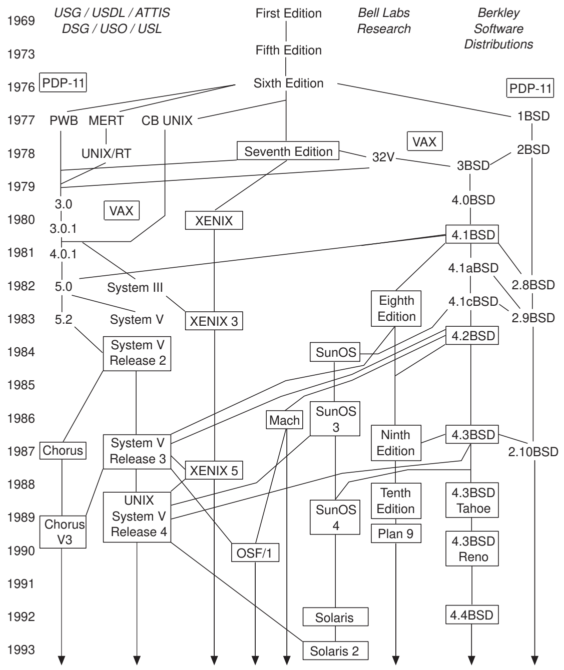
Module 21: The UNIX System

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

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*).
  - 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.

4.3BSD Layer Structure

(the users)		
shells and commands compilers and interpreters system libraries		
system-call interface to the kernel		
signals terminal handling character I/O system terminal drivers	file system swapping block I/O system disk and tape drivers	CPU scheduling page replacement demand paging virtual memory
kernal interface to the hardware		
terminal controllers terminals	device controllers disks and tapes	memory controllers physical memory

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

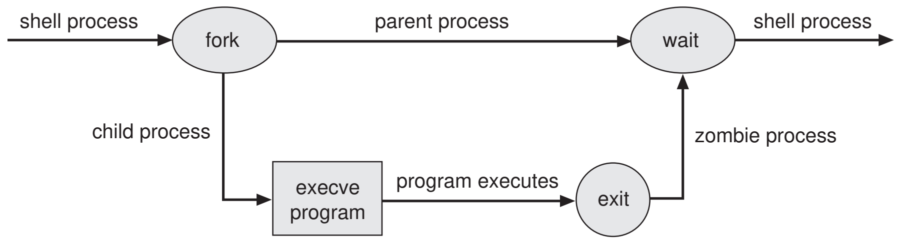
File Manipulation

- 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: **creat, open, read, write, close, unlink, trunc**.

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 one 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'd

- 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'd

- **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 ˆC).
- 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'd)

- 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: **getitimer**/**setitimer**.
- 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 travel 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'd)

- 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 systems.
- 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 from its process structure to a *text structure*.
  - always resident in main memory
  - records how many processes are using the text segment
  - records where the page table for the text segment can be found on disk when it is swapped

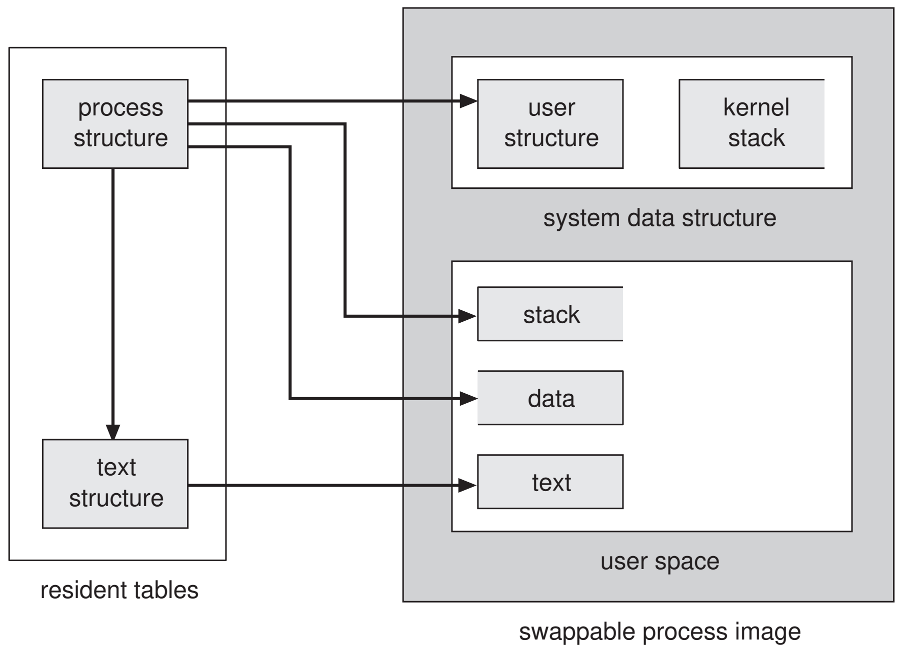
Process Control Blocks (Cont'd)

- The *page tables* record information on the mapping from the process' virtual memory to physical memory.
- Information about the process that is needed only when the process is resident is kept in the *user structure* (or *u structure*).
  - mapped read-only into user virtual address space
  - writable by the kernel
  - maintains the current directory and the table of open files

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'd)

- **vfork** does *not* copy the data and stack to the 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 systems 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'd)

- 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.
- In 4.3BSD, swap space is allocated in pieces that are multiples of a power of 2 and a minimum size, up to a maximum size determined by the size of the swap-space partition on the disk.

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 to the 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 sizes 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'd)

- 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 pointers 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 pointers 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.

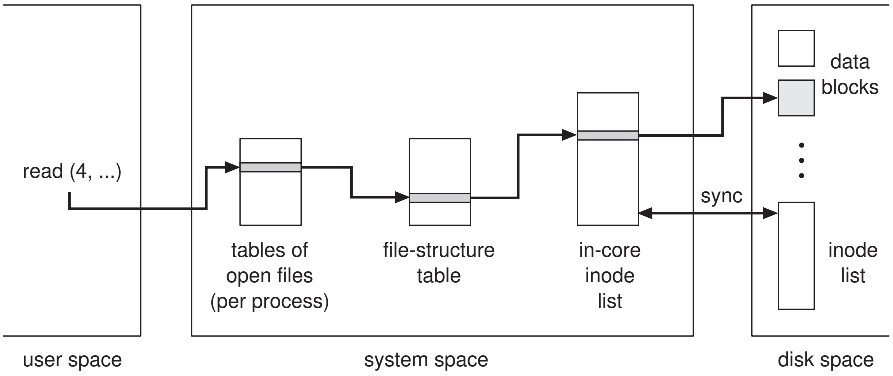
Directories (Cont'd)

- 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 by 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



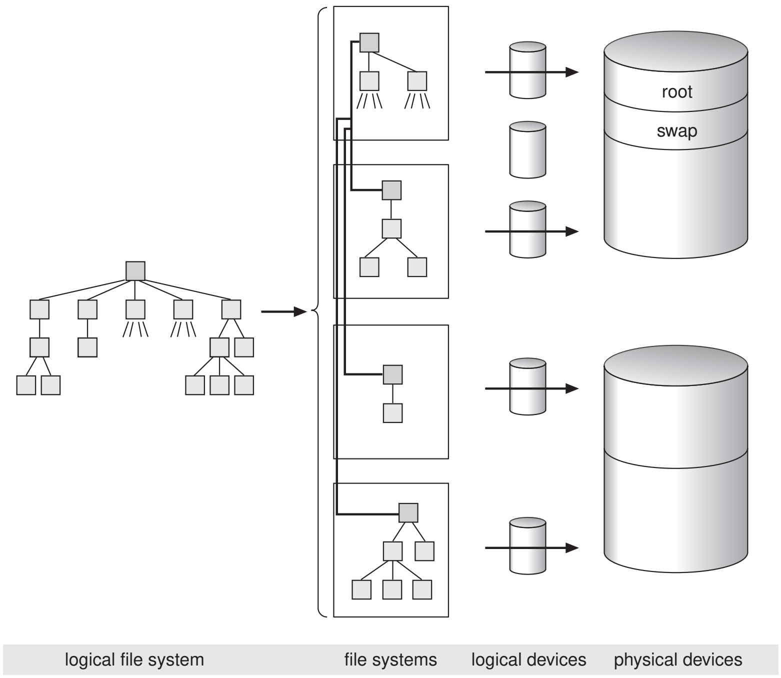
Disk Structures

- 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 from using all available space for a large file.
  - Speeds up searches on backup tapes and restoring partitions from tape.

Disk Structures (Cont'd)

- 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



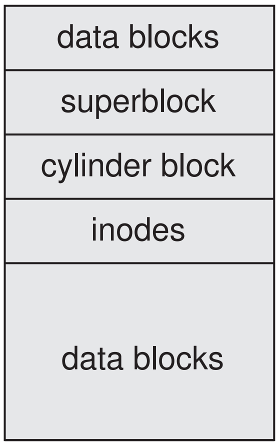
Implementations

- 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 sizes 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 from 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 Policies

- 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.
- 4.3 BSD 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.

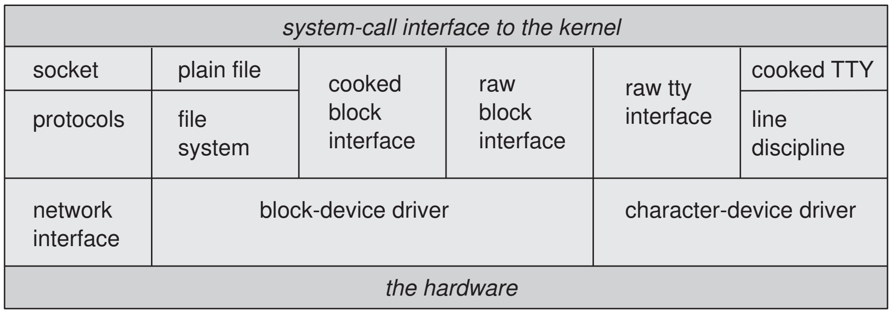
4.3 BSD Cylinder Group



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

- Consists 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'd)

- 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 dequeuing 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 from the raw queue — *raw mode* (used by full-screen editors and other programs that need to react to every keystroke).

Interprocess Communication

- Most UNIX systems have not permitted *shared memory* because the PDP-11 hardware did not encourage it.
- 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 endpoint 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 communicating in the same domain use the same *address format*.
- A single socket can communicate in only one domain — the three domains currently implemented in 4.3 BSD are:
  - the UNIX domain (AF_UNIX)
  - the Internet domain (AF_INET)
  - the XEROX Network Services (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'd)

- 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 4.3 BSD.
- 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.
- 4.3 BSD supports the DARPA Internet protocols UDP, TCP, IP, and ICMP on a wide range of Ethernet, token-ring, and ARPANET interfaces.
- The 4.3 BSD networking implementation, and to a certain extent the *socket* facility, is more oriented toward the ARPANET Reference Model (ARM).

Network Reference Models and Layering

ISO reference model	ARPANET reference model	4.2BSD layers	example layering
application	process applications	user programs and libraries	telnet
presentation			
session		sockets	sock_stream
transport	host–host	protocol	TCP
network data link			IP
hardware	network interface	network interfaces	Ethernet driver
	network hardware	network hardware	interlan controller