Operating Systems

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12 lectures for CST Ia

Easter Term 2000

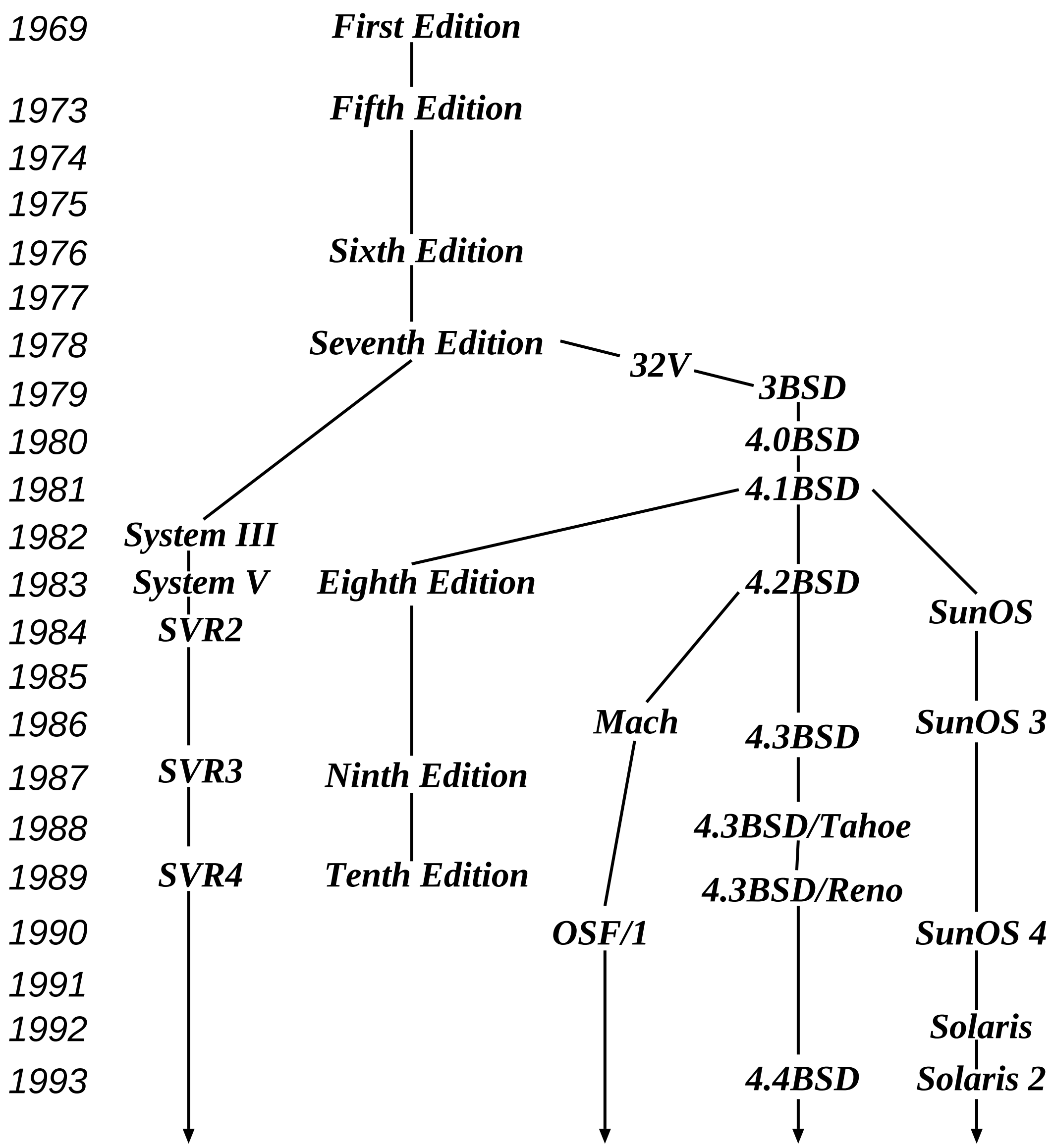
Part III: Case Studies

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.
- 6th 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

Unix Family Tree (Simplified)



Design Features

Ritchie and Thompson, CACM, July 74, UNIX (new) features:

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.

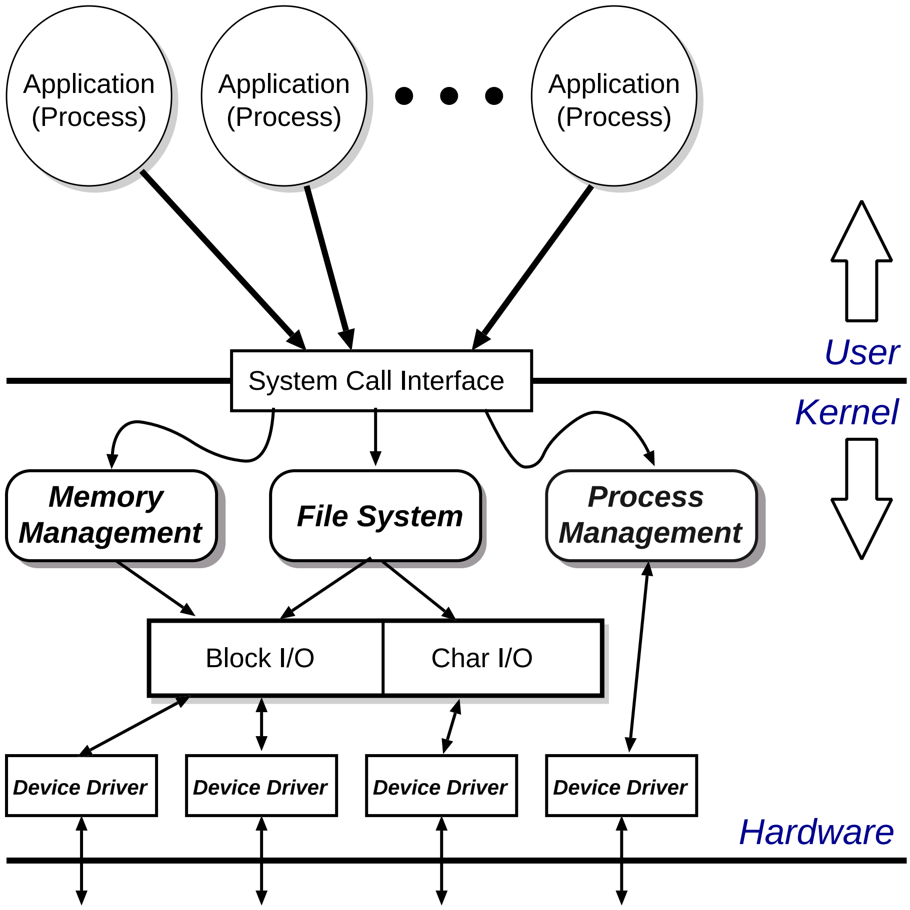
Features which were not included:

- real time

- multiprocessor support

Fixing the above is *hard* . . .

Structural Overview

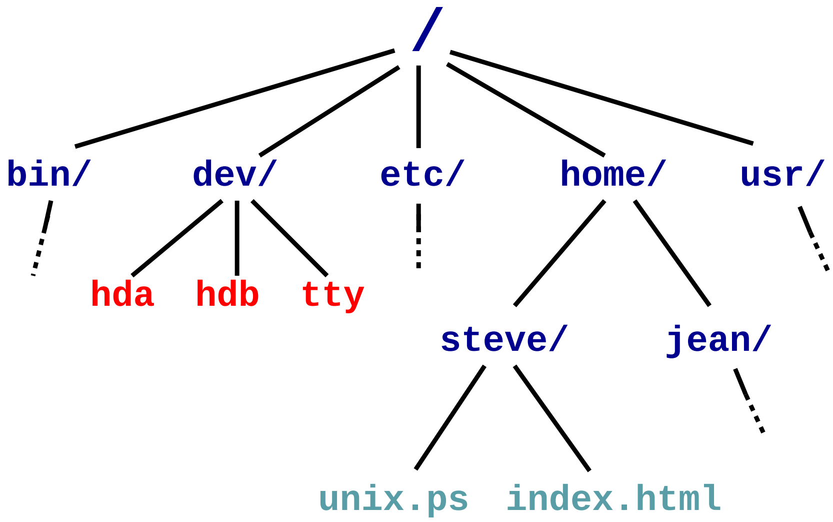


- Clear separation between *user* and *kernel* portions.
- Processes are unit of scheduling and protection.
- All I/O looks like operations on *files*.

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*.
- 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/)

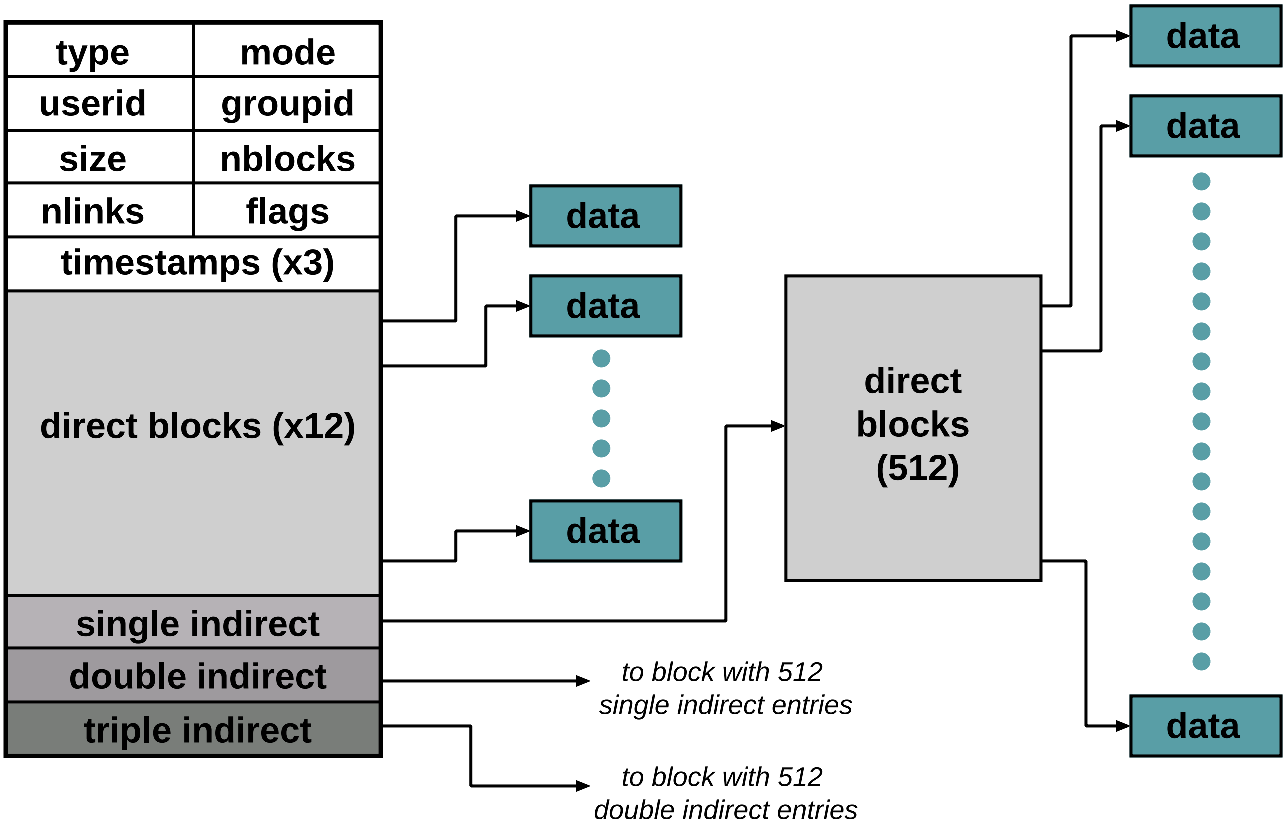
Aside: Password File

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

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

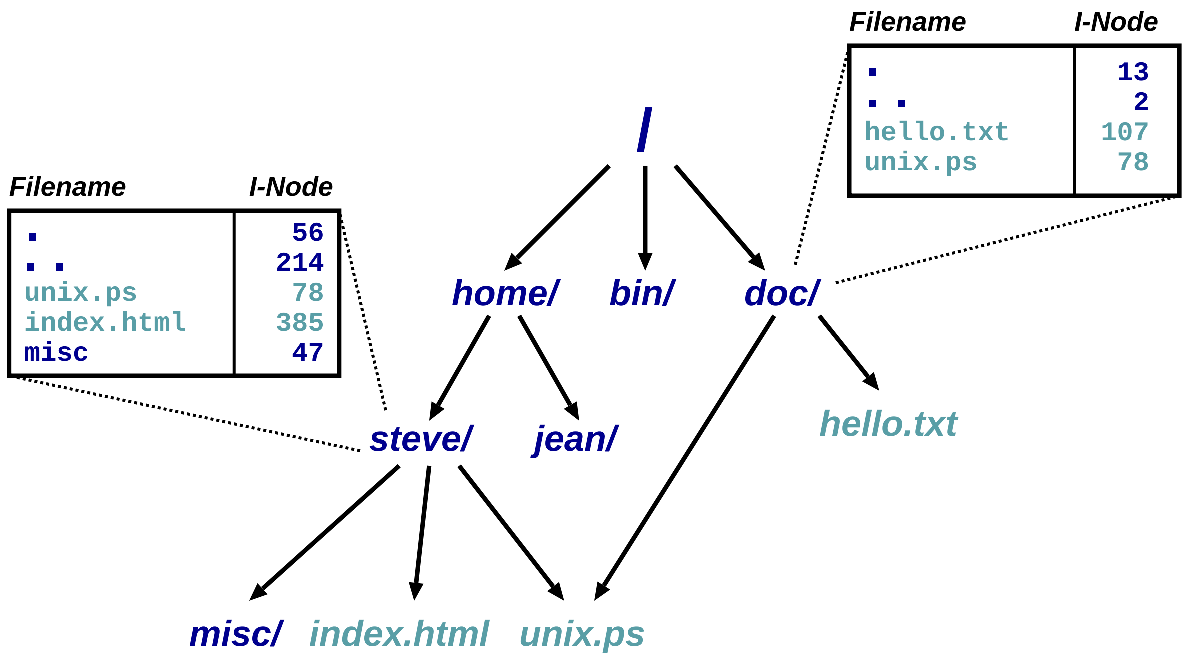
- Use *one-way function* to encrypt passwords.
- To login:
  1. Get user name
  2. Get password
  3. Encrypt password
  4. Check against version in `/etc/password`
  5. If ok, instantiate login shell.
- Publicly readable since lots of useful info there.
- Problem: off-line attack.
- Solution: *shadow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

File System Implementation



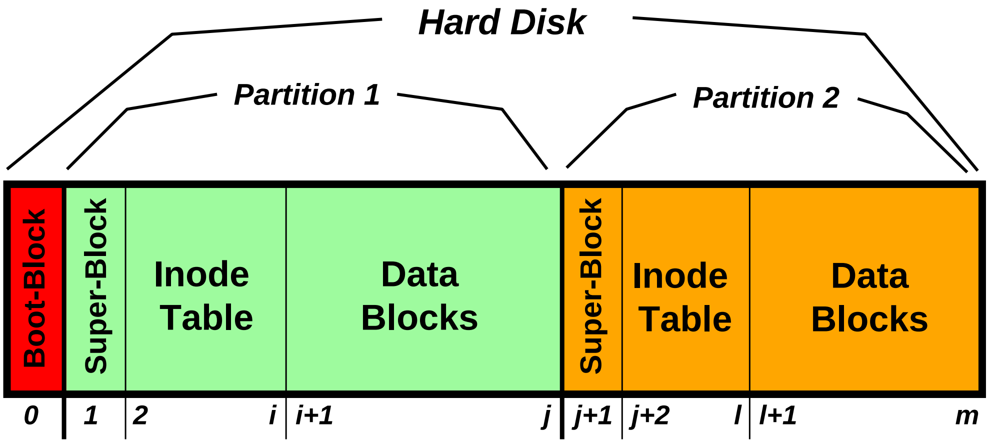
- Inside kernel, a file is represented by a data structure called an index-node or *i-node*.
- Holds file *meta-data*:
  a) Owner, permissions, reference count, etc.
  b) Location on disk of actual data (file contents).
- Where is the filename kept?

Directories and Links



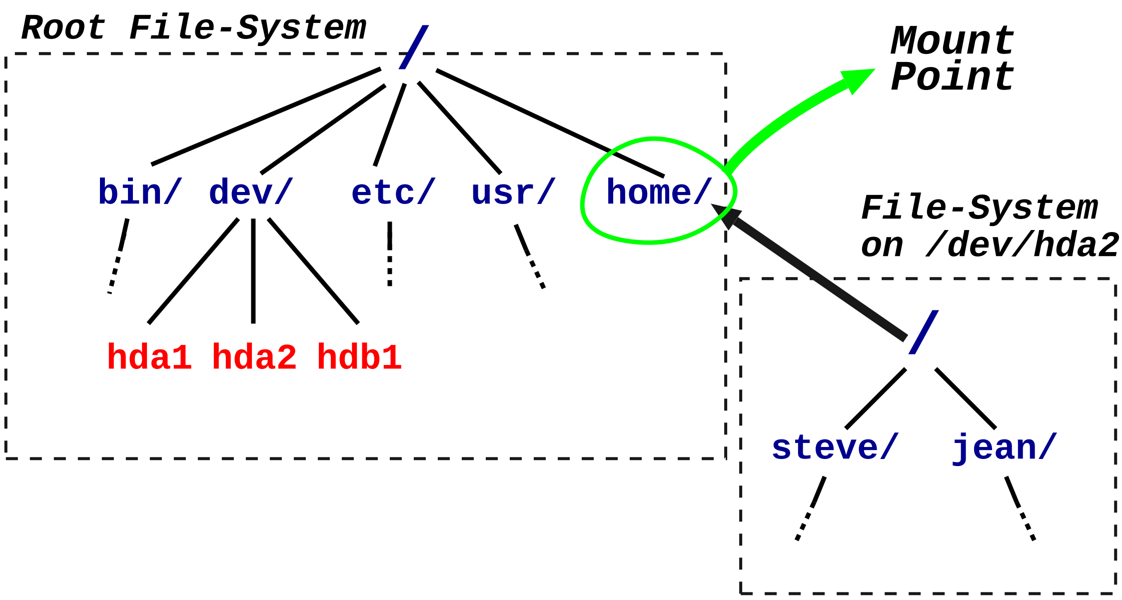
- Directory is a file which maps filenames to i-nodes.
- An instance of a file in a directory is a (hard) *link*.
- (this is why have reference count in i-node).
- Directories can have at most 1 (real) link. Why?
- Also get *soft-* or *symbolic*-links: a ‘normal’ file which contains a filename.

On-Disk Structures



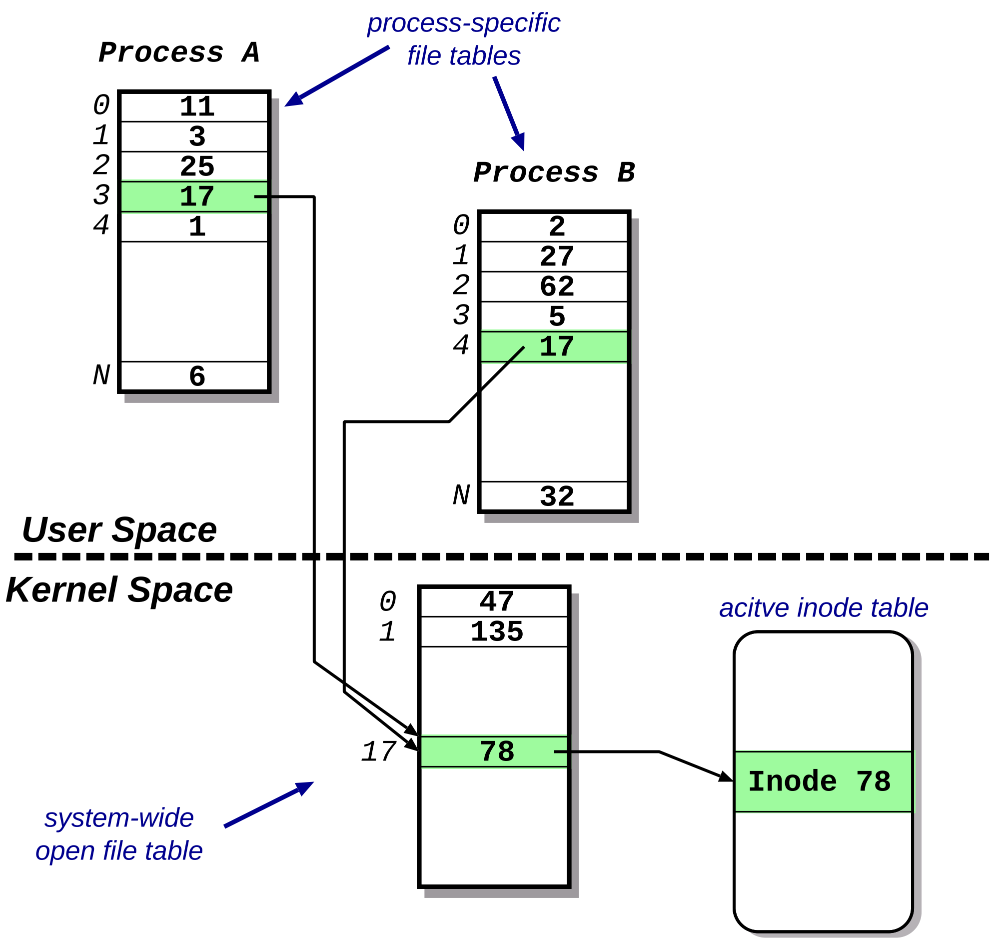
- A disk is made up of a *boot block* and one or more *partitions*.
- (a partition is just a contiguous range of N fixed-size blocks of size k for some N and k).
- A Unix file-system resides within a partition.
- *Superblock* contains info such as:
  - number of blocks in file-system
  - number of free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

Mounting File-Systems



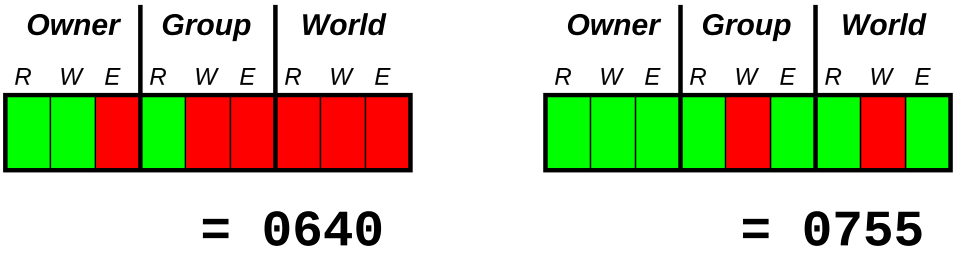
- Entire file-systems can be *mounted* on an existing directory.
- At very start, only '/' exists ⇒ need to mount a *root file-system*.
- Subsequently can mount other file-systems, e.g. `mount("/dev/hda2", "/home", options)`
- Provides a *unified name-space*: e.g. access `/home/steve/` directly.
- Cannot 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)
    - ⇒ anyone user can run it.
    - ⇒ it can update `score` file.
    - ⇒ but users can't cheat.
- And what do *these* mean for directories?

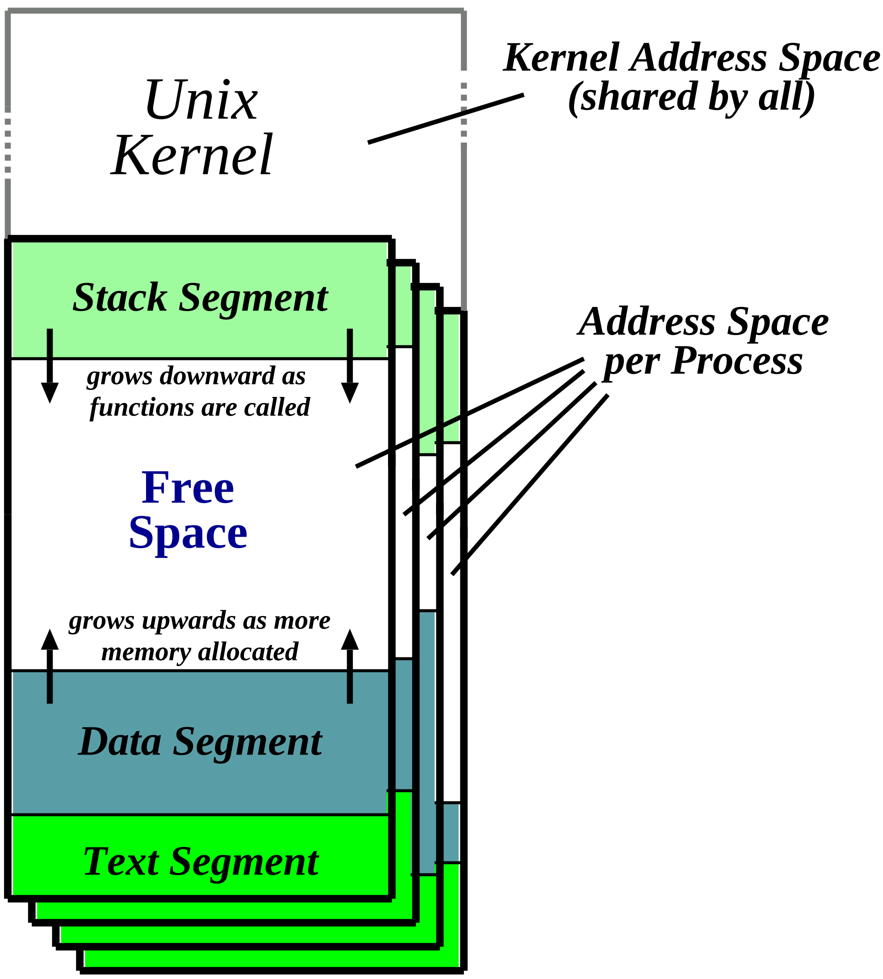
Consistency Issues

- 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

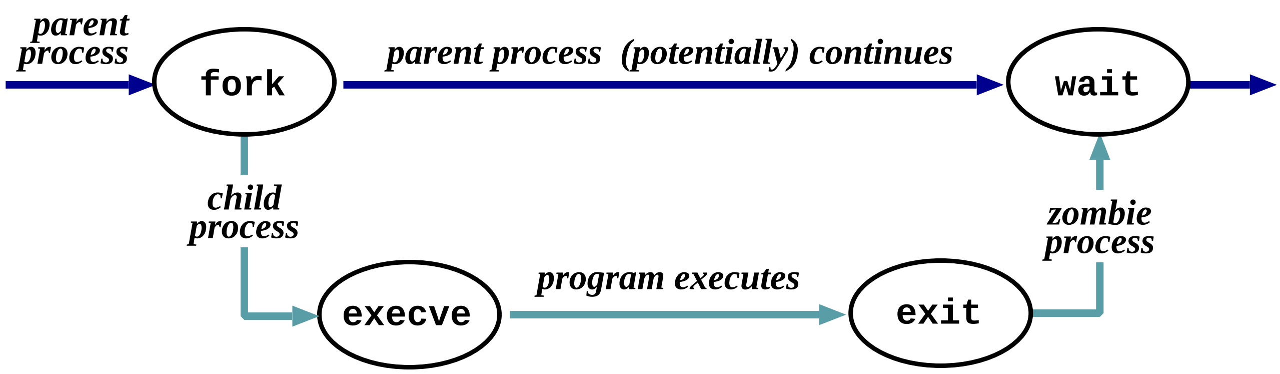
- Files are unstructured byte streams.
- Everything is a file: ‘normal’, directories, symbolic links, special files.
- Hierarchy built from root (‘/’).
- Unified name-space (multiple file-systems may be mounted).
- Low-level implementation based around *inodes*.
- Disk contains list of inodes (and of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

Processes



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

Unix Process Dynamics



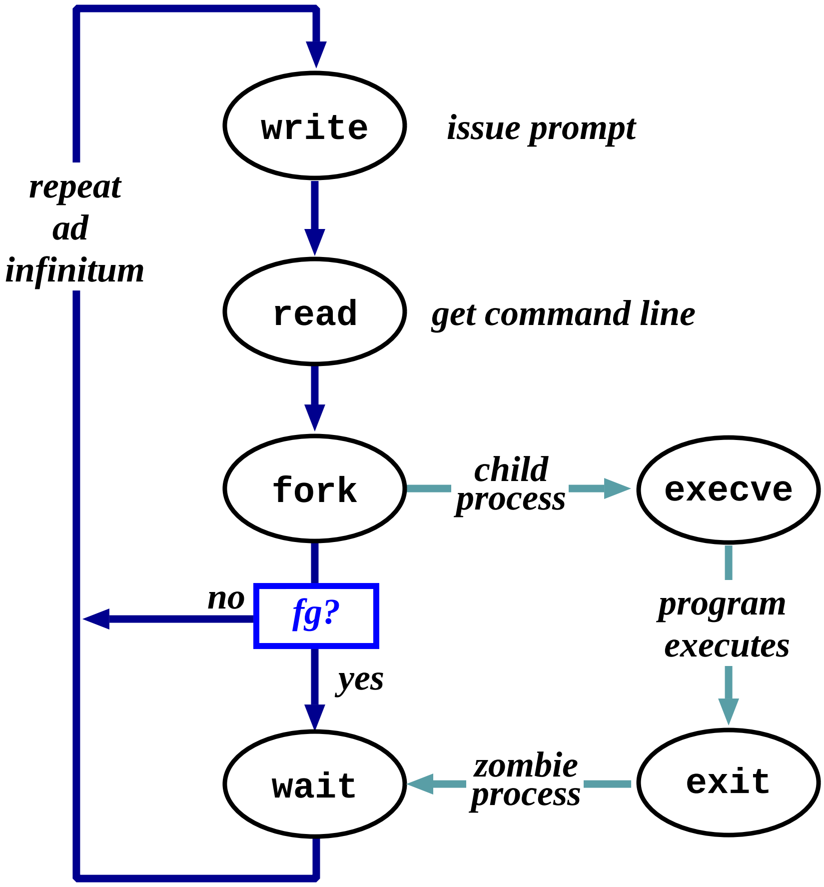
- Process represented by a *process id* (pid)
- Hierarchical scheme: parents create children.
- Four basic primitives:
  - *pid* = **fork** ()
  - reply = **execve**(*pathname*, *argv*, *envp*)
  - **exit**(*status*)
  - *pid* = **wait** (*status*)
- **fork()** nearly *always* followed by **exec()**

  $\Rightarrow$ **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 conf 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

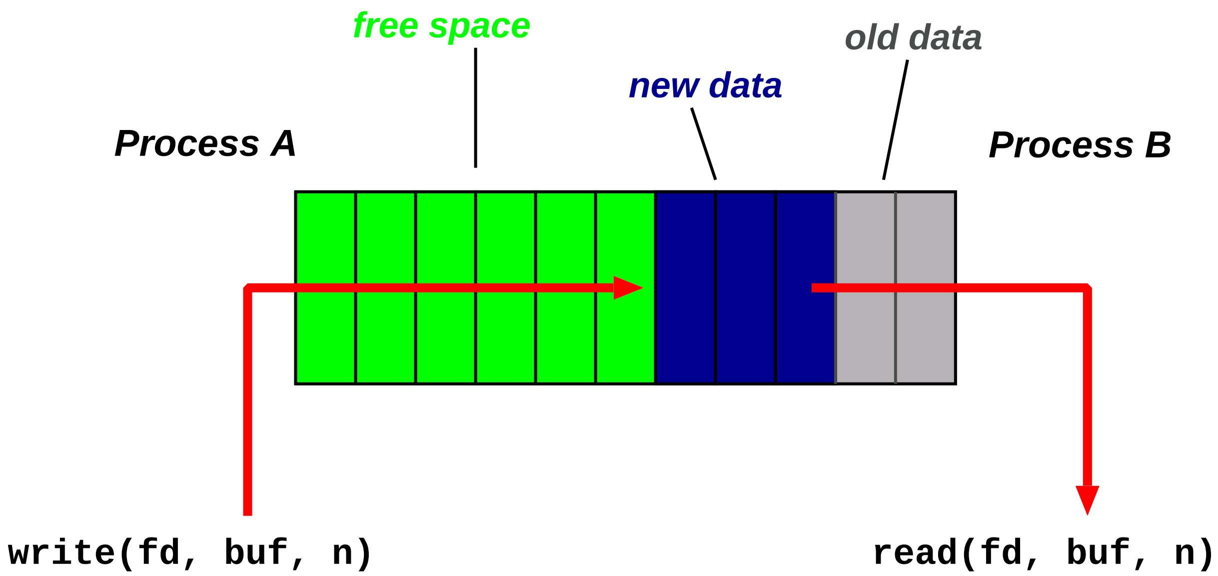
```
# pwd
/home/steve
# ls -F
IRAM.micro.ps                gnome_sizes        prog-nc.ps
Mail/                        ica.tgz            rafe/
OSDI99_self_paging.ps.gz     lectures/          rio107/
TeX/                         linbot-1.0/        src/
adag.pdf                     manual.ps          store.ps.gz
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`.
- 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.
- NB: redirection causes some subtleties . . .

Pipes

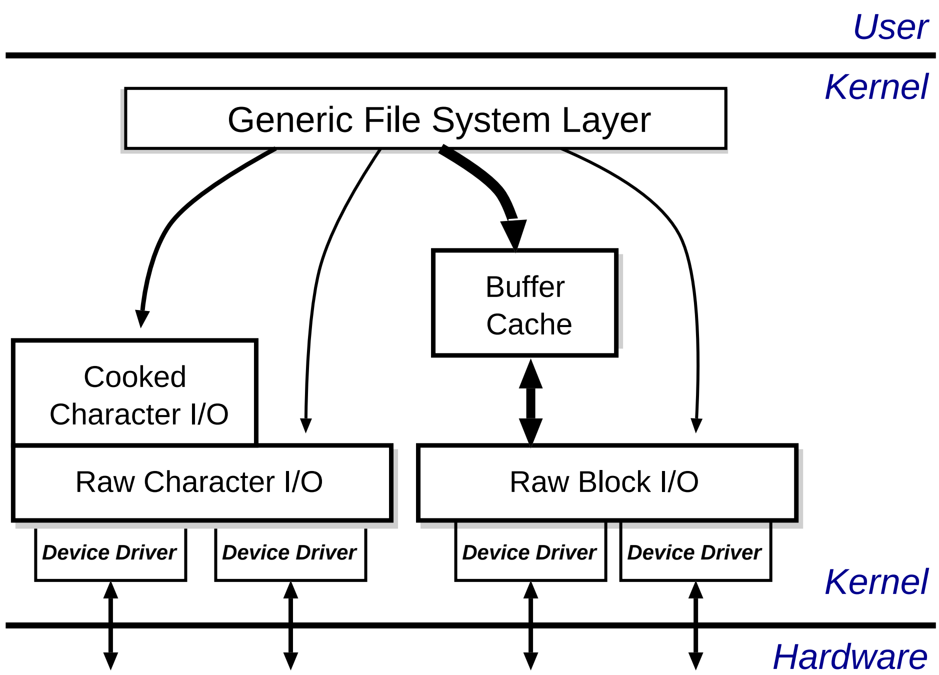


- One of the basic Unix IPC schemes.
- Logically consists of a pair of fds
- e.g. reply = **pipe**(int fds[2])
- Concept of “full” and “empty” pipes.
- Only allows communication between processes with a common ancestor (why?).
- *Named pipes* address this.

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`.
- Signals also 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.
- Q: when does data actually hit disk?
- Can cache metadata too — problems?

Unix Process Scheduling

- Round robin scheduling within discrete priorities
- Same quantum for all processes (100ms)
- Clock interrupts at regular intervals (10ms) — used for accounting
- Priorities are based on usage and *nice* (negative = higher priority):

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

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

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

- $nice_j$ is a user controllable adjustment parameter $\in [-20, 20]$.
- $load_j(i)$ is the sampled average length of the run queue in which process j resides, over the last minute of operation
- Priorities recomputed once per second, at which time a new scheduling decision is made

Summary

- Main Unix features are:
  - file abstraction
  - hierarchical namespace
  - heavy-weight processes
  - IPC: pipes & signals
  - I/O: block and character
  - dynamic priority scheduling.
- But V7 had poor IPC, memory management, concurrency.
- Later systems address these ...

Windows NT: History

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

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

Bloated and suckful $\Rightarrow$

- 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*

NT 5.0 aka Windows 2000 released February 2000 ...

NT Design Principles

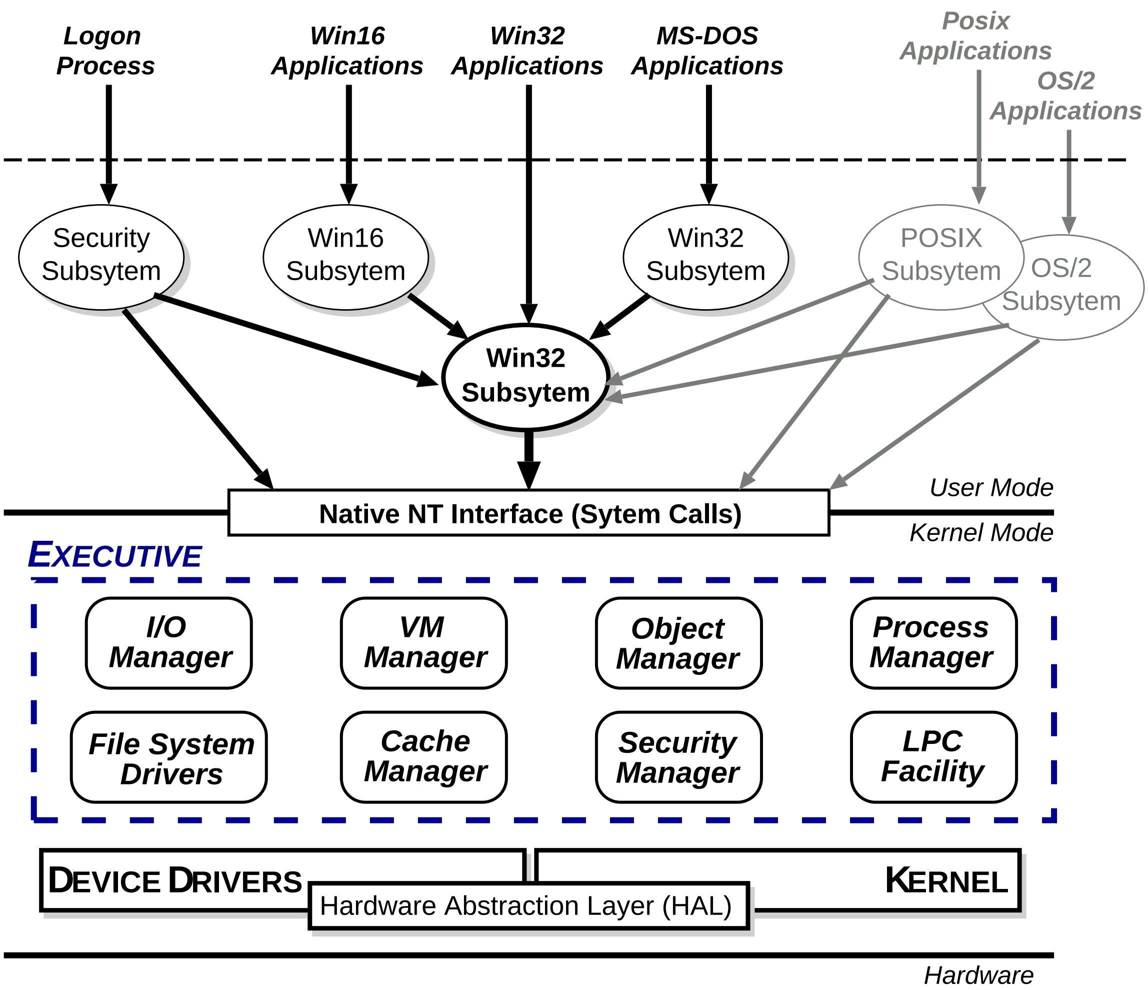
Key goals for the system were:

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

The 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** are 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.

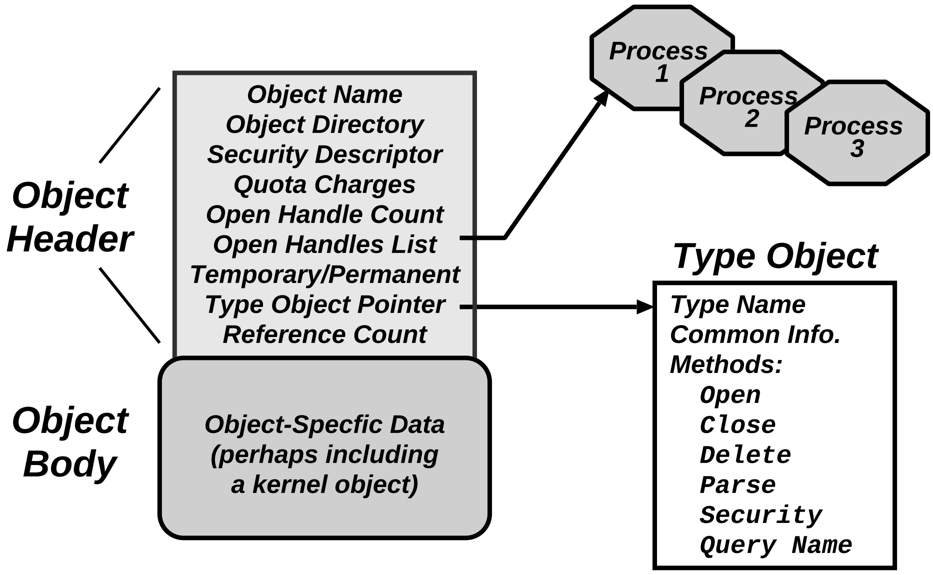
Threads are:

- 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

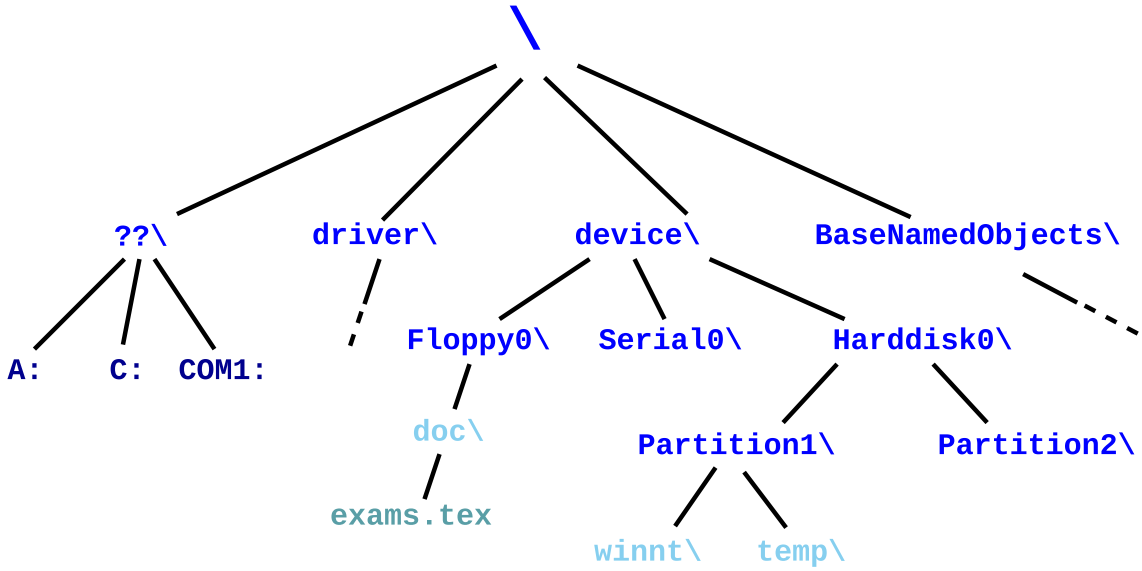
- Hybrid static/dynamic priority scheduling:
  - Priorities 16–31: “real time” (static priority).
  - Priorities 1–15: “variable” (dynamic) priority.
- Default quantum 2 ticks (∼20ms) on Workstation, 12 ticks (∼120ms) on Server.
- Threads have *base* and *current* (≥ base) priorities.
  - On return from 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(object-name, access-mode)`
  - `result = service(handle, arguments)`

Object Namespace



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

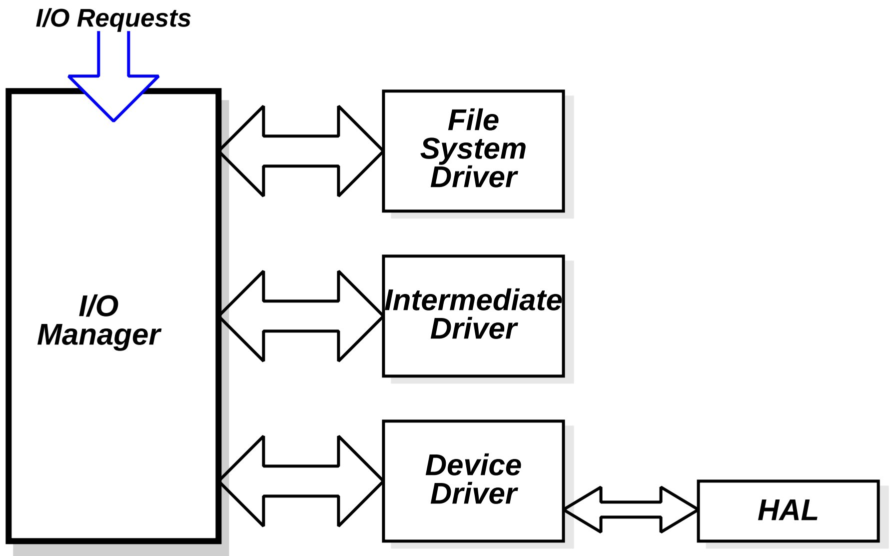
Process Manager

- 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 completely orthogonally.

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* ($\approx$ software segments)
  - based verus non-based.
  - also used for *memory-mapped files*

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* . . .

File System

- The fundamental structure of the NT filing system (NTFS) is a *volume*
  - Created by the NT disk administrator utility
  - Based on a logical disk partition
  - May occupy a portion of a disk, and entire disk, or span across several disks.
- A file in NTFS is not a simple byte stream, as in MS-DOS or UNIX, rather, it is a structured object consisting of *attributes*.
- Every file in NTFS is described by one or more records in an array stored in a special file called the Master File Table (MFT).
- NTFS has a number of advanced features, e.g.
  - security (access checks on open)
  - unicode based names
  - use of a log for efficient recovery
  - support for sparse and compressed files
- (but only recently are features being used)

Summary

- Main Windows NT features are:
  - layered/modular architecture
  - generic use of objects throughout
  - multi-threaded processes
  - multiprocessor support
  - asynchronous I/O subsystem
  - advanced filing system
  - preemptive priority-based scheduling
- HAL, Kernel & Executive: rather decent actually.
- But ...