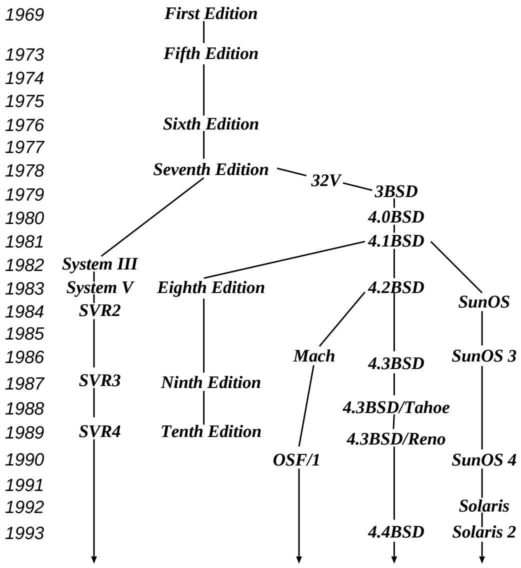
UNIX: Introduction

- Unix first developed in 1969 at Bell Labs (Thompson & Ritchie)
- Originally written in PDP-7 asm, but then (1973) rewritten in the 'new' high-level language C

  $\Rightarrow$ easy to port, alter, read, etc.
- 6^{th} edition ("V6") was widely available (1976).
  - source avail $\Rightarrow$ people could write new tools.
  - nice features of other OSes rolled in promptly.
- By 1978, V7 available (for both the 16-bit PDP-11 and the new 32-bit VAX-11).
- Since then, two main families:
  - AT&T: "System V", currently SVR4.
  - Berkeley: "BSD", currently 4.3BSD/4.4BSD.
- Standardisation efforts (e.g. POSIX, X/OPEN) to homogenise.
- Best known "UNIX" today is probably *linux*, but also get FreeBSD, NetBSD, and (commercially) Solaris, OSF/1, IRIX, and Tru64.

Unix Family Tree (Simplified)



Design Features

Ritchie and Thompson writing in CACM, July 74, identified the following (new) features of UNIX:

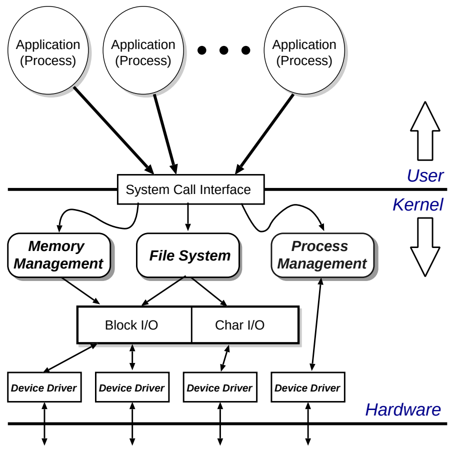
1. A hierarchical file system incorporating demountable volumes.
2. Compatible file, device and inter-process I/O.
3. The ability to initiate asynchronous processes.
4. System command language selectable on a per-user basis.
5. Over 100 subsystems including a dozen languages.
6. A high degree of portability.

Features which were not included:

- real time
- multiprocessor support

Fixing the above is pretty hard.

Structural Overview

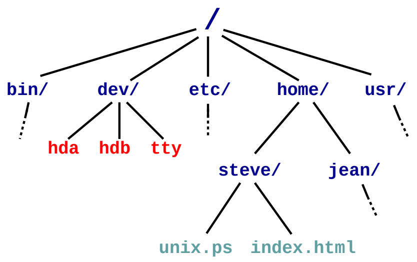


- Clear separation between *user* and *kernel* portions.
- Processes are unit of scheduling and protection.
- All I/O looks like operations on *files*.

File Abstraction

- A file is an unstructured sequence of bytes.
- Represented in user-space by a *file descriptor* (fd)
- Operations on files are:
  - *fd* = **open** (*pathname*, *mode*)
  - *fd* = **creat**(*pathname*, *mode*))
  - bytes = **read**(*fd*, *buffer*, *nbytes*)
  - count = **write**(*fd*, *buffer*, *nbytes*)
  - reply = **seek**(*fd*, *offset*, *whence*)
  - reply = **close**(*fd*)
- Devices represented by *special files*:
  - support above operations, although perhaps with bizarre semantics.
  - also have `ioctl`'s: allow access to device-specific functionality.
- Hierarchical structure supported by *directory files*.

Directory Hierarchy



- Directories map names to files (and directories).
- Have distinguished *root directory* called '/'
- Fully qualified pathnames ⇒ perform traversal from root.
- Every directory has '.' and '..' entries: refer to self and parent respectively.
- Shortcut: current working directory (*cwd*).
- In addition *shell* provides access to *home directory* as ~*username* (e.g. ~steve/)

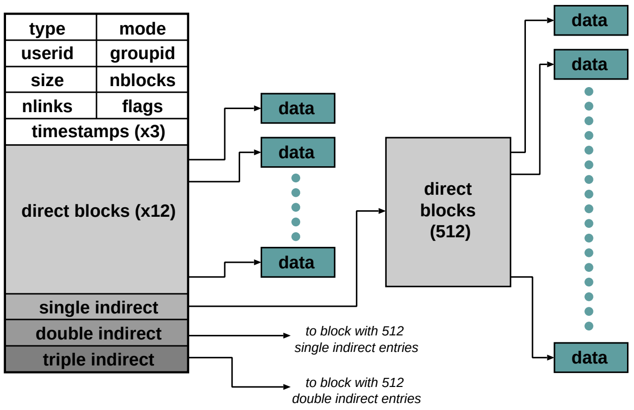
Aside: Password File

- `/etc/passwd` holds list of password entries.
- Each entry roughly of the form:

  user-name:encrypted-passwd:home-directory:shell

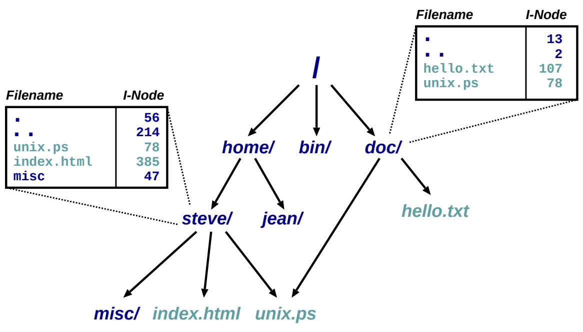
- Use *one-way function* to encrypt passwords.
  - i.e. a function which is easy to compute in one direction, but has a hard to compute inverse.
- To login:
  1. Get user name
  2. Get password
  3. Encrypt password
  4. Check against version in `/etc/password`
  5. If ok, instantiate login shell.
- Publicly readable since lots of useful info there.
- Problem: off-line attack.
- Solution: *shadow passwords* (`/etc/shadow`)

File System Implementation



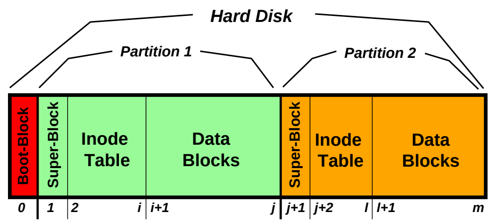
- Inside kernel, a file is represented by a data structure called an index-node or *i-node*.
- Holds file *meta-data*:
  1. Owner, permissions, reference count, etc.
  2. Location on disk of actual data (file contents).
- Where is the filename kept?

Directories and Links



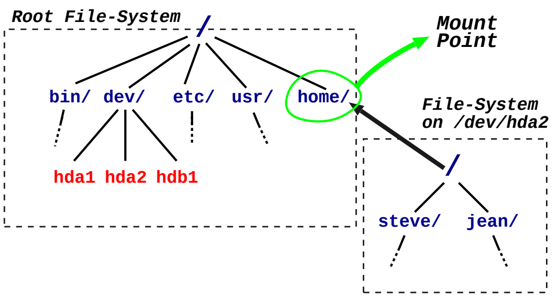
- Directory is a file which maps filenames to i-nodes.
- An instance of a file in a directory is a (hard) *link*.
- (this is why have reference count in i-node).
- Directories can have at most 1 (real) link. Why?
- Also get *soft-* or *symbolic*-links: a 'normal' file which contains a filename.

On-Disk Structures



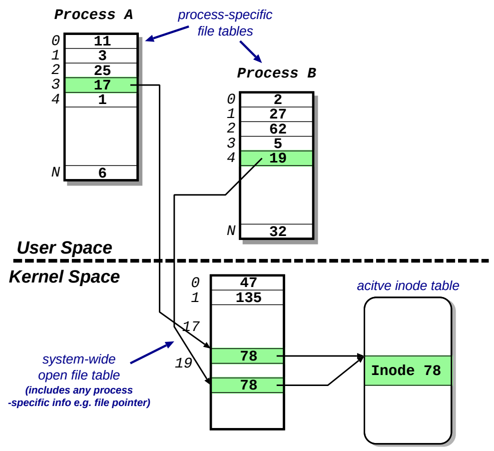
- A disk is made up of a *boot block* followed by one or more *partitions*.
- (a partition is just a contiguous range of N fixed-size blocks of size k for some N and k).
- A Unix file-system resides within a partition.
- *Superblock* contains info such as:
  - number of blocks in file-system
  - number of free blocks in file-system
  - start of the free-block list
  - start of the free-inode list.
  - various bookkeeping information.

Mounting File-Systems



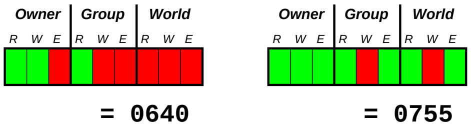
- Entire file-systems can be *mounted* on an existing directory in an already mounted filesystem.
- At very start, only '/' exists ⇒ need to mount a *root file-system*.
- Subsequently can mount other file-systems, e.g. `mount("/dev/hda2", "/home", options)`
- Provides a *unified name-space*: e.g. access `/home/steve/` directly.
- Cannot have hard links across mount points: why?
- What about soft links?

In-Memory Tables



- Recall process sees files as *file descriptors*
- In implementation these are just indices into *process-specific open file table*
- Entries point to *system-wide open file table*. Why?
- These in turn point to (in memory) inode table.

Access Control



- Access control information held in each inode.
- Three bits for each of *owner*, *group* and *world*: read, write and execute.
- What do these mean for directories?
- In addition have *setuid* and *setgid* bits:
  - normally processes inherit permissions of invoking user.
  - setuid/setgid allow user to "become" someone else when running a given program.
  - e.g. `prof` owns both executable `test` (0711 and setuid), and `score` file (0600)

  ⇒ any user can run it.

  ⇒ it can update `score` file.

  ⇒ but users can't cheat.

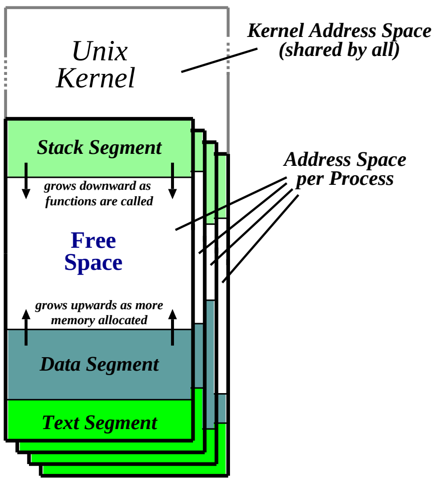
Consistency Issues

- To delete a file, use the `unlink` system call.
- From the shell, this is `rm <filename>`
- Procedure is:
  1. check if user has sufficient permissions on the file (must have *write* access).
  2. check if user has sufficient permissions on the directory (must have *write* access).
  3. if ok, remove entry from directory.
  4. Decrement reference count on inode.
  5. if now zero:
     (a) free data blocks.
     (b) free inode.
- If *crash*: must check entire file-system:
  - check if any block unreferenced.
  - check if any block double referenced.

Unix File-System: Summary

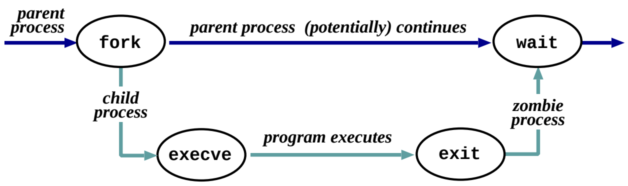
- Files are unstructured byte streams.
- Everything is a file: 'normal' files, directories, symbolic links, special files.
- Hierarchy built from root ('/').
- Unified name-space (multiple file-systems may be mounted on any leaf directory).
- Low-level implementation based around *inodes*.
- Disk contains list of inodes (along with, of course, actual data blocks).
- Processes see *file descriptors*: small integers which map to system file table.
- Permissions for owner, group and everyone else.
- Setuid/setgid allow for more flexible control.
- Care needed to ensure consistency.

Unix Processes



- Recall: a process is a program in execution.
- Have three *segments*: `text`, `data` and `stack`.
- Unix processes are *heavyweight*.

Unix Process Dynamics



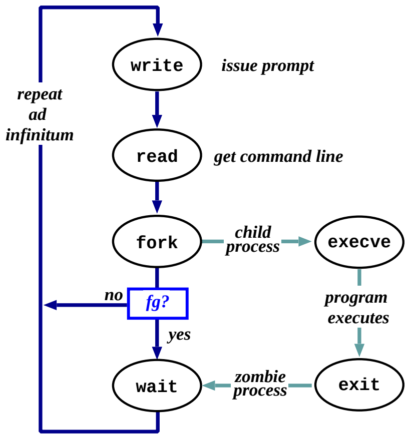
- Process represented by a *process id* (pid)
- Hierarchical scheme: parents create children.
- Four basic primitives:
  - *pid* = **fork** ()
  - reply = **execve**(*pathname*, *argv*, *envp*)
  - **exit**(*status*)
  - *pid* = **wait** (*status*)
- **fork()** nearly *always* followed by **exec()**

  $\Rightarrow$ **vfork()** and/or COW.

Start of Day

- Kernel (`/vmunix`) loaded from disk (how?) and execution starts.
- Root file-system mounted.
- Process 1 (`/etc/init`) hand-crafted.
- init reads file `/etc/inittab` and for each entry:
  1. opens terminal special file (e.g. `/dev/tty0`)
  2. duplicates the resulting fd twice.
  3. forks an `/etc/tty` process.
- each tty process next:
  1. initialises the terminal
  2. outputs the string "`login:`" & waits for input
  3. execve()'s `/bin/login`
- login then:
  1. outputs "`password:`" & waits for input
  2. encrypts password and checks it against `/etc/passwd`.
  3. if ok, sets uid & gid, and execve()'s shell.
- Patriarch init resurrects `/etc/tty` on exit.

The Shell



- Shell just a process like everything else.
- Uses *path* for convenience.
- Conventionally '&' specifies *background*.
- Parsing stage (omitted) can do lots. . .

Shell Examples

```
# pwd
/home/steve
# ls -F
IRAM.micro.ps                gnome_sizes       prog-nc.ps
Mail/                        ica.tgz           rafe/
OSDI99_self_paging.ps.gz     lectures/         rio107/
TeX/                         linbot-1.0/       src/
adag.pdf                     manual.ps         store.ps.gz
docs/                        past-papers/      wolfson/
emacs-lisp/                  pbosch/           xeno_prop/
fs.html                      pepsi_logo.tif
# cd src/
# pwd
/home/steve/src
# ls -F
cdq/          emacs-20.3.tar.gz  misc/       read_mem.c
emacs-20.3/   ispell/            read_mem*   rio007.tgz
# wc read_mem.c
     95     225    2262 read_mem.c
# ls -lF r*
-rwxrwxr-x    1 steve  user    34956 Mar 21  1999 read_mem*
-rw-rw-r--    1 steve  user     2262 Mar 21  1999 read_mem.c
-rw-------    1 steve  user    28953 Aug 27 17:40 rio007.tgz
# ls -l /usr/bin/X11/xterm
-rwxr-xr-x    2 root   system 164328 Sep 24 18:21 /usr/bin/X11/xterm*
```

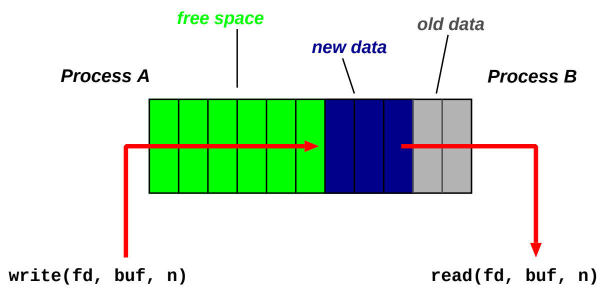
- Prompt is '#'.
- Use `man` to find out about commands.
- User friendly?

Standard I/O

- Every process has three fds on creation:
  - **stdin**: where to read input from.
  - **stdout**: where to send output.
  - **stderr**: where to send diagnostics.
- Normally inherited from parent, but shell allows *redirection* to/from a file, e.g.:
  - `ls >listing.txt`
  - `ls >&listing.txt`
  - `sh <commands.sh`.
- Actual file not always appropriate; e.g. consider:

  ```
  ls >temp.txt;
  wc <temp.txt >results
  ```
- *Pipeline* is better (e.g. `ls | wc >results`)
- Most Unix commands are *filters* ⇒ can build almost arbitrarily complex command lines.
- Redirection can cause some buffering subtleties.

Pipes

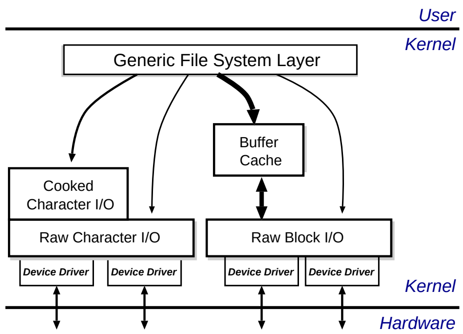


- One of the basic Unix IPC schemes.
- Logically consists of a pair of fds
- e.g. reply = **pipe**(int fds[2])
- Concept of "full" and "empty" pipes.
- Only allows communication between processes with a common ancestor (why?).
- *Named pipes* address this.

Signals

- Problem: pipes need planning ⇒ use *signals*.
- Similar to a (software) interrupt.
- Examples:
  - `SIGINT` : user hit Ctrl-C.
  - `SIGSEGV` : program error.
  - `SIGCHLD` : a death in the family. . .
  - `SIGTERM` : . . . or closer to home.
- Unix allows processes to *catch* signals.
- e.g. Job control:
  - `SIGTTIN`, `SIGTTOU` sent to bg processes
  - `SIGCONT` turns bg to fg.
  - `SIGSTOP` does the reverse.
- Cannot catch `SIGKILL` (hence `kill -9`)
- Signals can also be used for timers, window resize, process tracing, . . .

I/O Implementation



- Recall:
  - everything accessed via the file system.
  - two broad categories: block and char.
- Low-level stuff gory and machdep ⇒ ignore.
- Character I/O low rate but complex ⇒ most functionality in the "cooked" interface.
- Block I/O simpler but performance matters ⇒ emphasis on the *buffer cache*.

The Buffer Cache

- Basic idea: keep copy of some parts of disk in memory for speed.
- On read do:
  1. Locate relevant blocks (from inode)
  2. Check if in buffer cache.
  3. If not, read from disk into memory.
  4. Return data from buffer cache.
- On write do *same* first three, and then update version in cache, not on disk.
- "Typically" prevents 85% of implied disk transfers.
- Question: when does data actually hit disk?
- Answer: call `sync` every 30 seconds to flush dirty buffers to disk.
- Can cache metadata too — problems?
- need mutual exclusion and condition synchronisation
  e.g. WAIT for a buffer
  e.g. WAIT for full (data transfer comlete.

Unix Process Scheduling

- Priorities 0–127; user processes $\geq$ `PUSER` $= 50$.
- Round robin within priorities, quantum 100ms.
- Priorities are based on usage and *nice*, i.e.

$$P_j(i) = Base_j + \frac{CPU_j(i-1)}{4} + 2 \times nice_j$$

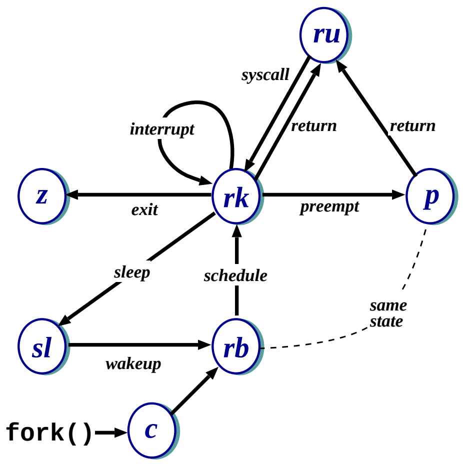
gives the priority of process j at the beginning of interval i where:

$$CPU_j(i) = \frac{2 \times load_j}{(2 \times load_j) + 1} CPU_j(i-1) + nice_j$$

and $nice_j$ is a (partially) user controllable adjustment parameter $\in [-20, 20]$.

- $load_j$ is the sampled average length of the run queue in which process j resides, over the last minute of operation
- so if e.g. load is 1 $\Rightarrow \sim$ 90% of 1 seconds CPU usage "forgotten" within 5 seconds.

Unix Process States



ru	=	running (user-mode)	rk	=	running (kernel-mode)
z	=	zombie	p	=	pre-empted
sl	=	sleeping	rb	=	runnable
c	=	created			

- Note: above is simplified — see CS section 23.14 for detailed descriptions of all states/transitions.

Summary

- Main Unix features are:
  - file abstraction
    - a file is an unstructured sequence of bytes
    - (not really true for device and directory files)
  - hierarchical namespace
    - directed acyclic graph (if exclude soft links)
    - can recursively mount filesystems
  - heavy-weight processes
  - IPC: pipes & signals
  - I/O: block and character
  - dynamic priority scheduling
    - base priority level for all processes
    - priority is lowered if process gets to run
    - over time, the past is forgotten
- But V7 had inflexible IPC, inefficient memory management, and poor kernel concurrency.
- Later versions address these issues.

Windows NT: History

After OS/2, MS decide they need "**N**ew **T**echnology":

- 1988: Dave Cutler recruited from DEC.
- 1989: team (∼ 10 people) starts work on a new OS with a micro-kernel architecture.
- July 1993: first version (3.1) introduced

Bloated and suckful (smh22) ⇒

- NT 3.5 released in September 1994: mainly size and performance optimisations.
- Followed in May 1995 by NT 3.51 (support for the Power PC, and more performance tweaks)
- July 1996: NT 4.0
  - new (windows 95) look 'n feel
  - various functions pushed back into kernel (most notably graphics rendering functions)
  - ongoing upgrades via *service packs*

Windows NT: Evolution

- Feb 2000: NT 5.0 aka Windows 2000
  - borrows from windows 98 look 'n feel
  - both *server* and *workstation* versions, latter of which starts to get wider use
  - big push to finally kill DOS/Win 9x family
  - (fails due to internal politicking)
- Windows XP (NT 5.1)launched Oct 2001
  - home and professional⇒finally kills win 9x
  - various "editions" (media center[2003] 64-bit[2005]) and service packs (SP1, SP2).
- Server product 2K3 (NT 5.2)released 2003
  - basically the same, modulo registry tweaks, support contract and, of course, cost
  - a plethora of editions . . .
- Windows Vista (NT 6.0) due Q4 2006
  - new Aero UI, new WinFX API
  - missing Longhorn bits like WinFS, Msh
- Longhorn Server (NT x.y?) probably 2007 . . .

NT Design Principles

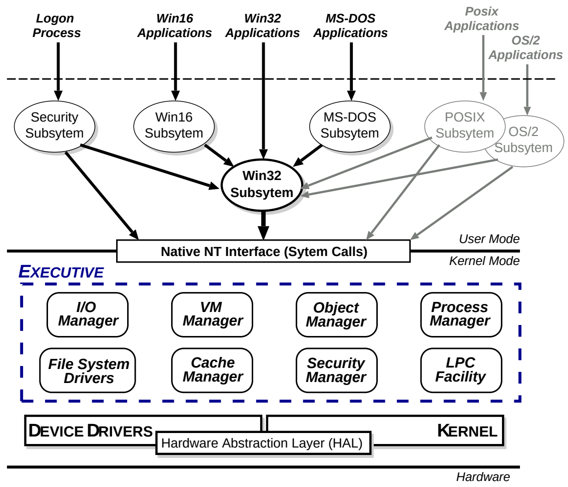
Key goals for the system were:

- portability
- security
- POSIX compliance
- multiprocessor support
- extensibility
- international support
- compatibility with MS-DOS/Windows applications

This led to the development of a system which was:

- written in high-level languages (C and C++)
- based around a micro-kernel, and
- constructed in a layered/modular fashion.

Structural Overview



- Kernel Mode: HAL, Kernel, & Executive
- User Mode:
  - environmental subsystems
  - protection subsystem

HAL

- Layer of software (`HAL.DLL`) which hides details of underlying hardware
- e.g. interrupt mechanisms, DMA controllers, multiprocessor communication mechanisms
- Many HALs exist with same *interface* but different *implementation* (often vendor-specific)

Kernel

- Foundation for the executive and the subsystems
- Execution is never preempted.
- Four main responsibilities:
  1. CPU scheduling
  2. interrupt and exception handling
  3. low-level processor synchronisation
  4. recovery after a power failure
- Kernel is objected-oriented; all objects either *dispatcher objects* and *control objects*

Processes and Threads

NT splits the "virtual processor" into two parts:

1. A **process** is the unit of resource ownership. Each process has:
   - a security token,
   - a virtual address space,
   - a set of resources (*object handles*), and
   - one or more *threads*.
2. A **thread** is the unit of dispatching. Each thread has:
   - a scheduling state (ready, running, etc.),
   - other scheduling parameters (priority, etc),
   - a context slot, and
   - (generally) an associated process.

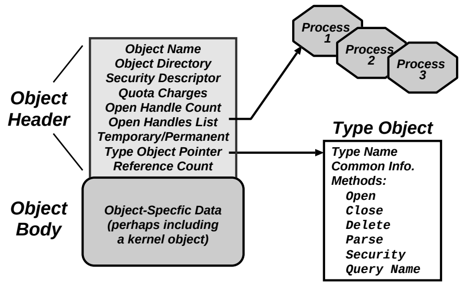
Threads are:

- co-operative: all threads in a process share the same address space & object handles.
- lightweight: require less work to create/delete than processes (mainly due to shared VAS).

CPU Scheduling

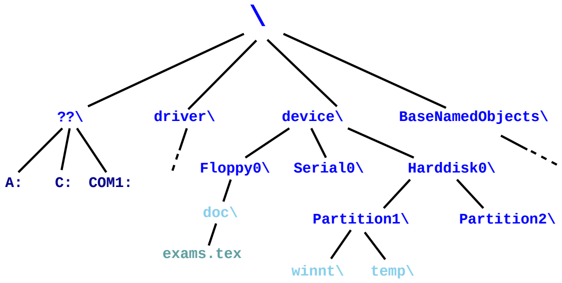
- Hybrid static/dynamic priority scheduling:
  - Priorities 16–31: "real time" (static priority).
  - Priorities 1–15: "variable" (dynamic) priority.
- Default quantum 2 ticks (∼20ms) on Workstation, 12 ticks (∼120ms) on Server.
- Threads have *base* and *current* ($\geq$ base) priorities.
  - On return from I/O, current priority is *boosted* by driver-specific amount.
  - Subsequently, current priority decays by 1 after each completed quantum.
  - Also get boost for GUI threads awaiting input: current priority boosted to 14 for one quantum (but quantum also doubled)
  - Yes, this is true.
- On Workstation also get *quantum stretching*:
  - ". . . performance boost for the foreground application" (window with focus)
  - fg thread gets double or triple quantum.

Object Manager



- Every resource in NT is represented by an *object*
- The Object Manager (part of the Executive) is responsible for:
  - creating objects and *object handles*
  - performing security checks
  - tracking which processes are using each object
- Typical operation:
  - `handle = open(objectname, accessmode)`
  - `result = service(handle, arguments)`

Object Namespace



- Recall: objects (optionally) have a name
- Object Manager manages a hierarchical namespace:
  - shared between all processes ⇒ sharing
  - implemented via *directory objects*
  - each object protected by an access control list.
  - *naming domains* (implemented via `parse`) mean file-system namespaces can be integrated
- Also get *symbolic link objects*: allow multiple names (aliases) for the same object.
- Modified view presented at API level. . .

Process Manager

- Provides services for creating, deleting, and using threads and processes.
- Very flexible:
  - no built in concept of parent/child relationships or process hierarchies
  - processes and threads treated orthogonally.
  - ⇒ can support Posix, OS/2 and Win32 models.

Virtual Memory Manager

- NT employs paged virtual memory management
- The VMM provides processes with services to:
  - allocate and free virtual memory
  - modify per-page protections
- Can also share portions of memory:
  - use *section objects* (≈ software segments)
  - based versus non-based.
  - also used for *memory-mapped files*

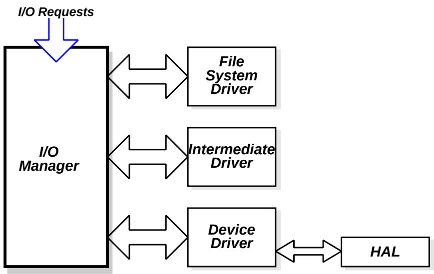
Security Reference Manager

- NTs object-oriented design supports a *uniform mechanism* for runtime access and audit checks
  - every time a process opens a handle to an object, check process security token and object's ACL
  - cf. Unix (file-system, networking, shared memory etc . . .)

Local Procedure Call Facility

- LPC (or IPC) passes requests and results between client and server processes within a single machine.
- Used to request services from the various NT environmental subsystems.
- Three variants of LPC channels:
  1. small messages ($\leq$ 256 bytes): copy messages between processes
  2. zero copy: avoid copying large messages by pointing to a shared memory section object created for the channel.
  3. *quick LPC*: used by the graphical display portions of the Win32 subsystem.

I/O Manager

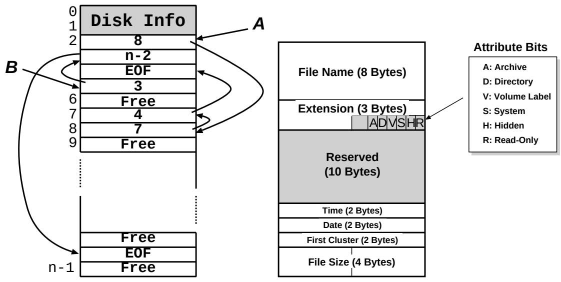


- The I/O Manager is responsible for:
  - file systems
  - cache management
  - device drivers
- Basic model is *asynchronous*:
  - each I/O operation explicitly split into a request and a response
  - *I/O Request Packet* (IRP) used to hold parameters, results, etc.
- File-system & device drivers are *stackable*. . .

Cache Manager

- Cache Manager caches "virtual blocks":
  - viz. keeps track of cache "lines" (blocks) 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 blocks all in virtual address space.
  - decouples physical & virtual cache systems: e.g.
    - ∗ virtually cache in 256K blocks,
    - ∗ physically *cluster* up to 64K.
  - NT virtual memory manager responsible for actually doing the I/O.
  - allows lots of FS cache when VM system lightly loaded, little when system is thrashing.
- NT/2K 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: FAT16



- A file is a linked list of *clusters*: a cluster is a set of 2^n contiguous disk blocks, $n \geq 0$.
- Each entry in the `FAT` contains either:
  - the index of another entry within the `FAT`, or
  - a special value `EOF` meaning "end of file", or
  - a special value `Free` meaning "free".
- Directory entries contain index into the `FAT`
- `FAT16` could only handle partitions up to $(2^{16} \times c)$ bytes ⇒ max 2Gb partition with 32K clusters.
- (and big cluster size is *bad*)

File Systems: FAT32

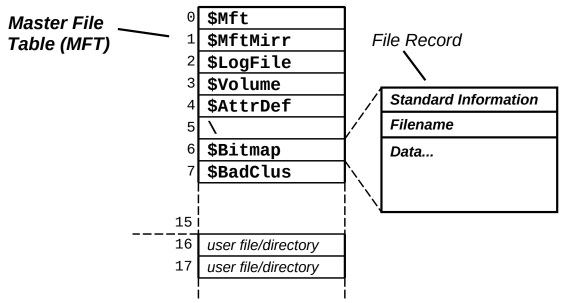
- Obvious extension: instead of using 2 bytes per entry, `FAT32` uses 4 bytes per entry

⇒ can support e.g. 8Gb partition with 4K clusters

- Further enhancements with `FAT32` include:
  - can locate the root directory anywhere on the partition (in `FAT16`, the root directory had to immediately follow the `FAT`(s)).
  - can use the backup copy of the `FAT` instead of the default (more fault tolerant)
  - improved support for demand paged executables (consider the 4K default cluster size . . .).
- `VFAT` on top of `FAT32` does long name support: unicode strings of up to 256 characters.
  - want to keep same directory entry structure for compatibility with e.g. DOS
  - ⇒ use *multiple* directory entries to contain successive parts of name.
  - abuse `V` attribute to avoid listing these

Still pretty primitive. . .

File-Systems: NTFS



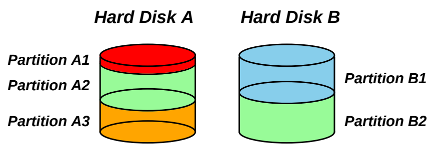
- Fundamental structure of NTFS is a *volume*:
  - based on a logical disk partition
  - may occupy a portion of a disk, an entire disk, or span across several disks.
- An NTFS file is described by an array of records in a special file called the Master File Table (MFT).
- The MFT is indexed by a *file reference* (a 64-bit unique identifier for a file)
- A file itself is a structured object consisting of a set of attribute/value pairs of variable length. . .

NTFS: Recovery

- To aid recovery, all file system data structure updates are performed inside *transactions*:
  - before a data structure is altered, the transaction writes a log record that contains redo and undo information.
  - after the data structure has been changed, a commit record is written to the log to signify that the transaction succeeded.
  - after a crash, the file system can be restored to a consistent state by processing the log records.
- Does not guarantee that all the user file data can be recovered after a crash — just that metadata files will reflect some prior consistent state.
- The log is stored in the third metadata file at the beginning of the volume (`$Logfile`)
  - NT has a generic *log file service*

  ⇒ could in principle be used by e.g. database
- Overall makes for far quicker recovery after crash
- (modern Unix fs [ext3, xfs] use similar scheme)

NTFS: Fault Tolerance



- `FtDisk` driver allows multiple partitions to be combined into a logical volume:
  - logically concatenate multiple disks to form a large logical volume, a *volume set*.
  - based on the concept of RAID = **R**edundant **A**rray of **I**nexpensive **D**isks:
  - e.g. RAID level 0: interleave multiple partitions round-robin to form a *stripe set*
  - e.g. RAID level 1 increases robustness by using a *mirror set*: two equally sized partitions on two disks with identical data contents.
  - (other more complex RAID levels also exist)
- `FtDisk` can also handle *sector sparing* where the underlying SCSI disk supports it
- (if not, NTFS supports s/w *cluster remapping*)

NTFS: Other Features

- Security:
  - security derived from the NT object model.
  - each file object has a *security descriptor attribute* stored in its MFT record.
  - this atrribute contains the access token of the owner of the file plus an access control list
- Compression:
  - NTFS can divide a file's data into *compression units* (blocks of 16 contiguous clusters)
  - NTFS also has support for *sparse files*
    - clusters with all zeros not allocated or stored
    - instead, gaps are left in the sequences of VCNs kept in the file record
    - when reading a file, gaps cause NTFS to zero-fill that portion of the caller's buffer.
- Encryption:
  - Use symmetric key to encrypt files; file attribute holds this key encrypted with user *public key*
  - Problems: private key pretty easy to obtain; and administrator can bypass entire thing anyhow.

Environmental Subsystems

- User-mode processes layered over the native NT executive services to enable NT to run programs developed for other operating systems.
- NT uses the Win32 subsystem as the main operating environment; Win32 is used to start all processes. It also provides all the keyboard, mouse and graphical display capabilities.
- MS-DOS environment is provided by a Win32 application called the *virtual dos machine* (VDM), a user-mode process that is paged and dispatched like any other NT thread.
- 16-Bit Windows Environment:
  - Provided by a VDM that incorporates *Windows on Windows*
  - Provides the Windows 3.1 kernel routines and stub routings for window manager and GDI functions.
- The POSIX subsystem is designed to run POSIX applications following the POSIX.1 standard which is based on the UNIX model.

Summary

- Main Windows NT features are:
  - layered/modular architecture:
  - generic use of objects throughout
  - multi-threaded processes
  - multiprocessor support
  - asynchronous I/O subsystem
  - NTFS filing system (vastly superior to FAT32)
  - preemptive priority-based scheduling
- Design essentially more advanced than Unix.
- Implementation of lower levels (HAL, kernel & executive) actually rather decent.
- But: has historically been crippled by
  - almost exclusive use of Win32 API
  - legacy device drivers (e.g. VXDs)
  - lack of demand for "advanced" features
- Continues to evolve:
  - Windows *Vista* (NT 6.0) due Q4 2006
  - *Longhorn* due 2007–2009
  - *Singularity* research OS. . .

Course Review

- Part I: Computer Organisation
  - fetch-execute cycle, data representation, etc
  - mainly for getting up to speed for h/w courses
- Part II: Operating System Functions
  - OS structures: h/w support, kernel vs. μ-kernel
  - Processes: states, structures, scheduling
  - Memory: virtual addresses, sharing, protection
  - Filing: directories, meta-data, file operations.
- Part III: Concurrency Control
  - multithreaded processes
  - mutual exclusion and condition synchronisation
  - implementation of concurrency control
- Part IV: Case Studies
  - UNIX and Windows NT