

# I/O Systems



The role of the operating system in computer I/O is to manage and control I/O operations and I/O devices. Although related topics appear in other chapters, here we bring together the pieces to paint a complete picture. In this chapter we describe I/O structure, devices, device drivers, caching, and terminal I/O.

## Exercises

- 13.1** When multiple interrupts from different devices appear at about the same time, a priority scheme could be used to determine the order in which the interrupts would be serviced. Discuss what issues need to be considered in assigning priorities to different interrupts.

**Answer:** A number of issues need to be considered in order to determine the priority scheme to be used to determine the order in which the interrupts need to be serviced. First, interrupts raised by devices should be given higher priority than traps generated by the user program; a device interrupt can therefore interrupt code used for handling system calls. Second, interrupts that control devices might be given higher priority than interrupts that simply perform tasks such as copying data served up a device to user/kernel buffers, since such tasks can always be delayed. Third, devices that have real-time constraints on when their data is handled should be given higher priority than other devices. Also, devices that do not have any form of buffering for its data would have to be assigned higher priority since the data could be available only for a short period of time.

- 13.2** What are the advantages and disadvantages of supporting memory-mapped I/O to device-control registers?

**Answer:** The advantage of supporting memory-mapped I/O to device-control registers is that it eliminates the need for special I/O instructions from the instruction set and therefore also does not require the enforcement of protection rules that prevent user programs from executing these I/O instructions. The disadvantage is that the resulting flexibility needs to be handled with care; the memory translation units need to ensure that the memory addresses associated with the device control registers are not accessible by user programs in order to ensure protection.

13.3 Consider the following I/O scenarios on a single-user PC.

- a. A mouse used with a graphical user interface
- b. A tape drive on a multitasking operating system (assume no device preallocation is available)
- c. A disk drive containing user files
- d. A graphics card with direct bus connection, accessible through memory-mapped I/O

For each of these I/O scenarios, would you design the operating system to use buffering, spooling, caching, or a combination? Would you use polled I/O, or interrupt-driven I/O? Give reasons for your choices.

**Answer:**

- a. A mouse used with a graphical user interface  
Buffering may be needed to record mouse movement during times when higher-priority operations are taking place. Spooling and caching are inappropriate. Interrupt-driven I/O is most appropriate.
- b. A tape drive on a multitasking operating system (assume no device preallocation is available)  
Buffering may be needed to manage throughput difference between the tape drive and the source or destination of the I/O. Caching can be used to hold copies of data that resides on the tape, for faster access. Spooling could be used to stage data to the device when multiple users desire to read from or write to it. Interrupt-driven I/O is likely to allow the best performance.
- c. A disk drive containing user files  
Buffering can be used to hold data while in transit from user space to the disk, and visa versa. Caching can be used to hold disk-resident data for improved performance. Spooling is not necessary because disks are shared-access devices. Interrupt-driven I/O is best for devices such as disks that transfer data at slow rates.
- d. A graphics card with direct bus connection, accessible through memory-mapped I/O  
Buffering may be needed to control multiple access and for performance (double-buffering can be used to hold the next screen image while displaying the current one). Caching and spooling are not necessary due to the fast and shared-access natures of the device. Polling and interrupts are useful only for input and for I/O completion detection, neither of which is needed for a memory-mapped device.

13.4 In most multiprogrammed systems, user programs access memory through virtual addresses, while the operating system uses raw physical addresses to access memory. What are the implications of this design on the initiation of I/O operations by the user program and their execution by the operating system?

**Answer:** The user program typically specifies a buffer for data to be transmitted to or from a device. This buffer exists in user space and is specified by a virtual address. The kernel needs to issue the I/O operation and needs to copy data between the user buffer and its own kernel buffer before or after the I/O operation. In order to access the user buffer, the kernel needs to translate the virtual address provided by the user program to the corresponding physical address within the context of the user program's virtual address space. This translation is typically performed in software and therefore incurs overhead. Also, if the user buffer is not currently present in physical memory, the corresponding page(s) need to be obtained from the swap space. This operation might require careful handling and might delay the data copy operation.

- 13.5 What are the various kinds of performance overheads associated with servicing an interrupt?

**Answer:** When an interrupt occurs the currently executing process is interrupted and its state is stored in the appropriate process control block. The interrupt service routine is then dispatched in order to deal with the interrupt. On completion of handling of the interrupt, the state of the process is restored and the process is resumed. Therefore, the performance overheads include the cost of saving and restoring process state and the cost of flushing the instruction pipeline and restoring the instructions into the pipeline when the process is restarted.

- 13.6 Describe three circumstances under which blocking I/O should be used. Describe three circumstances under which nonblocking I/O should be used. Why not just implement nonblocking I/O and have processes busy-wait until their device is ready?

**Answer:** Generally, blocking I/O is appropriate when the process will be waiting only for one specific event. Examples include a disk, tape, or keyboard read by an application program. Non-blocking I/O is useful when I/O may come from more than one source and the order of the I/O arrival is not predetermined. Examples include network daemons listening to more than one network socket, window managers that accept mouse movement as well as keyboard input, and I/O-management programs, such as a copy command that copies data between I/O devices. In the last case, the program could optimize its performance by buffering the input and output and using non-blocking I/O to keep both devices fully occupied.

Non-blocking I/O is more complicated for programmers, because of the asynchronous rendezvous that is needed when an I/O occurs. Also, busy waiting is less efficient than interrupt-driven I/O so the overall system performance would decrease.

- 13.7 Typically, at the completion of a device I/O, a single interrupt is raised and appropriately handled by the host processor. In certain settings, however, the code that is to be executed at the completion of the I/O can be broken into two separate pieces, one of which executes immediately after the I/O completes and schedules a second interrupt for the remaining piece of code to be executed at a later time. What is the purpose of using this strategy in the design of interrupt handlers?

**Answer:** The purpose of this strategy is to ensure that the most critical aspect of the interrupt handling code is performed first and the less critical portions of the code are delayed for the future. For instance, when a device finishes an I/O operation, the device-control operations corresponding to declaring the device as no longer being busy are more important in order to issue future operations. However, the task of copying the data provided by the device to the appropriate user or kernel memory regions can be delayed for a future point when the CPU is idle. In such a scenario, a lower-priority interrupt handler is used to perform the copy operation.

- 13.8 Some DMA controllers support direct virtual memory access, where the targets of I/O operations are specified as virtual addresses and a translation from virtual to physical address is performed during the DMA. How does this design complicate the design of the DMA controller? What are the advantages of providing such a functionality?

**Answer:** Direct virtual memory access allows a device to perform a transfer from two memory-mapped devices without the intervention of the CPU or the use of main memory as a staging ground; the device simply issues memory operations to the memory-mapped addresses of a target device and the ensuing virtual address translation guarantees that the data is transferred to the appropriate device. This functionality, however, comes at the cost of having to support virtual address translation on addresses accessed by a DMA controller and requires the addition of an address-translation unit to the DMA controller. The address translation results in both hardware and software costs and might also result in coherence problems between the data structures maintained by the CPU for address translation and corresponding structures used by the DMA controller. These coherence issues would also need to be dealt with and results in further increase in system complexity.

- 13.9 UNIX coordinates the activities of the kernel I/O components by manipulating shared in-kernel data structures, whereas Windows NT uses object-oriented message passing between kernel I/O components. Discuss three pros and three cons of each approach.

**Answer:**

Three pros of the UNIX method: Very efficient, low overhead and low amount of data movement. Fast implementation—no coordination needed with other kernel components. Simple, so less chance of data loss

Three cons: No data protection, and more possible side effects from changes so more difficult to debug. Difficult to implement new I/O methods: new data structures needed rather than just new objects. Complicated kernel I/O subsystem, full of data structures, access routines, and locking mechanisms

- 13.10 Write (in pseudocode) an implementation of virtual clocks, including the queuing and management of timer requests for the kernel and applications. Assume that the hardware provides three timer channels.

**Answer:** Each channel would run the following algorithm:

```

    /** data definitions */

    // a list of interrupts sorted in earliest-time-first order
    List interruptList

    // the list that associates a request with an entry in
    interruptList
    List requestList

    // an interrupt-based timer
    Timer timer

    while (true) {
        /** Get the next earliest time in the list */
        timer.setTime = interruptList.next();

        /** An interrupt will occur at time timer.setTime */

        /** now wait for the timer interrupt
         i.e. for the timer to expire */

        notify( requestList.next() );
    }

```

- 13.11** Discuss the advantages and disadvantages of guaranteeing reliable transfer of data between modules in the STREAMS abstraction.

**Answer:** Reliable transfer of data requires modules to check whether space is available on the target module and to block the sending module if space is not available. This check requires extra communication between the modules, but the overhead enables the system to provide a stronger abstraction than one which does not guarantee reliable transfer. The stronger abstraction typically reduces the complexity of the code in the modules. In the STREAMS abstraction, however, there is unreliability introduced by the driver end, which is allowed to drop messages if the corresponding device cannot handle the incoming data. Consequently, even if there is reliable transfer of data between the modules, messages could be dropped at the device if the corresponding buffer fills up. This requires retransmission of data and special code for handling such retransmissions, thereby somewhat limiting the advantages that are associated with reliable transfer between the modules.

