Talked about Threads, Processes, and Memory

Now for "slower memory", e.g. Disks (Chapter 10 Mass Storage Structures)

"Disks" come in a variety of flavors ...

- RAM disk -- dedicate some ram to look like disk
- SSDs (Solid State Disks)
- Hard Disk -- Many Flavors
- Optical Disks
- Network "Disks"
- Magnetic Tape?
- Thumb drives, ......

- Communications with these devices over a "BUS"
  - Parallel or Serial
  - Advanced Technology Attachment (ATA, parallel)
  - serial ATA (SATA, serial)
  - universal serial bus (USB)
  - fibre channel (FC)
  - various flavors of "SCSI" (Small Computer System Interface)
  - others ....
Typical disks:

- Sector -- a single unit of read/write
- Head -- a device to physical read/write on the disk
- Platter -- a side of a disk on which a head reads/writes
- Arm -- device on which heads are mounted, moves in and out
- Cylinder -- all sectors addressable without moving the arm
- Rotational speed in RPM (rotations per minute)
  - 5400, 7200, 10000, 15000 RPM
- Interesting times:
  - Transfer rate, seek time, rotational latency

Typical operations:
- Seek to a cylinder
- Read/Write a sector, select platter and sector on the platter
- More recent (LBA): Read/Write logical disk sector, no seek involved

Solid-State Disks
- nonvolatile memory used like a hard drive
- DRAM with a battery
- flash-memory
- Advantages?
Mass Storage

Tape -- still used in some places
- Sequential structure, no random access
- Transfer speeds similar to disk when ready

Disk Structure for most modern disks:
- Addressed as a large one-dimensional array of logical blocks
- Logical block size some power of 2, 512 usually the smallest
- Bad block mapping makes it hard to map logical block to disk geometry
- Recent disks -- use same linear size per sector
  - Longer tracks have more sectors
  - Drive speed changes as head moves in/out

Disk Attachment -- Where is the disk
- Host-Attached storage
  - "same box"
  - High-end, Fibre channel (FC)
    - Multiple disks, multiple hosts
- Network-Attached storage
  - NFS, CIFS, Andrew -- network based file systems (later)
  - iSCSI -- SCSI over IP
Host Attached Storage vs Network Attached Storage

- Network issues -- storage on network causes network traffic
- Storage Area Network -- e.g. storage devices on one NIC, LAN on another

Disk Scheduling

- Idea that you have a "queue" of disk requests
- How to best schedule them
  - Light load ... no issue
  - Heavy load ... how to best schedule them
    - FCFS scheduling
    - Shortest seek time scheduling
      - may cause starvation
    - Scan algorithm
      - AKA elevator algorithm
    - Circular scan
    - LOOK scheduling, look before moving the arm
Other topics

Things to read about

- disk formatting
- bad block management
- Swap space management
- RAID (Redundant arrays of independent disks)
  - making larger virtual disks by striping (RAID 0)
    - Performance gains by parallelism
    - No redundant bits
  - making error correction/recovery by redundant disks
    - RAID 1: mirrored disks
    - RAID 2: Memory-style error-correcting codes (ECC)
    - RAID 3, 4, 5, 6: other techniques ...
- Stable-Storage -- Information is never lost
  - How to implement it?
    - multiple storage devices
    - NVRAM as a cache
File Systems Interface (Ch 11)

- File System -- an abstraction on top of storage
- Typical Services
  - File abstraction
  - File manipulation
  - File protection
- Most visible service of OS
- Large code base in most OSes
File System Basics

File abstraction

- Bag of bits?

- known content? (e.g. is .txt for OS or users?)
  - By the OS?
    - executable files
  - By user land Tools?
    - required

- Standard attributes
  - Name: (symbolic, human readable)
  - Identifier: unique tag
  - Type: system tag
  - Location: where it is located on the storage
  - Size: both logical and physical size (if different)
  - Protection: who has what kind of access
  - Time, date, user identification, ...
File Operations

- Creation: Adding information
- Writing: adding information, file position pointer
- Reading: file position pointer also
- Deleting: removing information
- Truncating a file: removing information

May be many other file management routines
- renaming, moving, status, ...

Management of files in the kernel
- Open syscall: looking up information ... look up file only once
- Kernel keeps an "Open File Table" in the kernel
- Open syscall:
  - lookup file in file system (could be expensive)
  - "cache" information in the open file table
  - return a "handle", some data to uniquely represent file
- Close syscall:
  - done using the file, allow file to reclaim space
Open and Close with shared files
- multiple applications may open file at the same time
- in systems with fork(), both processes have access to files
- Typically ... two levels of tables in this case
  - Kernel wide "open file table"
  - Per process "local file table" that points to open file table
- Kernel global open file table
  - File pointer -- offset into file
  - File-open count -- how many local file entries point here
  - Information for file location on disk
  - Access rights
- Local table
  - Open flags and pointer to global open file table
- Locks -- shared or exclusive
  - shared read locks
  - exclusive locks
  - mandatory or advisory
  - deadlock issues here
File Types

- Kinds of data in files
  - executable, text, scripts, DataBase, ...

- How does OS know what is in the file?
  - file name ... extension (DOS, Windows)
    - .cpp -- file type?
      - C pre-processor input?
    - .app?
      - OS X, extension on a directory!
  - extra information?
    - Mac: creator -- program that created a file

- know how to rebuild executable files? (TOPS 20)
  - Used time information with source to executable
  - Source changed, recompile before running

- UNIX?
  - "magic" numbers to start off files

- file(1) command
File Structure

☐ Executable ... OS needs to know structure to load file
  ☐ Blitz: OpenFile.LoadExecutable

☐ Other files?
  ☐ VMS -- knew structure of system files
  ☐ Problem?
    ☐ what if your app doesn’t want to use a known structure

☐ Text vs Data?
  ☐ Bag of bits?

☐ Mac -- Resource and Data "fork"

☐ Windows -- Multiple "streams" per file

☐ Internal structure
  ☐ Any kind of packing?
  ☐ Standard encoding?
    ☐ Line in a text file? NL, CR/NL, CR
    ☐ MPE/3000: text file, 80 character lines, all chars present
Access Methods

User level access to the file:
- Sequential
  - "tape model"
  - Sequential access
  - Possibly do "skip +/-n records"
- Rewind
- Go to end
  - (Tape model, multiple files per tape, double EOF => EOT)

- Direct (relative access)
  - Each read/write includes "record" number
  - Each number is a "relative record" number to start of file

Should an OS provide both?
- How about sequential access using direct files?
  - like UNIX: keep a file pointer
- How about direct access using sequential files?
  - very bad!
Other Access Methods?

- Hash table?
  - e.g. Key/Data pairs as basic storage element
  - Also can be stored by trees
- Index file -- keep keys, pointer to data
- IBM ISAM -- indexed sequential-access method
  - two level of indexes to access file
General Disk Structure

File system may depend on storage
- RAM disk -- short life, temp file systems, simple structures
- Collection of disks -- long life, reliable, error protection, hot swapping
- Large disk, subdisks (minidisks, partitions, slices)
  - Allows multiple kinds of file systems on one disk
- Special kinds of file systems?
  - procfs -- a file system interface to "process manager"
  - ZFS -- a "pool" based "general file system"
  - coda, smb, afs, nfs ... -- network file systems
- Volume -- contains a FS.
  - May be anywhere from part of a disk to multiple disks

Directory Operations
- lookup (search)
- add (create)
- delete
- list
- rename
- traverse the file system
Directory Structures

Single level directory
- Blitz "Stub file system"

Two level directory
- user/file -- top level contains no files
- Or volume:/user/file

Tree structured directories
- current directory, absolute path, relative path

Acyclic Graph structured
- Directory have just "links" to files or directories
- single file can appear in many directories

General Graph structured
- Acyclic?
- Livermore Timesharing System ... full graph
  - traversal algorithms had to detect cycles

Data stored in Directory Entry
- Full information: e.g. DOS
- Pointer to full information: e.g. UNIX UFS
Volume access

Each file system is placed on a "volume"
Multiple volumes to access, How?

☐ DOS/Windows (in USER space)
   ☐ volume ID
   ☐ path within that volume
   ☐ User needs to see the volume

☐ UNIX -- File System "mount"
   ☐ Associates a directory on one file system with the root of another
   ☐ System mounts one file system as "Root"
   ☐ Other file systems are mounted on directories of Root
   ☐ User does not need to see mounts
   ☐ User does not need to know file system types
   ☐ Automounting ...
      ☐ to the desktop (Mac)

☐ Windows?
   ☐ internally does mounts
   ☐ exposes volume via special "mounts"
   ☐ now allows full mounts
File Sharing

On the same OS with multiple users
- need protection and sharing to be considered
- what kinds of sharing
  - read only sharing?
  - read/write sharing?

Remote file systems
- NFS, DFS, SMB, FTP -- different kinds of files
  - (Some systems can "mount" remote files via ftp.)
- Lots of issues in remote file systems -- not much here yet
- client-server fs peer-to-peer
- authentication systems ... distributed naming services ...
- larger number of failure modes
File consistency

How are files shared ... how do reads and writes interact

- Immutable-Shared-Files semantics
  - Once shared, a file can never change

- Session Semantics
  - File gets a "snapshot" at open
  - Changes are not committed until close
  - Changes are not visible unless opened after a close

- UNIX Semantics
  - Writes are visible immediately to any process with an open file
  - Allow processes to interfere with each other.

- Network file systems have done all 3.
  - NFS -- UNIX
  - AFS, Coda -- mostly session semantics
    - (process on the same machine get UNIX semantics)
Protection

reliability -- safe from physical damage
protection -- safe from improper access
Protection may depend of use of file system

- Operations to control: read, write, execute, append, delete, list..
  - Possibly others ... rename, copy, create
- Special directories ...
  - take and give directories at LLNL

Approaches to access control

- Access Control Lists
  - each file has a list of users and allowed operations
  - not on the list? no access
  - Drawback?
    - Long lists
- Domain based access:
  - Owner, Group, Universe
    - Each file has protection for each domain
    - Access checks user’s domain membership
    - Drawback?
      - Hard to select a single user
Typical implementations
- Primary protection by domain
- Secondary protection by ACLs

Examples:
- UNIX: primary protections: read, write, execute
- NT: full control, modify, read&execute, read, write, ...
  - ACL "who" can be a domain or a user
- DOS: nothing!

Variety of ways to set these:
- NT: typically a GUI
- Solaris: has both UNIX and ACL
  - getfacl(1) and setfacl(1)
Typically file systems are stored on disks of some kind...
They provide:
- **rewrite**: read data, modify, write back to same location
- **random access to any block of data** ... may take time
Basic File Systems

Typical hardware components
- Disk
- Device Driver -- knows how to control disk
- Basic File System -- uses Device Driver to operate, manages buffers, caches
- File-organization module -- knows about file structure
- Logical file system -- manages meta-data information
  - meta-data -- data about the file, size, date, ...
- Management of open files ...
  - Idea of a Virtual File system ...
  - One interface to ALL file systems implemented by OS
    - UNIX V-node
  - All file systems implement same API for OS to use
  - Core OS knows nothing about actual FS detail
- Best if implemented as a layers of "independent" subsystems
- FUSE -- more recent Abstraction ...
  - Implementation of a file system in user space
  - OS passes API calls to user space
  - User space program (daemon) implements FS
Implementation Issues

On Disk Structures Vs In Memory Structures

- On Disk:
  - Total information to access all data

- In Memory:
  - Caches of On Disk information
  - Dynamic information:
    - Mount information
    - Open files and file pointers
    - per-process information (file handle, file descriptor)

- Issue:
  - Keeping data in memory in sync with disk
  - partial writes to disk in case of OS failure
Typical Disk Structures:

- Boot control "block" -- information needed by ROM/OS for boot
- Volume control "block" -- core information on FS
  - UFS: superblock, NTFS: master file table
- Directory Formats
- FS block management structures
- File/Directory block management
Directory Implementation

Directory:
- Keeps names of files with method to lookup meta-data
- Simple Method: linear
  - Fixed or variable sized entries
  - Entry data depends on kind of FS
  - Search time $O(n)$, $n$ number of entries
  - Insert/Delete time?
- Hash table:
  - $O(1)$ search time, insert, delete time
  - collision techniques?
  - base hash table size
  - dynamic issues hash tables
- Some kind of tree storage:
  - trees in a linear file?
Allocation methods

Allocation of data blocks (sectors) for files

- Simple: Contiguous Allocation
  - Define a linear ordering of sectors
  - File starts at LBA (logical block address) X
  - data contained in next Y blocks

- Issues?
  - random access -- easy
  - sequential access -- easy
  - dynamic file size -- hard
  - creating a new file, unknown space needs
    - Start in largest block
  - extending a file -- hard
  - ends up with external fragmentation
  - may need a de-fragmentation function

- Live or offline?
- Used by RT-11, PDP-11 computers
Linked Allocation
- directory/meta-data has first block address
- each block has a "next block" address in the block

Issues?
- creating -- easy
- writing/extending -- easy
- sequential access -- easy, may take longer than contiguous
- random access -- hard
- ends up with internal fragmentation
- dynamic file size -- easy
- data in each sector is less than sector size

Reliability?
- data corrupted (link) => lose the remainder of file

Doubly linked list?
- Store filename, block number?
Linked allocation (continued)

- **FAT** -- File allocation table (MSDOS, OS-2)
  - array of block numbers, one for each data block on FS
  - links are in the FAT, no loss of data on disk
  - not allocated: 0 entry or on a free list
  - Disk reads for FAT and file
Indexed allocation

- Block of "pointers to data blocks"
- Each file has its own index block
- Directory has pointer to index block

Issues?

- Create, read, write, append, random access .... easy
  - Run out of space in index block?
- Small files ... lots of wasted space in index block
- Small index blocks ... small files
- Linked scheme, last entry in index block is to next index block
- Multi-level index scheme, top level points to index blocks ...

UNIX UFS combined method

- Inode: small index block, other file attributes
- Indirect block: regular index block
- 2nd indirect block: index block to index regular index blocks
- 3rd indirect ...
FS Performance ... a major component of "system feels fast"

- FAT/NTFS systems -- De-fragmentation -> get files closer to contiguous
- Berkeley’s changes to UFS for FFS
  - Allocate file in the same cylinder, not just contiguous
  - Other disk related tweaks .... of which many are not valid any more

Free-Space Management / Free disk space management needs to be done

- Keep track of unallocated blocks
- May use unallocated blocks to help keep track

- Bit Vectors
  - one bit per FS block
  - 0 allocated, 1 free
  - Advantage
    - compact
    - ffs (find first set) instructions
  - Disadvantage
    - large bit maps (e.g. 1TB file system)
    - ffs instructions need all bits in memory
Linked List

- Either in the Disk Blocks or the FAT
- Advantage -- relative easy
- Disadvantage -- May be hard to allocate from same cylinder ...

Counting (aka run length encoding)

- Free blocks usually come in groups
- Linked list has first block, number of blocks free
  - Advantages
    - An empty disk has one entry in the list.
  - Disadvantages
    - Turns into simple linked list after much use
**Space Maps**
- Sun’s ZFS -- designed for a huge number of files
- Can include multiple file systems
- Meta Data I/O is of importance
- Divides space into meta-slabs each with a spacemap
- One spacemap easily fits into memory ... read, modify, write
- ZFS also depends on transaction processing and log file systems
  - more later on log file systems
Efficiency and Performance

Disk is the major bottleneck in OSes.
- name lookups can be expensive
- space allocation can be costly
- Size of pointers to files => space used to store them
  - 16, 32, 64 bit pointers
  - ZFS: 128 bit pointers
- reading and writing can cause system to slow down
  - e.g. write a block, now need it again
  - (page out, page fault is an example)
- Buffer cache
  - Cache of Disk blocks Read/Written
  - Page cache and FS cache VS Unified buffer cache
  - LRU replacement algorithm in cache
- Synchronous vs Asynchronous writes
- Read Ahead for buffer management of read files
File System Maintenance

File de-fragmentation
☐ Why needed?
☐ Which FSes need this?

File system consistency checker
☐ diskchk in DOS
☐ fsck in UNIX
☐ Make sure all structures are in tact.
   ☐ Free blocks and Used Blocks add up to total
   ☐ File meta-data matches reality (e.g. nlinks)
Log-Structured File Systems

- DB style transactions as applied to file systems
- Tries to make sure that we never need to repair much

**Basic Idea**
- Write to the "log" what will be done (e.g. metadata)
- Do what you said
- Write to log you have done it.
- Log can be a circular buffer of appropriate size
- At "recovery time" can see that a log entry was not finished
  - Abort or reply entry
- Log writes are sequential and thus very fast

- Used in many file systems now, NTFS, LFS (BSD), ext3fs

Other types of things have been used to improve speed and reliability
- Not much time to recover many things

Backups -- another way to preserve your FS data
- Full backups vs Incremental backups
NFS - Network File System

<< Not complete yet >>