I/O Management

Chapter 5

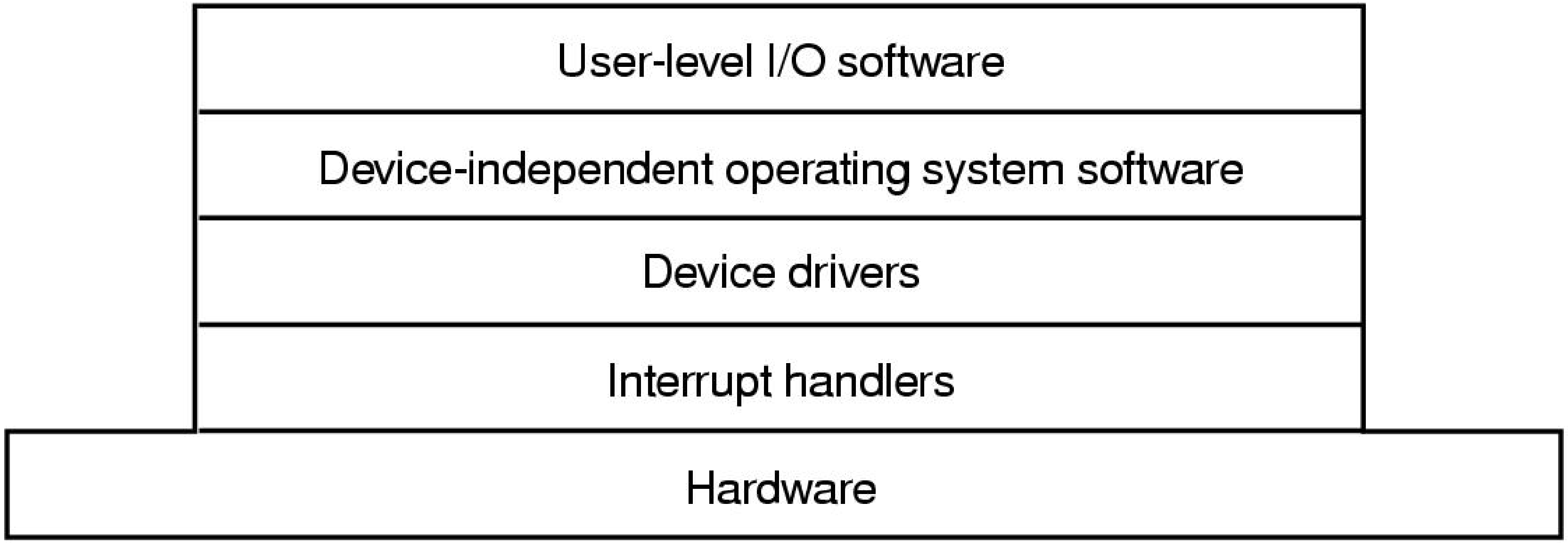
Operating System Design Issues

- Efficiency
  - Most I/O devices slow compared to main memory (and the CPU)
    - Use of multiprogramming allows for some processes to be waiting on I/O while another process executes
    - Often I/O still cannot keep up with processor speed
    - Swapping may used to bring in additional Ready processes
      - More I/O operations
- **Optimise I/O efficiency – especially Disk & Network I/O**

Operating System Design Issues

- The quest for generality/uniformity:
  - Ideally, handle all I/O devices in the same way
    - Both in the OS and in user applications
  - Problem:
    - Diversity of I/O devices
    - Especially, different access methods (random access versus stream based) as well as vastly different data rates.
    - Generality often compromises efficiency!
  - Hide most of the details of device I/O in lower-level routines so that processes and upper levels see devices in general terms such as read, write, open, close.

I/O Software Layers



Layers of the I/O Software System

Interrupt Handlers

- Interrupt handlers are best "hidden"
  - Can execute at almost any time
    - Raise (complex) concurrency issues in the kernel
    - Have similar problems within applications if interrupts are propagated to user-level code (via signals, upcalls).
  - Generally, systems are structured such that drivers starting an I/O operations block until interrupts notify them of completion
    - Example dev_read() waits on semaphore that the interrupt handler signals.
- Interrupt procedure does its task
  - then unblocks driver waiting on completion

Interrupt Handler Steps

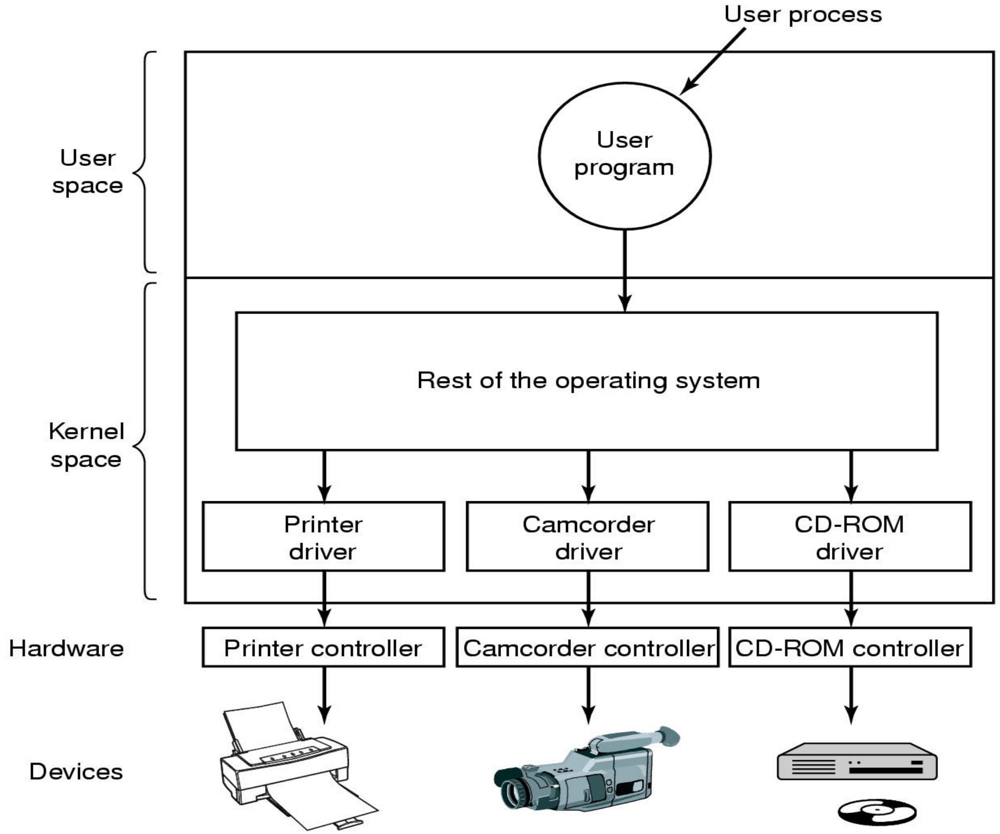
- Steps must be performed in software upon occurrence of an interrupt
  - Save regs not already saved by hardware interrupt mechanism
  - (Optionally) set up context (address space) for interrupt service procedure
    - Typically, handler runs in the context of the currently running process
      - No expensive context switch
  - Set up stack for interrupt service procedure
    - Handler usually runs on the kernel stack of current process
      - Implies handler cannot block as the unlucky current process will also be blocked ⇒ might cause deadlock
  - Ack/Mask interrupt controller, reenable other interrupts

Interrupt Handler Steps

- Run interrupt service procedure
  - Acknowledges interrupt at device level
  - Figures out what caused the interrupt
    - Received a network packet, disk read finished, UART transmit queue empty
  - If needed, it signals blocked device driver
- In some cases, will have woken up a higher priority blocked thread
  - Choose newly woken thread to schedule next.
  - Set up MMU context for process to run next
- Load new/original process' registers
- Re-enable interrupt; Start running the new process

Device Drivers

- Logical position of device drivers is shown here
- Drivers (originally) compiled into the kernel
  - Including OS/161
  - Device installers were technicians
  - Number and types of devices rarely changed
- Nowadays they are dynamically loaded when needed
  - Linux modules
  - Typical users (device installers) can't build kernels
  - Number and types vary greatly
    - Even while OS is running (e.g hot-plug USB devices)



Device Drivers

- Drivers classified into similar categories
  - Block devices and character (stream of data) device
- OS defines a standard (internal) interface to the different classes of devices
- Device drivers job
  - translate request through the device-independent standard interface (open, close, read, write) into appropriate sequence of commands (register manipulations) for the particular hardware
  - Initialise the hardware at boot time, and shut it down cleanly at shutdown

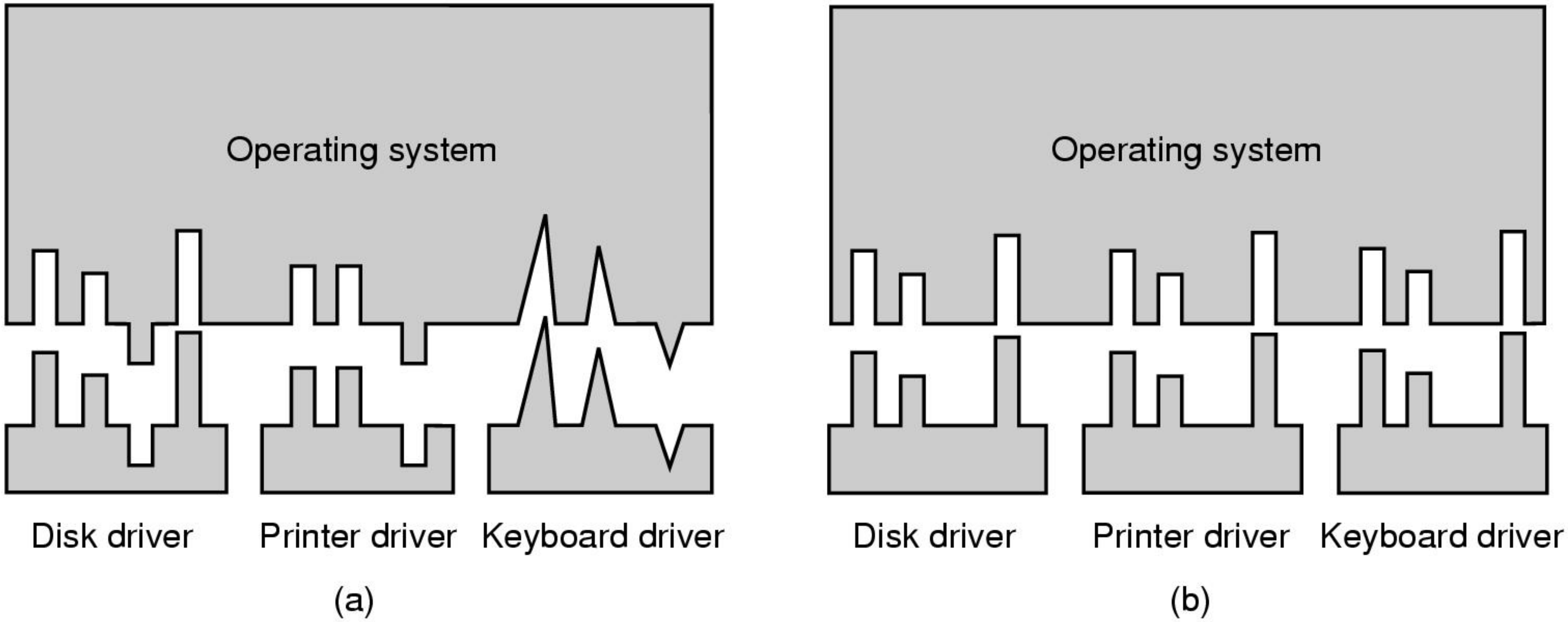
Device Driver

- After issuing the command to the device, the device either
  - Completes immediately and the driver simply returns to the caller
  - Or, device must process the request and the driver usually blocks waiting for an I/O complete interrupt.
- Drivers are reentrant as they can be called by another process while a process is already blocked in the driver.
  - Reentrant: Code that can be executed by more than one thread (or CPU) at the same time
    - Manages concurrency using synch primitives

Device-Independent I/O Software

- There is commonality between drivers of similar classes
- Divide I/O software into device-dependent and device-independent I/O software
- Device independent software includes
  - Buffer or Buffer-cache management
  - Managing access to dedicated devices
  - Error reporting

Device-Independent I/O Software



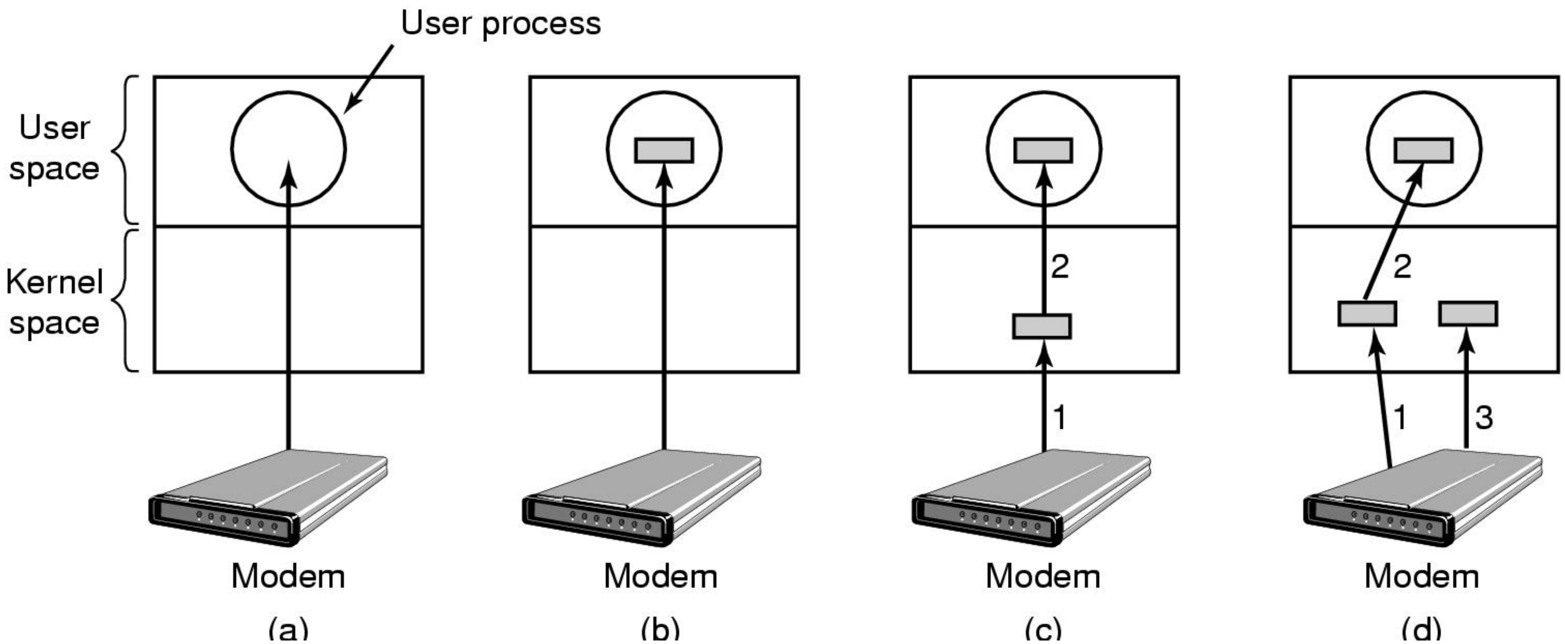
(a) Without a standard driver interface

(b) With a standard driver interface

Driver $\Leftrightarrow$ Kernel Interface

- Major Issue is uniform interfaces to devices and kernel
  - Uniform device interface for kernel code
    - Allows different devices to be used the same way
      - No need to rewrite filesystem to switch between SCSI, IDE or RAM disk
    - Allows internal changes to device driver with fear of breaking kernel code
  - Uniform kernel interface for device code
    - Drivers use a defined interface to kernel services (e.g. kmalloc, install IRQ handler, etc.)
    - Allows kernel to evolve without breaking existing drivers
  - Together both uniform interfaces avoid a lot of programming implementing new interfaces

Device-Independent I/O Software



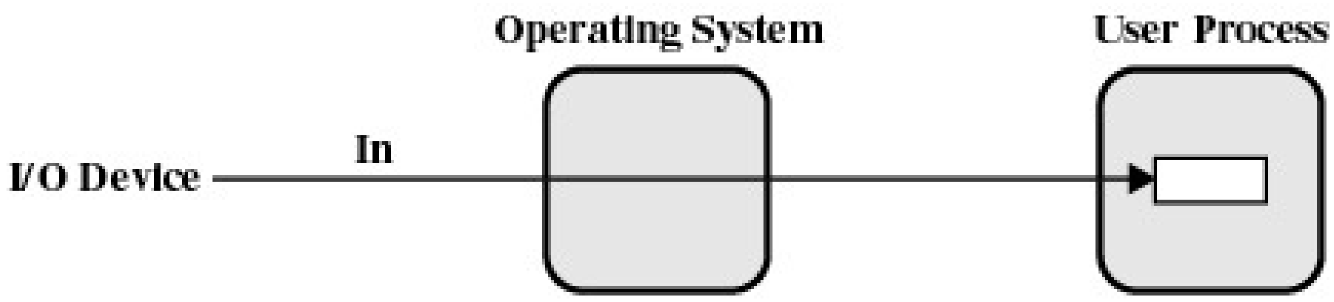
(a) Unbuffered input
(b) Buffering in user space
(c) *Single buffering* in the kernel followed by copying to user space
(d) Double buffering in the kernel

No Buffering

- Process must read/write a device a byte/word at a time
  - Each individual system call adds significant overhead
  - Process must what until each I/O is complete
    - Blocking/interrupt/waking adds to overhead.
    - Many short runs of a process is inefficient (poor CPU cache temporal locality)

User-level Buffering

- Process specifies a memory *buffer* that incoming data is placed in until it fills
  - Filling can be done by interrupt service routine
  - Only a single system call, and block/wakeup per data buffer
    - Much more efficient



User-level Buffering

- Issues
  - What happens if buffer is paged out to disk
    - Could lose data while buffer is paged in
    - Could lock buffer in memory (needed for DMA), however many processes doing I/O reduce RAM available for paging. Can cause deadlock as RAM is limited resource
  - Consider write case
    - When is buffer available for re-use?
      - Either process must block until potential slow device drains buffer
      - or deal with asynchronous signals indicating buffer drained

Single Buffer

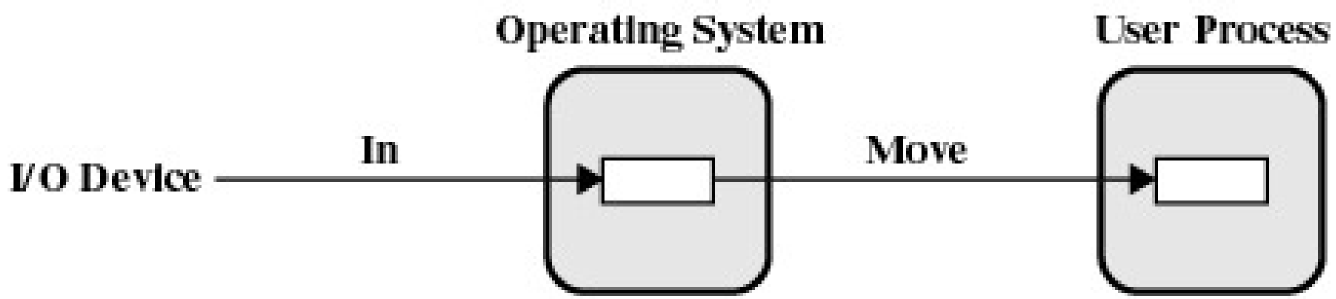
- Operating system assigns a buffer in main memory for an I/O request
- Stream-oriented
  - Used a line at time
  - User input from a terminal is one line at a time with carriage return signaling the end of the line
  - Output to the terminal is one line at a time

Single Buffer

- Block-oriented
  - Input transfers made to buffer
  - Block moved to user space when needed
  - Another block is moved into the buffer
    - Read ahead

Single Buffer

– User process can process one block of data while next block is read in
– Swapping can occur since input is taking place in system memory, not user memory
– Operating system keeps track of assignment of system buffers to user processes



(b) Single buffering

Single Buffer Speed Up

- Assume
  - *T* is transfer time from device
  - *C* is computation time to process incoming packet
  - *M* is time to copy kernel buffer to user buffer
- Computation and transfer can be done in parallel
- Speed up with buffering

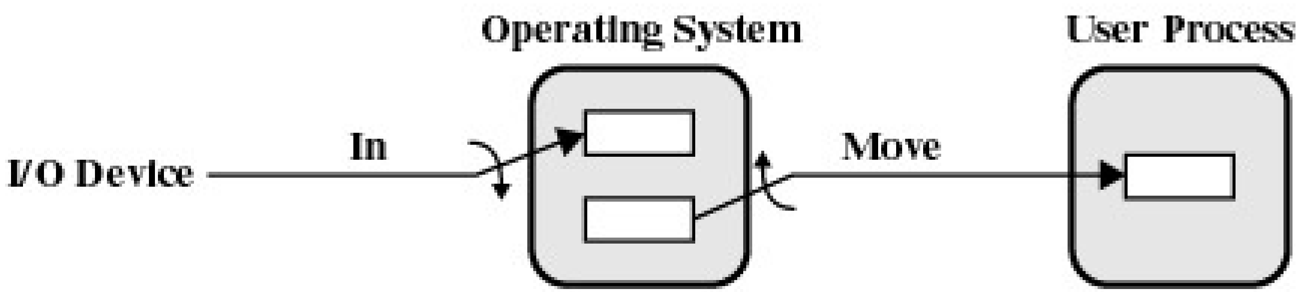
$$\frac{T + C}{\max(T, C) + M}$$

Single Buffer

- What happens if kernel buffer is full, the user buffer is swapped out, and more data is received???
  - We start to lose characters or drop network packets

Double Buffer

- Use two system buffers instead of one
- A process can transfer data to or from one buffer while the operating system empties or fills the other buffer



(c) Double buffering

Double Buffer Speed Up

- Computation and Memory copy can be done in parallel with transfer
- Speed up with double buffering

$$\frac{T + C}{\max(T, C + M)}$$

- Usually *M* is much less than *T* giving a favourable result

Double Buffer

- May be insufficient for really bursty traffic
  - Lots of application writes between long periods of computation
  - Long periods of application computation while receiving data
  - Might want to read-ahead more than a single block for disk

Circular Buffer

- More than two buffers are used
- Each individual buffer is one unit in a circular buffer
- Used when I/O operation must keep up with process

(d) Circular buffering

Important Note

- Notice that buffering, double buffering, and circular buffering are all

Bounded-Buffer Producer-Consumer Problems

Is Buffering Always Good?

$$\frac{T+C}{\max(T,C)+M}$$

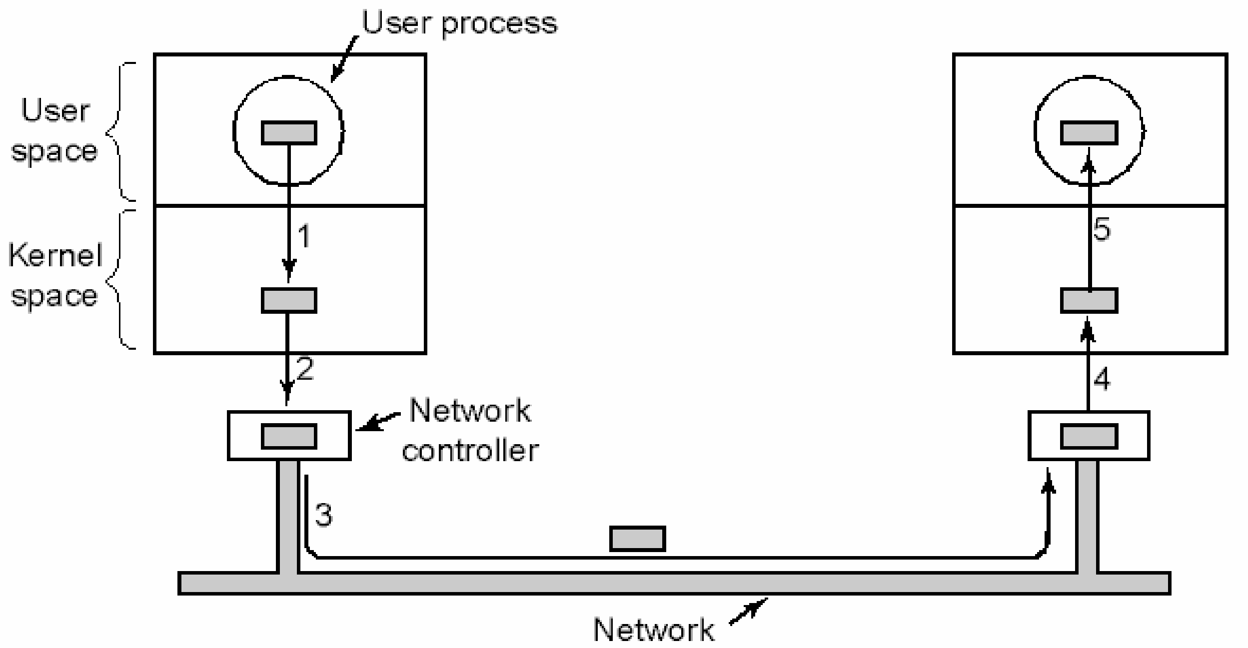
Single

$$\frac{T+C}{\max(T,C+M)}$$

Double

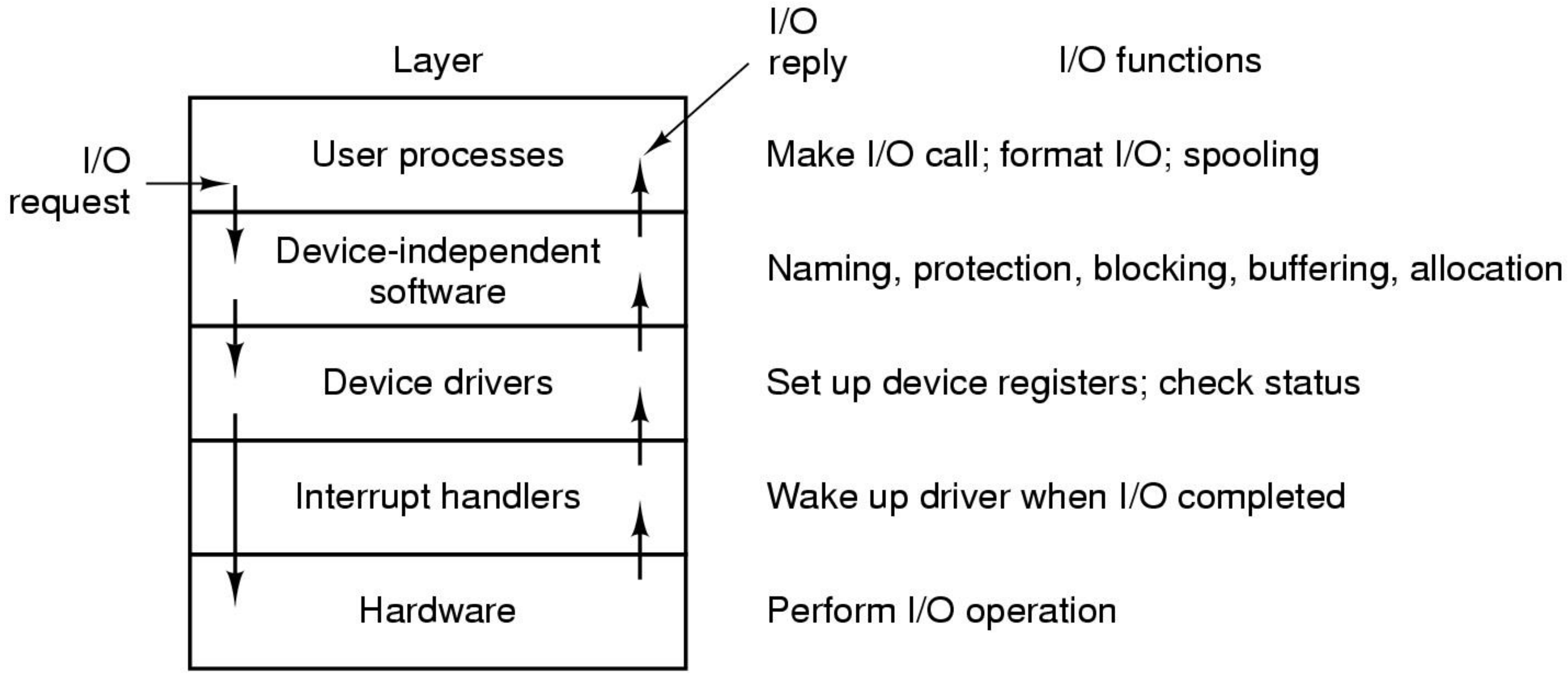
- Can *M* be similar or greater than *C* or *T*?

Buffering in Fast Networks



- Networking may involve many copies
- Copying reduces performance
  - Especially if copy costs are similar to or greater than computation or transfer costs
- Super-fast networks put significant effort into achieving zero-copy
- Buffering also increases latency

I/O Software Summary



Layers of the I/O system and the main functions of each layer