Operating Systems Functions

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8 lectures for CST Ib and Diploma

Lent Term 2000

Handout 3

I/O Devices

- Typically several external 'devices' which interact with computer via I/O:
  1. Human readable: graphical displays, keyboard, mouse, printers
  2. Machine readable: disks, tapes, CD, sensors
  3. Communications: line drivers, modems, network interfaces

- They differ significantly from one another with respect to
  1. Data rate – several orders of magnitude between keyboard and network
  2. Application – affects policy
  3. Complexity of control
  4. Unit of transfer
  5. Data representation
  6. Error handling

Devices

How are devices accessed by programs:

- OS deals with processor and devices:
  - I/O instructions v. memory mapped (where?)
  - I/O hardware type (e.g. 10's of serial chips)
  - polled v. interrupt driven
  - processor interrupt mechanism
- programs access virtual devices:
  - terminal streams not terminals
  - windows not frame buffer
  - event stream not raw mouse
  - files not disk blocks
  - printer spooler not parallel port
  - transport protocols not raw Ethernet
- virtual devices implemented:
  - in kernel, e.g. files, terminal devices
  - in demons, e.g. spooler, windowing
  - in libaries, e.g. terminal screen control, sockets

Processor and Devices

Users must be prevented from accessing physical devices and associated data structures:

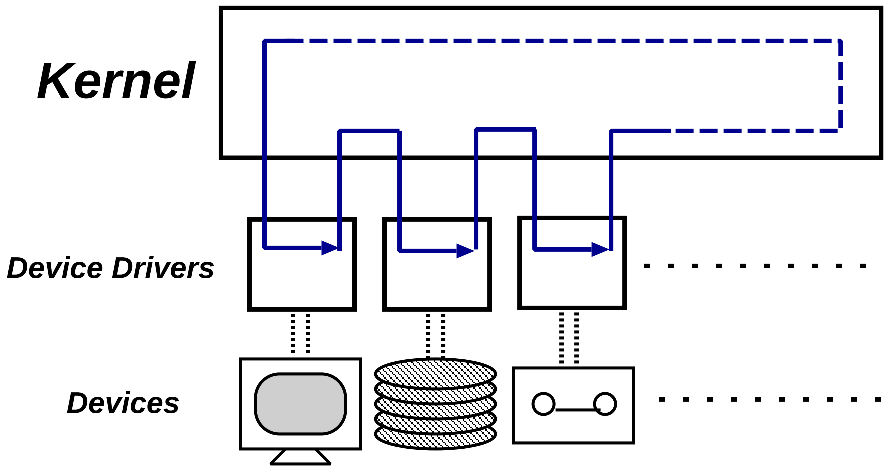
- data protection: e.g. passwords typed in on terminal
- bozo programmer: illegal sequence of actions to an I/O device could lock processor
- multiplexing: concurrent use of device must be properly controlled

How:

- trust: all device actions dealt with by kernel.
- multiplexing: monitors, locks etc. in kernel
- typical mechanisms:
  - make I/O instructions only available in supervisor mode, and/or
  - make I/O devices only available in supervisor memory map (c/f memory management).

Polling

Continuously interrogate devices:



A mechanism of limited use:

- how does the ‘user’ get a look in
  — need to trust them.
- poor worst case response.
- how is priority done?
- but, very simple to program and can know worst case performance
  - in a terminal
  - real time control
  - dally in interrupt handler

Polling Example: Serial Output

```
#define COM1     0x3F8       /* COM1 Port Address        */
#define THR      0x0         /* Xmit Holding Reg Offset */
#define LSR      0x5         /* Line Status Reg Offset  */
#define COM1_THR (COM1+THR)  /* THR Port Address        */
#define COM1_LSR (COM1+LSR)  /* LSR Port Address        */

...

void serial_out(unsigned char c) {
  while(!(inb(COM1_LSR) & 0x20)); /* Wait 'til THR free */
  outb(c, COM1_THR);               /* Put "c" into THR   */
  while(!(inb(COM1_LSR) & 0x20)); /* Wait 'til "c" gone */
}
```

On x86, `inb`/`outb` are part of instruction set. On other architectures, need to provide mapping onto 'physical' addresses: e.g. on Alpha machines with alcor chipset:

```
#define ALCOR_IO    0x8580000000UL

unsigned int inb(unsigned long addr)
{
    long result = *(volatile unsigned int *)
                    ((addr << 5) + ALCOR_IO + 0x00);
    result >>= (addr & 3) * 8;
    return 0xffUL & result;
}
```

Interrupts

Polling poor $\Rightarrow$ most OSs use interrupts.

Most modern processors provide at least a basic interrupt mechanism:

- at end of each instruction, check interrupt line(s) for pending interrupt
- save program counter
- save processor status
- change processor mode
- jump to well known address (or its contents)

Some processors provide:

- multiple levels of interrupts
- hardware vectoring of interrupts
- mode dependent registers

Direct Memory Access

Can reduce interrupt overhead with DMA:

- get the device to read and write processor memory directly
- one interrupt at end of data transfer
- a generic DMA "command" might include:
  - source address
  - source increment / decrement / do nothing
  - sink address
  - sink increment / decrement / do nothing
  - transfer size
- DMA channels are often implemented on devices themselves:
  - e.g. a disk controller
  - pass disk address, memory address and size
  - give instruction to read or write
- Also get "stand-alone" programmable DMA controllers (e.g. PC-AT)

Interrupts: Implementation

Interrupt handler maps from h/w interrupts to ISR invocations. Handler may need to:

- save more registers
- demultiplex interrupt in software
- establish a language environment (e.g. a C run time stack)

Interrupt Service Routines (ISRs):

- device, not processor, specific (unless asm!)
- for programmed I/O device:
  - transfer data
  - clear interrupt (sometimes a side effect of transfer)
- for DMA device:
  - acknowledge transfer
- request another transfer if any more I/O requests pending on device
- signal any waiting threads
- enter scheduler or return

Question: who is scheduling who?

Interrupt Handler Implementation

```
_do_irq:
  sub   r14,  r14, #4   @ Fix up link register
  stmfd r13!, {r0-r6, r12, r14}

  @ first time through loop - pick up current ints.

  mov  r4, #0x3200000   @ IOC Base
  ldrb r5, [r4, #0x14]  @ IRQ Request A
  ldrb r6, [r4, #0x24]  @ IRQ Request B

do_irq_loop:
  tst r6, #0x0a
  blne _unexpected_hardware_signals
  tst r5, #0x80
  beq I_3

  mov r0, #0x20
  strb r0, [r4, #0x18]  @ disable this interrupt
  bl _irq_atm_interface
```

Interrupt Handler Implementation

```
I_3:
  tst  r6, #0x20        @ eXpansion Cards are on Bit 5
  blne _xcb_interrupt   @ ARM Podule Bus

  tst  r6, #0xc0        @ kart ints are SRx & STx bits 6, 7
  blne _kbd_irq         @ Keyboard IRQ

  tst  r6, #0x04        @ R6551 on bit 2 SLCI - pin IL2
  blne _r6551_irq       @ Serial line controller

  tst r5, #0x20         @ timer 0 is bit 5
  beq I_2
  mov r0, #0x20
  strb r0, [r4, #0x14]  @ Clear timer

  bl _inttimer        @ Advance the clock
  bl _clocksweep      @ Any timers gone off?

I_2:
   @ loop back in case there are more ints
   ldrb r5, [r4, #0x14]    @ IRQ Request A
   ldrb r6, [r4, #0x24]    @ IRQ Request B
   orrs r0, r5, r6
   bne do_irq_loop    @ something happening? go round
```

Interrupt Handler Implementation

```
no_more_ints:
  ldr r12, _cur_thread    @ load current tcb
  cmp r12, #0             @ do we have a thread?
  ldmeqfd r13!, {r0-r6, r12, r15}^  @ nope - return

  ldr r0, I_RP        @ address of reschedule flag
  ldr r1, [r0]        @ load it
  mov r2, #0
  str r2, [r0]        @ clear it
  cmp r1, #0          @ reschedule needed?
  ldmeqfd r13!, {r0-r6, r12, r15}^  @ nope - return

  @ Regs are on stack.
  ldmfd r13!, {r0-r6}           @ previous r0 to r6
  stmea r12!, {r0-r11}          @ and save
  ldmfd r13!, {r0,r1}           @ previous r12 and r15
  stmea r12!, {r0, r13, r14}^   @ and save
  stmea r12!, {r1}              @ save prev r15

  @ Irqs off not fiqs, Supervisor mode
  teqp r15, #SUPER_MODE|IBIT  @ 26-bit magic
  mov r0, r0                  @ nop
  stmea r12!, {r13, r14}      @ Supervisor r13 and r14
  mov r0, #7                  @ Setup "reason" and
  bl _scheduler               @ invoke scheduler
  b _do_brick_wall
```

ISR Implementation

```
#define R6551_DATA   ((volatile u_char *)0x33b0000) /* Data R/W     */
#define R6551_STATUS ((volatile u_char *)0x33b0004) /* Status R     */
#define R6551_CNTRL  ((volatile u_char *)0x33b000c) /* Control R/W  */
#define R6551_CMD    ((volatile u_char *)0x33b0008) /* Command R/W  */
#define R6551_RESET  ((volatile u_char *)0x33b0004) /* Soft Reset W */

#define CMD_IRQ_INIT    0x0a    /* all ints off, RTS_bar low */
#define CMD_IRQ_OFF     0x0b    /* TX ints off, DTR_bar low */
#define CMD_IRQ_ON      0x07    /* TX ints on, DTR_bar low */

#define STATUS_IRQ_PEND 0x80    /* interrupt pending */
#define STATUS_TDRE     0x10    /* TDR empty => can send */
#define STATUS_IRQ_TDRE (STATUS_IRQ_PEND | STATUS_TDRE)

static char     r6551_buf[R6551_BUFSIZE];
static int      r6551_producer  = 0;
static int      r6551_consumer  = 0;
static int      r6551_freespace = R6551_BUFSIZE;

void r6551_irq()
{
    u_char c = *R6551_STATUS;
    if(!(c & STATUS_IRQ_TDRE)) return;

    /* need to send next data */
    if(r6551_producer != r6551_consumer) {
        *R6551_DATA = r6551_buf[r6551_consumer++];
        if(r6551_consumer == R6551_BUFSIZE)
            r6551_consumer = 0;
        r6551_freespace++;
    } else { /* no data to tx - disable the interrupt */
        *R6551_CMD = CMD_IRQ_OFF;
    }
}
```

I/O Buffering

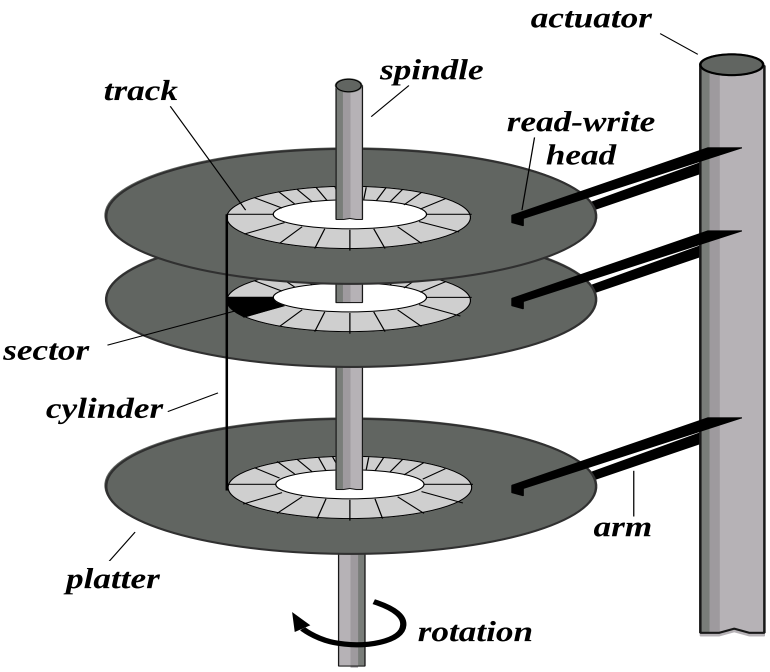
- Important that a process waiting on I/O does not consume excess system resources
- CPU should reschedule and run another process
- To avoid difficulties of page management OS can use some form of *buffering*:
  1. Single buffering — OS assigns a system buffer to the user request
  2. Double buffering — process consumes from one buffer while system fills the next
  3. Circular buffers — most useful for burst-oriented I/O
- Many aspects of buffering dictated by device type:
  - character devices ⇒ line probably sufficient.
  - network devices ⇒ bursty (time & space).
  - block devices ⇒ lots of fixed size transfers.
  - (last usually major user of buffer memory)

I/O: Summary

- Messiest part of OS:
  - huge variety of devices.
  - large variety of device “classes”.
- Key design issues:
  1. Efficiency
     - Key performance issue is that of I/O buffering
     - Also important to schedule I/O to meet performance requirements of system
  2. Stability
     - Need to handle heavy I/O loads.
     - Decoupling ISR and device driver is good.
  3. Generality
     - Want to provide useful abstraction (e.g. Unix files)
     - But need to be careful don’t lose performance/functionality (e.g. direct access, asynchrony).

Disk I/O

- Performance of disk I/O is crucial to swapping/paging and file system operation
- Key parameters:
  1. Wait for controller and disk.
  2. Seek to the appropriate disk cylinder
  3. Rotational delay for the desired block to come under the head
  4. Data transfer
- Performance depends critically on **how the disk is organised**



Disk Scheduling

- In a typical multiprogramming environment have multiple users queueing for access to disk

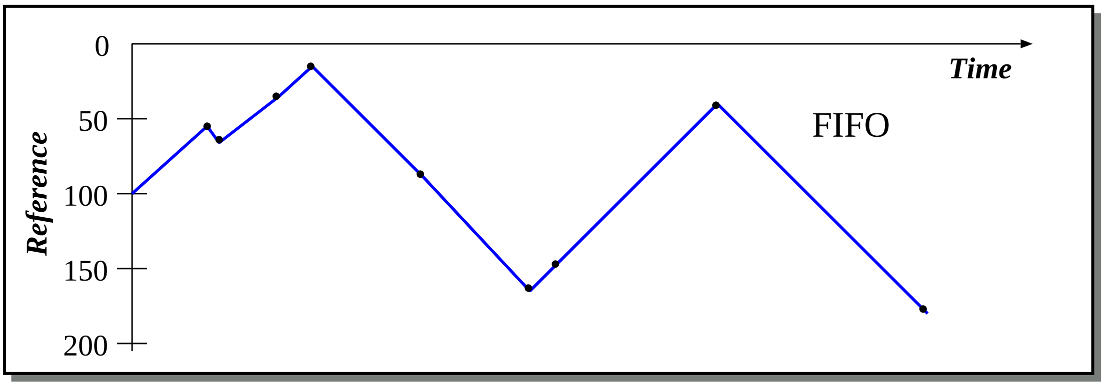
- Also have VM system requests to load/swap/page processes/pages

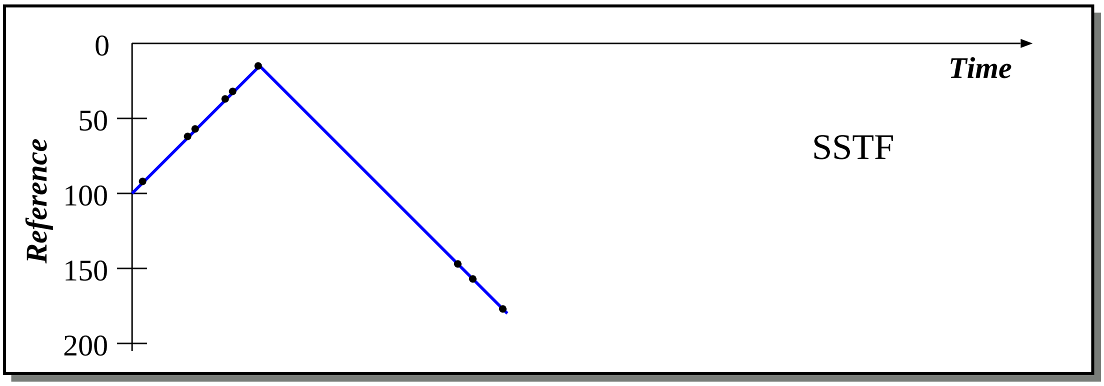
- We want to provide best performance to all users — specifically reducing seek time component

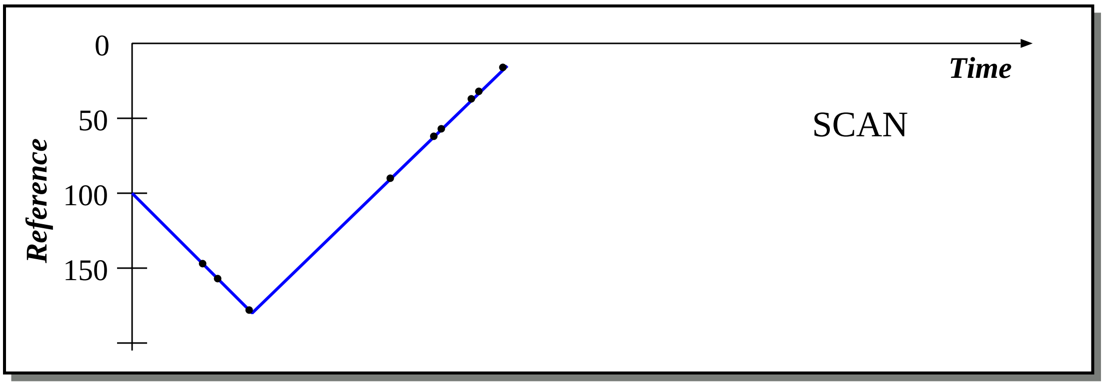
- Several policies for scheduling a set of disk requests onto the device, e.g.

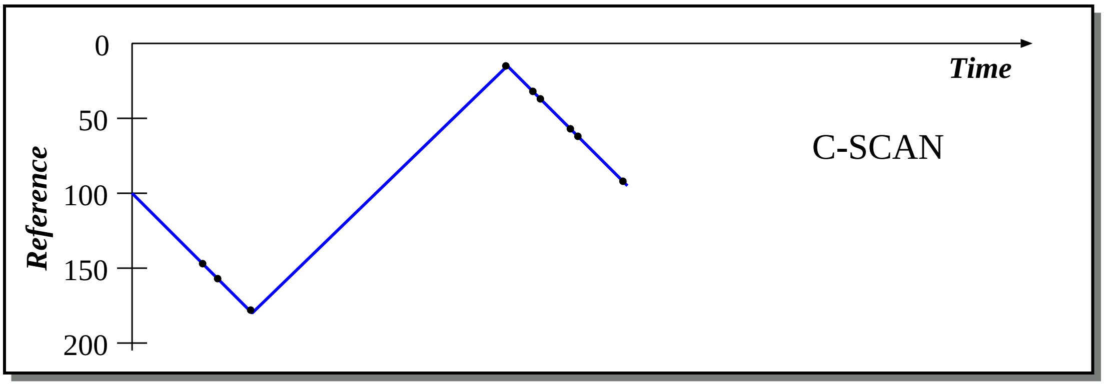
  1. FIFO: perform requests in their arrival order
  2. SSTF: if the disk controller knows where the head is (hope so!) then it can schedule the request with the shortest seek from the current position
  3. SCAN ("elevator algorithm"): relieves problem that an unlucky request could receive bad performance due to queue position
  4. C-SCAN: scan in one direction only
  5. N-step-SCAN and FSCAN: ensure that the disk head always moves

Reference String = 55,58,39,18,90,160,150,38,184





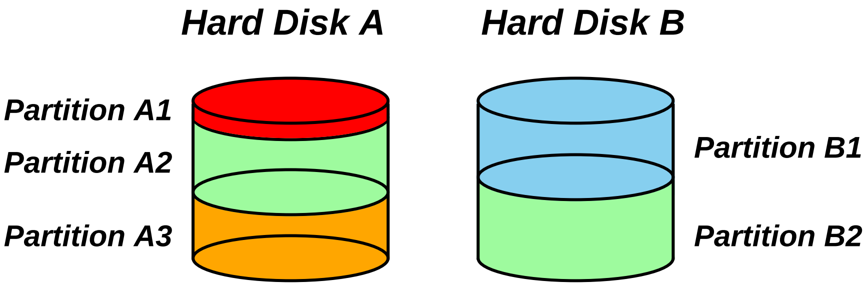




Other Disk Scheduling Issues

- Priority: usually beyond disk controller's control.
  - System decides to prioritise, for example by ensuring that swaps get done before I/O.
  - Alternatively interactive processes might get greater priority over batch processes.
  - Or perhaps short requests given preference over larger ones.
- SRT disk scheduling (e.g. Cello, USD):
  - Per client/process scheduling parameters.
  - Two stage: admission, then queue.
  - Problem: overall performance?
- 2-D Scheduling:
  - Try to reduce rotational latency.
  - Typically require h/w support.
- Bad blocks:
  - Remapping typically transparent ⇒ can undo scheduling benefits.

Logical Volumes



Modern OSs tend to abstract away from physical disk; instead use *logical volume* concept.

- Partitions first step.
- Augment with "soft partitions":
  - allow v. large number of partitions on one disk.
  - can customize, e.g. "real-time" volume.
  - aggregation: can make use of v. small partitions.
- Overall gives far more flexibility:
  - e.g. dynamic resizing of partitions
  - e.g. *striping* for performance.
- E.g. IRIX `xlm`, OSF/1 `lvm`, NT `FtDisk`.
- Other big opportunity is *reliability* ...

RAID

RAID = **R**edundant **A**rrays of **I**nexpensive **D**isks:

- Uses various combinations of striping and *mirroring* to increase performance.
- Can implement (some levels) in h/w or s/w
- Many levels exist:
  - RAID0: striping over n disks (so actually !**R**)
  - RAID1: simple mirroring, i.e. write n copies of data to n disks (where n is 2 ;-).
  - RAID2: hamming ECC (for disks with no built-in error detection)
  - RAID3: stripe data on multiple disks and keep parity on a dedicated disk. Done at byte level $\Rightarrow$ need spindle-synchronised disks.
  - RAID4: same as RAID3, but block level.
  - RAID5: same as RAID4, but no dedicated parity disk (round robin instead).
- AutoRAID trades off RAIDs 3 and 5.

Disk Cacheing

- Cache holds copy of some of disk sectors.
- Can reduce access time by applications if the required data follows the locality principle
- Design Issues
  - Transfer data by DMA or by shared memory ?
  - Replacement strategy: LRU, LFU, etc.
  - Reading ahead: e.g. track based.
  - Write through or write back ?
  - Partitioning? (USD ...)
- Typically O/S also provides a cache in s/w:
  - May be done per volume, or overall.
  - Also get *unified* caches — treat VM and FS caching as part of the same thing.
- Software caching issues:
  - Should we treat all filesystems the same?
  - Do applications know better?

4.3 BSD Unix Buffer Cache

- Name? well *buffers* data to/from disk, and *caches* recently used information.
- Modern Unix deals with *logical* blocks, i.e. FS block within a given partition / logical volume.
- "Typically" prevents 85% of implied disk transfers.
- Implemented as a hash table:
  - Hash on (`devno, blockno`) to see if present.
  - Linked list used for collisions.
- Also have **LRU** list (for replacement).
- Internal interface:
  - `bread()`: get data & lock buffer.
  - `brelse()`: unlock buffer (clean).
  - `bdwrite()`: mark buffer dirty (lazy write).
  - `bawrite()`: asynchronous write.
  - `bwrite()`: synchronous write.
- Uses `sync` every 30 secs for consistency.
- Limited prefetching (read-ahead).

NT Cache Manager

- NT Cache Manager caches "virtual blocks":
  - viz. keeps track of cache "lines" as offsets within a *file* rather than a volume.
  - disk layout & volume concept abstracted away.
  - ⇒ no translation required for cache hit.
  - ⇒ can get more intelligent prefetching
- Completely unified cache:
  - cache "lines" all in virtual address space.
  - decouples physical & virtual cache systems: e.g. virtually cache in 256K blocks, physically *cluster* up to 64Kb.
  - NT virtual memory manager responsible for actually doing I/O.
  - allows lots of FS cache when VM system lightly loaded, little when system is thrashing.
  - is this good?
- NT also provides some user control:
  - if specify `temporary` attrib when creating file ⇒ will never be flushed to disk unless necessary.
  - if specify `write_through` attrib when opening a file ⇒ all writes will synchronously complete.

File systems

What is a filing system:

- Directory service, provides
  - naming mechanism
  - access control
  - existence control
  - concurrency control
- Storage service, provides
  - integrity, data needs to survive:
    - hardware errors
    - OS errors
    - user errors
  - archiving
  - mechanism to implement directory service

What is a file?

- an ordered sequence of bytes (UNIX)
- an ordered sequence of records (ISO FTAM)

File Mapping Algorithms

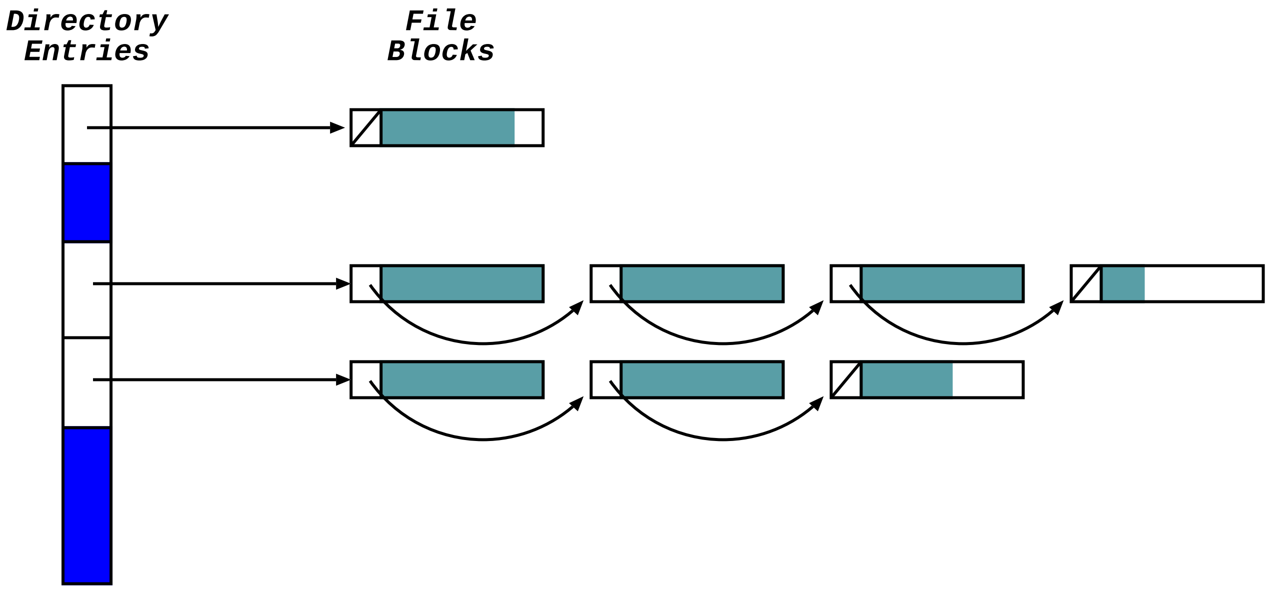
How is a file mapped to blocks:

1. chaining in the material
2. chaining in a map
3. table of pointers to blocks
4. extents

Aspects to consider:

- integrity checking after crash
- automatic recovery after crash
- efficiency for different access patterns
  - of data structure itself
  - of IO operations to access it
- ability to extend files
- efficiency at high utilization of disk capacity

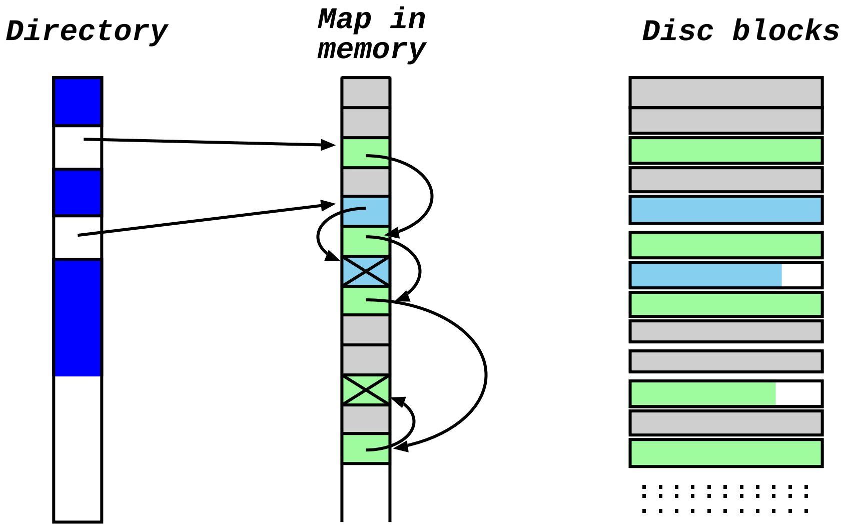
Chaining in the Media



Each disk block has pointer to next block in file.
Can also chain free blocks.

- OK for sequential access – poor for random access
- cost to find disk address of block n in a file:
  - best case: n disk reads
  - worst case: n disk reads
- Some problems:
  - not all of file block is file info
  - integrity check tedious . . .

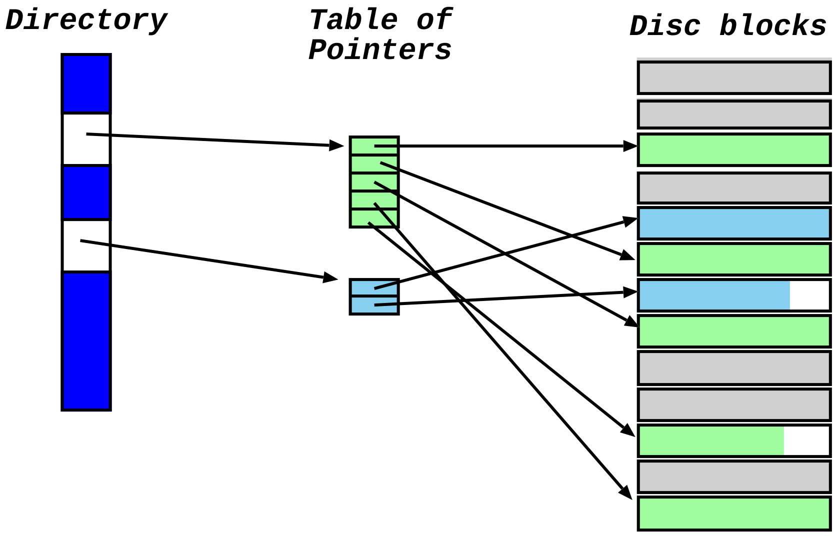
Chaining in a map



Maintain the chains of pointers in a map (in memory), mirroring disk structure.

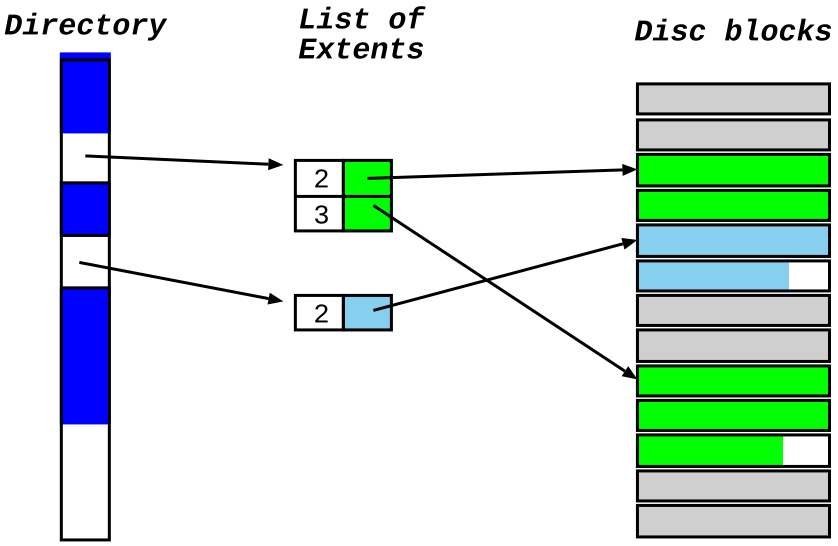
- disk blocks only contain file information
- integrity check easy: only need to check map
- handling of map is critical for
  - performance: must cache bulk of it.
  - reliability: must replicate on disk.
- cost to find disk address of block n in a file:
  - best case: n memory reads
  - worst case: n disk reads

Table of pointers



- access cost to find block n in a file
  - best case: 1 memory read
  - worst case: 1 disk read
- integrity check easy: only need to check tables
- free blocks managed independently (e.g. bitmap)
- table may get large ⇒ must chain tables, or build a tree of tables (e.g. UNIX inode)
- access cost for chain of tables? for hierarchy?

Extent lists



Use of contiguous blocks can increase performance . . .

- list of disk addresses and lengths (extents)
- access cost: [perhaps] a disk read and then a searching problem, O(log(number of extents))
- can use bitmap to manage free space (e.g. QNX)
- system may have some maximum #extents
  - could copy file (i.e. compact into one extent)
  - or could chain tables or use a hierarchy as for table of pointers.

File meta-data I

What information is held about a file?

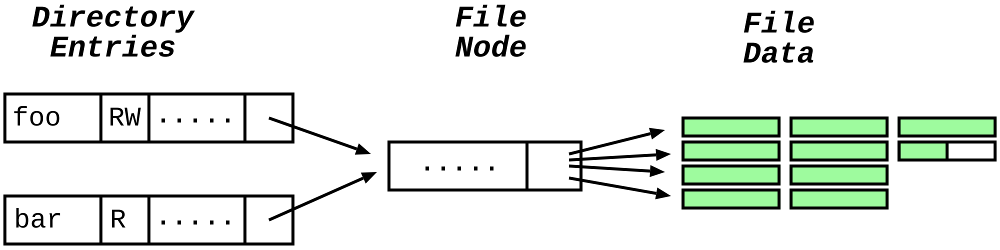
- times: creation, access and change?
- access control: who and how
- location of file data (see above)
- backup or archive information
- concurrency control

What is the name of a file?

- simple system: only name for file is human comprehensible text name
- perhaps want multiple text names for file
  - soft (symbolic) link: text name → text name
  - hard link: text name → file id
  - if we have hard links, must have reference counts on files

Together with the data structure describing the disk blocks, this information is known as the file *meta-data*.

File meta-data II



Where is file information kept:

- no hard links: keep it in the directory structure.
- hard links, keep file info separate from directory entries
  - file info in a block: OK if blocks small (e.g. TOPS10)
  - or in a table (UNIX i-node / v-node table)
- on OPEN, (after access check) copy info into memory for fast access
- on CLOSE, write updated file data and meta-data to disk

How do we handle *caching* meta-data?

Directory Name Space

- simplest - flat name space (e.g. Univac Exec 8)
- two level (e.g. CTSS, TOPS10)
- general hierarchy
  - a tree,
  - a directed (acyclic) graph (DAG)
- structure of name space often reflects data structures used to implement it
  - hierarchical name space ↔ hierarchical data structures
  - but, could have hierarchical name space and huge hash table!

General hierarchy:

- reflects structure of organisation, users' files etc.
- name is full path name, but can get rather long: e.g. /usr/groups/X11R5/src/mit/server/os/4.2bsd/utils.c
  - offer relative naming
  - login directory
  - current working directory

Directory Implementation

- directories often don't get very large (especially if access control is at the directory level rather than on individual files)

  ✓ often quick look up

  ✗ directories may be small compared to allocation unit

- But: assuming small dirs means lookup is naïve ⇒ trouble if get big dirs:
  - optimise for iteration.
  - keep entries sorted (e.g. use a B-Tree).

- Query based access:
  - Split filespace into system and user.
  - User wishes ‘easy’ retrieval.
  - What about access control?

Immutable files

Do away with concurrency problems — use write once files with atomic close! Implemented by:

- copy on write
- multiple version numbers: foo!11, foo!12
- invent new version number on close (i.e. sequence all close operations)

Problems:

- disk space
  - only keep last k versions (archive rest?)
  - have a explicit *keep* call
  - share disk blocks between different versions — complicated file system structures
- name without version usually means 'latest' — ambiguous
- and the killer ... directories aren't immutable!

But:

- concurrency control only required on version number
- could be used (for files) on unusual types of media
  - write once optical disks
  - erasable disks
  - remote servers (e.g. Cedar FS)
- provides an audit trail
  - required by the spooks
  - often implemented on top of normal file system; e.g. UNIX RCS
- coming back into vogue (e.g. Elephant)

Multi-level stores

Archiving (c.f. backup); keep frequently used files on fast media, migrate others to slower (cheaper) media. Can be done by:

- user – *encouraged* by accounting penalties
- system – migrate files by periodically looking at time of last use
- can provide transparent naming but not performance!

Integrate multi-level store and ideas from immutable files, e.g. Plan-9:

- file servers with fast disks
- write once optical juke box
- every night, mark all files immutable
- start migration of files which changed the previous day to optical disk
- access to archive explicit
  e.g. /archive/12Jan2000/users/smh/ ...

Integrity: Backups

Backup; keep (recent) copy of whole file system to allow recovery from:

- CPU software crash
- bad blocks on disk
- disk head crash
- fire, war, famine, pestilence

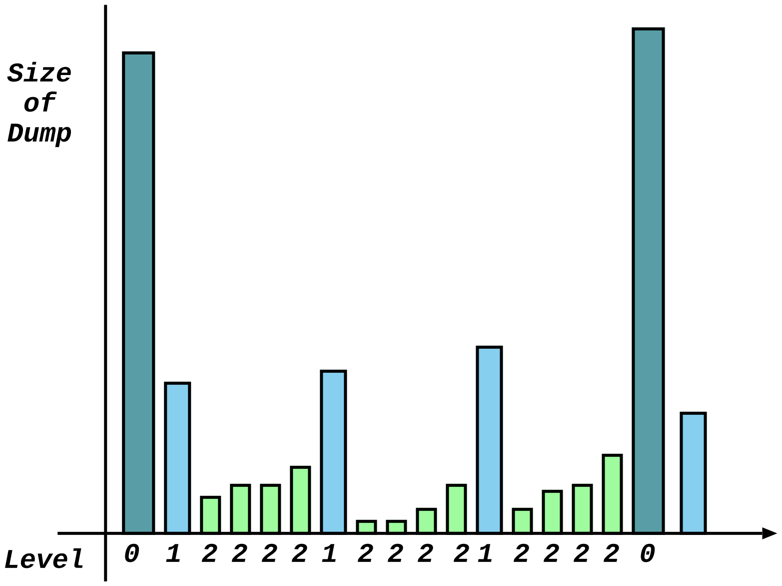
What is a *recent* copy:

- in real time systems (e.g. airline booking) recent means mirrored disks
- daily usually sufficient for ’normal’ machines

Can use *incremental* technique, e.g.

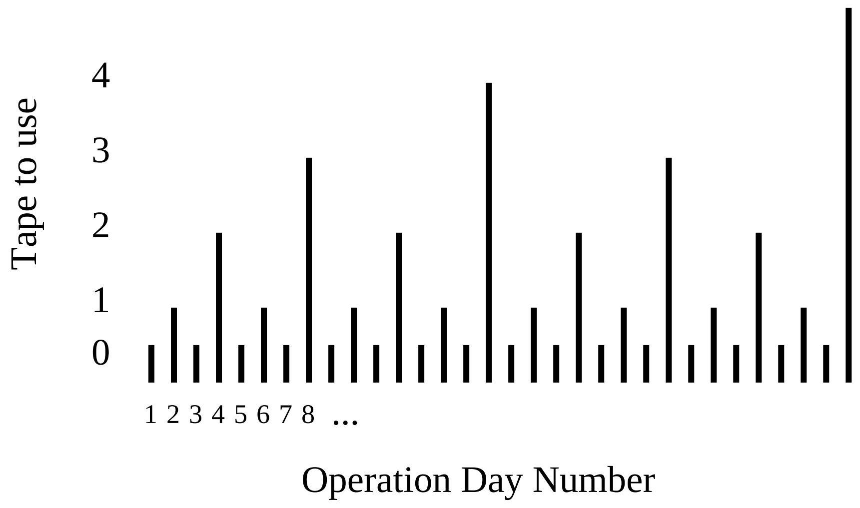
- full dump performed daily or weekly
  - copy whole file system to another disk or tape
  - could take hours [esp. if copy across a network]
  - best done while file system live (although can give us consistency problems).

- incremental dump performed hourly or daily
  - only copy files and directories that have changed since the last time.
  - can either mark files explicitly (perhaps at log out), or use last modification time in file meta-data.
- e.g. 3-level scheme



- to recover:
  - first restore full dump,
  - then add in incrementals.

Ruler Function



- Want to minimise #tapes needed, time to backup
- Want to maximise the time a file is held on backup
  - Number days starting at 1
  - On day n use tape t such that 2^t is highest power of 2 which divides n
  - whenever we use tape t, dump all files modified since we last used that tape, or any tape with a higher number
- If file is created on day c and deleted on day d a dump version will be saved substantially after d
- the length of time it is saved depends on $d - c$ and the exact values of c, d

Integrity: Processor crash

If the processor terminates unexpectedly – OS bug, power failure – the main problem is that modified data structures exist in memory and have not been completely written to disk.

- most failures affect only files being modified
- as disk is still intact, can usually recover a more recent version of file system from its state than from backup
- at start up after a crash run a *disk scavenger*
  - try to recover data structures from memory (bring back core memory!)
  - get current state of data structures from disk
  - identify inconsistencies (may require operator intervention)
  - isolate suspect files and reload from backup
  - correct data structures and update disk
- usually much faster and better (i.e. more recent) than recovery from backup.

- can make scavenger's job simpler:
  - replicate vital data structures
  - *spread* replicas around the disk
  - provide redundancy in data structures for consistency check
- even better: use *journal* [or *log*] file to assist with recovery.
  - record all meta-data operations in an append-only [infinite] file.
  - ensure log records always written prior to actual modification.
  - allows very fast recovery after a crash (e.g. a few seconds).
  - e.g. NTFS, XFS.

Log-Structured File Systems

Radically different file system design:

- Premise 1: CPUs getting faster faster than disks.
- Premise 2: memory cheap ⇒ large disk caches
- Premise 3: large cache ⇒ most disk reads "free".

⇒ performance bottleneck is writing & seeking.

Basic idea: solve write/seek problems by using a *log*:

- log is [logically] an append-only piece of storage comprising a set of *records*.
- all data & meta-data updates written to log.
- periodically flush entire log to disk in a single contiguous transfer:
  - high bandwidth transfer.
  - can make blocks of a file contiguous on disk.
- have two logs ⇒ one in use, one being written.

What are the problems here?

1. How do we find data in the log?
    - can keep basic UNIX structure (inodes, indirect blocks, etc)
    - then just need to find a file's inode ⇒ use *inode map*
    - inode maps live in fixed region on disk.
2. What do we do when the disk is full?
    - need asynchronous *scavenger* to run over old logs and free up some space.
    - two basic alternatives:
        1. compact live information to free up space.
        2. thread log through free space.
    - Neither great ⇒ use *segmented log*:
        - divide disk into large fixed-size segments.
        - compact within a segment, thread between segments.
        - when writing use only clean segments
        - occasionally clean segments
        - choosing segments to clean is hard ...

Log-structured file systems are the subject of ongoing debate in the OS community ...