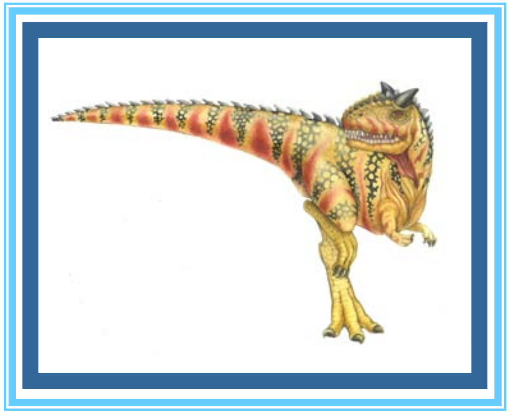
Appendix A: UnixBSD



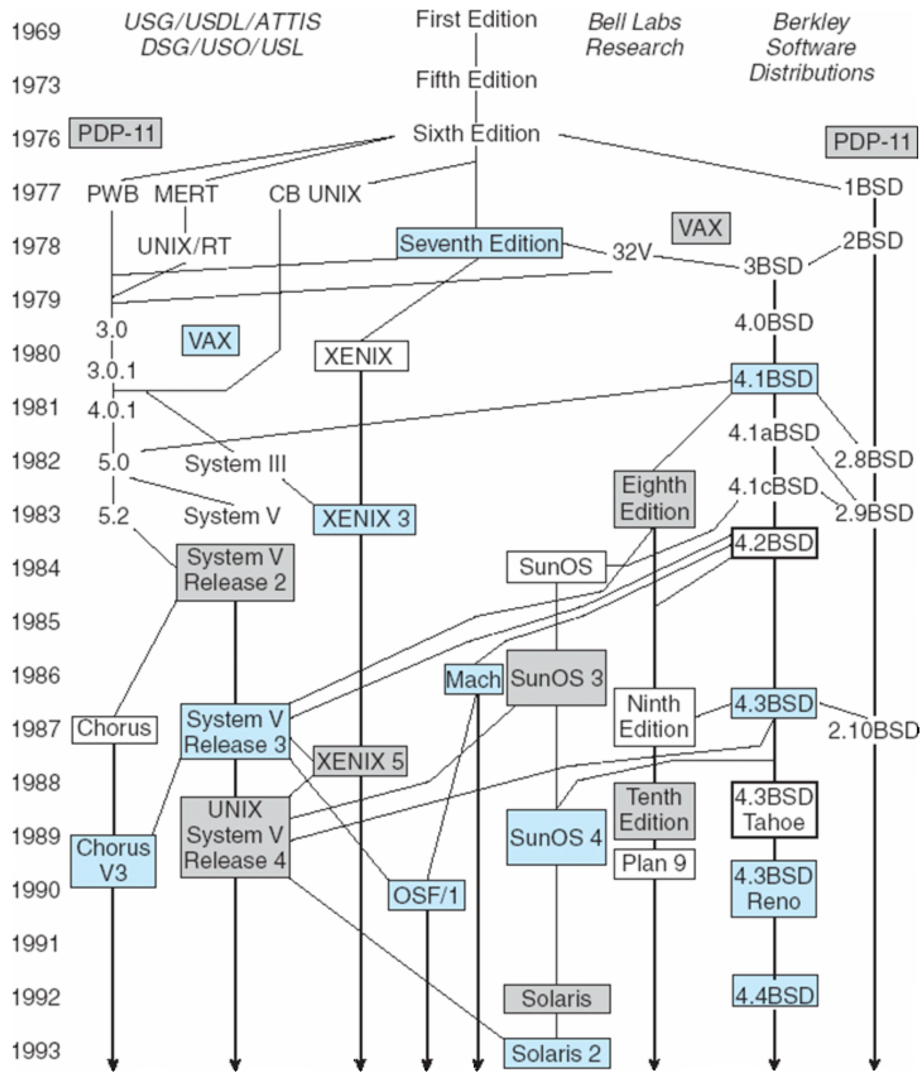
Module A: The FreeBSD System

- UNIX History
- Design Principles
- Programmer Interface
- User Interface
- Process Management
- Memory Management
- File System
- I/O System
- Interprocess Communication

UNIX History

- First developed in 1969 by Ken Thompson and Dennis Ritchie of the Research Group at Bell Laboratories; incorporated features of other operating systems, especially MULTICS
- The third version was written in C, which was developed at Bell Labs specifically to support UNIX
- The most influential of the non-Bell Labs and non-AT&T UNIX development groups — University of California at Berkeley (Berkeley Software Distributions - **BSD**)
  - 4BSD UNIX resulted from DARPA funding to develop a standard UNIX system for government use
  - Developed for the VAX, 4.3BSD is one of the most influential versions, and has been ported to many other platforms
- Several standardization projects seek to consolidate the variant flavors of UNIX leading to one programming interface to UNIX

History of UNIX Versions



Early Advantages of UNIX

- Written in a high-level language
- Distributed in source form
- Provided powerful operating-system primitives on an inexpensive platform
- Small size, modular, clean design

UNIX Design Principles

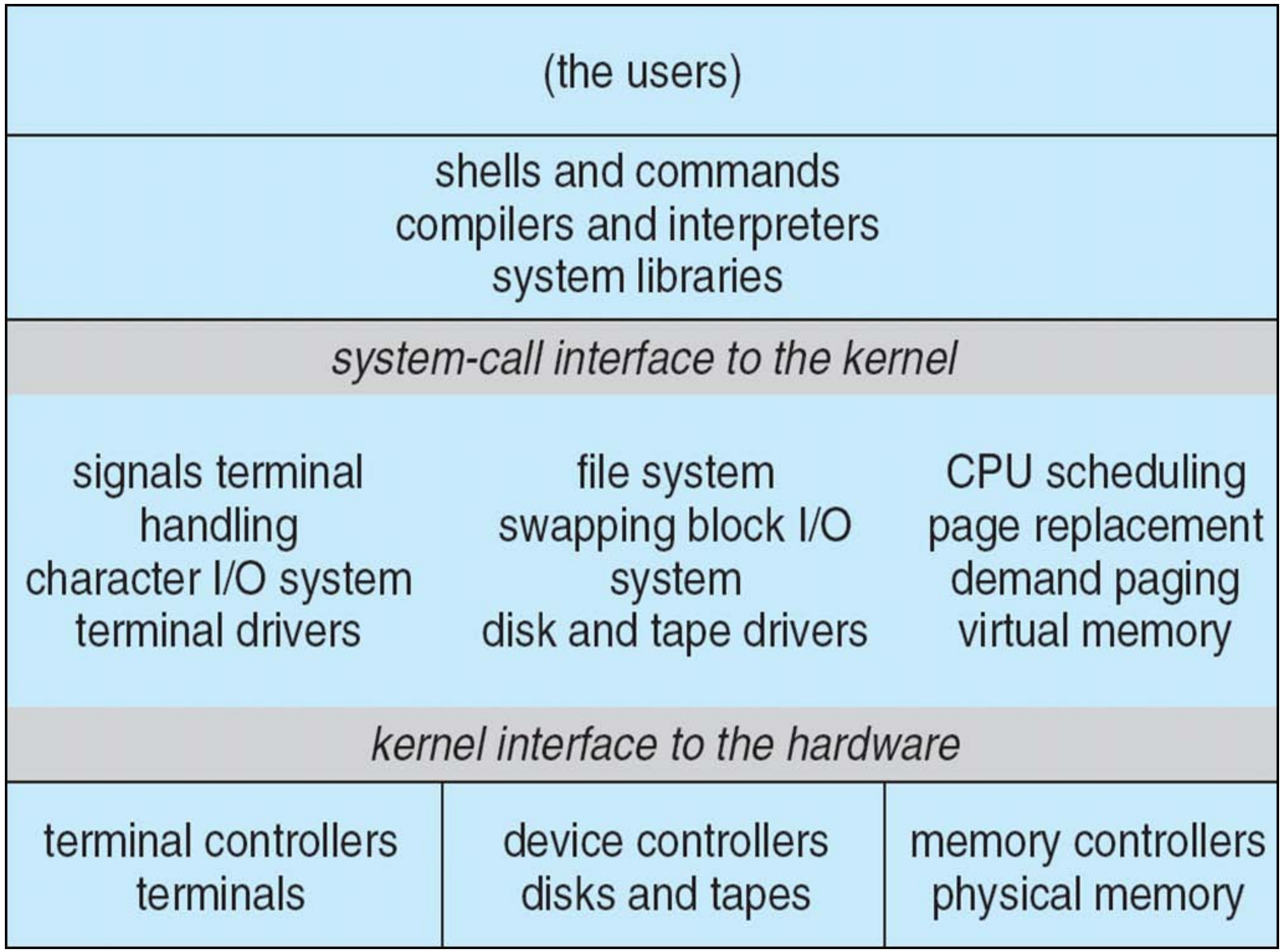
- Designed to be a time-sharing system
- Has a simple standard user interface (shell) that can be replaced
- File system with multilevel tree-structured directories
- Files are supported by the kernel as unstructured sequences of bytes
- Supports multiple processes; a process can easily create new processes
- High priority given to making system interactive, and providing facilities for program development

Programmer Interface

Like most computer systems, UNIX consists of two separable parts:

- Kernel: everything below the system-call interface and above the physical hardware
  - Provides file system, CPU scheduling, memory management, and other OS functions through system calls
- Systems programs: use the kernel-supported system calls to provide useful functions, such as compilation and file manipulation

4.4BSD Layer Structure



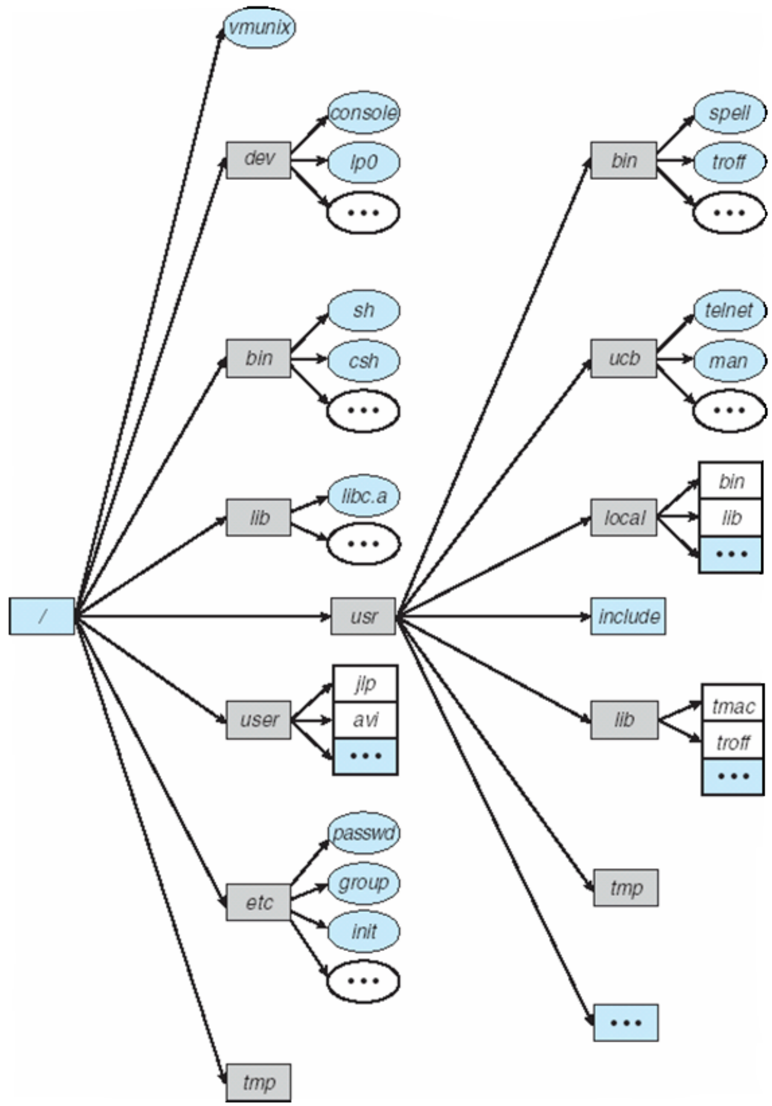
System Calls

- System calls define the programmer interface to UNIX
- The set of systems programs commonly available defines the user interface
- The programmer and user interface define the context that the kernel must support
- Roughly three categories of system calls in UNIX
  - File manipulation (same system calls also support device manipulation)
  - Process control
  - Information manipulation

File Manipulation

- A **file** is a sequence of bytes; the kernel does not impose a structure on files
- Files are organized in tree-structured **directories**
- Directories are files that contain information on how to find other files
- **Path name**: identifies a file by specifying a path through the directory structure to the file
  - Absolute path names start at root of file system
  - Relative path names start at the current directory
- System calls for basic file manipulation: `create, open, read, write, close, unlink, trunc`

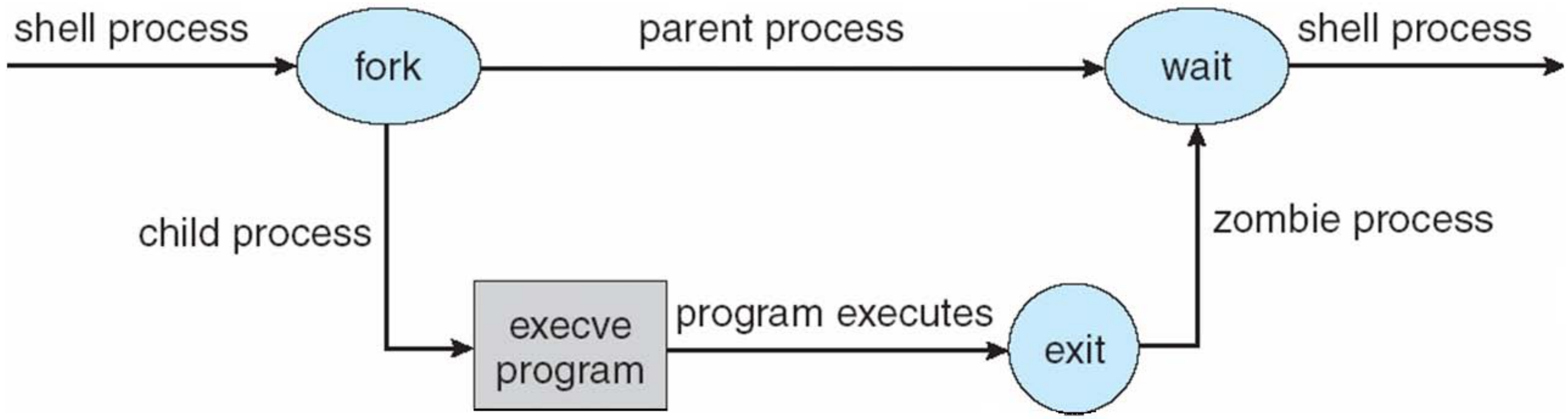
Typical UNIX Directory Structure



Process Control

- A process is a program in execution.
- Processes are identified by their process identifier, an integer
- Process control system calls
  - `fork` creates a new process
  - `execve` is used after a fork to replace on of the two processes's virtual memory space with a new program
  - exit terminates a process
  - A parent may `wait` for a child process to terminate; `wait` provides the process id of a terminated child so that the parent can tell which child terminated
  - `wait3` allows the parent to collect performance statistics about the child
- A **zombie** process results when the parent of a **defunct** child process exits before the terminated child.

Illustration of Process Control Calls



Process Control (Cont.)

- Processes communicate via pipes; queues of bytes between two processes that are accessed by a file descriptor
- All user processes are descendants of one original process, *init*
- *init* forks a *getty* process: initializes terminal line parameters and passes the user's *login name* to *login*
  - *login* sets the numeric *user identifier* of the process to that of the user
  - executes a **shell** which forks subprocesses for user commands

Process Control (Cont.)

- **setuid** bit sets the effective user identifier of the process to the user identifier of the owner of the file, and leaves the *real user identifier* as it was

- **setuid** scheme allows certain processes to have more than ordinary privileges while still being executable by ordinary users

Signals

- Facility for handling exceptional conditions similar to software interrupts
- The **interrupt** signal, `SIGINT`, is used to stop a command before that command completes (usually produced by ^C)
- Signal use has expanded beyond dealing with exceptional events
  - Start and stop subprocesses on demand
  - `SIGWINCH` informs a process that the window in which output is being displayed has changed size
  - Deliver urgent data from network connections

Process Groups

- Set of related processes that cooperate to accomplish a common task
- Only one process group may use a terminal device for I/O at any time
  - The foreground job has the attention of the user on the terminal
  - Background jobs – nonattached jobs that perform their function without user interaction
- Access to the terminal is controlled by process group signals

Process Groups (Cont.)

- Each job inherits a controlling terminal from its parent
  - If the process group of the controlling terminal matches the group of a process, that process is in the foreground
  - `SIGTTIN` or `SIGTTOU` freezes a background process that attempts to perform I/O; if the user foregrounds that process, `SIGCONT` indicates that the process can now perform I/O
  - `SIGSTOP` freezes a foreground process

Information Manipulation

- System calls to set and return an interval timer: `getitmer/setitmer`

- Calls to set and return the current time: `gettimeofday/settimeofday`

- Processes can ask for
  - their process identifier: `getpid`
  - their group identifier: `getgid`
  - the name of the machine on which they are executing: `gethostname`

Library Routines

- The system-call interface to UNIX is supported and augmented by a large collection of library routines
- Header files provide the definition of complex data structures used in system calls
- Additional library support is provided for mathematical functions, network access, data conversion, etc.

User Interface

- Programmers and users mainly deal with already existing systems programs: the needed system calls are embedded within the program and do not need to be obvious to the user.

- The most common systems programs are file or directory oriented
  - Directory: `mkdir, rmdir, cd, pwd`
  - File: `ls, cp, mv, rm`

- Other programs relate to editors (e.g., `emacs, vi`) text formatters (e.g., `troff, TEX`), and other activities

Shells and Commands

- **Shell** – the user process which executes programs (also called command interpreter)
- Called a shell, because it surrounds the kernel
- The shell indicates its readiness to accept another command by typing a prompt, and the user types a command on a single line
- A typical command is an executable binary object file
- The shell travels through the *search path* to find the command file, which is then loaded and executed
- The directories `/bin` and `/usr/bin` are almost always in the search path

Shells and Commands (Cont.)

- Typical search path on a BSD system:

  ```
  ( ./home/prof/avi/bin /usr/local/bin /usr/ucb/bin /usr/bin )
  ```

- The shell usually suspends its own execution until the command completes

Standard I/O

- Most processes expect three file descriptors to be open when they start:
  - *standard input* – program can read what the user types
  - *standard output* – program can send output to user’s screen
  - *standard error* – error output

- Most programs can also accept a file (rather than a terminal) for standard input and standard output

- The common shells have a simple syntax for changing what files are open for the standard I/O streams of a process — I/O *redirection*

Standard I/O Redirection

command	meaning of command
% *ls* > *filea*	direct output of *ls* to file *filea*
% *pr* < *filea* > *fileb*	input from *filea* and output to *fileb*
% *lpr* < *fileb*	input from *fileb*
% % make program > & errs	save both standard output and standard error in a file

Pipelines, Filters, and Shell Scripts

- Can coalesce individual commands via a vertical bar that tells the shell to pass the previous command's output as input to the following command

```
% ls | pr | lpr
```

- Filter – a command such as pr that passes its standard input to its standard output, performing some processing on it

- Writing a new shell with a different syntax and semantics would change the user view, but not change the kernel or programmer interface

- X Window System is a widely accepted iconic interface for UNIX

Process Management

- Representation of processes is a major design problem for operating system
- UNIX is distinct from other systems in that multiple processes can be created and manipulated with ease
- These processes are represented in UNIX by various control blocks
  - Control blocks associated with a process are stored in the kernel
  - Information in these control blocks is used by the kernel for process control and CPU scheduling

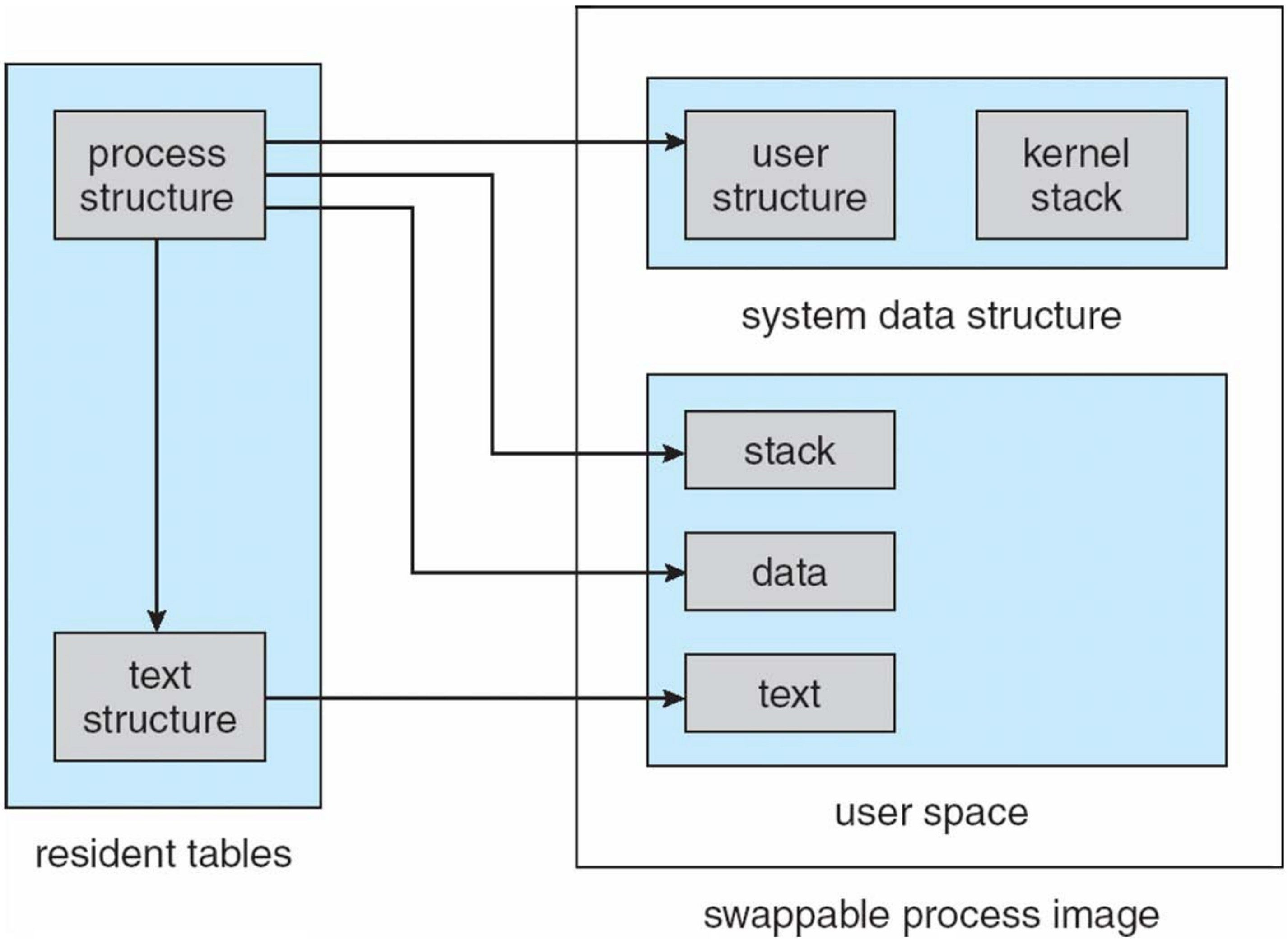
Process Control Blocks

- The most basic data structure associated with processes is the **process structure**
  - unique process identifier
  - scheduling information (e.g., priority)
  - pointers to other control blocks
- The **virtual address space** of a user process is divided into text (program code), data, and stack segments
- Every process with sharable text has a pointer form its process structure to a **text structure**
  - always resident in main memory
  - records how many processes are using the text segment
  - records were the page table for the text segment can be found on disk when it is swapped

System Data Segment

- Most ordinary work is done in **user mode**; system calls are performed in **system mode**
- The system and user phases of a process never execute simultaneously
- A **kernel stack** (rather than the user stack) is used for a process executing in system mode
- The kernel stack and the user structure together compose the **system data** segment for the process

Finding parts of a process using process structure



Allocating a New Process Structure

- Fork allocates a new process structure for the child process, and copies the user structure
  - new page table is constructed
  - new main memory is allocated for the data and stack segments of the child process
  - copying the user structure preserves open file descriptors, user and group identifiers, signal handling, etc.

Allocating a New Process Structure (Cont.)

- `vfork` does *not* copy the data and stack to t he new process; the new process simply shares the page table of the old one
  - new user structure and a new process structure are still created
  - commonly used by a shell to execute a command and to wait for its completion
- A parent process uses `vfork` to produce a child process; the child uses `execve` to change its virtual address space, so there is no need for a copy of the parent
- Using `vfork` with a large parent process saves CPU time, but can be dangerous since any memory change occurs in both processes until `execve` occurs
- `execve` creates no new process or user structure; rather the text and data of the process are replaced

CPU Scheduling

- Every process has a **scheduling priority** associated with it; larger numbers indicate lower priority
- Negative feedback in CPU scheduling makes it difficult for a single process to take all the CPU time
- Process aging is employed to prevent starvation
- When a process chooses to relinquish the CPU, it goes to **sleep** on an **event**
- When that event occurs, the system process that knows about it calls `wakeup` with the address corresponding to the event, and *all* processes that had done a *sleep* on the same address are put in the ready queue to be run

Memory Management

- The initial memory management schemes were constrained in size by the relatively small memory resources of the PDP machines on which UNIX was developed.
- Pre 3BSD system use swapping exclusively to handle memory contention among processes: If there is too much contention, processes are swapped out until enough memory is available
- Allocation of both main memory and swap space is done first-fit

Memory Management (Cont.)

- Sharable text segments do not need to be swapped; results in less swap traffic and reduces the amount of main memory required for multiple processes using the same text segment.

- The *scheduler process* (or *swapper*) decides which processes to swap in or out, considering such factors as time idle, time in or out of main memory, size, etc.

Paging

- Berkeley UNIX systems depend primarily on paging for memory-contention management, and depend only secondarily on swapping.

- **Demand paging** – When a process needs a page and the page is not there, a page fault tot he kernel occurs, a frame of main memory is allocated, and the proper disk page is read into the frame.

- A `pagedaemon` process uses a modified second-chance page-replacement algorithm to keep enough free frames to support the executing processes.

- If the scheduler decides that the paging system is overloaded, processes will be swapped out whole until the overload is relieved.

File System

- The UNIX file system supports two main objects: files and directories.
- Directories are just files with a special format, so the representation of a file is the basic UNIX concept.

Blocks and Fragments

- Most of the file system is taken up by *data blocks*

- 4.2BSD uses *two* block sized for files which have no indirect blocks:
  - All the blocks of a file are of a large *block* size (such as 8K), except the last
  - The last block is an appropriate multiple of a smaller *fragment size* (i.e., 1024) to fill out the file
  - Thus, a file of size 18,000 bytes would have two 8K blocks and one 2K fragment (which would not be filled completely)

Blocks and Fragments (Cont.)

- The **block** and **fragment** sizes are set during file-system creation according to the intended use of the file system:
  - If many small files are expected, the fragment size should be small
  - If repeated transfers of large files are expected, the basic block size should be large

- The maximum block-to-fragment ratio is 8 : 1; the minimum block size is 4K (typical choices are 4096 : 512 and 8192 : 1024)

Inodes

- A file is represented by an **inode** — a record that stores information about a specific file on the disk
- The inode also contains 15 pointer to the disk blocks containing the file's data contents
  - First 12 point to **direct blocks**
  - Next three point to **indirect blocks**
    - First indirect block pointer is the address of a **single indirect block** — an index block containing the addresses of blocks that do contain data
    - Second is a **double-indirect-block** pointer, the address of a block that contains the addresses of blocks that contain pointer to the actual data blocks.
    - A **triple indirect** pointer is not needed; files with as many as 232 bytes will use only double indirection

Directories

- The inode type field distinguishes between plain files and directories
- Directory entries are of variable length; each entry contains first the length of the entry, then the file name and the inode number
- The user refers to a file by a path name,whereas the file system uses the inode as its definition of a file
  - The kernel has to map the supplied user path name to an inode
  - Directories are used for this mapping

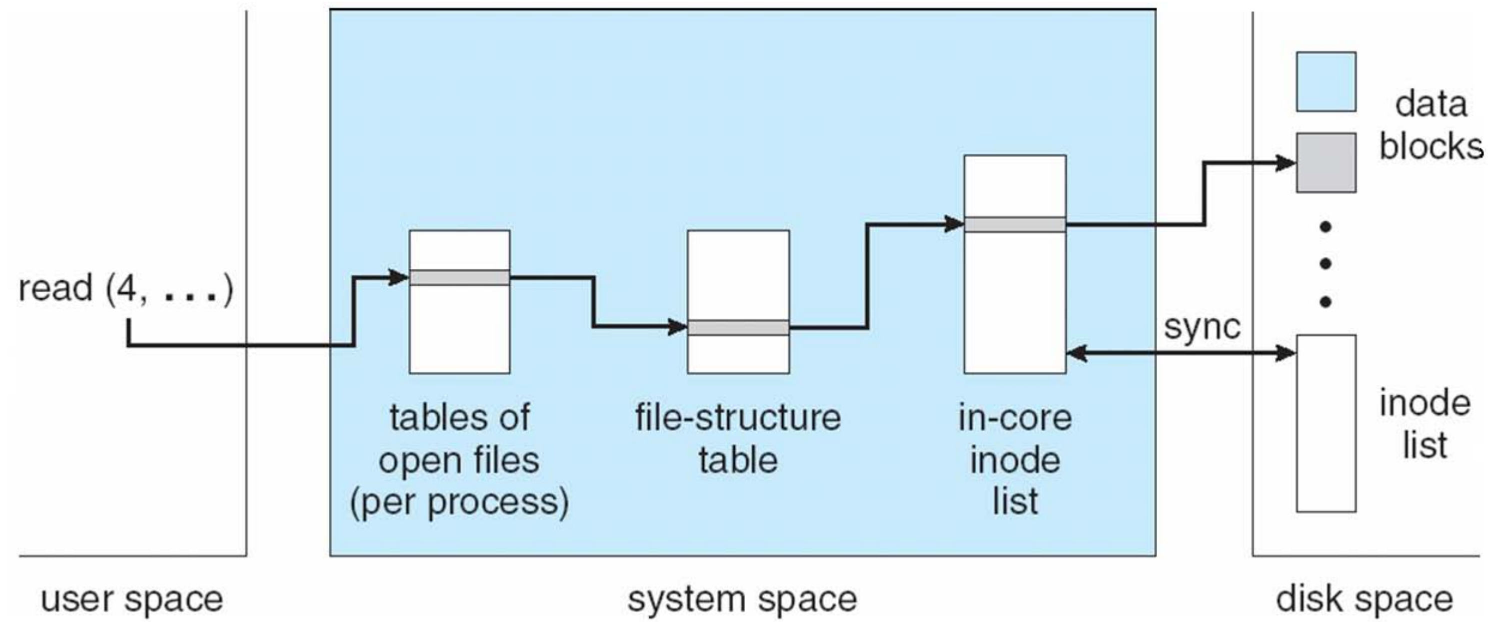
Directories (Cont.)

- First determine the starting directory:
  - If the first character is “/”, the starting directory is the root directory
  - For any other starting character, the starting directory is the current directory
- The search process continues until the end of the path name is reached and the desired inode is returned
- Once the inode is found, a file structure is allocated to point to the inode
- 4.3BSD improved file system performance by adding a directory name cache to hold recent directory-to-inode translations

Mapping of a File Descriptor to an Inode

- System calls that refer to open files indicate the file is passing a file descriptor as an argument
- The file descriptor is used by the kernel to index a table of open files for the current process
- Each entry of the table contains a pointer to a file structure
- This file structure in turn points to the inode
- Since the open file table has a fixed length which is only setable at boot time, there is a fixed limit on the number of concurrently open files in a system

File-System Control Blocks



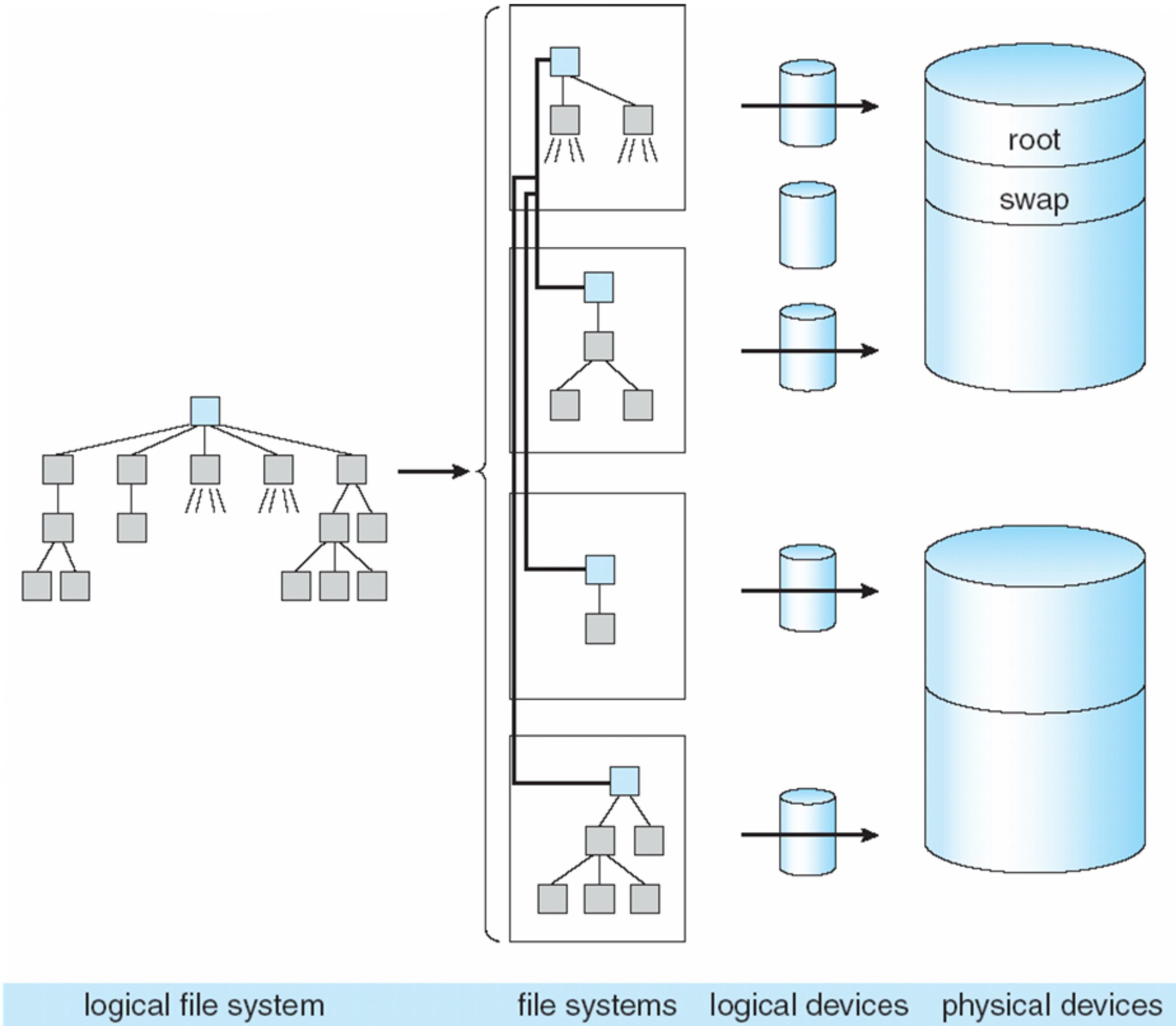
Disk Structures

- The one file system that a user ordinarily sees may actually consist of several physical file systems, each on a different device
- Partitioning a physical device into multiple file systems has several benefits
  - Different file systems can support different uses
  - Reliability is improved
  - Can improve efficiency by varying file-system parameters
  - Prevents one program form using all available space for a large file
  - Speeds up searches on backup tapes and restoring partitions from tape

Disk Structures (Cont.)

- The *root file* system is always available on a drive
- Other file systems may be **mounted** — i.e., integrated into the directory hierarchy of the root file system
- The following figure illustrates how a directory structure is partitioned into file systems, which are mapped onto logical devices, which are partitions of physical devices

Mapping File System to Physical Devices



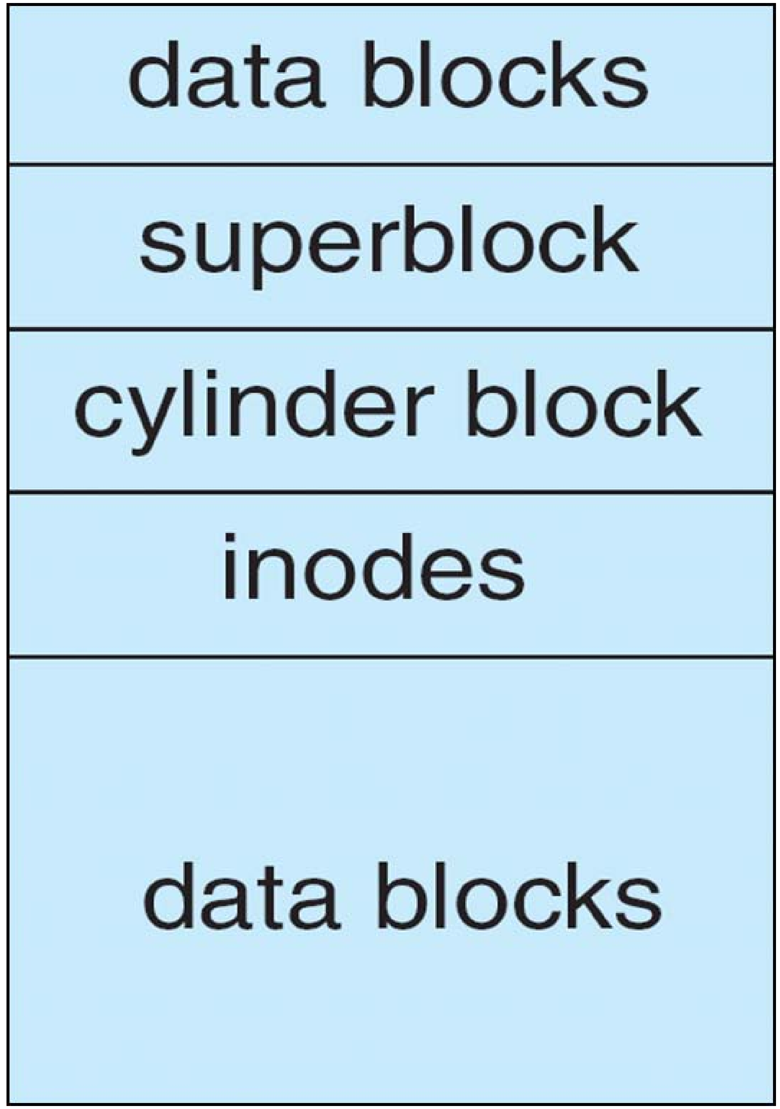
Implementations

- The user interface to the file system is simple and well defined, allowing the implementation of the file system itself to be changed without significant effect on the user
- For Version 7, the size of inodes doubled, the maximum file and file system sized increased, and the details of free-list handling and superblock information changed
- In 4.0BSD, the size of blocks used in the file system was increased form 512 bytes to 1024 bytes — increased internal fragmentation, but doubled throughput
- 4.2BSD added the Berkeley Fast File System, which increased speed, and included new features
  - New directory system calls
  - `truncate` calls
  - Fast File System found in most implementations of UNIX

Layout and Allocation Policy

- The kernel uses a <*logical device number, inode number*> pair to identify a file
  - The logical device number defines the file system involved
  - The inodes in the file system are numbered in sequence
- 4.3BSD introduced the *cylinder group* — allows localization of the blocks in a file
  - Each cylinder group occupies one or more consecutive cylinders of the disk, so that disk accesses within the cylinder group require minimal disk head movement
  - Every cylinder group has a superblock, a cylinder block, an array of inodes, and some data blocks

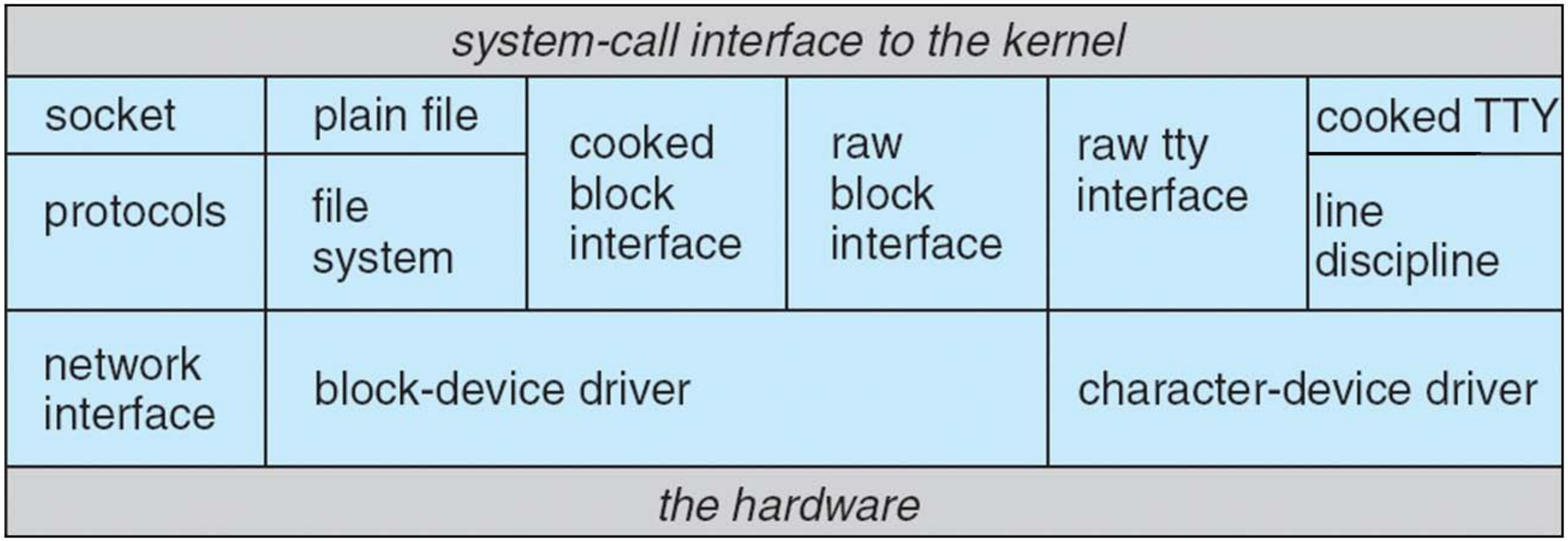
4.3BSD Cylinder Group



I/O System

- The I/O system hides the peculiarities of I/O devices from the bulk of the kernel
- Consists of a buffer caching system, general device driver code, and drivers for specific hardware devices
- Only the device driver knows the peculiarities of a specific device

4.3 BSD Kernel I/O Structure



Block Buffer Cache

- Consist of buffer headers, each of which can point to a piece of physical memory, as well as to a device number and a block number on the device.
- The buffer headers for blocks not currently in use are kept in several linked lists:
  - Buffers recently used, linked in LRU order (LRU list)
  - Buffers not recently used, or without valid contents (AGE list)
  - EMPTY buffers with no associated physical memory
- When a block is wanted from a device, the cache is searched.
- If the block is found it is used, and no I/O transfer is necessary.
- If it is not found, a buffer is chosen from the AGE list, or the LRU list if AGE is empty.

Block Buffer Cache (Cont.)

- Buffer cache size effects system performance; if it is large enough, the percentage of cache hits can be high and the number of actual I/O transfers low.

- Data written to a disk file are buffered in the cache, and the disk driver sorts its output queue according to disk address — these actions allow the disk driver to minimize disk head seeks and to write data at times optimized for disk rotation.

Raw Device Interfaces

- Almost every block device has a character interface, or *raw device interface* — unlike the block interface, it bypasses the block buffer cache.
- Each disk driver maintains a queue of pending transfers.
- Each record in the queue specifies:
  - whether it is a read or a write
  - a main memory address for the transfer
  - a device address for the transfer
  - a transfer size
- It is simple to map the information from a block buffer to what is required for this queue.

C-Lists

- Terminal drivers use a character buffering system which involves keeping small blocks of characters in linked lists.
- A `write` system call to a terminal enqueues characters on a list for the device. An initial transfer is started, and interrupts cause dequeueing of characters and further transfers.
- Input is similarly interrupt driven
- It is also possible to have the device driver bypass the canonical queue and return characters directly form the raw queue — *raw mode* (used by full-screen editors and other programs that need to react to every keystroke).

Interprocess Communication

- The *pipe* is the IPC mechanism most characteristic of UNIX
  - Permits a reliable unidirectional byte stream between two processes
  - A benefit of pipes small size is that pipe data are seldom written to disk; they usually are kept in memory by the normal block buffer cache
- In 4.3BSD, pipes are implemented as a special case of the **socket** mechanism which provides a general interface not only to facilities such as pipes, which are local to one machine, but also to networking facilities.
- The socket mechanism can be used by unrelated processes.

Sockets

- A socket is an endpont of communication.
- An in-use socket it usually bound with an address; the nature of the address depends on the **communication domain** of the socket.
- A characteristic property of a domain is that processes communication in the same domain use the same **address format**.
- A single socket can communicate in only one domain — the three domains currently implemented in 4.3BSD are:
  - the UNIX domain (AF_UNIX)
  - the Internet domain (AF_INET)
  - the XEROX Network Service (NS) domain (AF_NS)

Socket Types

- *Stream sockets* provide reliable, duplex, sequenced data streams. Supported in Internet domain by the TCP protocol. In UNIX domain, pipes are implemented as a pair of communicating stream sockets.
- **Sequenced packet sockets** provide similar data streams, except that record boundaries are provided
  - Used in XEROX AF_NS protocol
- **Datagram sockets** transfer messages of variable size in either direction. Supported in Internet domain by UDP protocol.
- **Reliably delivered message sockets** transfer messages that are guaranteed to arrive (Currently unsupported).
- **Raw sockets** allow direct access by processes to the protocols that support the other socket types; e.g., in the Internet domain, it is possible to reach TCP, IP beneath that, or a deeper Ethernet protocol
  - Useful for developing new protocols

Socket System Calls

- The `socket` call creates a socket; takes as arguments specifications of the communication domain, socket type, and protocol to be used and returns a small integer called a **socket descriptor**.
- A name is bound to a socket by the `bind` system call.
- The `connect` system call is used to initiate a connection.
- A server process uses `socket` to create a socket and `bind` to bind the well-known address of its service to that socket
  - Uses `listen` to tell the kernel that it is ready to accept connections from clients
  - Uses `accept` to accept individual connections
  - Uses `fork` to produce a new process after the `accept` to service the client while the original server process continues to listen for more connections

Socket System Calls (Cont.)

- The simplest way to terminate a connection and to destroy the associated socket is to use the `close` system call on its socket descriptor.

- The `select` system call can be used to multiplex data transfers on several file descriptors and /or socket descriptors.

Network Support

- Networking support is one of the most important features in 4.3BSD.
- The socket concept provides the programming mechanism to access other processes, even across a network.
- Sockets provide an interface to several sets of protocols.
- Almost all current UNIX systems support UUCP.
- 4.3BSD supports the DARPA Internet protocols UDP, TCP, IP, and ICMP on a wide range of Ethernet, token-ring, and ARPANET interfaces.
- The 4.3BSD networking implementation, and to a certain extent the socket facility, is more oriented toward the ARPANET Reference Model (ARM).

Network Reference models and Layering

<table>
<tr><th>ISO reference model</th><th>ARPANET reference model</th><th>4.2BSD layers</th><th>example layering</th></tr>
<tr><td>application</td><td rowspan="3">process applications</td><td rowspan="2">user programs and libraries</td><td rowspan="2">telnet</td></tr>
<tr><td>presentation</td></tr>
<tr><td>session transport</td><td>sockets</td><td>sock_stream</td></tr>
<tr><td></td><td rowspan="2">host–host</td><td rowspan="2">protocol</td><td>TCP</td></tr>
<tr><td rowspan="2">network data link</td><td>IP</td></tr>
<tr><td rowspan="2">network interface</td><td rowspan="2">network interfaces</td><td rowspan="2">Ethernet driver</td></tr>
<tr><td>hardware</td></tr>
<tr><td></td><td>network hardware</td><td>network hardware</td><td>interlan controller</td></tr>
</table>

End of Appendix A