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

---

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

Inode Contents

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

---

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

Inode Contents

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

---

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

Inode Contents

- 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

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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
double indirect
triple indirect

Inode Contents

- 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

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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.

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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

Inode Contents

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

Disk

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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.

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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

Inode Contents

- 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 ☺

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Unix Inode Block Addressing Scheme

mode
2 owners
3 timestamps
size
block count
direct blocks (12)
single indirect
double indirect
triple indirect

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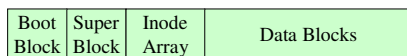
- System V Disk Layout (s5fs)
  - Boot Block
    - contain code to bootstrap the OS
  - Super Block
    - Contains attributes of the file system itself
      - e.g. size, number of inodes, start block of inode array, start of data block area, free inode list, free data block list
  - Inode Array
  -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

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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….

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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

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Ext2fs Directories

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

7	Inode No
12	Rec Length
2	Name Length
'f' '1' 0 0	Name
43	
16	
5	
'f' 'i' 'l' 'e'	
'2' 0 0 0	
85	
12	
2	
'f' '3' 0 0	
0	

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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

7	Inode No
12	Rec Length
2	Name Length
'f' '1' 0 0	Name
7	
16	
5	
'f' 'i' 'l' 'e'	
'2' 0 0 0	
7	
12	
2	
'f' '3' 0 0	
0	

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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

- 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)
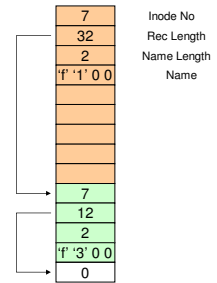
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Ext2fs Directories

- Deleting a filename
  - rm file2

7	Inode No
12	Rec Length
2	Name Length
'f' '1' 0 0	Name
7	
16	
5	
'f' 'i' 'l' 'e'	
'2' 0 0 0	
7	
12	
2	
'f' '3' 0 0	
0	

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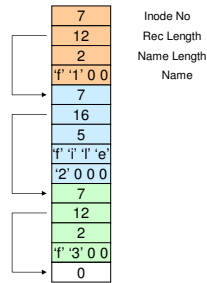
Ext2fs Directories

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

7	Inode No
32	Rec Length
2	Name Length
'f' '1' 0 0	Name
7	
12	
2	
'f' '3' 0 0	
0	

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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?

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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….

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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….

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An Option?

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

fd

fp
i-ptr → inode

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Issues

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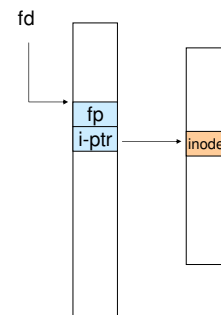
- File descriptor 1 is stdout
  – Stdout is
    • console for some processes
   • A file for others
- Entry 1 needs to be different per process!

fp
i-ptr → inode

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Per-process File Descriptor Array

P1 fd
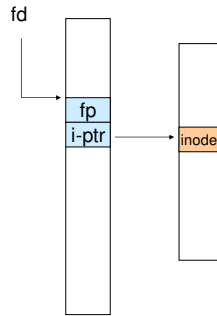
- Each process has its own open file array
  – Contains fp, i-ptr etc.
  – *Fd* 1 can be any inode for each process (console, log file).

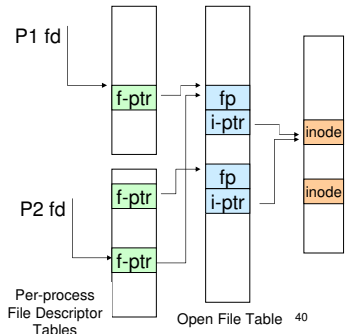P2 fd

fp
i-ptr → inode

inode

fp
i-ptr

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Issue

P1 fd
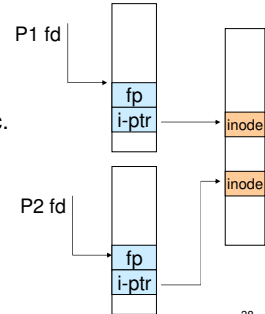
- Fork
  – Fork defines that the child shares the file pointer with the parent
- Dup2
  – Also defines the file descriptors share the file pointer
- With per-process table, we can only have independent file pointers
 – Even when accessing the same file

P2 fd

fp
i-ptr → inode

inode

fp
i-ptr

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

P1 fd
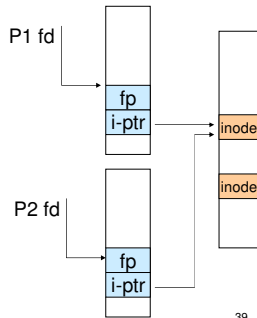
- Per-process file descriptor array
  – Contains pointers to *open file table entry*
- Open file table array
  – Contain entries with a fp and pointer to an inode.
- Provides
  – Shared file pointers if required
  – Independent file pointers if required
- Example:
  – All three *fds* refer to the same file, two share a file pointer, one has an independent file pointer

P2 fd

f-ptr →
fp
i-ptr → inode

f-ptr →
fp
i-ptr

inode

f-ptr →

Per-process File Descriptor Tables

Open File Table 40

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

P1 fd

- Used by Linux and most other Unix operating systems

P2 fd

f-ptr →
fp
i-ptr → inode

f-ptr →
fp
i-ptr

inode

f-ptr →

Per-process File Descriptor Tables
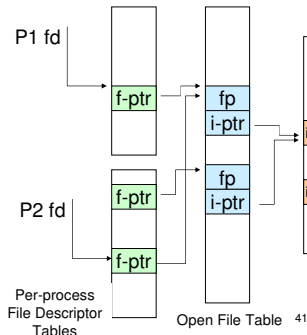
Open File Table 41

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

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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

VFS architecture
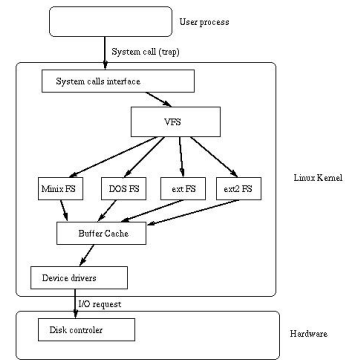
Virtual File System (VFS)

- 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

The file system independent code deals with vfs and vnodes
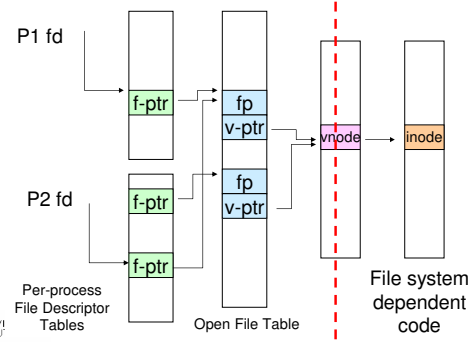
VFS Interface

- 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

Count the number of "references" to this vnode

Number of times vnode is currently open

Lock for mutual exclusive access to counts

```
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;
};
```

Pointer to FS specific vnode data (e.g. inode)

Pointer to FS containing the vnode

Array of pointers to functions operating on vnodes

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Access Vnodes via Vnode Operations

P1 fd

f-ptr

fp
v-ptr

vnode → inode

P2 fd

f-ptr

fp
v-ptr

f-ptr

Ext2fs_read
Ext2fs_write

Vnode Ops

Open File Table

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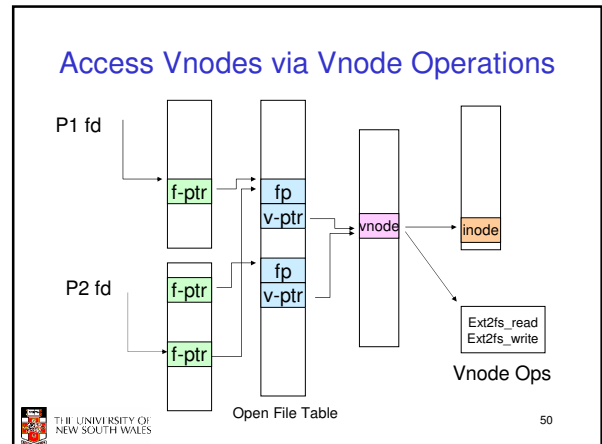
Vnode Ops

```
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);
```

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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);
};
```

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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);
```

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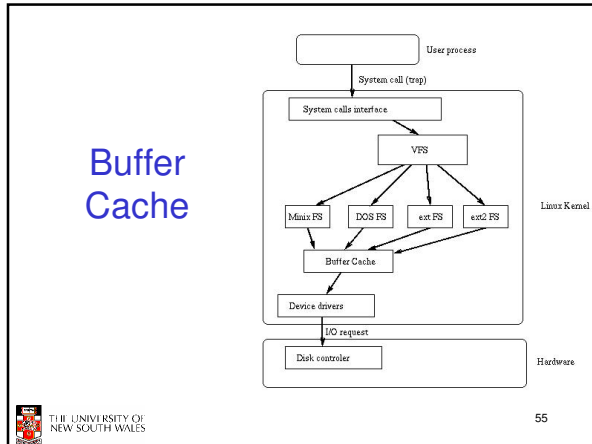
```
    emufs_file_gettype,
    emufs_tryseek,
    emufs_fsync,
    UNIMP,   /* mmap */
    emufs_truncate,
    NOTDIR,  /* namefile */

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

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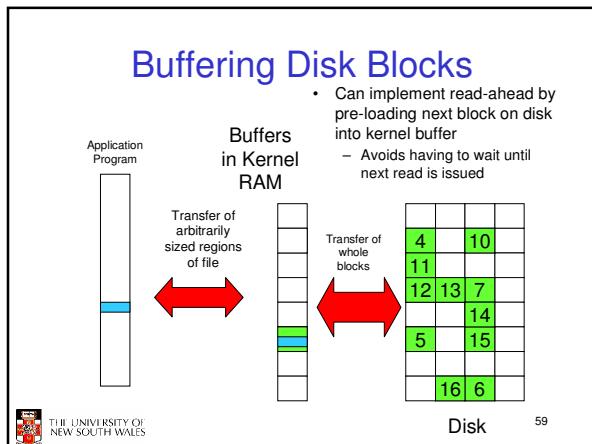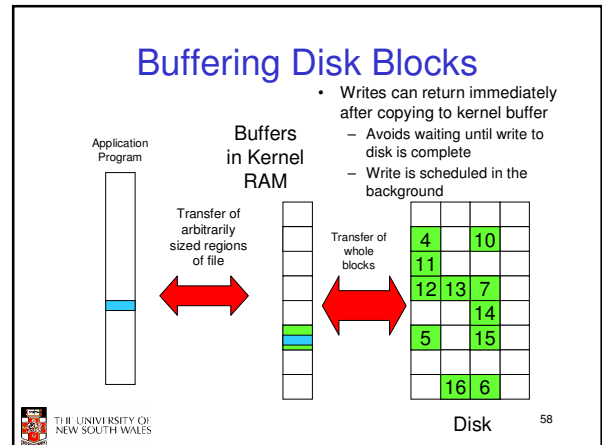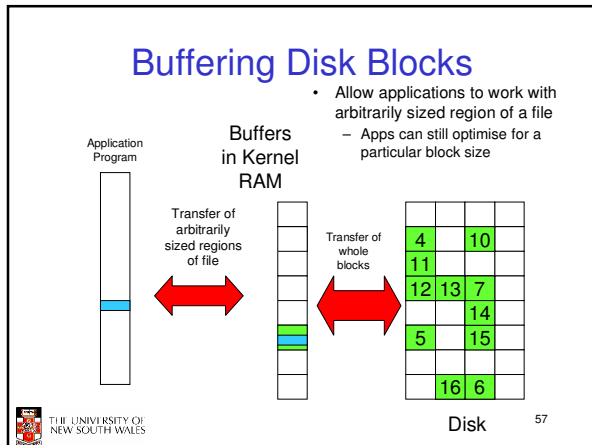
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Buffer Cache

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
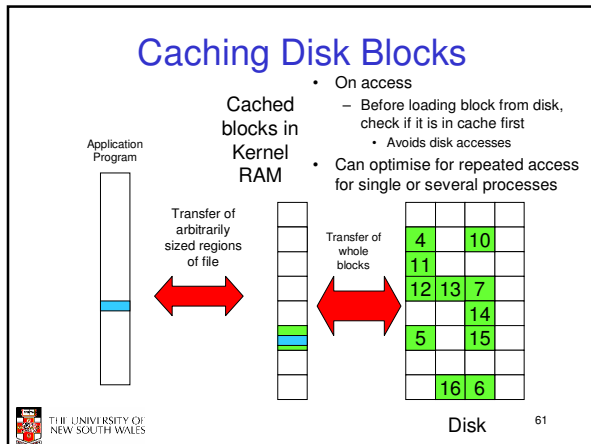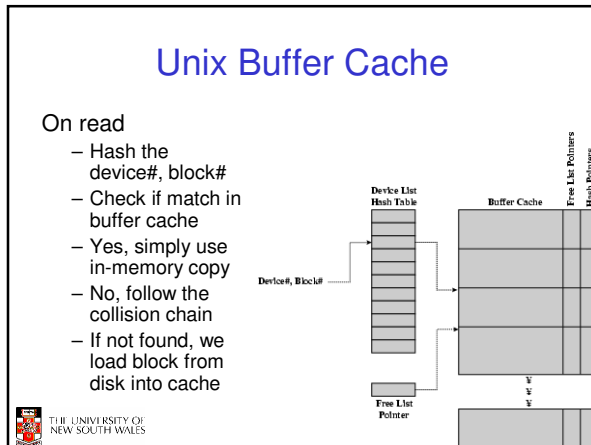 – Avoids having to wait until next read is issued

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

Cached blocks in Kernel RAM

- 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

Application Program

Transfer of arbitrarily sized regions of file

Transfer of whole blocks

4		10
11		
12	13	7
		14
5		15
	16	6

Disk

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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

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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

Device List Hash Table

Buffer Cache

Free List Pointers

Hash Pointers

Device#, Block#

Free List Pointer

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?

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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.

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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

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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

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