I/O Systems

I/O Systems:

The two main jobs of a computer are I/O and processing. In many cases, the main job is I/O, and the processing is merely incidental. For instance, when we browse a web page or edit a file, our immediate interest is to read or enter some information, not to compute an answer.

The role of the operating system in computer I/O is to manage and control I/O operations and I/O devices. The control of devices connected to the computer is a major concern of operating-system designers.

Because I/O devices vary so widely in their function and speed (consider a mouse, a hard disk, and a tape robot), varied methods are needed to control them. These methods form the I/O subsystem of the kernel, which separates the rest of the kernel from the complexities of managing I/O devices.

I/O Hardware:

Computers operate a great many kinds of devices. Most fit into the general categories of storage devices (disks, tapes), transmission devices (network connections, Bluetooth), and human-interface devices (screen, keyboard, mouse, audio in and out). Other devices are more specialized, such as those involved in the steering of a jet.

Despite the incredible variety of I/O devices, though, we need only a few concepts to understand how the devices are attached and how the software can control the hardware.

A device communicates with a computer system by sending signals over a cable or even through the air. The device communicates with the machine via a connection point, or **port**—for example, a serial port.

If devices share a common set of wires, the connection is called a bus. A **bus** is a set of wires and a rigidly defined protocol that specifies a set of messages that can be sent on the wires.

In terms of the electronics, the messages are conveyed by patterns of electrical voltages applied to the wires with defined timings. When device *A* has a cable that plugs into device *B*, and device *B* has a cable that plugs into device *C*, and device *C* plugs into a port on the computer, this arrangement is called a **daisy chain**. A daisy chain usually operates as a bus.

Buses are used widely in computer architecture and vary in their signaling methods, speed, throughput, and connection methods. A typical PC bus structure appears in figure:

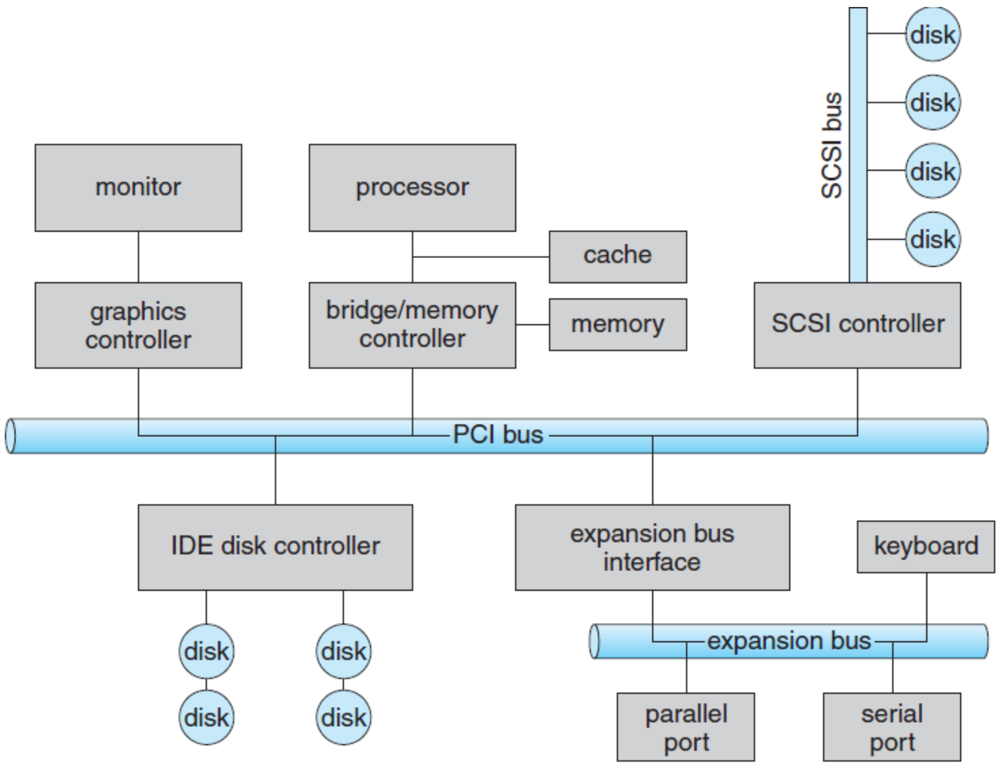


Figure: A typical PC bus structure

In the figure, a **PCI bus** (the common PC system bus) connects the processor–memory subsystem to fast devices, and an **expansion bus** connects relatively slow devices, such as the keyboard and serial and USB ports. In the upper-right portion of the figure, four disks are connected together on a **Small Computer System Interface (SCSI)** bus plugged into a SCSI controller.

Other common buses used to interconnect main parts of a computer include **PCI Express (PCIe)**, with throughput of up to 16 GB per second, and **HyperTransport**, with throughput of up to 25 GB per second.

A **controller** is a collection of electronics that can operate a port, a bus, or a device. A serial-port controller is a simple device controller. It is a single chip (or portion of a chip) in the computer that controls the signals on the wires of a serial port. By contrast, a SCSI bus controller is not simple.

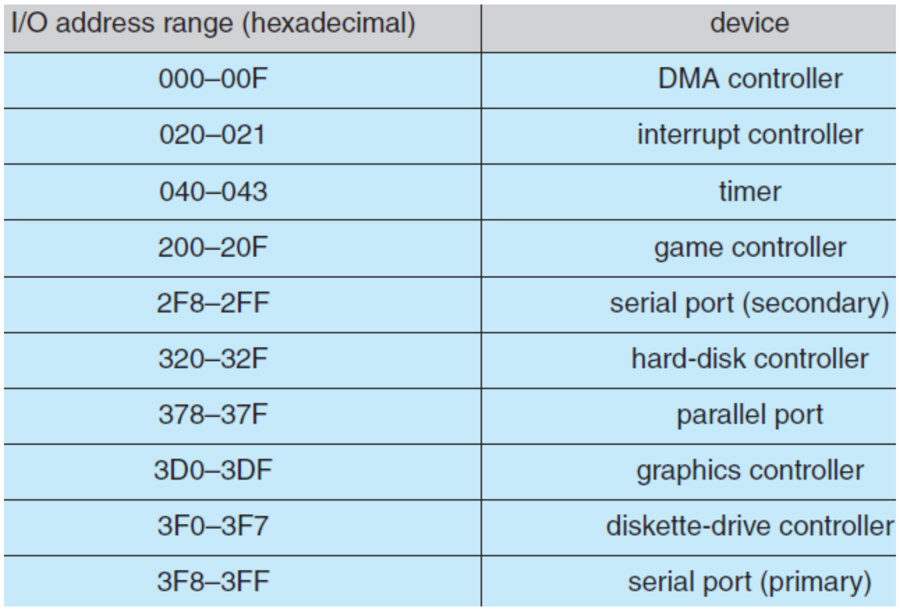
Because the SCSI protocol is complex the SCSI bus controller is often implemented as a separate circuit board (or a **host adapter**) that plugs into the computer.

It typically contains a processor, microcode, and some private memory to enable it to process the SCSI protocol messages. Some devices have their own built-in controllers. If you look at a disk drive, you will see a circuit board attached to one side. This board is the disk controller.

It implements the disk side of the protocol for some kind of connection—SCSI or **Serial Advanced Technology Attachment (SATA)**, for instance. It has microcode and a processor to do many tasks, such as bad-sector mapping, prefetching, buffering, and caching.

How can the processor give commands and data to a controller to accomplish an I/O transfer? The short answer is that the controller has one or more registers for data and control signals. The processor communicates with the controller by reading and writing bit patterns in these registers. One way in which this communication can occur is through the use of **special I/O instructions** that specify the transfer of a byte or word to an I/O port address. Alternatively, the device controller can support **memory-mapped I/O**.

Some systems use both techniques. For instance, PCs use I/O instructions to control some devices and memory-mapped I/O to control others. Figure below shows the usual I/O port addresses for PCs.



I/O address range (hexadecimal)	device
000–00F	DMA controller
020–021	interrupt controller
040–043	timer
200–20F	game controller
2F8–2FF	serial port (secondary)
320–32F	hard-disk controller
378–37F	parallel port
3D0–3DF	graphics controller
3F0–3F7	diskette-drive controller
3F8–3FF	serial port (primary)

Figure: Device I/O port locations on PCs (partial)

An I/O port typically consists of four registers, called the status, control, data-in, and data-out registers.

• The **data-in register** is read by the host to get input.

• The **data-out register** is written by the host to send output.

• The **status register** contains bits that can be read by the host. These bits indicate states, such as whether the current command has completed, whether a byte is available to be read from the data-in register, and whether a device error has occurred.

• The **control register** can be written by the host to start a command or to change the mode of a device. For instance, a certain bit in the control register of a serial port chooses between full-duplex and half-duplex communication, another bit enables parity checking, a third bit sets the word length to 7 or 8 bits, and other bits select one of the speeds supported by the serial port.

The data registers are typically 1 to 4 bytes in size. Some controllers have FIFO chips that can hold several bytes of input or output data to expand the capacity of the controller beyond the size of the data register. A FIFO chip can hold a small burst of data until the device or host is able to receive those data.

Polling:

The complete protocol for interaction between the host and a controller can be intricate, but the basic handshaking notion is simple. We explain handshaking with an example. Assume that 2 bits are used to coordinate the producer–consumer relationship between the controller and the host. The controller indicates its state through the busy bit in the status register.

The controller sets the busy bit when it is busy working and clears the busy bit when it is ready to accept the next command. The host signals its wishes via the command-ready bit in the command register.

The host sets the command-ready bit when a command is available for the controller to execute. For this example, the host writes output through a port, coordinating with the controller by handshaking as follows:

1. The host repeatedly reads the busy bit until that bit becomes clear.

2. The host sets the write bit in the command register and writes a byte into the data-out register.

3. The host sets the command-ready bit.

4. When the controller notices that the command-ready bit is set, it sets the busy bit.

5. The controller reads the command register and sees the write command. It reads the data-out register to get the byte and does the I/O to the device.

6. The controller clears the command-ready bit, clears the error bit in the status register to indicate that the device I/O succeeded, and clears the busy bit to indicate that it is finished.

This loop is repeated for each byte. In step 1, the host is **busy-waiting** or **polling**: it is in a loop, reading the status register over and over until the busy bit becomes clear.

In many computer architectures, three CPU-instruction cycles are sufficient to poll a device: read a device register, logical--and to extract a status bit, and branch if not zero. Clearly, the basic polling operation is efficient. But polling becomes inefficient when it is attempted repeatedly yet rarely finds a device ready for service, while other useful CPU processing remains undone.

In such instances, it may be more efficient to arrange for the hardware controller to notify the CPU when the device becomes ready for service, rather than to require the CPU to poll repeatedly for an I/O completion. The hardware mechanism that enables a device to notify the CPU is called an **interrupt**.

Application I/O interface:

Here we discuss structuring techniques and interfaces for the operating system that enable I/O devices to be treated in a standard, uniform way. We explain, for instance, how an application can open a file on a disk without knowing what kind of disk it is and how new disks and other devices can be added to a computer without disruption of the operating system.

Like other complex software-engineering problems, the approach here involves abstraction, encapsulation, and software layering. Specifically, we can abstract away the detailed differences in I/O devices by identifying a few general kinds.

Each general kind is accessed through a standardized set of functions—an **interface**. he differences are encapsulated in kernel modules called device drivers that internally are custom-tailored to specific devices but that export one of the standard interfaces. **Figure** (A kernel I/O structure) illustrates how the I/O-related portions of the kernel are structured in software layers.

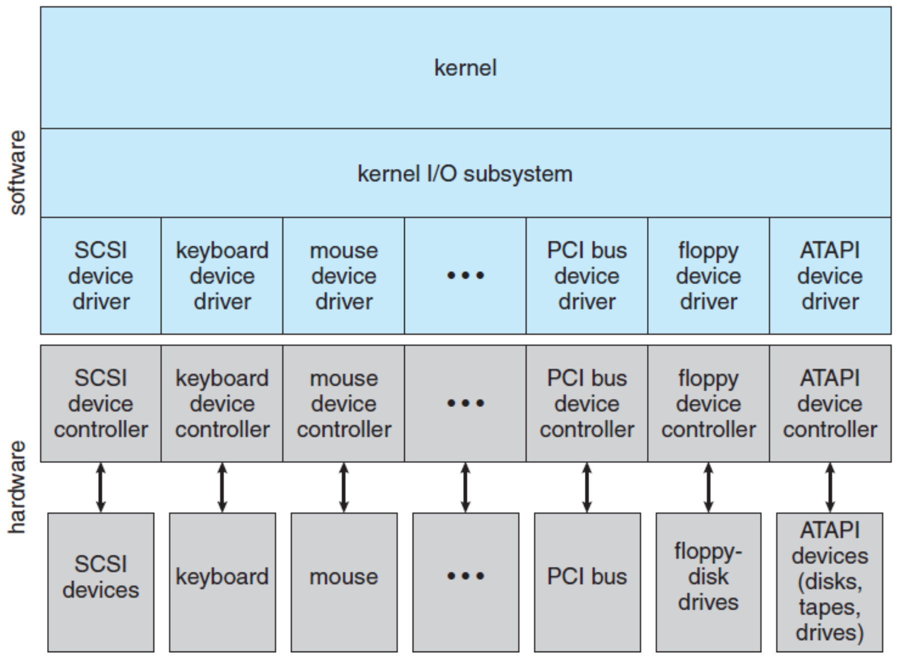


Figure: A kernel I/O structure

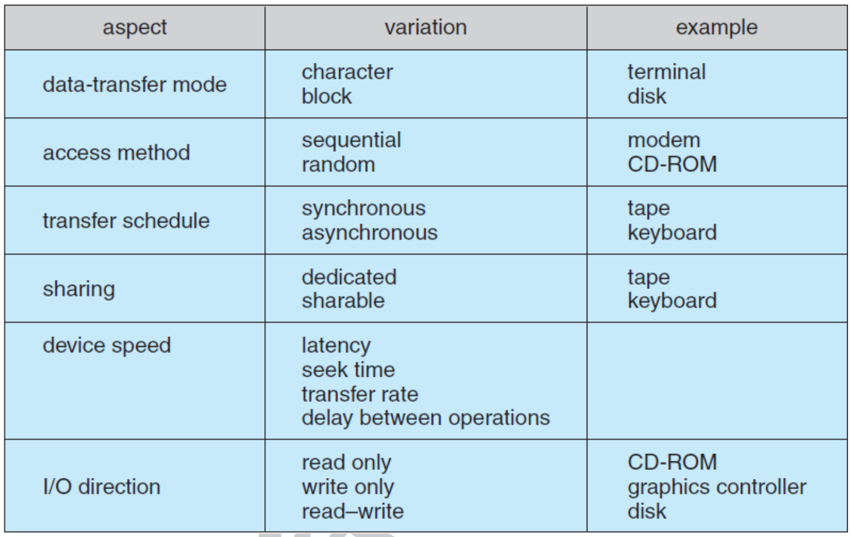
The purpose of the device-driver layer is to hide the differences among device controllers from the I/O subsystem of the kernel, much as the I/O system calls encapsulate the behavior of devices in a few generic classes that hide hardware differences from applications.

Making the I/O subsystem independent of the hardware simplifies the job of the operating-system developer. It also benefits the hardware manufacturers. They either design new devices to be compatible with an existing host controller interface (such as SATA), or they write device drivers to interface the new hardware to popular operating systems.

Thus, we can attach new peripherals to a computer without waiting for the operating-system vendor to develop support code. Unfortunately for device-hardware manufacturers, each type of operating system has its own standards for the device-driver interface. A given device may ship with multiple device drivers—for instance, drivers for Windows, Linux, AIX, and Mac OS X. Devices vary on many dimensions, as illustrated in Figure (Characteristics of I/O devices).

- ✓ **Character-stream or block**. A character-stream device transfer's bytes one by one, whereas a block device transfers a block of bytes as a unit.
- ✓ **Sequential or random access**. A sequential device transfers data in a fixed order determined by the device, whereas the user of a random-access device can instruct the device to seek to any of the available data storage locations.

- ✓ **Synchronous or asynchronous**. A synchronous device performs data transfers with predictable response times, in coordination with other aspects of the system. An asynchronous device exhibits irregular or unpredictable response times not coordinated with other computer events.
- ✓ **Sharable or dedicated**. A sharable device can be used concurrently by several processes or threads; a dedicated device cannot.



aspect	variation	example
data-transfer mode	character block	terminal disk
access method	sequential random	modem CD-ROM
transfer schedule	synchronous asynchronous	tape keyboard
sharing	dedicated sharable	tape keyboard
device speed	latency seek time transfer rate delay between operations	
I/O direction	read only write only read–write	CD-ROM graphics controller disk

Figure: Characteristics of I/O devices

- ✓ **Speed of operation**. Device speeds range from a few bytes per second to a few gigabytes per second.
- ✓ **Read–write, read only, or write only**. Some devices perform both input and output, but others support only one data transfer direction.

For the purpose of application access, many of these differences are hidden by the operating system, and the devices are grouped into a few conventional types. The resulting styles of device access have been found to be useful and broadly applicable.

Although the exact system calls may differ across operating systems, the device categories are fairly standard. The major access conventions include block I/O, character-stream I/O, memory-mapped file access, and network sockets.

Operating systems also provide special system calls to access a few additional devices, such as a time-of-day clock and a timer. Some operating systems provide a set of system calls for graphical display, video, and audio devices.

Most operating systems also have an **escape** (or **back door**) that transparently passes arbitrary commands from an application to a device driver. In UNIX, this system call is ioctl() (for "I/O control").

The ioctl() system call enables an application to access any functionality that can be implemented by any device driver, without the need to invent a new system call.

The ioctl() system call has three arguments:

- The ***first*** is a file descriptor that connects the application to the driver by referring to a hardware device managed by that driver.
- The ***second*** is an integer that selects one of the commands implemented in the driver.
- The ***third*** is a pointer to an arbitrary data structure in memory that enables the application and driver to communicate any necessary control information or data.

Block and Character Devices:

The **block-device interface** captures all the aspects necessary for accessing disk drives and other block-oriented devices. The device is expected to understand commands such as read() and write(). If it is a random-access device, it is also expected to have a seek() command to specify which block to transfer next.

Applications normally access such a device through a file-system interface. We can see that read(), write(), and seek() capture the essential behaviors of block-storage devices, so that applications are insulated from the low-level differences among those devices.

The operating system itself, as well as special applications such as database management systems, may prefer to access a block device as a simple linear array of blocks. This mode of access is sometimes called **raw I/O**. If the application performs its own buffering, then using a file system would cause extra, unneeded buffering.

Likewise, if an application provides its own locking of file blocks or regions, then any operating-system locking services would be redundant at the least and contradictory at the worst.

A keyboard is an example of a device that is accessed through a **character stream interface**. The basic system calls in this interface enable an application to get() or put() one character.

On top of this interface, libraries can be built that offer line-at-a-time access, with buffering and editing services (for example, when a user types a backspace, the preceding character is removed from the input stream).

This style of access is convenient for input devices such as keyboards, mice, and modems that produce data for input “spontaneously” —that is, at times that cannot necessarily be predicted by the application. This access style is also good for output devices such as printers and audio boards, which naturally fit the concept of a linear stream of bytes.

Network Devices:

Because the performance and addressing characteristics of network I/O differ significantly from those of disk I/O, most operating systems provide a network I/O interface that is different from the read()–write()–seek() interface used for disks. One interface available in many operating systems, including UNIX and Windows, is the network **socket** interface.

Think of a wall socket for electricity: any electrical appliance can be plugged in. By analogy, the system calls in the socket interface enable an application to create a socket, to connect a local socket to a remote address (which plugs this application into a socket created by another application), to listen for any remote application to plug into the local socket, and to send and receive packets over the connection.

To support the implementation of servers, the socket interface also provides a function called select() that manages a set of sockets. A call to select() returns information about which sockets have a packet waiting to be received and which sockets have room to accept a packet to be sent.

The use of select() eliminates the polling and busy waiting that would otherwise be necessary for network I/O. These functions encapsulate the essential behaviors of networks, greatly facilitating the creation of distributed applications that can use any underlying network hardware and protocol stack.

Many other approaches to inter process communication and network communication have been implemented. For instance, Windows provides one interface to the network interface card and a second interface to the network protocols. In UNIX, which has a long history as a proving ground for network technology, we find half-duplex pipes, full-duplex FIFOs, full-duplex STREAMS, message queues, and sockets.

Clocks and Timers:

Most computers have hardware clocks and timers that provide three basic functions:

- Give the current time.
- Give the elapsed time.
- Set a timer to trigger operation *X* at time *T*.

These functions are used heavily by the operating system, as well as by time sensitive applications. Unfortunately, the system calls that implement these functions are not standardized across operating systems.

The hardware to measure elapsed time and to trigger operations is called a **programmable interval timer**. It can be set to wait a certain amount of time and then generate an interrupt, and it can be set to do this once or to repeat the process to generate periodic interrupts.

The scheduler uses this mechanism to generate an interrupt that will preempt a process at the end of its time slice. *The disk I/O subsystem uses it* to invoke the periodic flushing of dirty cache buffers to disk.

The network subsystem uses it to cancel operations that are proceeding too slowly because of network congestion or failures. *The operating system may also provide* an interface for user processes to use timers.

The operating system can support more timer requests than the number of timer hardware channels by simulating virtual clocks. To do so, the kernel (or the timer device driver) maintains a list of interrupts wanted by its own routines and by user requests, sorted in earliest-time-first order.

It sets the timer for the earliest time. When the timer interrupts, the kernel signals the requester and reloads the timer with the next earliest time. On many computers, the interrupt rate generated by the hardware clock is between 18 and 60 ticks per second.

Nonblocking and Asynchronous I/O:

Another aspect of the system-call interface relates to the choice between blocking I/O and nonblocking I/O. When an application issues a **blocking** system call, the execution of the application is suspended. The application is moved from the operating system’s run queue to a wait queue.

After the system call completes, the application is moved back to the run queue, where it is eligible to resume execution. When it resumes execution, it will receive the values returned by the system call.

The physical actions performed by I/O devices are generally asynchronous—they take a varying or unpredictable amount of time. Nevertheless, most operating systems use blocking system calls for the application interface, because blocking application code is easier to understand than nonblocking application code.

Some user-level processes need **nonblocking** I/O. One example is a user interface that receives keyboard and mouse input while processing and displaying data on the screen. Another example is a video application that reads frames from a file on disk while simultaneously decompressing and displaying the output on the display.

One way an application writer can overlap execution with I/O is to write a multithreaded application. Some threads can perform blocking system calls, while others continue executing. Some operating systems provide nonblocking I/O system calls.

A nonblocking call does not halt the execution of the application for an extended time. Instead, it returns quickly, with a return value that indicates how many bytes were transferred. An alternative to a nonblocking system call is an asynchronous system call.

An asynchronous call returns immediately, without waiting for the I/O to complete. The application continues to execute its code. The completion of the I/O at some future time is communicated to the application, either through the setting of some variable in the address space of the application or through the triggering of a signal or software interrupt or a call-back routine that is executed outside the linear control flow of the application.

The difference between nonblocking and asynchronous system calls is that a nonblocking read() returns immediately with whatever data are available—the full number of bytes requested, fewer, or none at all.

An asynchronous read() call requests a transfer that will be performed in its entirety but will complete at some future time. These two I/O methods are shown in **Figure** (Two I/O methods: (a) synchronous and (b) asynchronous).

A good example of nonblocking behavior is the select() system call for network sockets. This system call takes an argument that specifies a maximum waiting time. By setting it to 0, an application can poll for network activity without blocking.

But using select() introduces extra overhead, because the select() call only checks whether I/O is possible. For a data transfer, select() must be followed by some kind of read() or write() command.

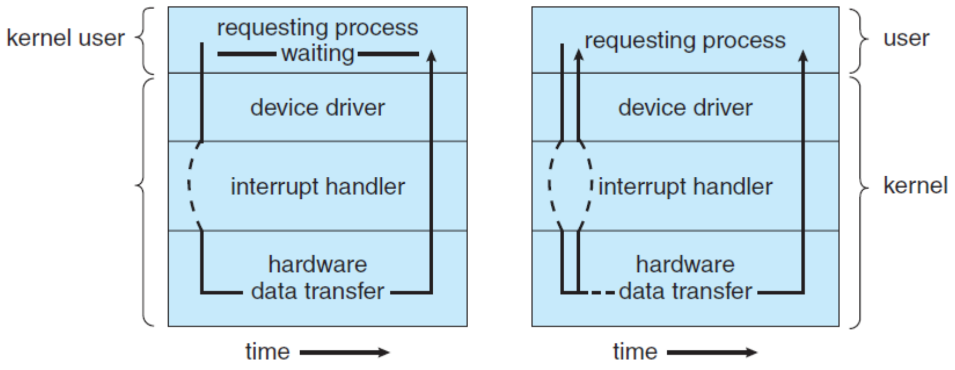


Figure: Two I/O methods: (a) synchronous and (b) asynchronous

Vectored I/O:

Vectored I/O allows one system call to perform multiple I/O operations involving multiple locations. For example, the ***UNIXreadv*** system call accepts a vector of multiple buffers and either reads from a source to that vector or writes from that vector to a destination.

The same transfer could be caused by several individual invocations of system calls, but this **scatter–gather** method is useful for a variety of reasons. Multiple separate buffers can have their contents transferred via one system call, avoiding context-switching and system-call overhead.

Without vectored I/O, the data might first need to be transferred to a larger buffer in the right order and then transmitted, which is inefficient.

Kernel I/O Subsystem:

Kernels provide many services related to I/O. Several services—scheduling, buffering, caching, spooling, device reservation, and error handling—are provided by the kernel's I/O subsystem and build on the hardware and device driver infrastructure. The I/O subsystem is also responsible for protecting itself from errant processes and malicious users.

I/O Scheduling:

To schedule a set of I/O requests means to determine a good order in which to execute them. The order in which applications issue system calls rarely is the best choice.

Scheduling can improve overall system performance, can share device access fairly among processes, and can reduce the average waiting time for I/O to complete.

Here is a simple example to illustrate. Suppose that a disk arm is near the beginning of a disk and that three applications issue blocking read calls to that disk. Application 1 requests a block near the end of the disk, application 2 requests one near the beginning, and application 3 requests one in the middle of the disk.

The operating system can reduce the distance that the disk arm travels by serving the applications in the order 2, 3, 1. Rearranging the order of service in this way is the essence of I/O scheduling.

Operating-system developers implement scheduling by maintaining await queue of requests for each device. When an application issues a blocking I/O system call, the request is placed on the queue for that device. The I/O scheduler rearranges the order of the queue to improve the overall system efficiency and the average response time experienced by applications.

The operating system may also try to be fair, so that no one application receives especially poor service, or it may give priority service for delay-sensitive requests.

When a kernel supports asynchronous I/O, it must be able to keep track of many I/O requests at the same time. For this purpose, the operating system might attach the wait queue to a **device-status table**. The kernel manages this table, which contains an entry for each I/O device, as shown in Figure below:

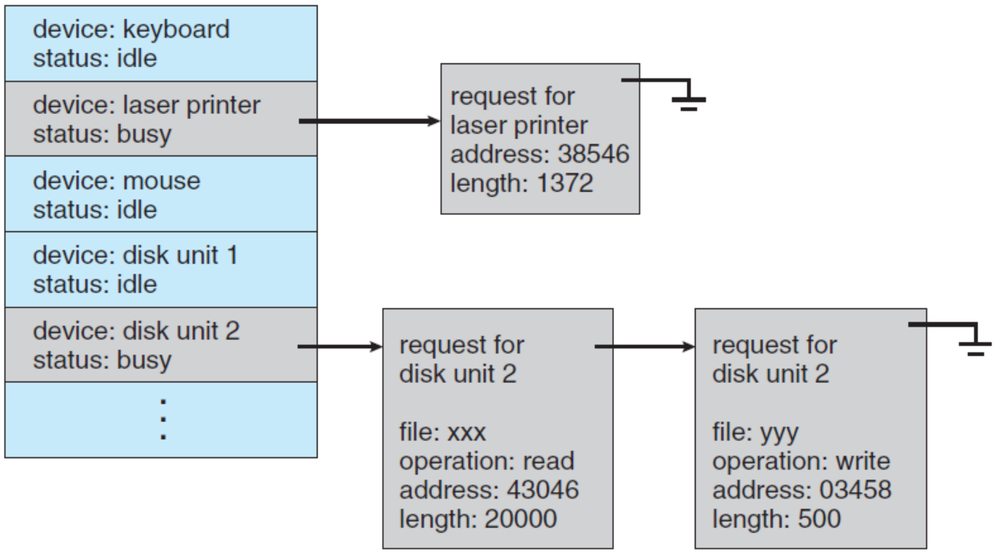


Figure: Device-status table

Each table entry indicates the device's type, address, and state (not functioning, idle, or busy). If the device is busy with a request, the type of request and other parameters will be stored in the table entry for that device.

Scheduling I/O operations is one way in which the I/O subsystem improves the efficiency of the computer. Another way is by using storage space in main memory or on disk via ***buffering***, ***caching***, and ***spooling***.

Buffering:

A **buffer**, of course, is a memory area that stores data being transferred between two devices or between a device and an application. Buffering is done for three reasons. One reason is to cope with a speed mismatch between the producer and consumer of a data stream.

A second use of buffering is to provide adaptations for devices that have different data-transfer sizes. Such disparities are especially common in computer networking, where buffers are used widely for fragmentation and reassembly of messages.

A third use of buffering is to support copy semantics for application I/O. An example will clarify the meaning of "copy semantics." Suppose that an application has a buffer of data that it wishes to write to disk. It calls the write() system call, providing a pointer to the buffer and an integer specifying the number of bytes to write.

After the system call returns, what happens if the application changes the contents of the buffer? With **copy semantics**, the version of the data written to disk is guaranteed to be the version at the time of the application system call, independent of any subsequent changes in the application's buffer.

A simple way in which the operating system can guarantee copy semantics is for the write() system call to copy the application data into a kernel buffer before returning control to the application. The disk write is performed from the kernel buffer, so that subsequent changes to the application buffer have no effect.

Caching:

A **cache** is a region of fast memory that holds copies of data. Access to the cached copy is more efficient than access to the original. For instance, the instructions of the currently running process are stored on disk, cached in physical memory, and copied again in the CPU's secondary and primary caches.

The difference between a buffer and a cache is that a buffer may hold the only existing copy of a data item, whereas a cache, by definition, holds a copy on faster storage of an item that resides elsewhere.

Caching and buffering are distinct functions, but sometimes a region of memory can be used for both purposes. For instance, to preserve copy semantics and to enable efficient scheduling of disk I/O, the operating system uses buffers in main memory to hold disk data.

These buffers are also used as a cache, to improve the I/O efficiency for files that are shared by applications or that are being written and reread rapidly. When the kernel receives a file I/O request, the kernel first accesses the buffer cache to see whether that region of the file is already available in main memory.

Spooling and Device Reservation:

A **spool** is a buffer that holds output for a device, such as a printer, that cannot accept interleaved data streams. Although a printer can serve only one job at a time, several applications may wish to print their output concurrently, without having their output mixed together.

The operating system solves this problem by intercepting all output to the printer. Each application's output is spooled to a separate disk file. When an application finishes printing, the spooling system queues the corresponding spool file for output to the printer. The spooling system copies the queued spool files to the printer one at a time.

In some operating systems, spooling is managed by a system daemon process. In others, it is handled by an in-kernel thread. In either case, the operating system provides a control interface that enables users and system administrators to display the queue, remove unwanted jobs before those jobs print, suspend printing while the printer is serviced, and so on.

Error Handling:

An operating system that uses protected memory can guard against many kinds of hardware and application errors, so that a complete system failure is not the usual result of each minor mechanical malfunction.

Devices and I/O transfers can fail in many ways, either for transient reasons, as when a network becomes overloaded, or for "permanent" reasons, as when a disk controller becomes defective. Operating systems can often compensate effectively for transient failures.

For instance, a disk read() failure results in a read() retry, and a network send() error results in a resend(), if the protocol so specifies. Unfortunately, if an important component experiences a permanent failure, the operating system is unlikely to recover.

As a general rule, an I/O system call will return one bit of information about the status of the call, signifying either success or failure. In the UNIX operating system, an additional integer variable named errno is used to return an error code—one of about a hundred values—indicating the general nature of the failure (for example, argument out of range, bad pointer, or file not open).

I/O Protection:

Errors are closely related to the issue of protection. A user process may accidentally or purposely attempt to disrupt the normal operation of a system by attempting to issue illegal I/O instructions. We can use various mechanisms to ensure that such disruptions cannot take place in the system.

To prevent users from performing illegal I/O, we define all I/O instructions to be privileged instructions. Thus, users cannot issue I/O instructions directly; they must do it through the operating system. To do I/O, a user program executes a system call to request that the operating system perform I/O on its behalf.

The operating system, executing in monitor mode, checks that the request is valid and, if it is, does the I/O requested. The operating system then returns to the user.

Kernel Data Structures:

The kernel needs to keep state information about the use of I/O components. It does so through a variety of in-kernel data structures, such as the open-file table structure.

The kernel uses many similar structures to track network connections, character-device communications, and other I/O activities. UNIX provides file-system access to a variety of entities, such as user files, raw devices, and the address spaces of processes.

Although each of these entities supports a read() operation, the semantics differ. For instance, to read a user file, the kernel needs to probe the buffer cache before deciding whether to perform a disk I/O.

To read a raw disk, the kernel needs to ensure that the request size is a multiple of the disk sector size and is aligned on a sector boundary. To read a process image, it is merely necessary to copy data from memory.

UNIX encapsulates these differences within a uniform structure by using an object-oriented technique. The open-file record, shown in Figure below, contains a dispatch table that holds pointers to the appropriate routines, depending on the type of file.

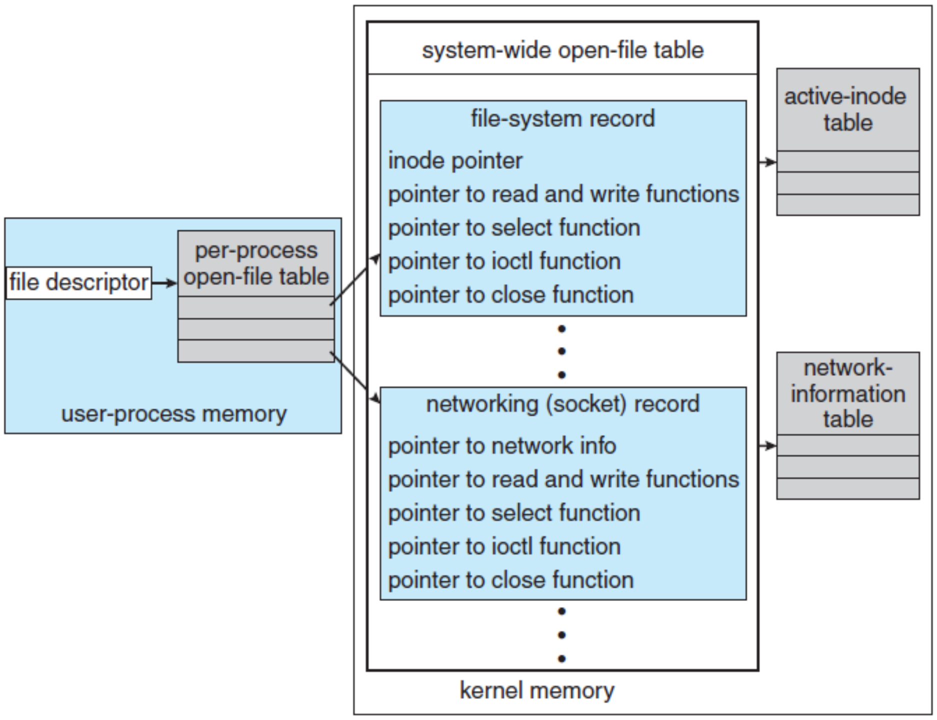

system-wide open-file table
file-system record
inode pointer
pointer to read and write functions
pointer to select function
pointer to ioctl function
pointer to close function
active-inode table
file descriptor
per-process open-file table
user-process memory
networking (socket) record
pointer to network info
pointer to read and write functions
pointer to select function
pointer to ioctl function
pointer to close function
network-information table
kernel memory

Figure: UNIX I/O kernel structure