# UNIX File Management

# UNIX File Management

- We will focus on two types of files
  - Ordinary files (stream of bytes)
  - Directories
- And mostly ignore the others
  - Character devices
  - Block devices
  - Named pipes
  - Sockets
  - Symbolic links

# UNIX index node *(inode)*

- Each file is represented by an Inode
- Inode contains all of a file's metadata
  - Access rights, owner,accounting info
  - (partial) block index table of a file
- Each inode has a unique number (within a partition)
  - System oriented name
  - Try 'ls –i' on Unix (Linux)
- Directories map file names to inode numbers
  - Map human-oriented to system-oriented names
  - Mapping can be *many-to-one*
    - Hard links

# Inode Contents

| |
|---|
| mode |
| uid |
| gid |
| atime |
| ctime |
| mtime |
| size |
| block count |
| reference count |
| direct blocks (10) |
| single indirect |
| double indirect |
| triple indirect |

- Mode
  - Type
    - Regular file or directory
  - Access mode
    - rwxrwxrwx
- Uid
  - User ID
- Gid
  - Group ID

# Inode Contents

| |
|---|
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| uid |
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| atime |
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| size |
| block count |
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| direct blocks (10) |
| single indirect |
| double indirect |
| triple indirect |

- atime
  - Time of last access
- ctime
  - Time when file was created
- mtime
  - Time when file was last modified

# Inode Contents

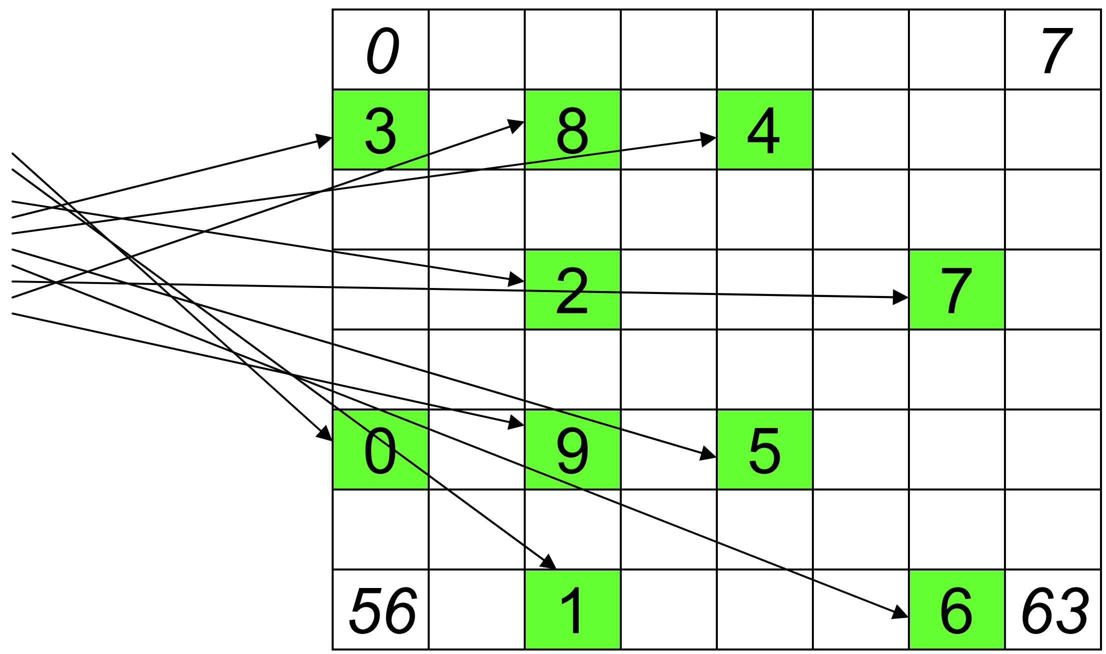
| |
|---|
| mode |
| uid |
| gid |
| atime |
| ctime |
| mtime |
| size |
| block count |
| reference count |
| direct blocks (10) |
| single indirect |
| double indirect |
| triple indirect |

- Size
  - Size of the file in bytes
- Block count
  - Number of disk blocks used by the file.
- Note that number of blocks can be much less than expected given the file size
  - Files can be sparsely populated
    - E.g. write(f,“hello”); lseek(f, 1000000); write(f, “world”);
    - Only needs to store the start an end of file, not all the empty blocks in between.
      - Size = 1000005
      - Blocks = 2 + overheads

# Inode Contents

| |
|---|
| mode |
| uid |
| gid |
| atime |
| ctime |
| mtime |
| size |
| block count |
| reference count |
| direct blocks (10)<br>40,58,26,8,12,<br>44,62,30,10,42 |
| single indirect |
| double indirect |
| triple indirect |

- Direct Blocks
  - Block numbers of first 10 blocks in the file
  - Most files are small
    - We can find blocks of file *directly* from the inode




Disk

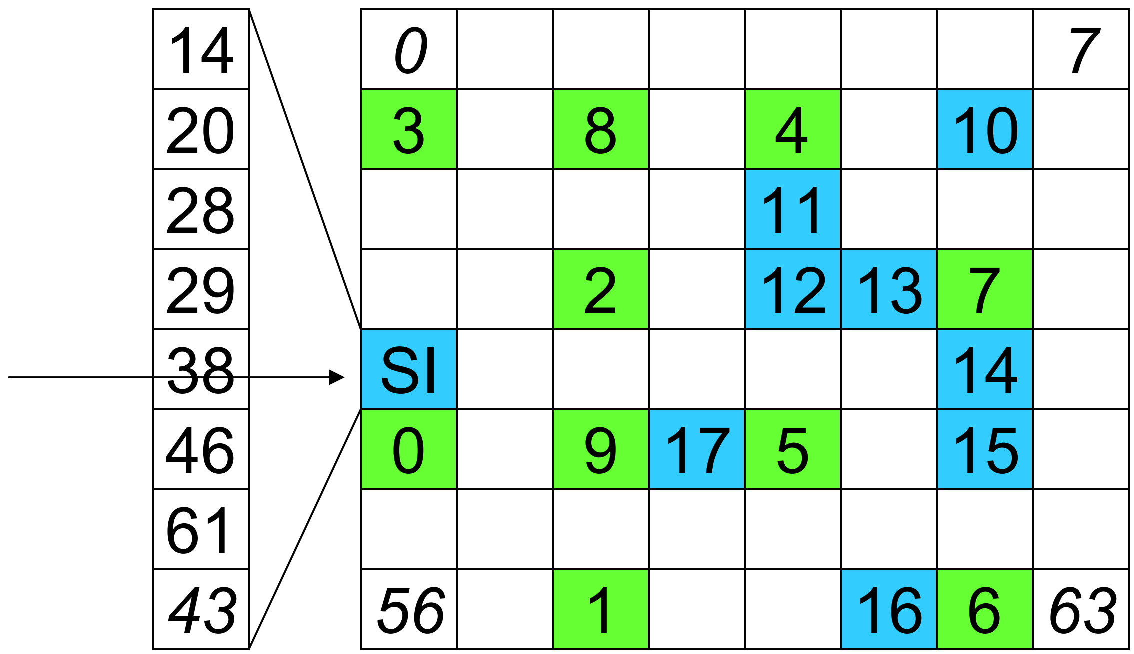
# Problem

- How do we store files greater than 10 blocks in size?
  - Adding significantly more direct entries in the inode results in many unused entries most of the time.

# Inode Contents

- Single Indirect Block
  - Block number of a block containing block numbers
    - In this case 8

| |
|---|
| mode |
| uid |
| gid |
| atime |
| ctime |
| mtime |
| size |
| block count |
| reference count |
| direct blocks (10) 40,58,26,8,12, 44,62,30,10,42 |
| single indirect: 32 |
| double indirect |
| triple indirect |




Disk

# Single Indirection

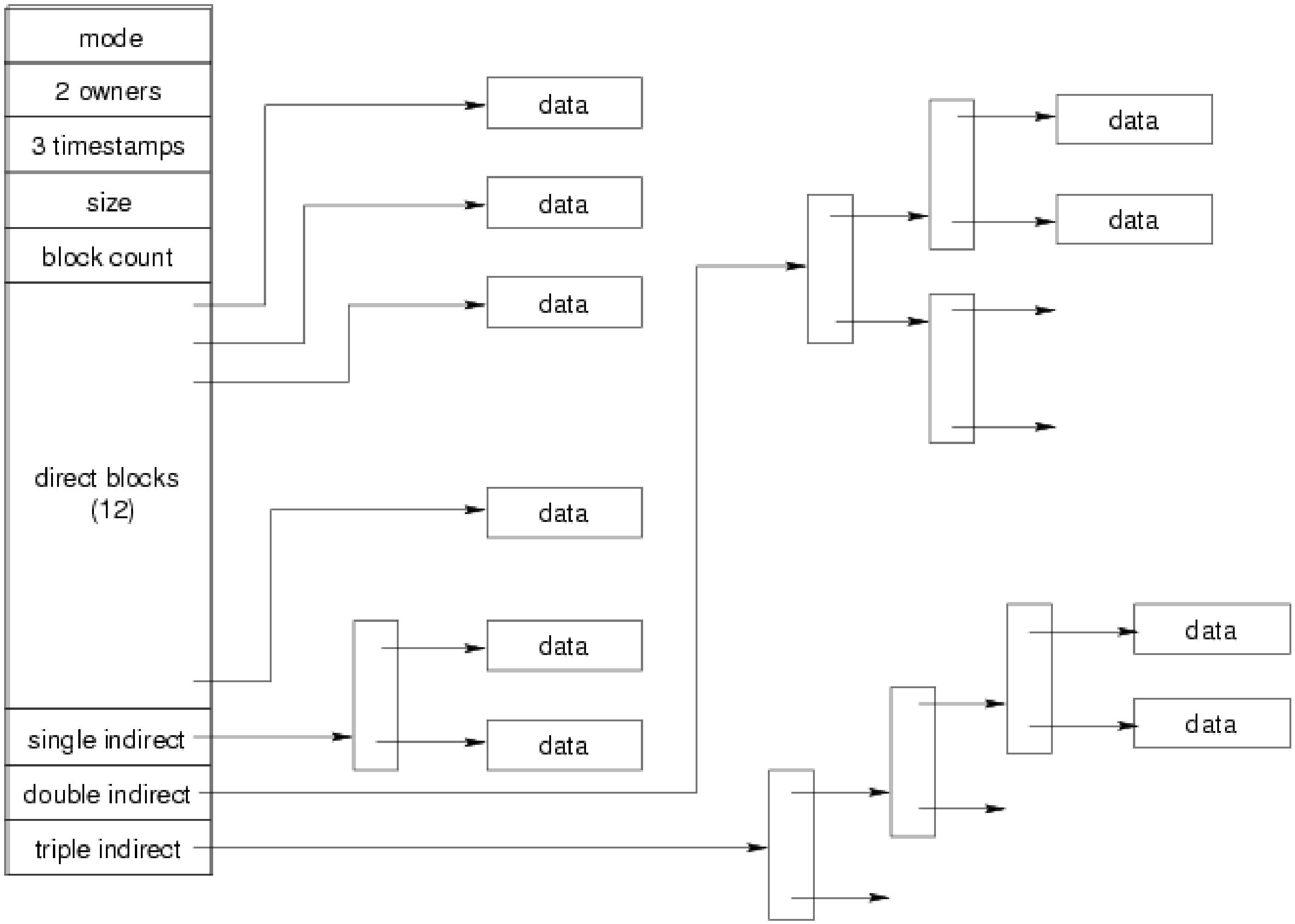
- Requires two disk access to read
  - One for the indirect block; one for the target block
- Max File Size
  - In previous example
    - 10 direct + 8 indirect = 18 block file
  - A more realistic example
    - Assume 1Kbyte block size, 4 byte block numbers
    - 10 * 1K + 1K/4 * 1K = 266 Kbytes
- For large majority of files (< 266 K), only one or two accesses required to read any block in file.

# Inode Contents

| |
|---|
| mode |
| uid |
| gid |
| atime |
| ctime |
| mtime |
| size |
| block count |
| reference count |
| direct blocks (10) 40,58,26,8,12, 44,62,30,10,42 |
| single indirect: 32 |
| double indirect |
| triple indirect |

- Double Indirect Block
  – Block number of a block containing block numbers of blocks containing block numbers
- Triple Indirect
  – Block number of a block containing block numbers of blocks containing block numbers of blocks containing block numbers ☺

# Unix Inode Block Addressing Scheme



# Max File Size

- Assume 4 bytes block numbers and 1K blocks
- The number of addressable blocks
  - Direct Blocks = 12
  - Single Indirect Blocks = 256
  - Double Indirect Blocks = 256 * 256 = 65536
  - Triple Indirect Blocks = 256 * 256 * 256 = 16777216
- Max File Size
  - 12 + 256 + 65536 + 16777216 = 16843020 = 16 GB

# Some Best and Worst Case Access Patterns

- To read 1 byte
  - Best:
    - 1 access via direct block
  - Worst:
    - 4 accesses via the triple indirect block
- To write 1 byte
  - Best:
    - 1 write via direct block (with no previous content)
  - Worst:
    - 4 reads (to get previous contents of block via triple indirect) + 1 write (to write modified block back)

# Worst Case Access Patterns with Unallocated Indirect Blocks

- Worst to write 1 byte
  - 4 writes (3 indirect blocks; 1 data)
  - 1 read, 4 writes (read-write 1 indirect, write 2; write 1 data)
  - 2 reads, 3 writes (read 1 indirect, read-write 1 indirect, write 1; write 1 data)
  - 3 reads, 2 writes (read 2, read-write 1; write 1 data)
- Worst to read 1 byte
  - If reading writes an zero-filled block on disk
    - Worst case is same as write 1 byte
  - If not, worst-case depends on how deep is the current indirect block tree.

# Inode Summary

- The inode contains the on disk data associated with a file
  - Contains mode, owner, and other bookkeeping
  - Efficient random and sequential access via *indexed allocation*
  - Small files (the majority of files) require only a single access
  - Larger files require progressively more disk accesses for random access
    - Sequential access is still efficient
  - Can support really large files via increasing levels of indirection

# Where/How are Inodes Stored

| | | | |
|---|---|---|---|
| Boot Block | Super Block | Inode Array | Data Blocks |

- System V Disk Layout (s5fs)
  - Boot Block
    - contain code to bootstrap the OS
  - Super Block
    - Contains attributes of the file system itself
      - e.g. size, number of inodes, start block of inode array, start of data block area, free inode list, free data block list
  - Inode Array
  - Data blocks

# Some problems with s5fs

- Inodes at start of disk; data blocks end
  - Long seek times
    - Must read inode before reading data blocks
- Only one superblock
  - Corrupt the superblock and entire file system is lost
- Block allocation suboptimal
  - Consecutive free block list created at FS format time
    - Allocation and de-allocation eventually randomises the list resulting the random allocation
- Inodes allocated randomly
  - Directory listing resulted in random inode access patterns

# Berkeley Fast Filesystem (FFS)

- Historically followed s5fs
  - Addressed many limitations with s5fs
  - Linux mostly similar, so we will focus on Linux

# The Linux Ext2 File System

- Second Extended Filesystem
  - Evolved from Minix filesystem (via “Extended Filesystem”)
- Features
  - Block size (1024, 2048, and 4096) configured as FS creation
  - Pre-allocated inodes (max number also configured at FS creation)
  - Block groups to increase locality of reference (from BSD FFS)
  - Symbolic links < 60 characters stored within inode
- Main Problem: unclean unmount → **`e2fsck`**
  - Ext3fs keeps a journal of (meta-data) updates
  - Journal is a file where updated are logged
  - Compatible with ext2fs

# Layout of an Ext2 Partition

| Boot Block | Block Group 0 | …. | Block Group *n* |
|---|---|---|---|

- Disk divided into one or more *partitions*
- Partition:
  - Reserved boot block,
  - Collection of equally sized *block groups*
  - All block groups have the same structure

# Layout of a Block Group

| Super Block | Group Descrip-tors | Data Block Bitmap | Inode Bitmap | Inode Table | Data blocks |
|---|---|---|---|---|---|
| 1 blk | *n* blks | 1 blk | 1 blk | *m* blks | *k* blks |

- *Replicated* super block
  - For e2fsck
- Group descriptors
- Bitmaps identify used inodes/blocks
- All block have the same number of data blocks
- Advantages of this structure:
  - Replication simplifies recovery
  - Proximity of inode tables and data blocks (reduces seek time)

# Superblocks

- Size of the file system, block size and similar parameters
- Overall free inode and block counters
- Data indicating whether file system check is needed:
  - Uncleanly unmounted
  - Inconsistency
  - Certain number of mounts since last check
  - Certain time expired since last check
- Replicated to provide redundancy to add recoverability

# Group Descriptors

- Location of the bitmaps
- Counter for free blocks and inodes in this group
- Number of directories in the group

# Performance considerations

- EXT2 optimisations
  - Read-ahead for directories
    - For directory searching
  - Block groups cluster related inodes and data blocks
  - Pre-allocation of blocks on write (up to 8 blocks)
    - 8 bits in bit tables
    - Better contiguity when there are concurrent writes
- FFS optimisations
  - Files within a directory in the same group

# Thus far…

- Inodes representing files laid out on disk.
- Inodes are referred to by number!!!
  - How do users name files? By number?
  - Try ls –i to see how useful inode numbers are….

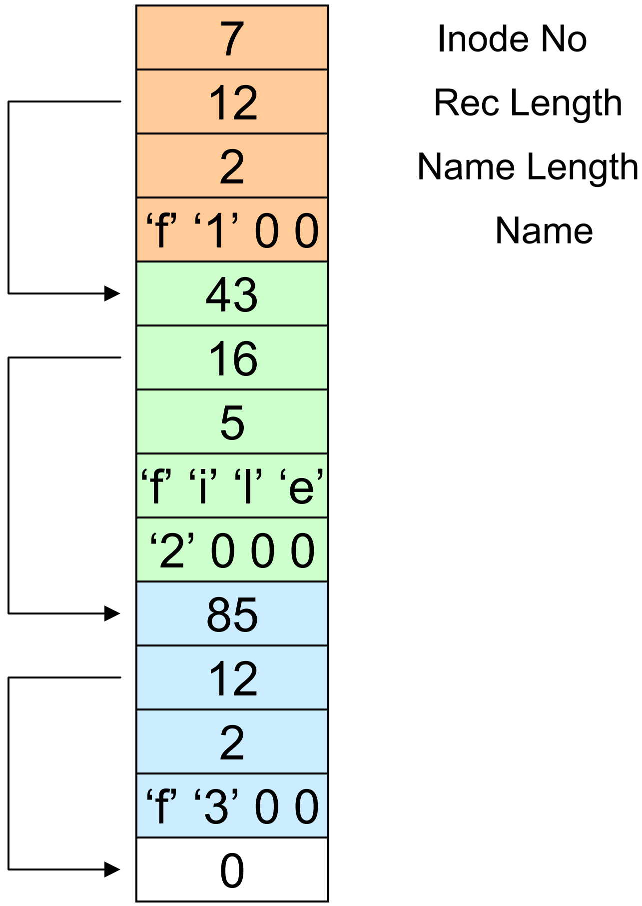
# Ext2fs Directories

| | | | | |
|---|---|---|---|---|
| inode | rec_len | name_len | type | name… |

- Directories are files of a special type
  - Consider it a file of special format, managed by the kernel, that uses most of the same machinery to implement it
    - Inodes, etc…
- Directories translate names to inode numbers
- Directory entries are of variable length
- Entries can be deleted in place
  - inode = 0
  - Add to length of previous entry
  - use null terminated strings for names

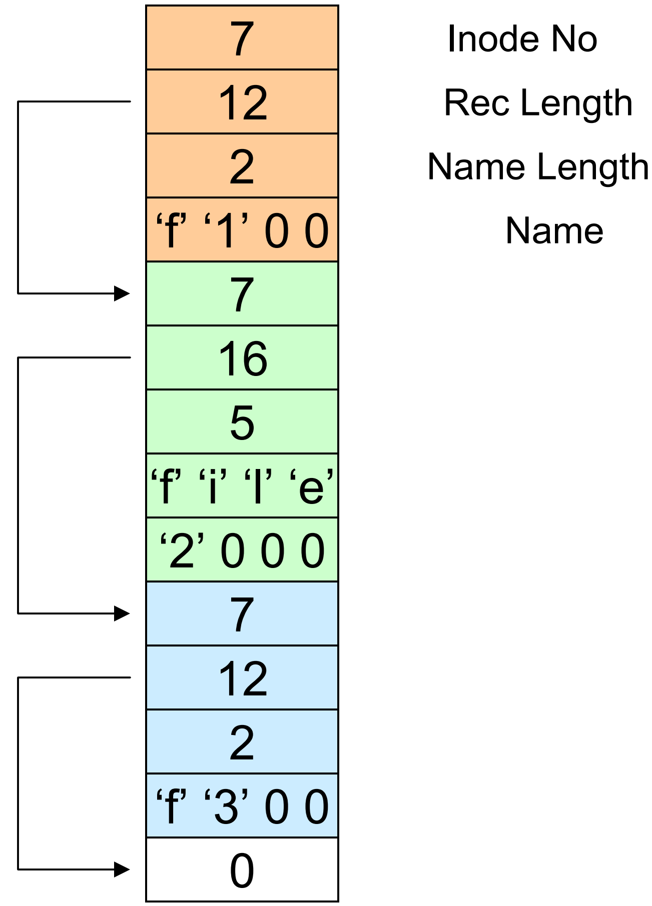
# Ext2fs Directories

- "f1" = inode 7
- "file2" = inode 43
- "f3" = inode 85



# Ext2fs Directories

- Note that inodes can have more than one name
  - Called a *Hard Link*
  - Inode (file) 7 has three names
    - "f1" = inode 7
    - "file2" = inode 7
    - "f3" = inode 7



# Inode Contents

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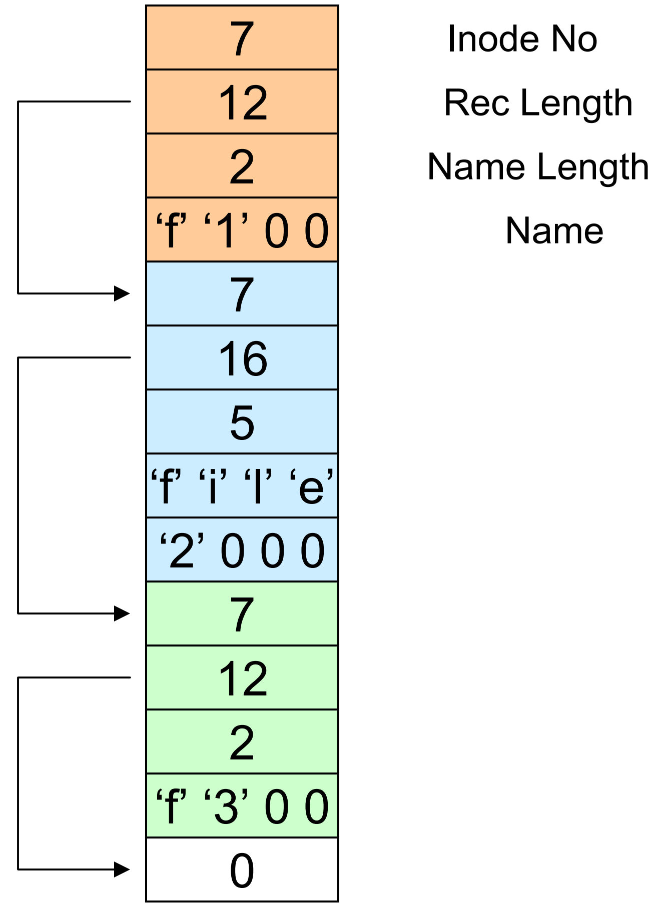
- We can have many name for the same inode.
- When we delete a file by name, i.e. remove the directory entry (link), how does the file system know when to delete the underlying inode?
  - Keep a *reference count* in the inode
    - Adding a name (directory entry) increments the count
    - Removing a name decrements the count
    - If the reference count == 0, then we have no names for the inode (it is unreachable), we can delete the inode (underlying file or directory)

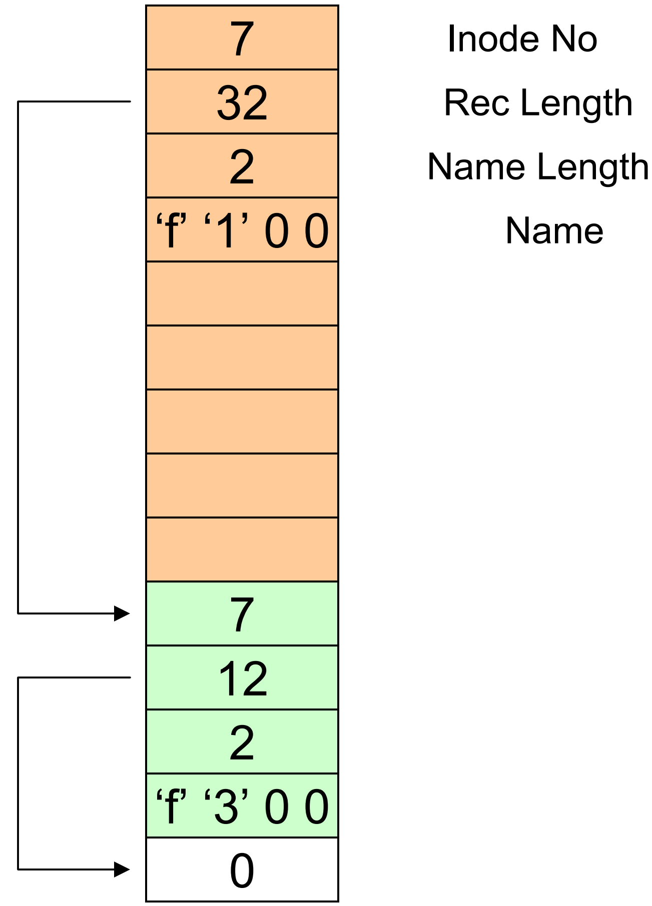
# Ext2fs Directories

- Deleting a filename
  - rm file2



# Ext2fs Directories

- Deleting a filename
  - rm file2
- Adjust the record length to skip to next valid entry



# Kernel File-related Data Structures and Interfaces

- We have reviewed how files and directories are stored on disk
- We know the UNIX file system-call interface
  - open, close, read, write, lseek,…..

- What is in between?

# What do we need to keep track of?

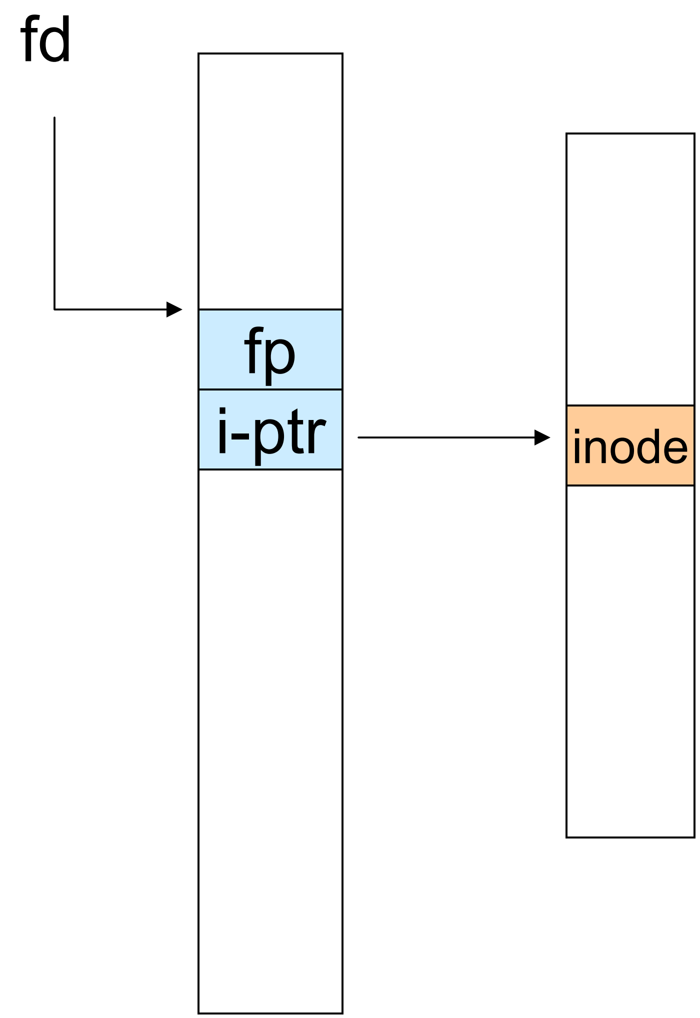
- File descriptors
  - Each open file has a file descriptor
  - Read/Write/lseek/…. use them to specify which file to operate on.
- File pointer
  - Determines where in the file the next read or write is performed
- Mode
  - Was the file opened read-only, etc….

# An Option?

- Use inode numbers as file descriptors and add a file pointer to the inode
- Problems
  - What happens when we concurrently open the same file twice?
    - We should get two separate file descriptors and file pointers….

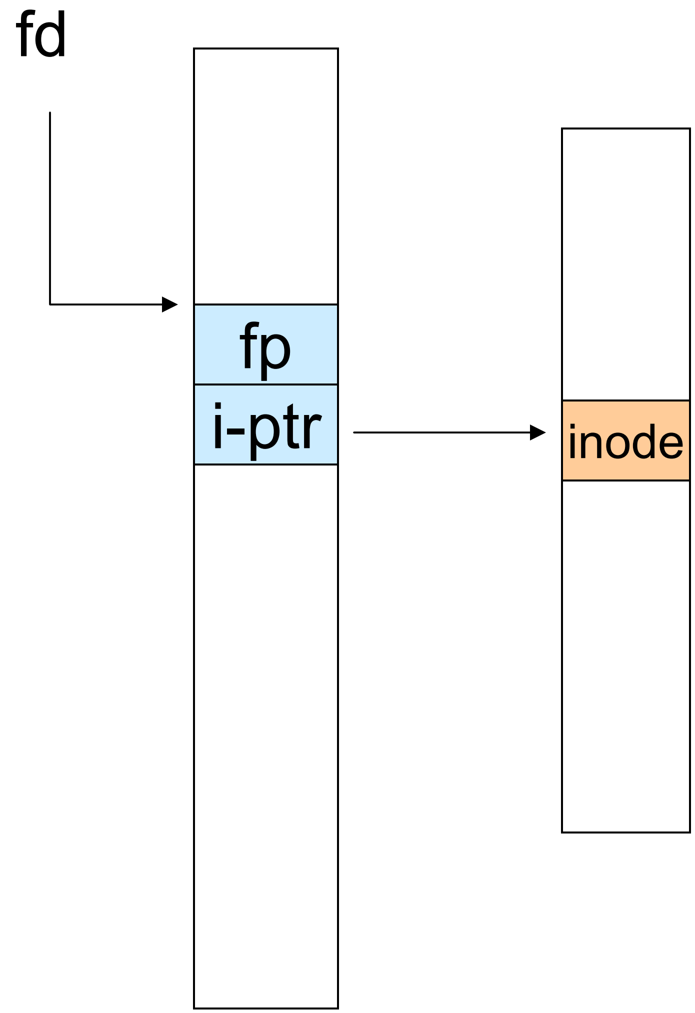
# An Option?

- Single global open file array
  - *fd* is an index into the array
  - Entries contain file pointer and pointer to an inode



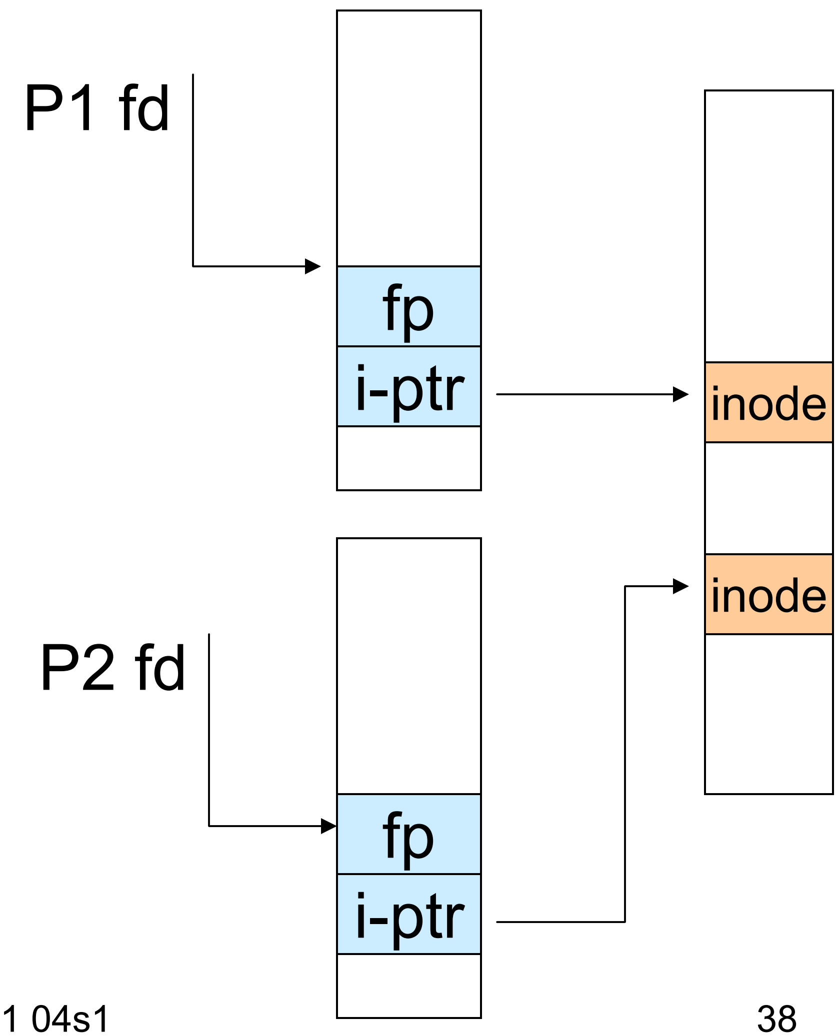
# Issues

- File descriptor 1 is stdout
  - Stdout is
    - console for some processes
    - A file for others
- Entry 1 needs to be different per process!



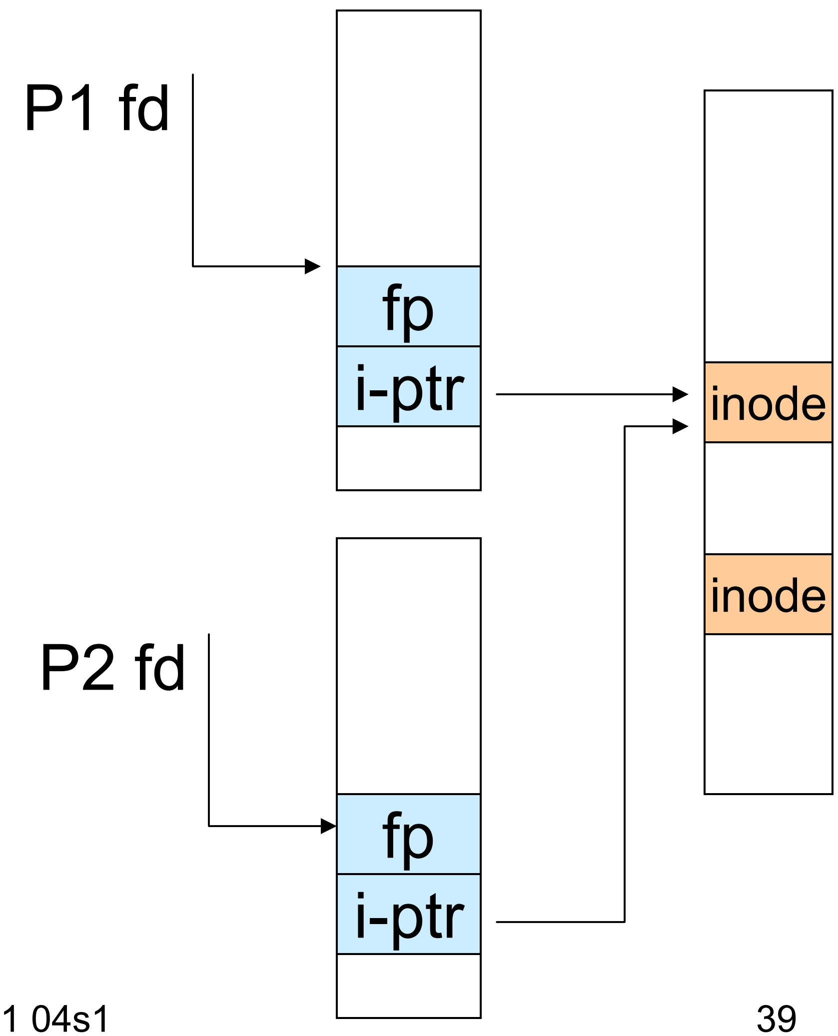
# Per-process File Descriptor Array

- Each process has its own open file array
  - Contains fp, i-ptr etc.
  - *Fd* 1 can be any inode for each process (console, log file).



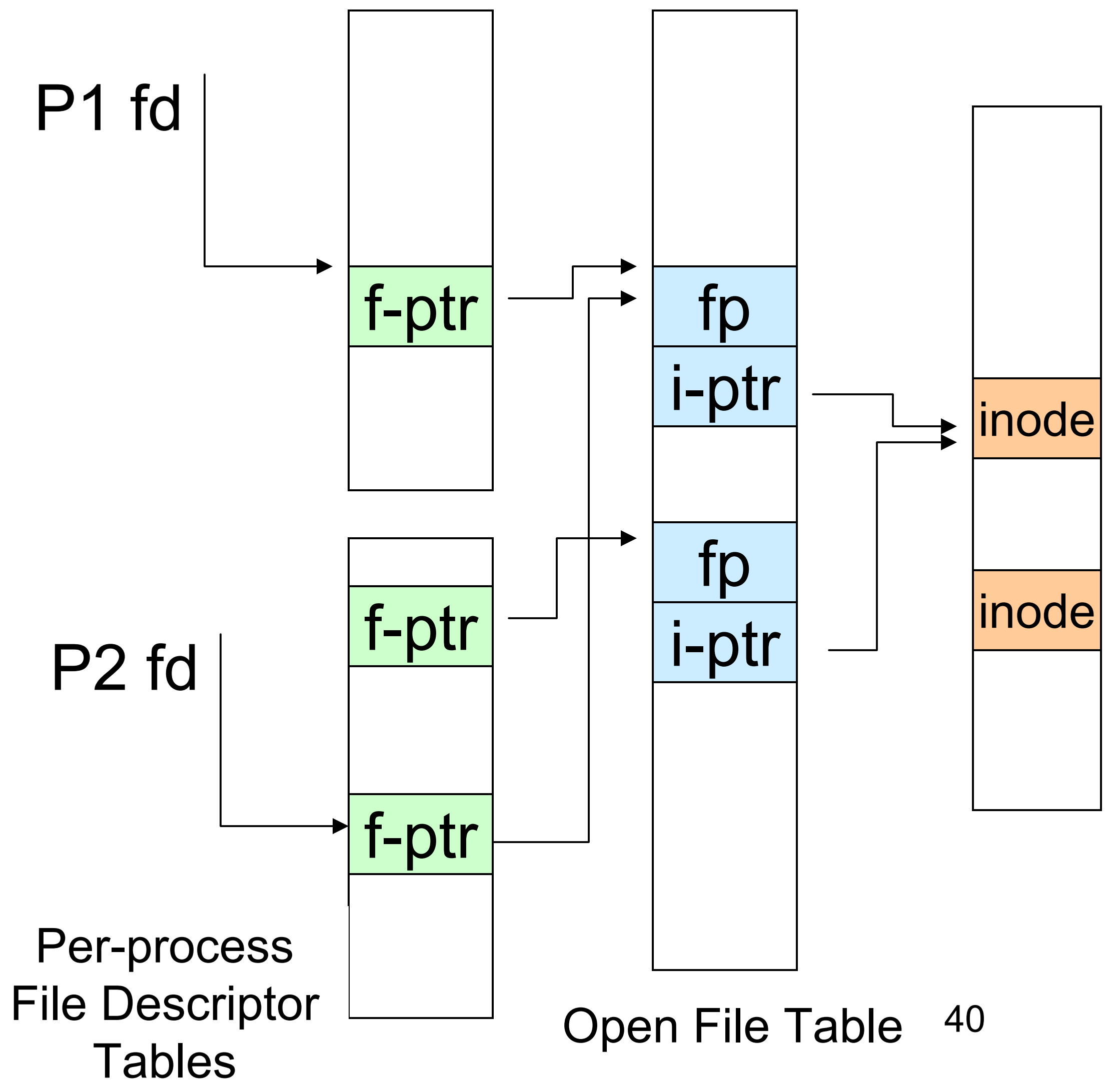
# Issue

- Fork
  - Fork defines that the child shares the file pointer with the parent
- Dup2
  - Also defines the file descriptors share the file pointer
- With per-process table, we can only have independent file pointers
  - Even when accessing the same file



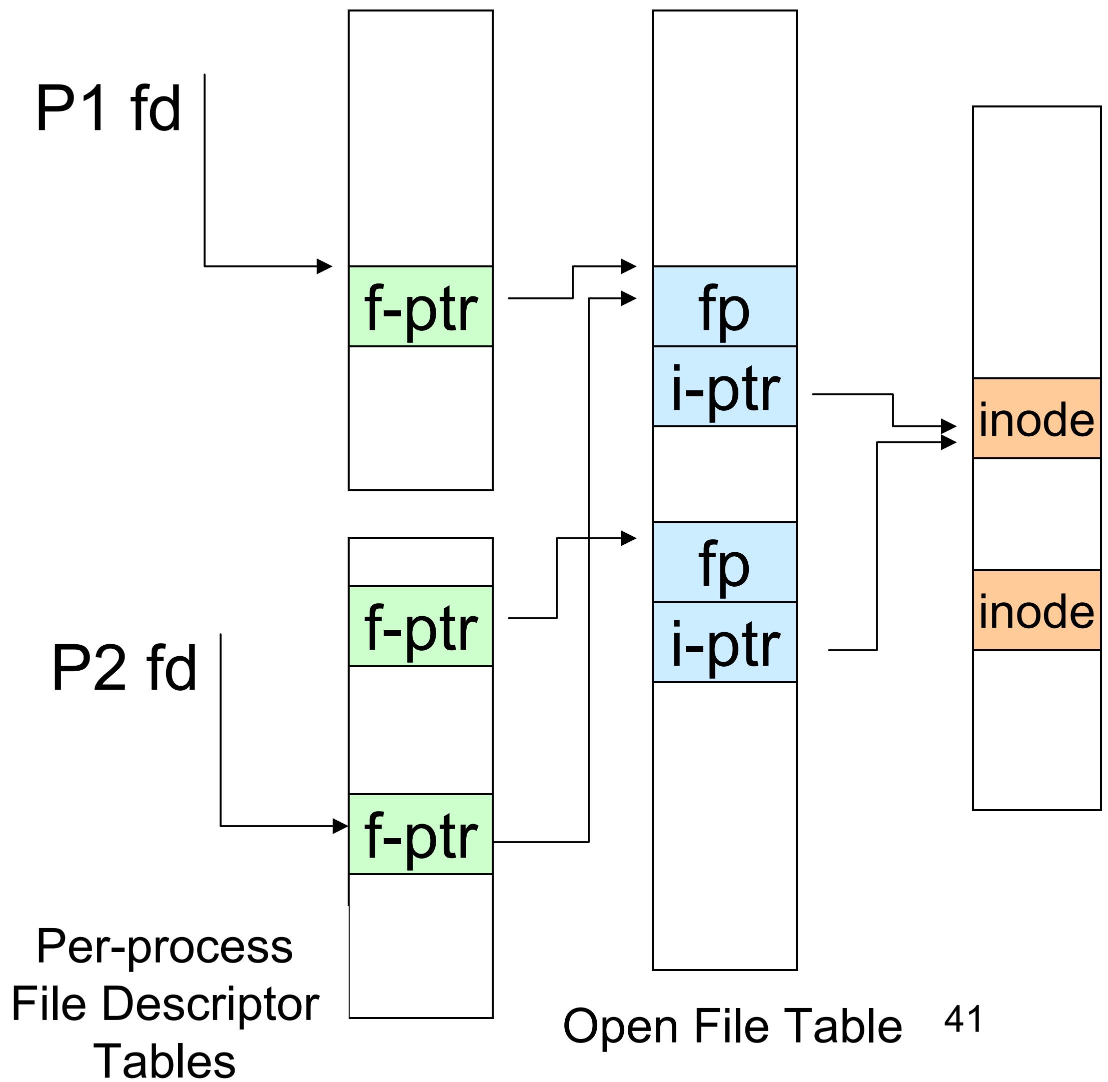
# Per-Process *fd* table with global open file table

- Per-process file descriptor array
  - Contains pointers to *open file table entry*
- Open file table array
  - Contain entries with a fp and pointer to an inode.
- Provides
  - Shared file pointers if required
  - Independent file pointers if required
- Example:
  - All three *fds* refer to the same file, two share a file pointer, one has an independent file pointer



# Per-Process *fd* table with global open file table

- Used by Linux and most other Unix operating systems



# Older Systems only had a single file system

- They had file system specific open, close, read, write, … calls.
- The open file table pointed to an in-memory representation of the inode
  - inode format was specific to the file system used (s5fs, Berkley FFS, etc)
- However, modern systems need to support many file system types
  - ISO9660 (CDROM), MSDOS (floppy), ext2fs, tmpfs

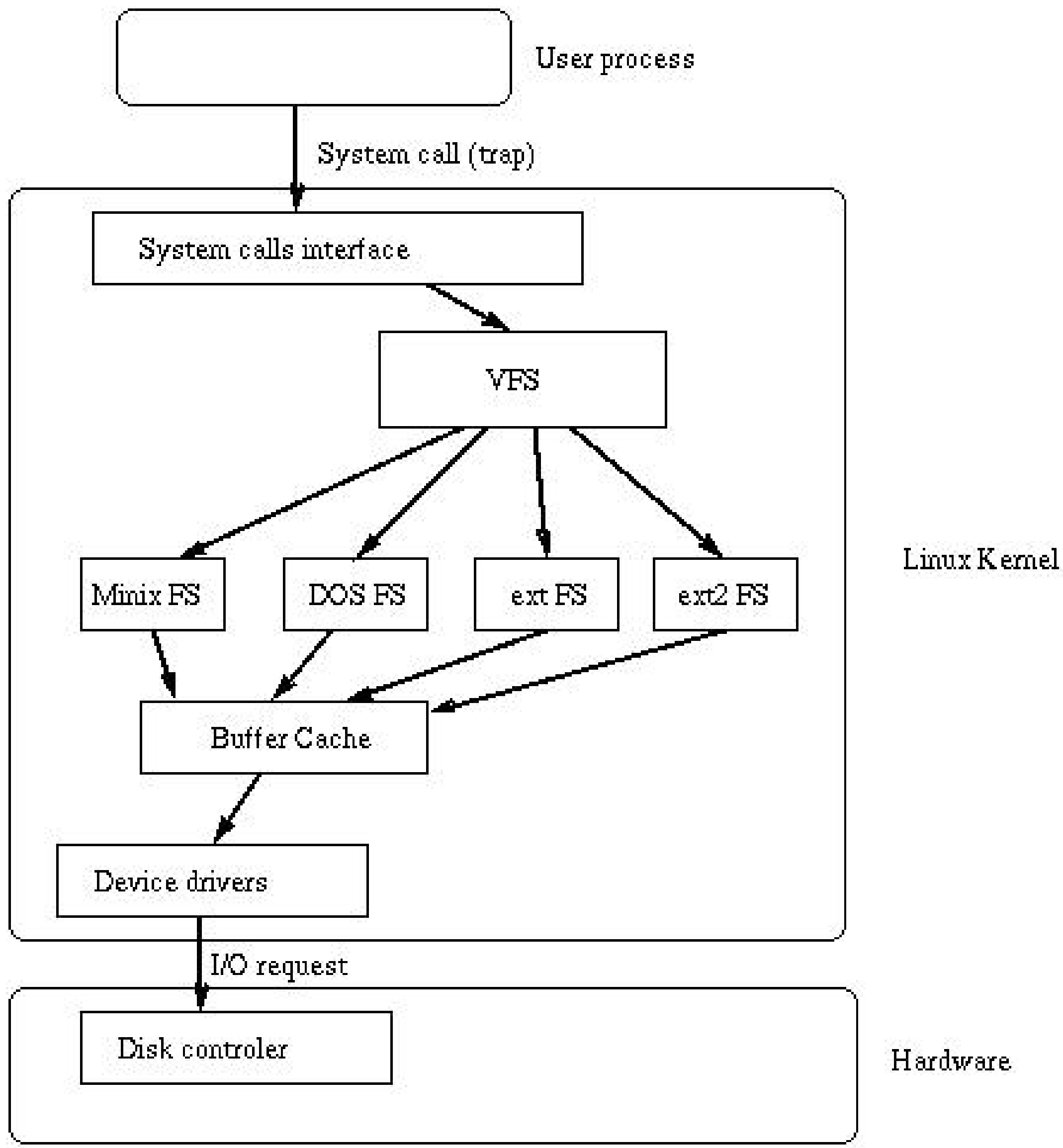
# Supporting Multiple File Systems

- Alternatives
  - Change the file system code to understand different file system types
    - Prone to code bloat, complex, non-solution
  - Provide a framework that separates file system independent and file system dependent code.
    - Allows different file systems to be "plugged in"
    - File descriptor, open file table and other parts of the kernel can be independent of underlying file system

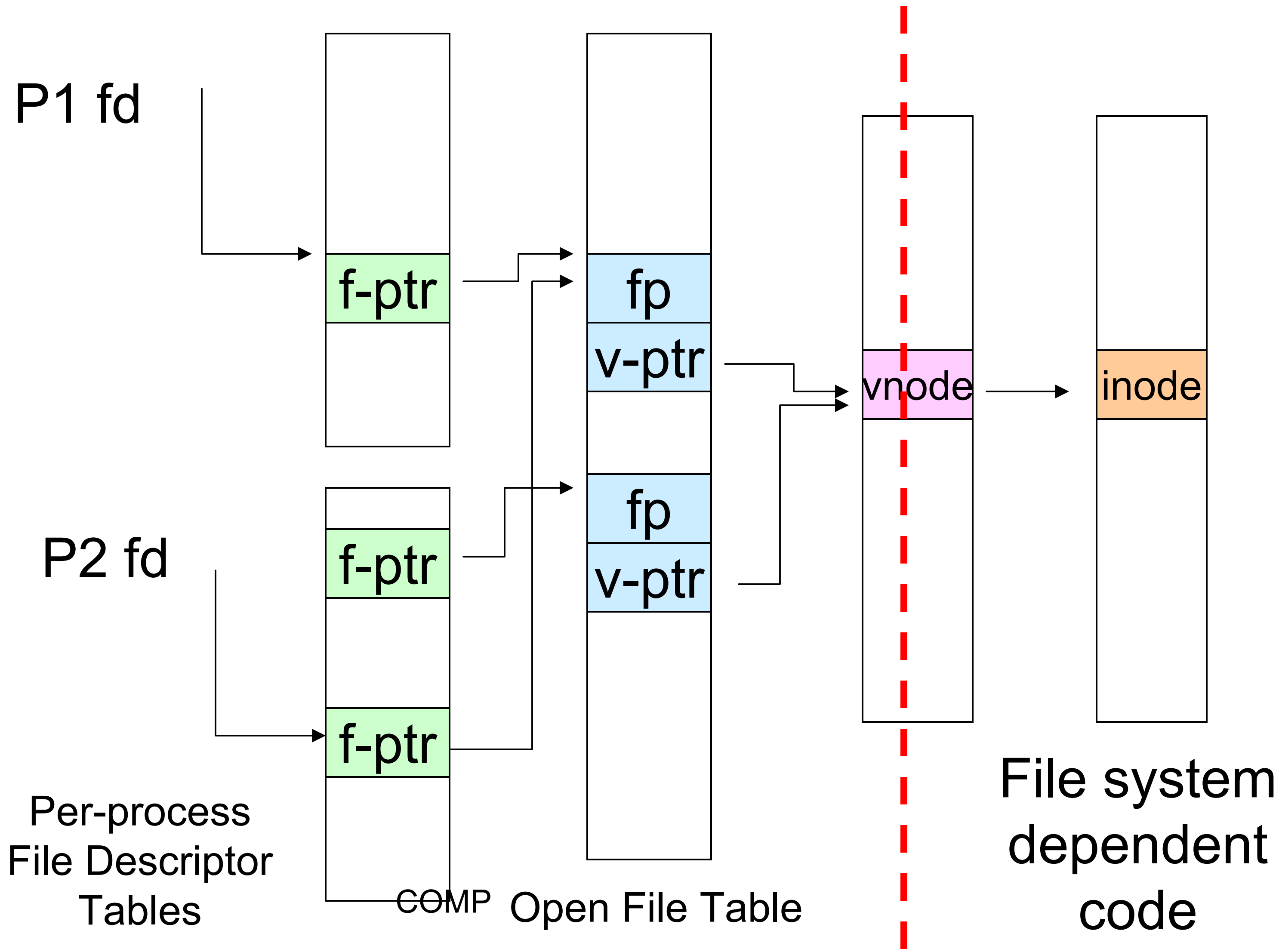
# Virtual File System (VFS)

- Provides single system call interface for many file systems
  - E.g., UFS, Ext2, XFS, DOS, ISO9660,…
- Transparent handling of network file systems
  - E.g., NFS, AFS, CODA
- File-based interface to arbitrary device drivers (`/dev`)
- File-based interface to kernel data structures (`/proc`)
- Provides an indirection layer for system calls
  - File operation table set up at file open time
  - Points to actual handling code for particular type
  - Further file operations redirected to those functions

# VFS architecture



# The file system independent code deals with vfs and vnodes



# VFS Interface

- Reference
  - S.R. Kleiman., "Vnodes: An Architecture for Multiple File System Types in Sun Unix," USENIX Association: Summer Conference Proceedings, Atlanta, 1986
  - Linux and OS/161 differ slightly, but the principles are the same
- Two major data types
  - vfs
    - Represents all file system types
    - Contains pointers to functions to manipulate each file system as a whole (e.g. mount, unmount)
      - Form a standard interface to the file system
  - vnode
    - Represents a file (inode) in the underlying filesystem
    - Points to the real inode
    - Contains pointers to functions to manipulate files/inodes (e.g. open, close, read, write,…)

# A look at OS/161's VFS

The OS161's file system type

Represents interface to a mounted filesystem

```
struct fs {
   int            (*fs_sync)(struct fs *);
   const char    *(*fs_getvolname)(struct fs *);
   struct vnode *(*fs_getroot)(struct fs *);
   int            (*fs_unmount)(struct fs *);

   void *fs_data;
};
```

Force the filesystem to flush its content to disk

Retrieve the volume name

Retrieve the vnode associates with the root of the filesystem

Unmount the filesystem
Note: mount called via function ptr passed to **vfs_mount**

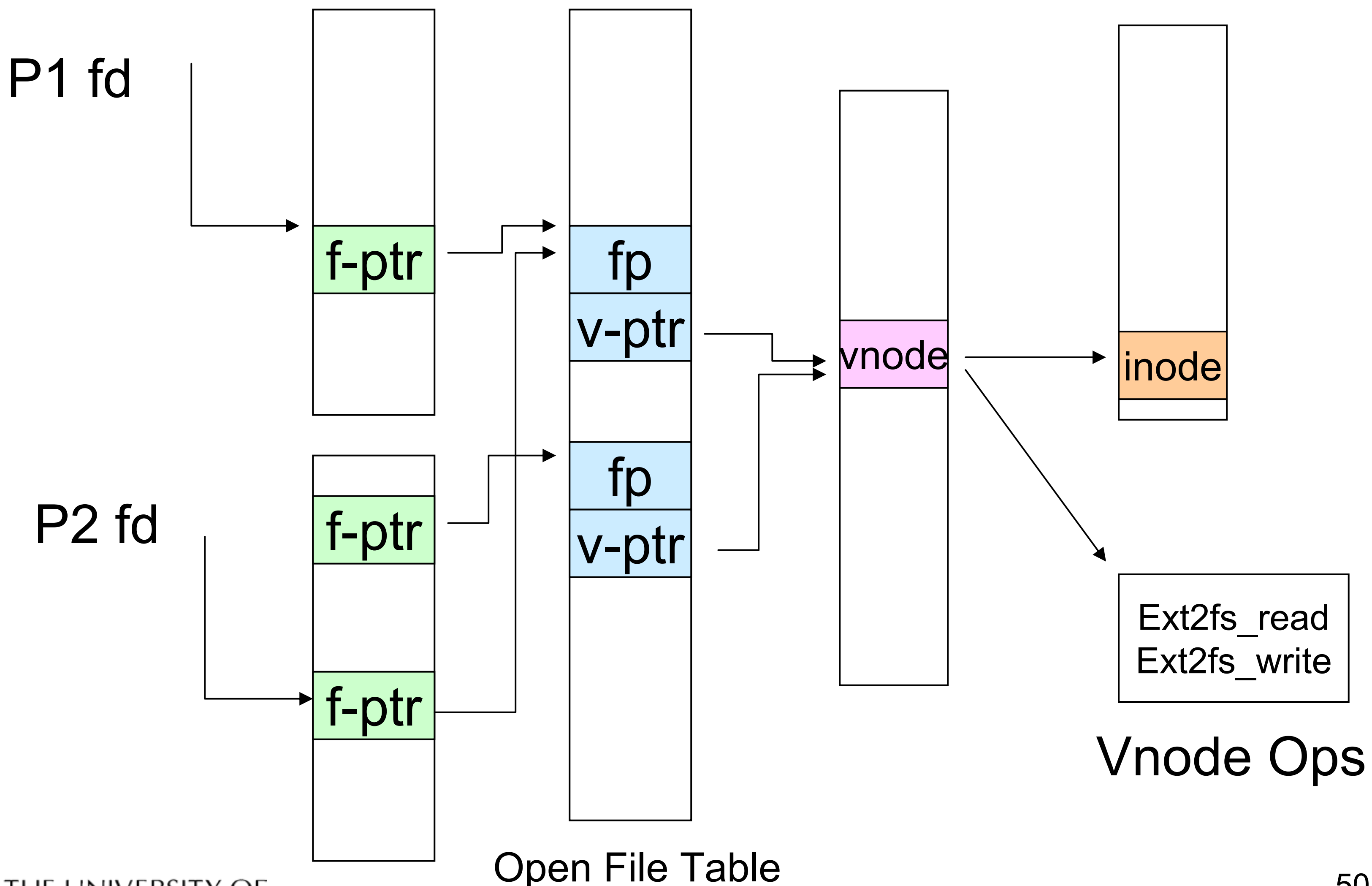
Private file system specific date

# Vnode

```
struct vnode {
  int vn_refcount;
  int vn_opencount;
  struct lock *vn_countlock;
  struct fs *vn_fs;
  void *vn_data;

  const struct vnode_ops *vn_ops;
};
```

- vn_refcount: Count the number of "references" to this vnode
- vn_opencount: Number of times vnode is currently open
- vn_countlock: Lock for mutual exclusive access to counts
- vn_fs: Pointer to FS containing the vnode
- vn_data: Pointer to FS specific vnode data (e.g. inode)
- vn_ops: Array of pointers to functions operating on vnodes

# Access Vnodes via Vnode Operations



# Vnode Ops

```
struct vnode_ops {
   unsigned long vop_magic;        /* should always be VOP_MAGIC */

   int (*vop_open)(struct vnode *object, int flags_from_open);
   int (*vop_close)(struct vnode *object);
   int (*vop_reclaim)(struct vnode *vnode);


   int (*vop_read)(struct vnode *file, struct uio *uio);
   int (*vop_readlink)(struct vnode *link, struct uio *uio);
   int (*vop_getdirentry)(struct vnode *dir, struct uio *uio);
   int (*vop_write)(struct vnode *file, struct uio *uio);
   int (*vop_ioctl)(struct vnode *object, int op, userptr_t data);
   int (*vop_stat)(struct vnode *object, struct stat *statbuf);
   int (*vop_gettype)(struct vnode *object, int *result);
   int (*vop_tryseek)(struct vnode *object, off_t pos);
   int (*vop_fsync)(struct vnode *object);
   int (*vop_mmap)(struct vnode *file /* add stuff */);
   int (*vop_truncate)(struct vnode *file, off_t len);
   int (*vop_namefile)(struct vnode *file, struct uio *uio);
```

# Vnode Ops

```
int (*vop_creat)(struct vnode *dir,
               const char *name, int excl,
               struct vnode **result);
int (*vop_symlink)(struct vnode *dir,
                 const char *contents, const char *name);
int (*vop_mkdir)(struct vnode *parentdir,
               const char *name);
int (*vop_link)(struct vnode *dir,
              const char *name, struct vnode *file);
int (*vop_remove)(struct vnode *dir,
                const char *name);
int (*vop_rmdir)(struct vnode *dir,
               const char *name);

int (*vop_rename)(struct vnode *vn1, const char *name1,
                struct vnode *vn2, const char *name2);


int (*vop_lookup)(struct vnode *dir,
                char *pathname, struct vnode **result);
int (*vop_lookparent)(struct vnode *dir,
                    char *pathname, struct vnode **result,
                    char *buf, size_t len);
};
```

# Vnode Ops

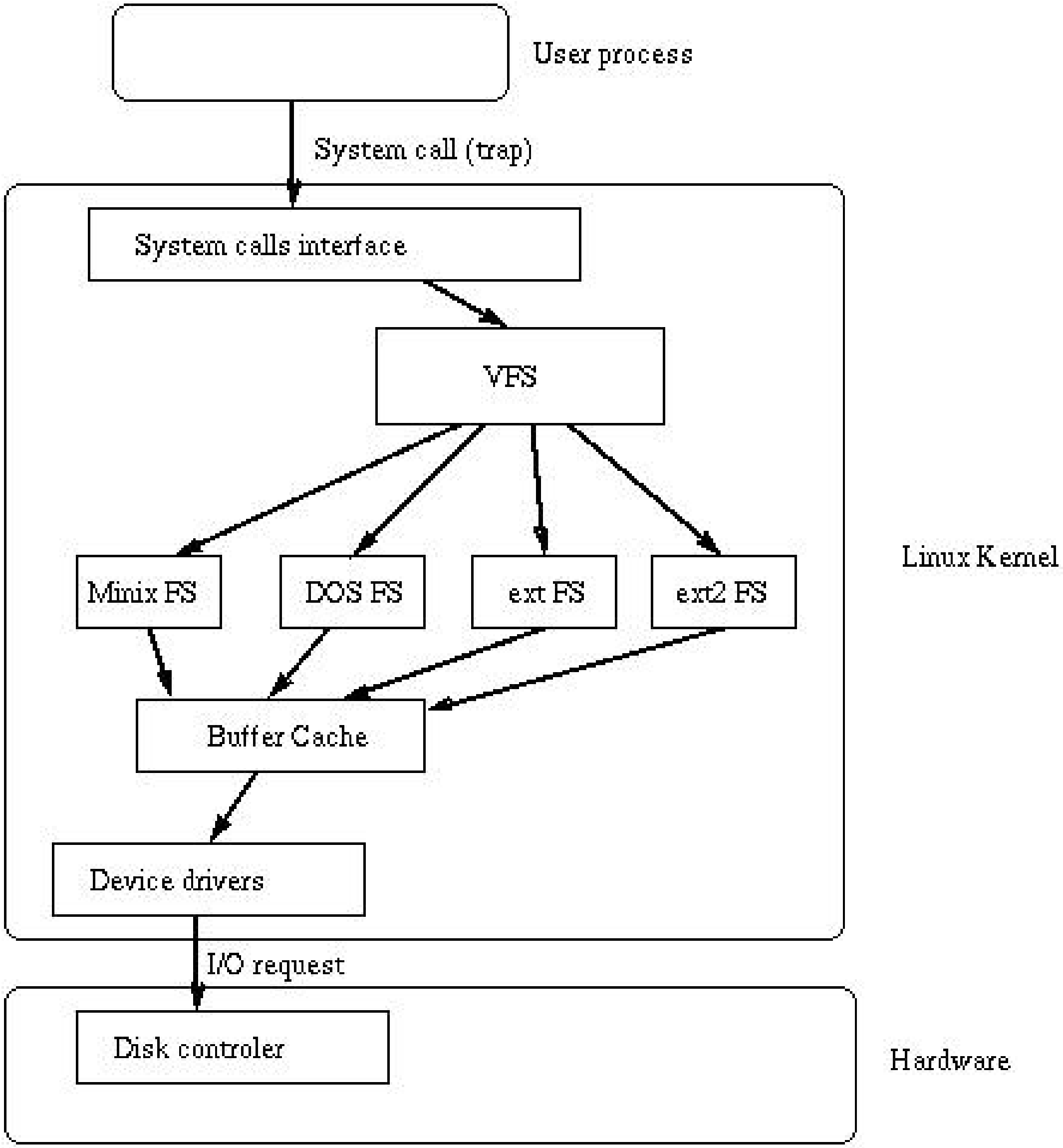
- Note that most operation are on vnodes. How do we operate on file names?
  - Higher level API on names that uses the internal VOP_* functions

```
int vfs_open(char *path, int openflags, struct vnode **ret);
void vfs_close(struct vnode *vn);
int vfs_readlink(char *path, struct uio *data);
int vfs_symlink(const char *contents, char *path);
int vfs_mkdir(char *path);
int vfs_link(char *oldpath, char *newpath);
int vfs_remove(char *path);
int vfs_rmdir(char *path);
int vfs_rename(char *oldpath, char *newpath);

int vfs_chdir(char *path);
int vfs_getcwd(struct uio *buf);
```

# Example: OS/161 emufs vnode ops

```
/*
 * Function table for emufs
   files.
 */
static const struct vnode_ops
   emufs_fileops = {
   VOP_MAGIC,   /* mark this a
   valid vnode ops table */

   emufs_open,
   emufs_close,
   emufs_reclaim,

   emufs_read,
   NOTDIR,   /* readlink */
   NOTDIR,   /* getdirentry */
   emufs_write,
   emufs_ioctl,
   emufs_stat,

   emufs_file_gettype,
   emufs_tryseek,
   emufs_fsync,
   UNIMP,    /* mmap */
   emufs_truncate,
   NOTDIR,   /* namefile */

   NOTDIR,   /* creat */
   NOTDIR,   /* symlink */
   NOTDIR,   /* mkdir */
   NOTDIR,   /* link */
   NOTDIR,   /* remove */
   NOTDIR,   /* rmdir */
   NOTDIR,   /* rename */

   NOTDIR,   /* lookup */
   NOTDIR,   /* lookparent */
};
```

# Buffer Cache

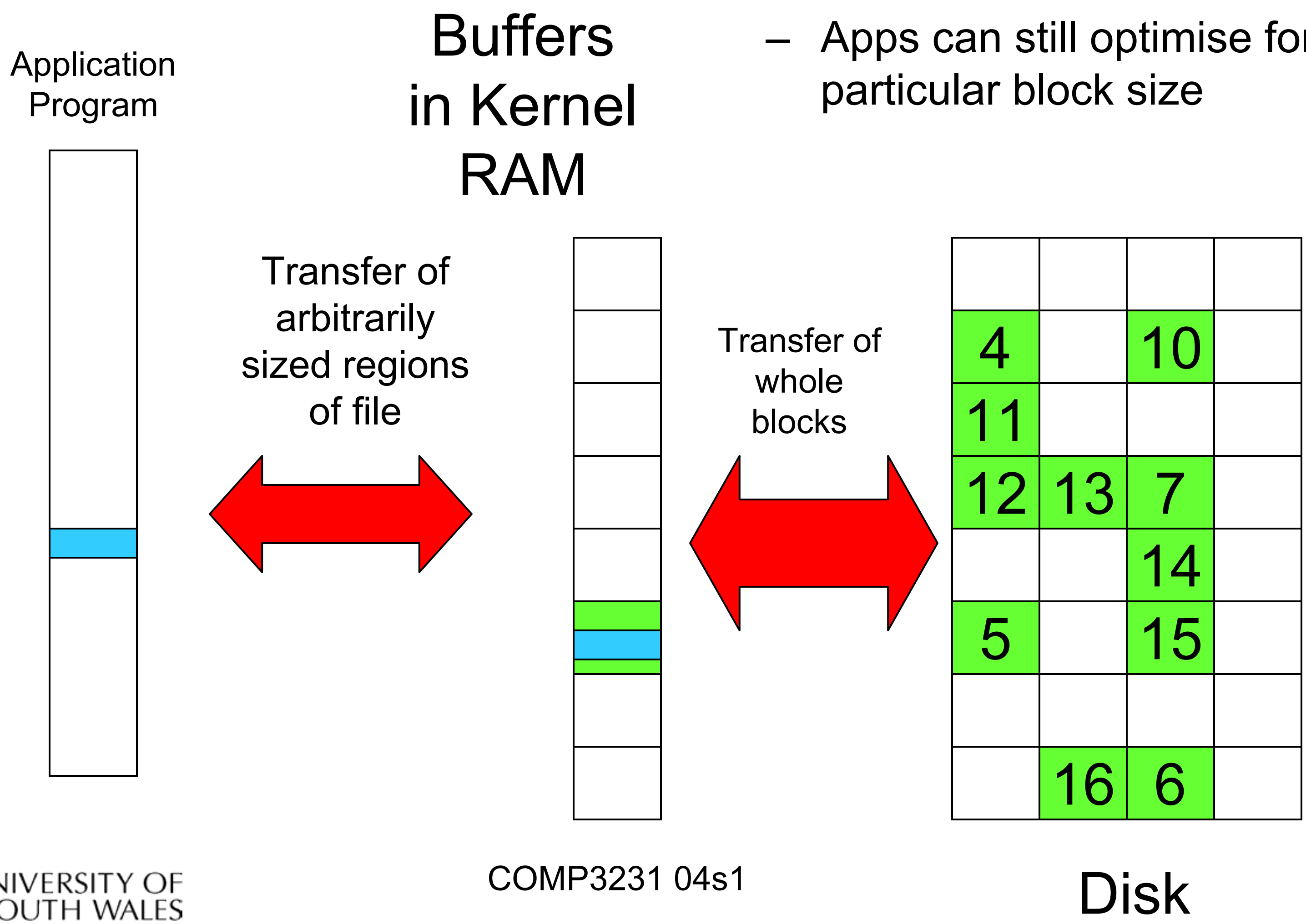


# Buffer

- Buffer:
  - Temporary storage used when transferring data between two entities
    - Especially when the entities work at different rates
    - Or when the unit of transfer is incompatible
    - Example: between application program and disk

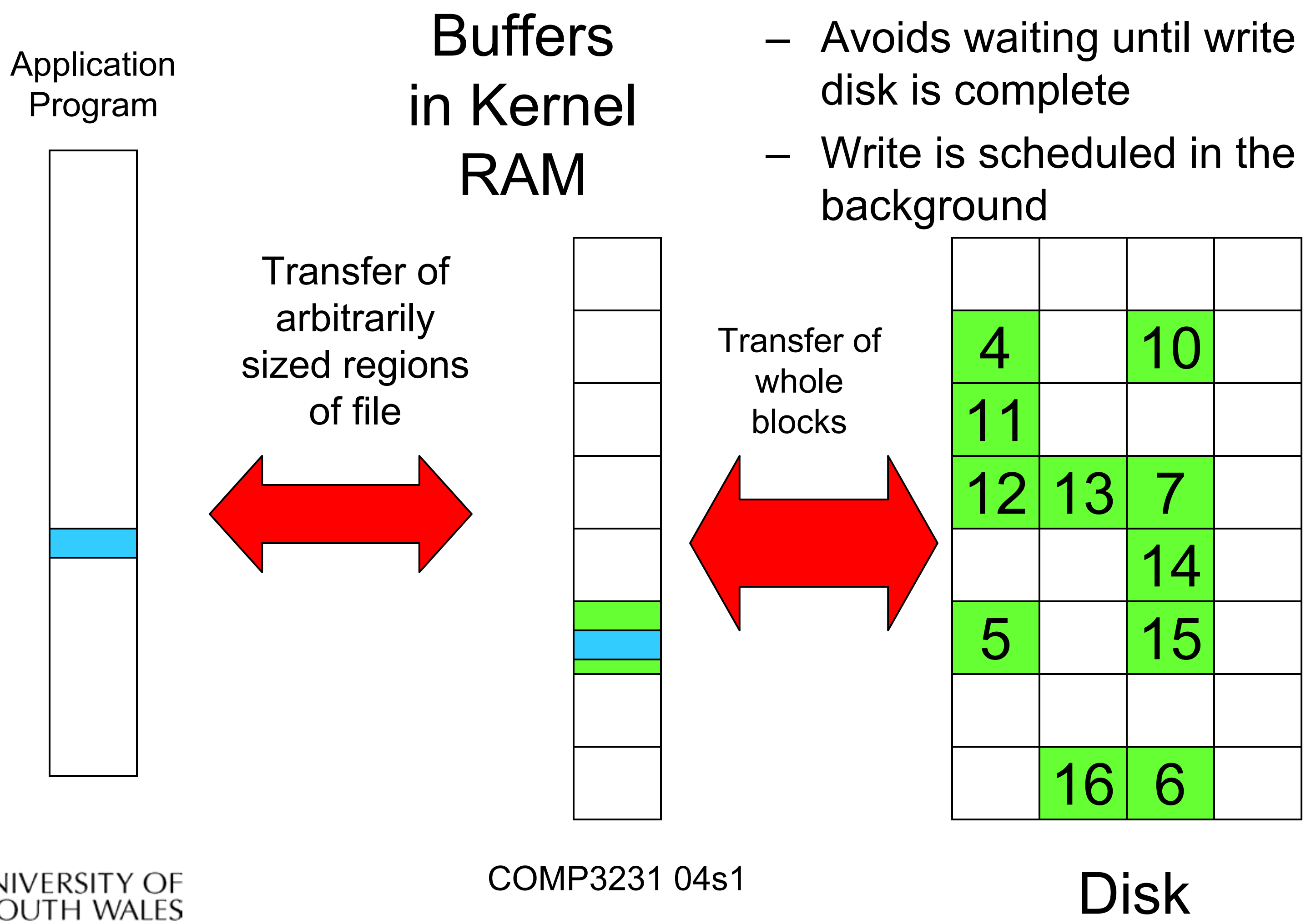
# Buffering Disk Blocks

- Allow applications to work with arbitrarily sized region of a file
  - Apps can still optimise for a particular block size



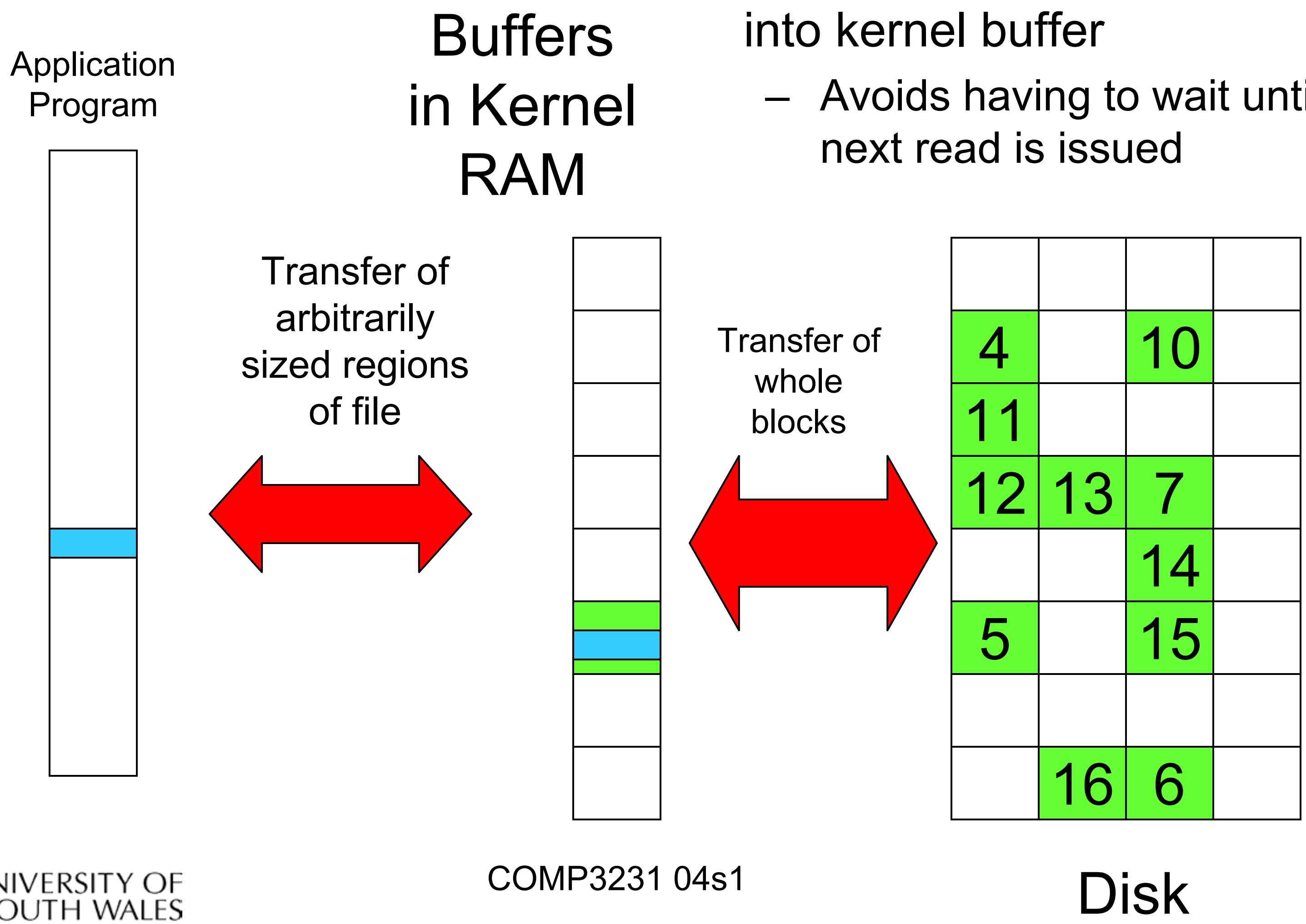
# Buffering Disk Blocks

- Writes can return immediately after copying to kernel buffer
  - Avoids waiting until write to disk is complete
  - Write is scheduled in the background



# Buffering Disk Blocks

- Can implement read-ahead by pre-loading next block on disk into kernel buffer
  - Avoids having to wait until next read is issued

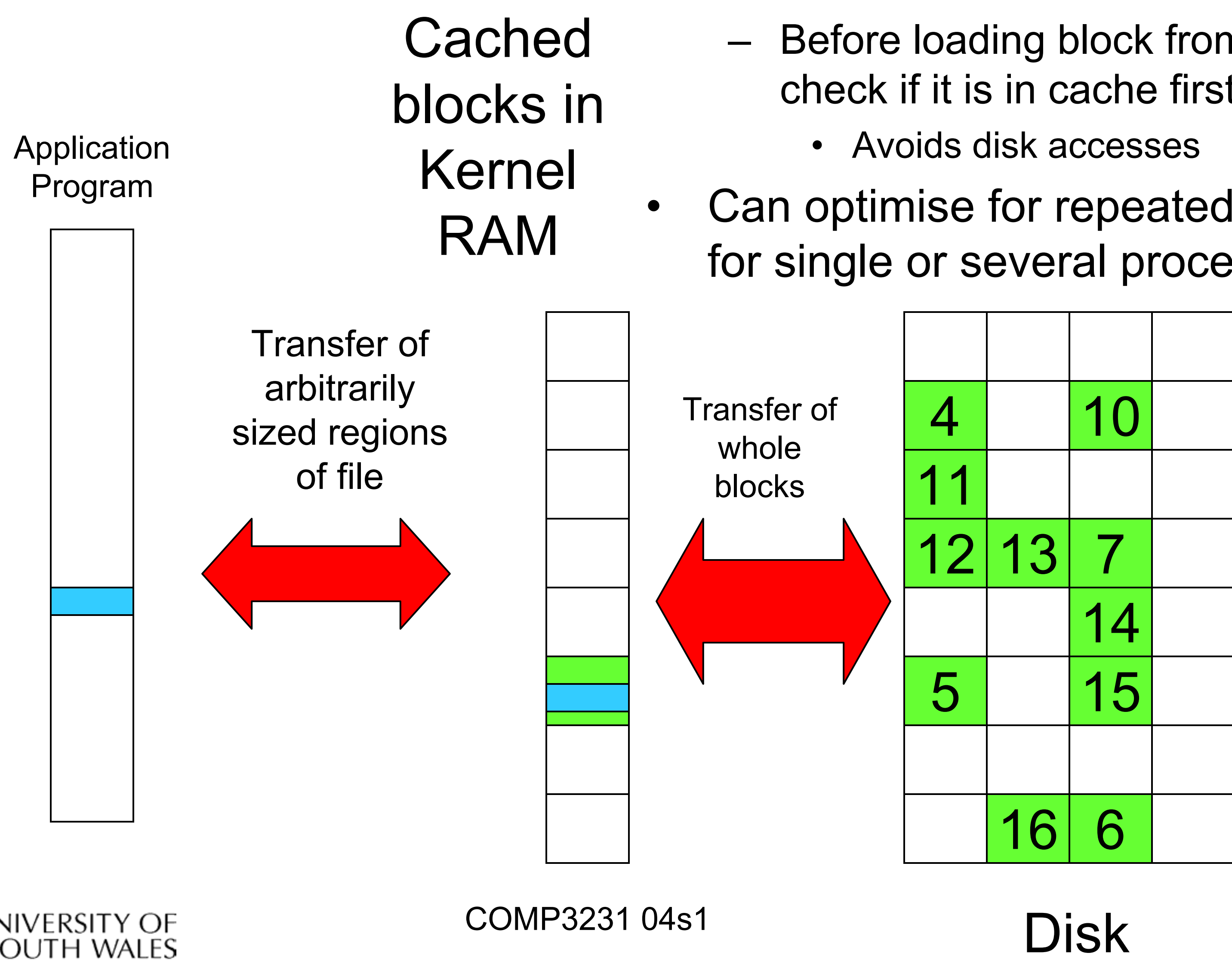


# Cache

- Cache:
  - Fast storage used to temporarily hold data to speed up repeated access to the data
    - Example: Main memory can cache disk blocks

# Caching Disk Blocks

- On access
  - Before loading block from disk, check if it is in cache first
    - Avoids disk accesses
- Can optimise for repeated access for single or several processes



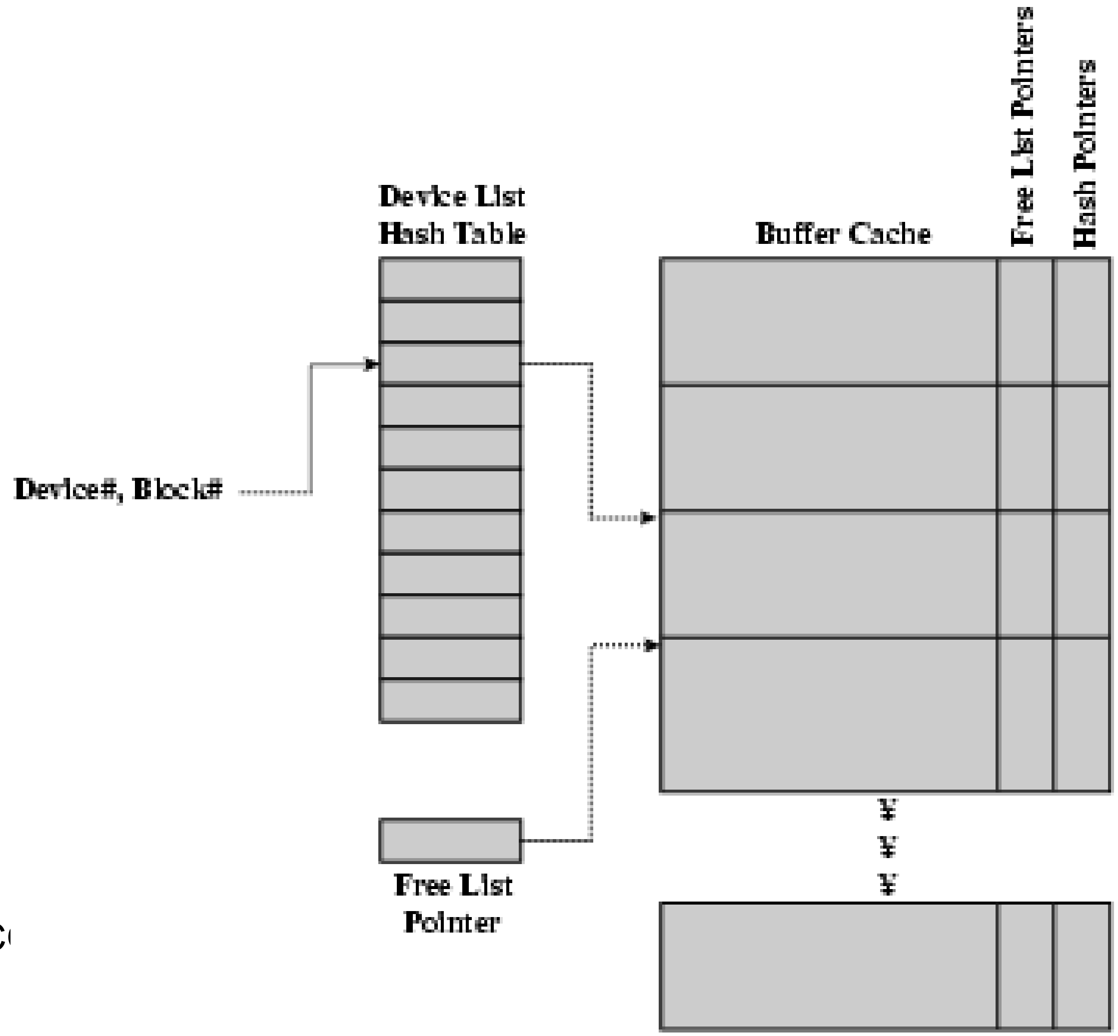
# Buffering and caching are related

- Data is read into buffer; extra cache copy would be wasteful
- After use, block should be put in cache
- Future access may hit cached copy
- Cache utilises unused kernel memory space; may have to shrink

# Unix Buffer Cache

On read

- Hash the device#, block#
- Check if match in buffer cache
- Yes, simply use in-memory copy
- No, follow the collision chain
- If not found, we load block from disk into cache



# Replacement

- What happens when the buffer cache is full and we need to read another block into memory?
  - We must choose an existing entry to replace
  - Similar to page replacement policy
    - Can use FIFO, Clock, LRU, etc.
    - Except disk accesses are much less frequent and take longer than memory references, so LRU is possible
    - However, is strict LRU what we want?
      - What is different between paged data in RAM and file data in RAM?

# File System Consistency

- Paged data is not expected to survive crashes or power failures
- File data is expected to survive
- Strict LRU could keep critical data in memory forever if it is frequently used.

# File System Consistency

- Generally, cached disk blocks are prioritised in terms of how critical they are to file system consistency
  - Directory blocks, inode blocks if lost can corrupt the entire filesystem
    - E.g. imagine losing the root directory
    - These blocks are usually scheduled for immediate write to disk
  - Data blocks if lost corrupt only the file that they are associated with
    - These block are only scheduled for write back to disk periodically
    - In UNIX, flushd (*flush daemon*) flushes all modified blocks to disk every 30 seconds

# File System Consistency

- Alternatively, use a write-through cache
  - All modified blocks are written immediately to disk
  - Generates much more disk traffic
    - Temporary files written back
    - Multiple updates not combined
  - Used by DOS
    - Gave okay consistency when
      - Floppies were removed from drives
      - Users were constantly resetting (or crashing) their machines
  - Still used, e.g. USB storage devices