified, (and done with)
  - log_write() is called
  - This copies the block in an array of blocks inside log, the block is not written in it's actual place in FS as of now
- when finally commit() is called, all modified blocks are copied to disk in the file system

# log

```
struct logheader { // ON DISK
  int n; // number of entries in use in block[] below
  int block[LOGSIZE]; // List of block numbers stored
};
struct log { // only in memory
  struct spinlock lock;
  int start;  // first log block on disk (starts with logheader)
  int size; // total number of log blocks (in use out of 30)
  int outstanding; // how many FS sys calls are executing.
  int committing;  // in commit(), please wait.
  int dev; // FS device
  struct logheader lh;  // copy of the on disk logheader
};
struct log log;
```

# log on disk


log.start
log.start + 1
log.start+30
boot block
super block
log
data of 52nd block
data of 68nd block
...
log
indoes | bitmap | data ....
block[30]
Start, size, etc
n =2
52
68
0
1
2
3
.....
29
logheader

# Typical use case of logging

```
/* In a system call code * /
begin_op();
...
bp = bread(...);
bp->data[...] = ...;
log_write(bp);
...
end_op();
```

prepare for logging. Wait if logging system is not ready or 'committing'. ++outstanding

read and get access to a data block – as a buffer

modify buffer

note down this buffer for writing, in log. proxy for bwrite(). Mark B_DIRTY. Absorb multiple writes into one.

Syscall done. write log and all blocks. --outstanding.

If outstanding = 0, commit().

match colors in code and comments on right-side

# Example of calls to logging

```
//file_write() code
begin_op();
ilock(f->ip);
   /*loop */ r = writei(f->ip, ...);
iunlock(f->ip);
end_op();
```

- each writei() in turn calls bread(), log_write() and brelse()
  - also calles iupdate(ip) which also calls bread, log_write and brelse
- Multiple writes are combined between begin_op() and end_op()

# Logging functions

- Initlog()
  - Set fields in global log.xyz variables, using FS superblock
  - Recovery if needed
  - Called from first forkret()
- Following three called by FS code
- begin_op(void)
  - Increment log.outstanding
- end_op(void)
  - Decrement log.oustanding and call commit() if it's zero
- log_write(buf *)
  - Remember the specified block number in log.lh.block[] array
  - Set the block to be dirty
- write_log(void)
  - Called only from commit()
  - Use block numbers specified in log.lh.block and copy those blocks from memory to log-blocks
- commit(void)
  - Called only from end_op()
  - write_log()
  - Write header to disk log-header
  - Copy from log blocks to actual FS blocks
  - Reset and write log header again

# Let’s see block allocation layer

| | |
|---|---|
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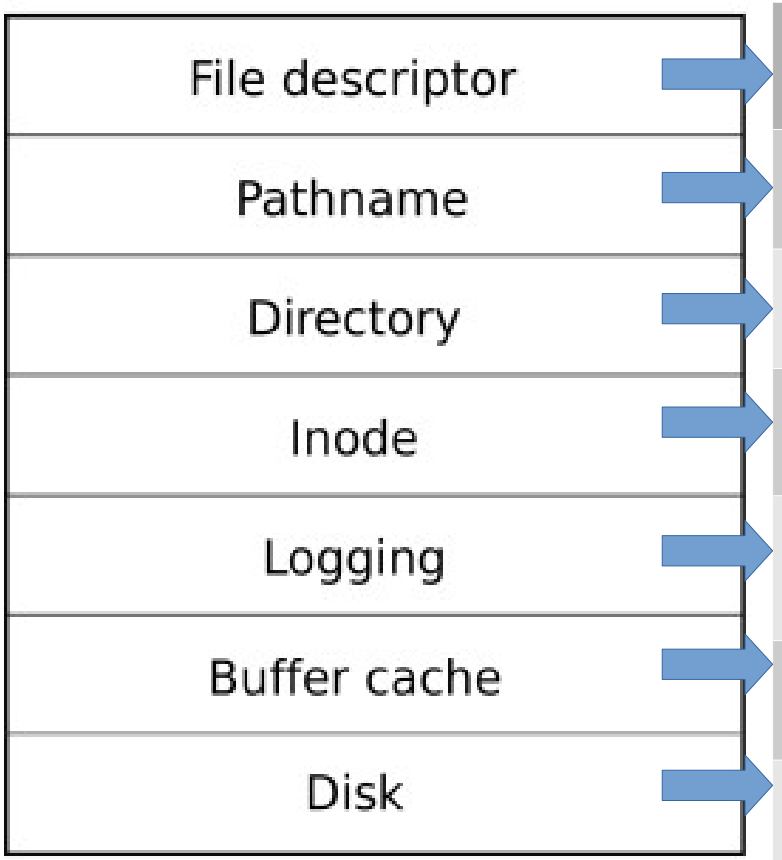


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Normally, any upper layer can call any lower layer below

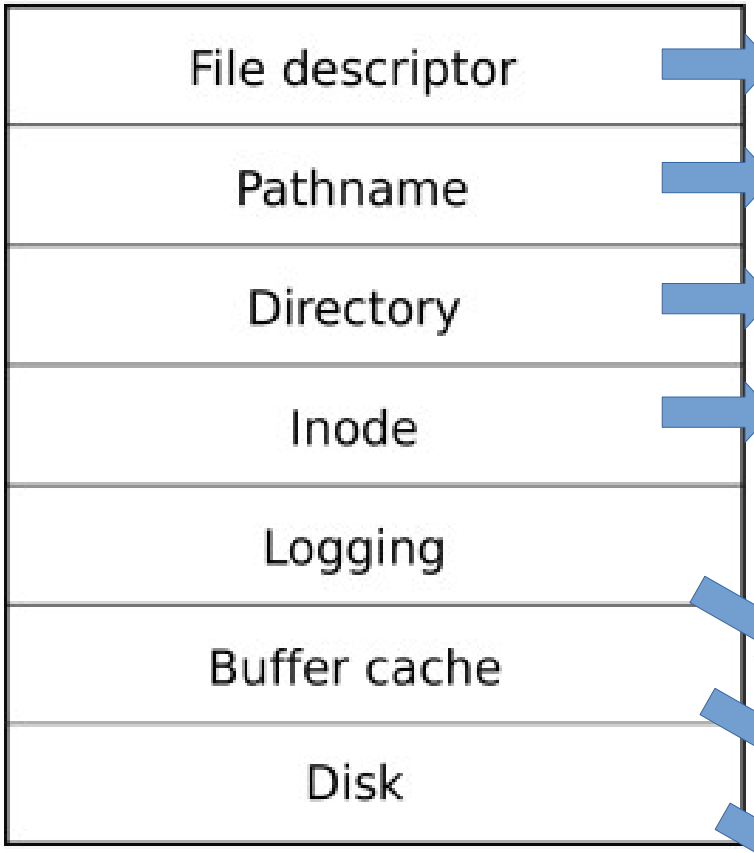
**Abhijit: Block allocator should be considered as another Layer!**

# allocating & deallocating blocks on DISK

- **balloc(devno)**
  - looks for a block whose bitmap bit is zero, indicating that it is free.
  - On finding updates the bitmap and returns the block.
  - balloc() calls bread()->bget to get a block from disk in a buffer.
    - Race prevented by the fact that the buffer cache only lets one process use any one bitmap block at a time.
  - Calls log_write(bp);
    - Thus writes to bitmap blocks are also logged
- **bfree(devno, blockno)**
  - finds the right bitmap block and clears the right bit.
  - Also calls log_write()

# Let’s see Inode Layer

| System Calls | open, read, write, close, link, pipe, mknod, unlink, fstat, mkdir, chdir, dup, |
|---|---|

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# On disk & in memory inodes

```
struct {
  struct spinlock lock;
  struct inode inode[NINODE];
} icache;

// On-disk inode structure
struct dinode {
  short type;     // File type
  short major;    // T_DEV Major device number
  short minor;    // Minor device number
  short nlink;    // Number of links
  uint size;      // Size of file (bytes)
  uint addrs[NDIRECT+1];   /
};
```

```
// in-memory copy of an inode
struct inode {
  uint dev;           // Device number
  uint inum;          // Inode number
  int ref;            // Reference count
  struct sleeplock lock; // protects everything below here
  int valid;          //  been read from disk?

  short type;         // copy of disk inode
  short major;
  short minor;
  short nlink;
  uint size;
  uint addrs[NDIRECT+1];
};
```

# In memory inodes

- Kernel keeps a subset of on disk inodes, those in use, in memory
  - as long as ‘ref’ is >0
- The iget and iput functions acquire and release pointers to an inode, modifying the ref count.
- See the caller graph of iget()
  - all those who call iget()
- Sleep lock in ‘inode’ protects
  - fields in inode
  - data blocks of inode

# iget and iupdate

- iget
  - searches for an existing/free inode in icache and returns pointer to one
  - if found, increments ref and returns pointer to inode
  - else gets empty inode , initializes, ref=1 and return
  - No lock held after iget()
  - Code must call ilock() after iget() to get lock
  - During lookup (later), many processes can iget() an inode, but only one holds the lock

- iupdate(inode *ip)
  - read on disk block of inode
  - get on disk inode
  - modify it as specified in ‘ip’
  - modify disk block of inode
  - log_write(disk block of inode)

# itrunc , iput

- iput(ip)
  - if ref is 1
    - itrunc(ip)
    - type = 0
    - iupdate(ip)
    - i->valid = 0 // free in memory
  - else
    - ref--

- itrunc(ip)
  - write all data blocks of inode to disk
    - using bfree()
  - ip->size = 0
    - Inode is freed from use
  - iupdate(ip)
  - called from iput() only when ‘ref’ becomes zero

# race in iput ?

- A concurrent thread might be waiting in ilock to use this inode
  - and won't be prepared to find the in ode is not longer allocated
- This is not possible. Why?
  - no way for a syscall to get a ref to a inode with ip->ref = 1

```
void
iput(struct inode *ip)
{
  acquiresleep(&ip->lock);
  if(ip->valid && ip->nlink == 0){
    acquire(&icache.lock);
    int r = ip->ref;
    release(&icache.lock);
    if(r == 1){
      // inode has no links and no other references: truncate and free.
      itrunc(ip);
```

# buffer and inode cache

- to read an inode, it's block must be read in a buffer
- So the buffer always contains a copy of the on-disk dinode
  - duplicate copy in in-memory inode
- The inode cache is write-through,
  - code that modifies a cached inode must immediately write it to disk with iupdate
- Inode may still exist in the buffer cache

# allocating inode

- ialloc(dev, type)
  - Loop over all disk inodes
  - read inode (from it's block)
  - if it's free (note inum)
  - zero on disk inode
  - write on disk inode (as zeroes)
  - return iget(dev, inum)
- panic if no free inodes

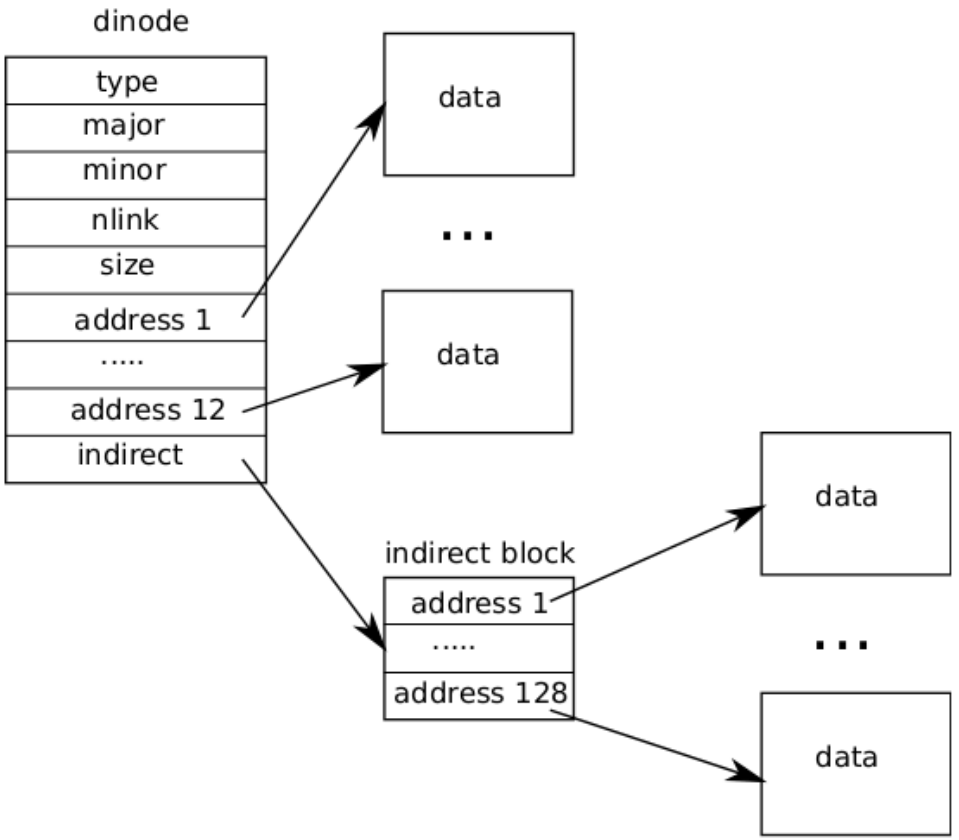
- ilock
  - code must acquire ilock before using inode's data/fields
  - llock reads inode if it's already not in memory

# Trouble with iput() and crashes

- iput() doesn't truncate a file immediately when the link count for the file drops to zero, because
  - some process might still hold a reference to the inode in memory: a process might still be reading and writing to the file, because it successfully opened it.
- if a crash happens before the last process closes the file descriptor for the file,
  - then the file will be marked allocated on disk but no directory entry points to it
- Unsolved problem.
- How to solve it?

# Get Inode data: bmap(ip, bn)

- **Allocate ‘bn’th block for the file given by inode ‘ip’**
- **Allocate block on disk and store it in either direct entries or block of indirect entries**
  - **allocate block of indirect entries if needed using balloc()**



# writing/reading data at a given offset in file

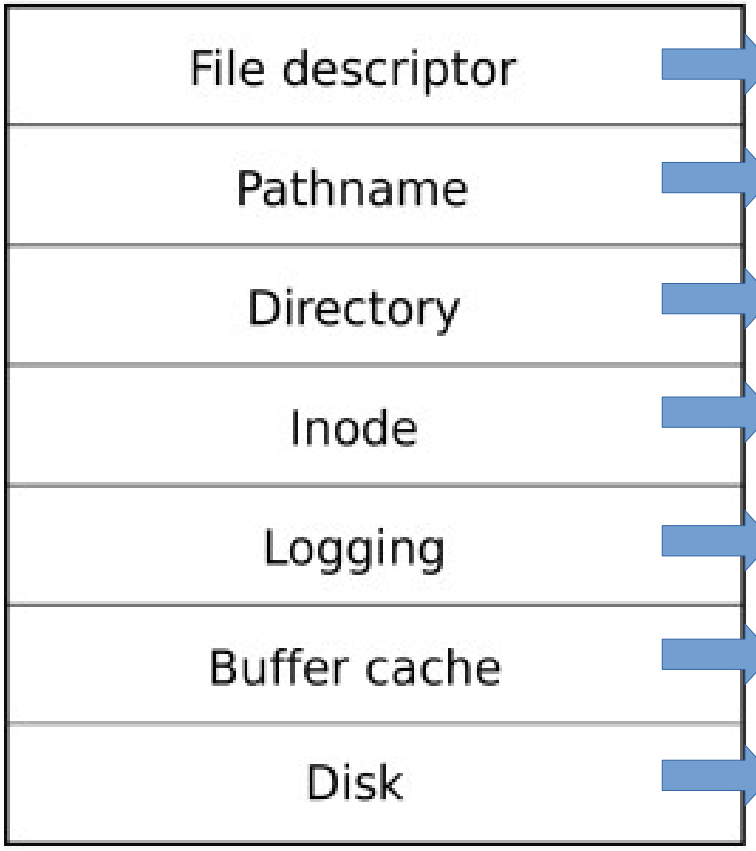
**readi(struct inode *ip, char *dst, uint off, uint n)**

**writei(struct inode *ip, char *src, uint off, uint n)**

- Calculate the block number in file where ‘off’ belongs
- Read sufficient blocks to read ‘n’ bytes
- using bread(), brelse()
- Call devsw.read if inode is a device Inode.
- Writei() also updates size if required

# Reading Directory Layer

| System Calls | open, read, write, close, link, pipe, mknod, unlink, fstat, mkdir, chdir, dup, |
|---|---|




**file.c** fileinit, filealloc, filedup, fileclose, filestat, fileread, filewrite,

**fs.c** namex, namei, nameiparent, skipelem

**fs.c** dirlookup, dirlink

**fs.c** iiinit, ialloc, iupdate,iget, idup, ilock, iunlock, iput, iunlockput, itrunc, stati, readi, writei, bmap,

Block allocation on disk: balloc, bfree
**log.c :** begin_op, end_op, initlog, commit,

**bio.c** binit, bget, bread, bwrite, brelse

**ide.c:** idewait, ideinit, idestart, ideintr, iderw

# directory entry

```
#define DIRSIZ 14


struct dirent {
  ushort inum;
  char name[DIRSIZ];
};
```

**Data of a directory file is a sequence of such entries. To find a name, just get all the data blocks and search the name**

**How to get the data for a directory? We already know the ans!**

# struct inode*
# dirlookup(struct inode *dp, char *name, uint *poff)

- **Given a pointer to directory inode (dp), name of file to be searched**
  - **return the pointer to inode of that file (NULL if not found)**
  - **set the 'offset' of the entry found, inside directories data blocks, in poff**
- **How was 'dp' obtained? Who should be calling dirlookup? Why is poff returned?**
  - **During resolution of pathnames?**
- **Code: call readi() to get data of dp, search name in it, name comes with inode-num, iget() that inode-num**

# int
# dirlink(struct inode *dp, char *name, uint inum)

- **Create a new entry for ‘name’_’inum’ in directory given by ‘dp’**
  - **inode number must have been obtained before calling this. How to do that?**
- **Use dirlookup() to verify entry does not exist!**
- **Get empty slot in directory’s data block**
- **Make directory entry**
- **Update directory inode! writei()**

# namex

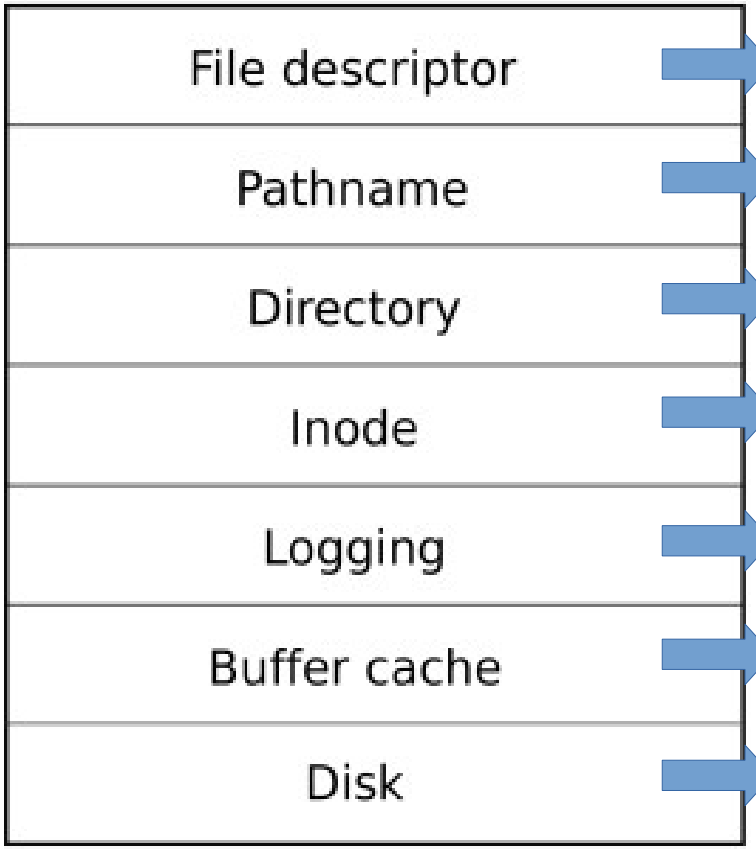
- Called by namei(), or nameiparent()
- Just iteratively split a path using “/” separator and get inode for last component
- iget() root inode, then
- Repeatedly calls
  - split on “/”, dirlookup() for next component
-

# races in namex()

- Crucial. Called so many times!
- one kernel thread is looking up a pathname another kernel thread may be changing the directory by calling unlink
  - when executing dirlookup in namex, the lookup thread holds the lock on the directory and dirlookup() returns an inode that was obtained using iget.
- Deadlock?  next points to the same inode as ip when looking up ".". Locking next before releasing the lock on ip would result in a deadlock.
  - namex unlocks the directory before obtaining a lock on next.

# File descriptor layer code

| | |
|---|---|
| System Calls | open, read, write, close, link, pipe, mknod, unlink, fstat, mkdir, chdir, dup, |




| |
|---|
| **file.c** fileinit, fileallocc, filedup, fileclose, filestat, fileread, filewrite, |
| **fs.c** namex, namei, nameiparent, skipelem |
| **fs.c** dirlookup, dirlink |
| **fs.c** iiinit, ialloc, iupdate,iget, idup, ilock, iunlock, iput, iunlockput, itrunc, stati, readi, writei, bmap, |
| Block allocation on disk: balloc, bfree<br>**log.c :** begin_op, end_op, initlog, commit, |
| **bio.c** binit, bget, bread, bwrite, brelse |
| **ide.c:** idewait, ideinit, idestart, ideintr, iderw |

# data structures related to “file” layer

```
struct file {
  enum { FD_NONE, FD_PIPE, FD_INODE } type;
  int ref; // reference count
  char readable;
  char writable;
  struct pipe *pipe; // used only if it works as a pipe
  struct inode *ip;
  uint off;
};
// interesting no lock in struct file !
```

```
struct proc {
...
  struct file *ofile[NOFILE];  // Open files per process
...
}
struct {
  struct spinlock lock;
  struct file file[NFILE];
} ftable; //global table from which ‘file’ is allocated to every process
```

Lock is used to protect updates to every entry in the array

# Multiple processes accessing same file.

- Each will get a different ‘struct file’
  - but share the inode !
  - different offset in struct file, for each process
  - Also true, if same process opens file many times
- File can be a PIPE (more later)
  - what about STDIN, STDOUT, STDERR files ?
  - Figure out!
- ref
  - used if the file was ‘duped’ or process forked . in that case the ‘struct file’ is shared

# file layer functions

- **filealloc**
  - find an empty struct file in ‘ftable’ and return it
  - set ref = 1
- **filedup(file *)**
  - simply ref++
- **fileclose**
  - --ref
  - if ref = 0
    - free struct file
    - iput() / pipeclose()
    - note – transaction if iput() called
- **filestat**
  - simply return fields from inode, after holding lock. on inodes for files only.

# file layer functions

- **fileread**
  - call readi() or piperead()
  - readi() later calls device-read or inode read (using bread())
- **filewrite**
  - call pipewrite() or writei()
  - writei() is called in a loop, within a transaction

- **Why does readi() call read on the device , why not fileread() itself call device read ?**

# pipes

```
struct pipe {
  struct spinlock lock;
  char data[PIPESIZE];
  uint nread;
 // number of bytes read
  uint nwrite;
 // number of bytes written
  int readopen;
  // read fd is still open
  int writeopen;
 // write fd is still open
};
```

- functions
  - pipealloc
  - pipeclose
  - piperead
  - pipewrite
-

# pipes

- **pipealloc**
  - allocate two struct file
  - allocate pipe itself using kalloc (it’s a big structure with array)
  - init lock
  - initialize both struct file as 2 ends (r/w)
- **pipewrite**
  - wait if pipe full
  - write to pipe
  - wakeup processes waiting to read
- **piperead**
  - wait if no data
  - read from pipe
  - wakeup processes waiting to write
- **Good producer consumer code !**

# Further to reading system call code now

- Now we are ready to read the code of system calls on file system
  - sys_open, sys_write, sys_read , etc.
- Advise: Before you read code of these, contemplate on what these functions should do using the functions we have studied so far.
- Also think of locks that need to be held.