Karlsruhe Institute of Technology

Betriebssysteme

I/O System

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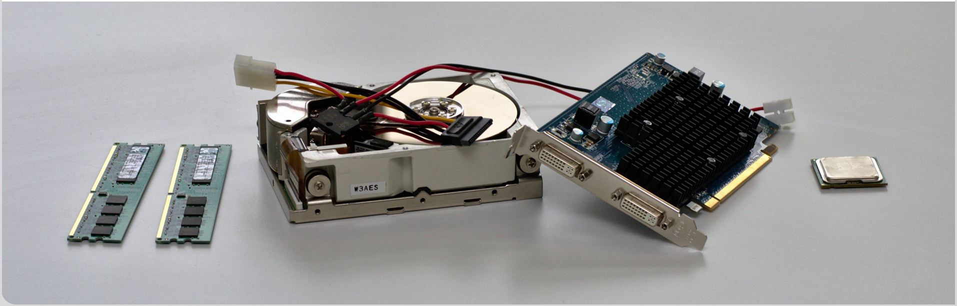
KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT) – OPERATING SYSTEMS GROUP



I/O Systems

- Device Management Objectives
- Device Characterization
- Device Interface
  - Control
  - Data Transfer
- Kernel I/O Subsystem
  - Device Independent Services
  - Device Drivers
  - Data Structures
  - Device Buffers

Device Management Objectives

- Abstraction from details of physical devices
- Uniform Naming that does not depend on HW details
- Serialization of I/O-operations by concurrent applications
- Protection of standard-devices against unauthorizes accesses
- Buffering, if data from/to a device cannot be stored in the final destination
- Error Handling of sporadic device errors
- Virtualizing physical devices via memory and time multiplexing (e.g. pty, RAM disk)

Characteristics of I/O Devices (1)

- **Block devices** include disk drives
  - Commands include `read`, `write`, `seek`
  - Raw I/O or file-system access
  - Memory-mapped file access possible
- **Character devices** include keyboards, mice, serial ports
  - Commands include `get, put`
  - Libraries layered on top allow line editing
- **Network devices** vary enough from block and character devices to have own interface
  - UNIX and Windows include socket interface
    - Separates network protocol from network operation
    - Includes `select` functionality

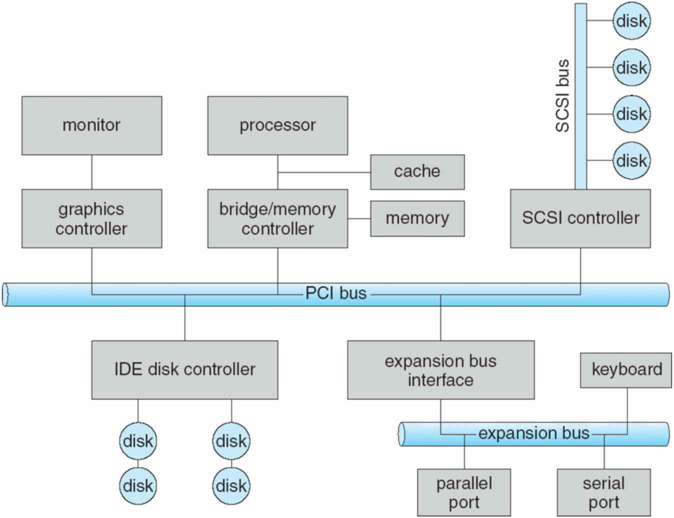
Characteristics of I/O Devices (2)

aspect	variation	example
data-transfer mode	character block	terminal disk
access method	sequential random	modern CD-ROM
transfer schedule	synchronous asynchronous	tape keyboards
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

Device Speed

Device	Data rate
Keyboard	10 bytes/sec
Mouse	100 bytes/sec
56K modem	7 KB/sec
Telephone channel	8 KB/sec
Dual ISDN lines	16 KB/sec
Laser printer	100 KB/sec
Scanner	400 KB/sec
Classic Ethernet	1.25 MB/sec
USB (Universal Serial Bus)	1.5 MB/sec
Digital camcorder	4 MB/sec
IDE disk	5 MB/sec
40 $\times$ CD-ROM	6 MB/sec
Fast Ethernet	12.5 MB/sec
ISA bus	16.7 MB/sec
EIDE (ATA-2) disk	16.7 MB/sec
FireWire (IEEE 1394)	50 MB/sec
XGA Monitor	60 MB/sec
SONET OC-12 network	78 MB/sec
SCSI Ultra 2 disk	80 MB/sec
Gigabit Ethernet	125 MB/sec
Ultrium tape	310 MB/sec
PCI bus	528 MB/sec
Sun Gigaplane XB backplane	20 GB/sec

A Typical PC Bus Structure



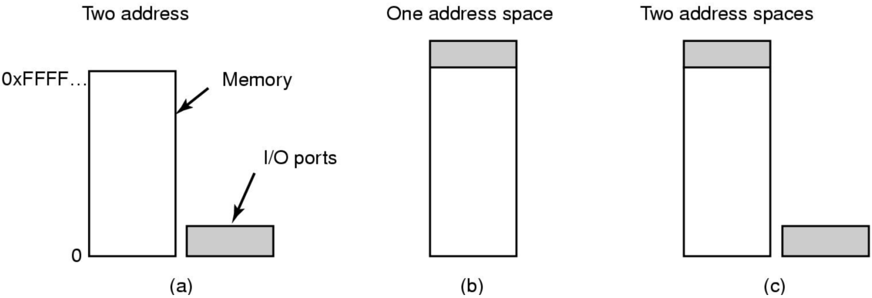
I/O Hardware

- Common components
  - Controller
  - Port (external connection point)
  - Bus (daisy chain or shared direct access)
- Devices have addresses, used by
  - Direct I/O instructions (e.g. to access x86 I/O ports)
  - Memory-mapped I/O
- Device addresses typically point to
  - Status register
  - Control register
  - Data-in register
  - Data-out register

Device I/O Port Locations on PCs (partial)

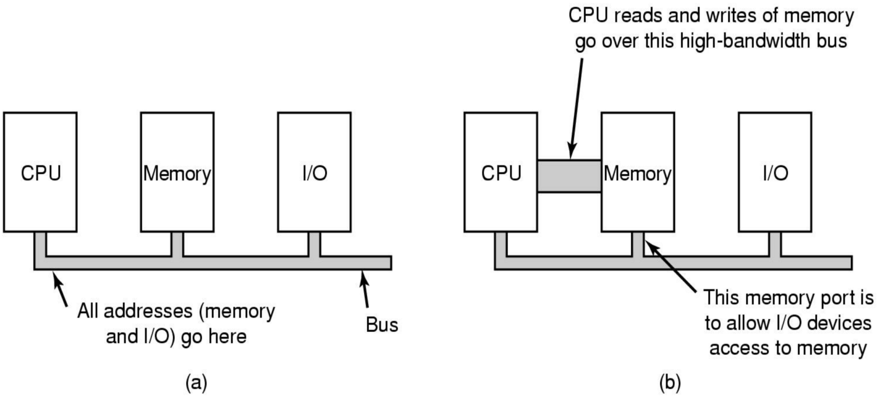
I/O address range (hexadecimal)	device
$000 - 00F$	DMA controller
$020 - 021$	interrupt controller
$040 - 043$	timer
$200 - 20F$	game controller
$2F8 - 2FF$	serial port (secondary)
$320 - 32F$	hard-disk controller
$378 - 37F$	parallel port
$3D0 - 3DF$	graphics controller
$3F0 - 3F7$	diskette-drive controller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

Memory-Mapped I/O (1)



- Separate I/O-address space and memory address space
  - `MOV R0, 4      //<4> → R0`
  - `IN R0, 4      // <port 4> → R0`
- Memory-mapped I/O // 1 common physical AS
- Hybrid (Pentium) // part of I/O space in memory part in an extra
  // address space

Memory-Mapped I/O (2)



(a) Single-bus architecture

(b) Dual-bus memory architecture

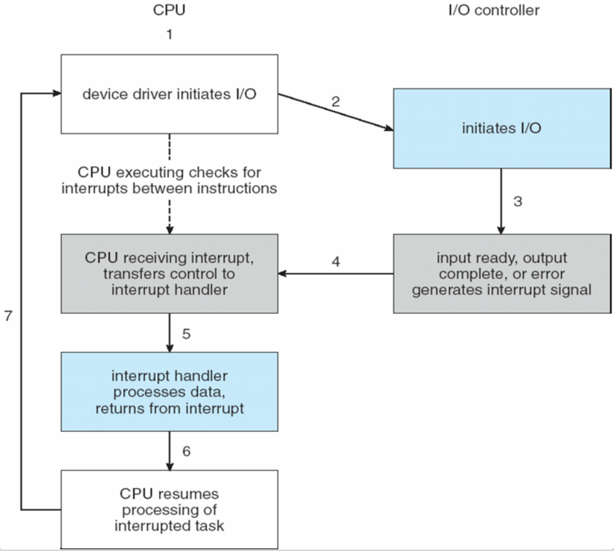
Techniques for I/O-Management

- Programmed I/O
  - Thread is busy-waiting for the I/O-operation to complete, processorcannot be used elsewhere
  - Kernel thread is Polling the state of an I/O device
    - command-ready
    - busy
    - Error
- Interrupt-driven I/O
  - I/O-command is issued
  - processor continues executing instructions
  - I/O-device sends an interrupt when I/O-command is done
- Direct Memory Access (DMA)
  - DMA module controls exchange of data between main memory and I/O device
  - processor interrupted after entire block has been transferred
  - bypasses CPU to transfer data directly between I/O device and memory

Intel Pentium Event-Vector Table

vector number	description
0	divide error
1	debug exception
2	null interrupt
3	breakpoint
4	INTO-detected overflow
5	bound range exception
6	invalid opcode
7	device not available
8	double fault
9	coprocessor segment overrun (reserved)
10	invalid task state segment
11	segment not present
12	stack fault
13	general protection
14	page fault
15	(Intel reserved, do not use)
16	floating-point error
17	alignment check
18	machine check
19 – 31	(Intel reserved, do not use)
32 – 255	maskable interrupts

Interrupt-Driven I/O Cycle



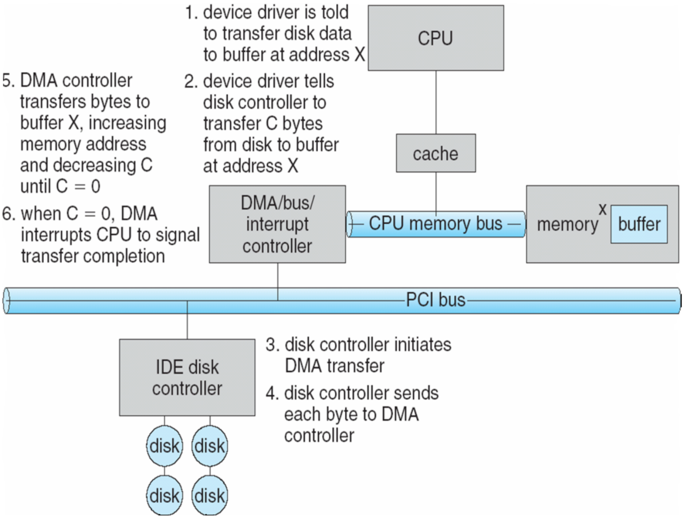
Steps for Handling an Interrupt (1)

1. Save registers no already saved by HW-interrupt mechanism
2. Set up context (address space) for interrupt service procedure
   - Typically, handler runs in the context of the currently running process/task ⇒ not that expensive context switch
3. Set up stack for interrupt service procedure
   - Handler usually runs on the kernel stack of the current process/kernel-level thread
   - Handler cannot block, otherwise the unlucky interrupted process/kernel-thread would also be blocked, might lead to starvation or even to a deadlock
4. Acknowledge/mask interrupt controller, thus re-enable other interrupts

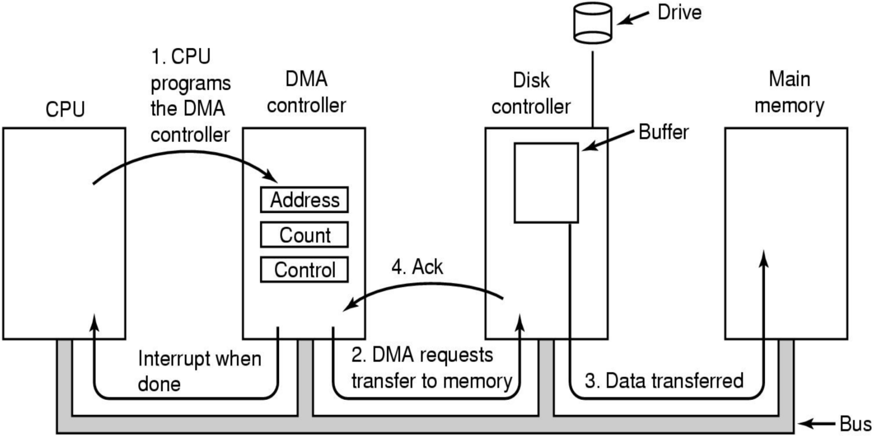
Steps for Handling an Interrupt (2)

5. Run interrupt service procedure
   - Acknowledge interrupt at device level
   - Figures out what caused the interrupt, e.g.
     - Received a network packet
     - Disk read has properly finished, . . .
   - If needed, it signals the blocked device driver
6. In some cases, we have to wake up a higher priority process/kernel level thread
   - Potentially schedule another process/kernel-level thread
   - Set up MMU context for process to run next
7. Load new/original process' registers
8. Return from Interrupt, start running new/original process

Six Step Process to Perform DMA Transfer

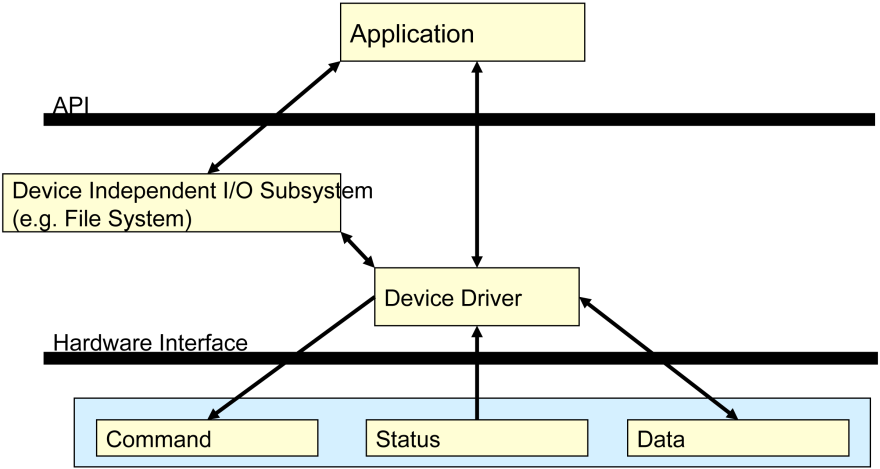


DMA Transfer with Fly-By Mode



- Word Mode ($\rightarrow$ cycle stealing)
- Burst Mode

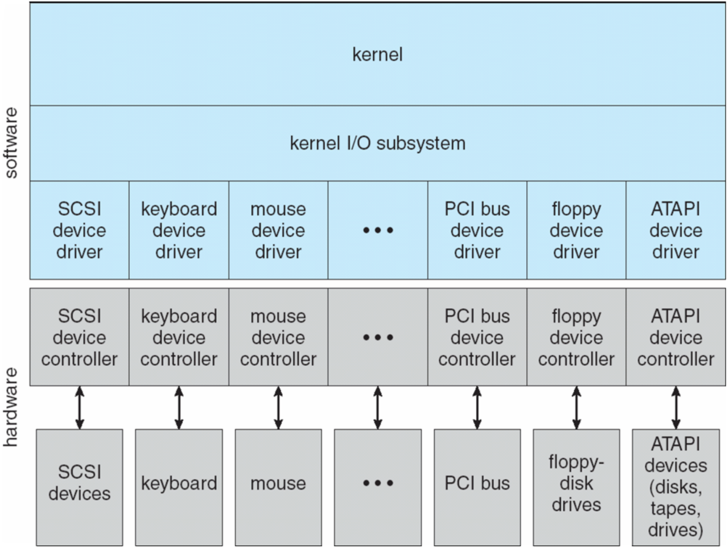
I/O System Organization



Application I/O Interface

- I/O system calls encapsulate device behaviors in generic classes
- Device-driver layer hides differences among I/O controllers from kernel
- Devices vary in many dimensions
  - **Character-stream** or **block**
  - **Sequential or random-access**
  - **Sharable or dedicated**
  - **Speed of operation**
  - **read-write, read only,** or **write only**

A Kernel I/O Structure



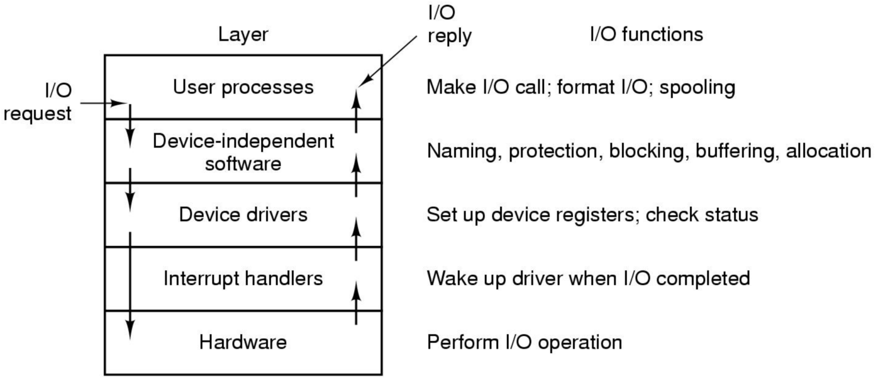
Kernel I/O Subsystem (1)

- Scheduling
  - Some I/O request ordering via per-device queue
  - Some OSs try fairness
- Buffering – store data in memory while transferring between devices
  - To cope with device speed mismatch
  - To cope with device transfer size mismatch
  - To maintain “copy semantics”
- Error handling
  - OS can recover from disk read, device unavailable, transient write failures
  - Most return an error number or code when I/O request fails
  - System error logs hold problem reports

Kernel I/O Subsystem (2)

- Protection
  - User process may accidentally or purposefully attempt to disrupt normal operation via illegal I/O instructions
  - I/O must be performed via system calls
    - Memory-mapped and I/O port memory locations must be protected too
- Spooling
  - Hold output for a device, if device can serve only one request at a time (i.e. printing)
- Device reservation – provides exclusive access to a device
  - System calls for allocation and deallocation
  - Watch out for deadlock

I/O Software Summary



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

Device-Independent I/O Software

- There is some commonality between drivers of similar classed ⇒
  - Divide I/O software into device-dependent and device independent I/O software, e.g.
    - Buffer or buffer-cache management, i.e. provide a device-independent block size
    - Allocating and releasing dedicate devices
    - Error reporting to upper levels, i.e. all errors the driver cannot resolve
  - Uniform device interface for kernel code
    - Allows different devices to be used in the same way, e.g. no need to rewrite your file-system when you are switching from IDE to SCSI or even to RAM disks
    - Allows internal changes of drivers without fearing of breaking kernel code
  - Uniform kernel interface for device code
    - Drivers use a defined interface to kernel service, e.g. `kmalloc`, install IRQ handler, etc.
    - Allows kernel to evolve without breaking device drivers

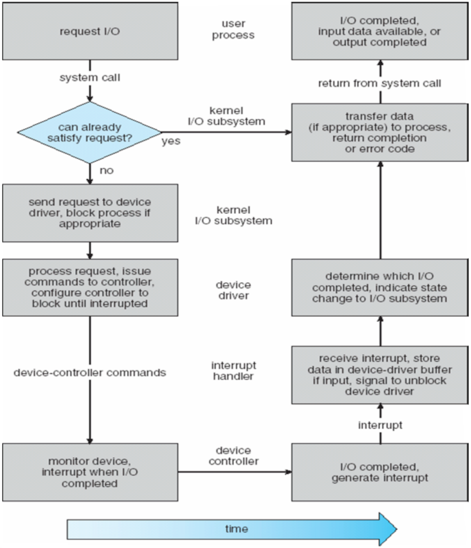
Device Driver

- Drivers classified into similar categories
  - Block devices and
  - Character (stream of data) devices
- OS defines standard (internal) interface to the different classes of device
  - Device drivers job
    - Translate user request through device-independent standard interface, (e.g. `open`, `read`, ..., `close`) into appropriate sequence of device or controller commands (register manipulation)
    - Initialize HW at boot time
    - Shut down HW

Device Driver

- After issue the command to the device, device either
  - completes immediately and the driver simply returns to the caller or it
  - processes request and the driver usually blocks waiting for an I/O (complete) interrupt signal
- 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 sync primitives

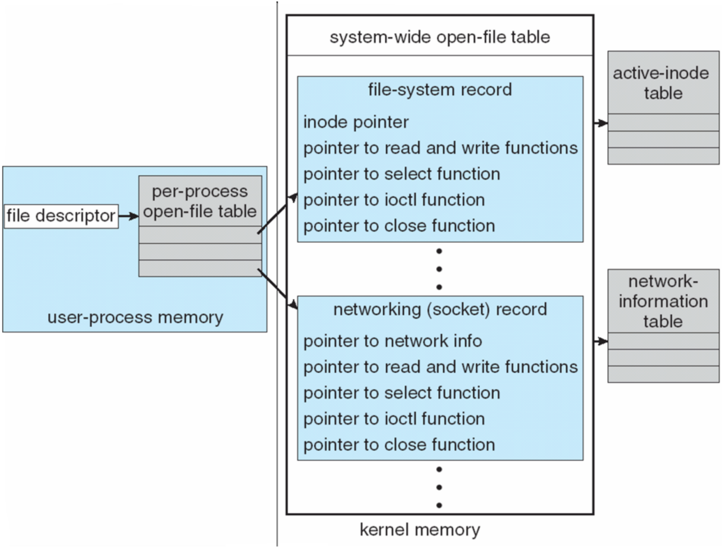
Life Cycle of an I/O Request



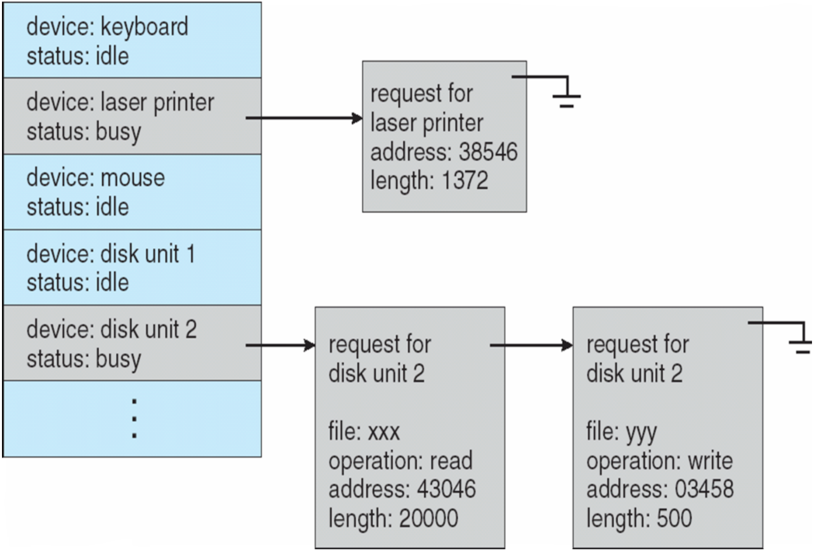
Kernel Data Structures

- Kernel keeps state info for I/O components, including open file tables, network connections, character device state
- Many, many complex data structures to track buffers, memory allocation, “dirty” blocks
- Some use object-oriented methods and message passing to implement I/O

UNIX I/O Kernel Structure



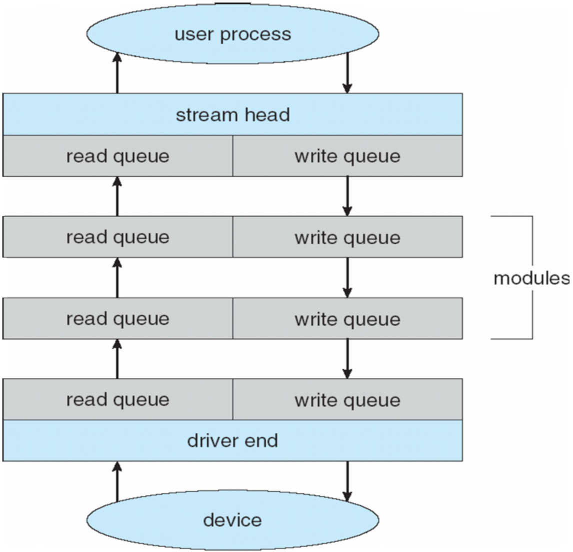
Device-status Table



STREAMS (e.g., in SVR4)

- **STREAM** – a full-duplex communication channel between a user-level process and a device in UNIX System V and beyond
- A STREAM consists of:
  - STREAM head interfaces with the user process
  - driver end interfaces with the device
  - zero or more STREAM modules between them
- Each module contains a **read queue** and a **write queue**
- Message passing is used to communicate between queues

The STREAMS Structure



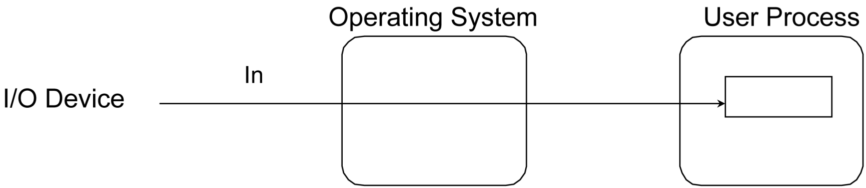
I/O Buffering

- Reasons for buffering
  - Otherwise threads must wait for I/O to complete before proceeding
  - Pages must remain in main memory during physical I/O
- Block-oriented
  - information is stored in fixed sized blocks
  - transfers are made a block at a time
  - used for disks and tapes
- Stream-oriented
  - transfer information as a stream of bytes
  - used for terminals, printers, communication ports, mouse and most other devices that are not secondary storage

No Buffering

- Process reads/writes a device a byte/word at a time
  - Each individual system call adds significant overhead
  - Process must wait until every I/O is complete
  - Blocking/Interrupt handling/unblocking adds to overhead
  - Many short CPU phases are inefficient, because
    - overhead induced by thread_switch
    - poor cache and TLB usage

User Level Buffering (1)



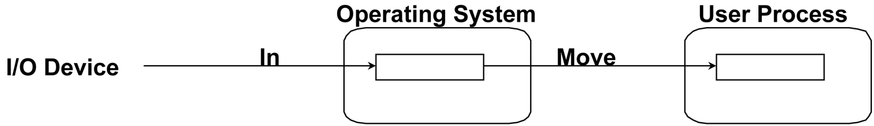
No buffering in OS

- Task specifies a memory buffer that incoming data is placed in until it fills
  - Filling can be done by interrupt service routine
  - Only one system_call and block/unblock per data buffer
    - More efficient than “NO BUFFERING”

User Level Buffering (2)

- Issues
  - *What happens if buffer is currently paged out to disk?*
    - You may loose data while buffer is paged in
    - You could lock/pin this buffer (needed for DMA), however, you have to trust the application programmer, that she/he is not starting a denial of service attack
  - *Additional problems with writing?*
    - *When is the buffer available for re-use?*

Single Buffer (1)



Single buffering

- 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
- OS keeps track of assignment of system buffers to user processes

Single Buffer (2)

- Stream-oriented
  - Buffer is an input line at time with carriage return signaling the end of the line
- Block-oriented
  - Input transfers made to system buffer
  - Buffer moved to user space when needed
  - Another block is read into system buffer

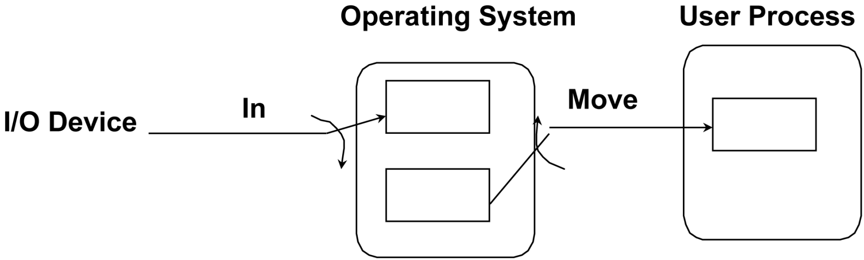
Single Buffer Speed Up

- Performance Model:
  - $T =$ transfer time from device
  - $C =$ copying time from system- to user-buffer
  - $P =$ processing time of complete buffer content
  - Processing and transfer can be done in parallel
  - Potential speed up with single buffering:

$$\frac{T + P}{max\{T, P\} + C}$$

- *What happens if system buffer is full, user buffer is swapped out, and more data is received?*
  - *Loose characters or drop network packets*

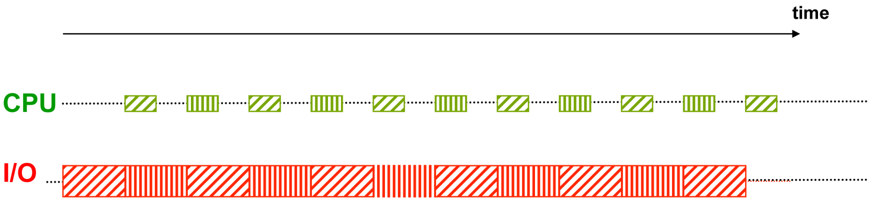
Double Buffer



- Use 2 system buffers instead of 1 (per user process)
- User process can write to or read from one buffer while the OS empties or fills the other buffer
- Speed up with double buffering:

$$\frac{T + P}{max\{T, P + C\}}$$

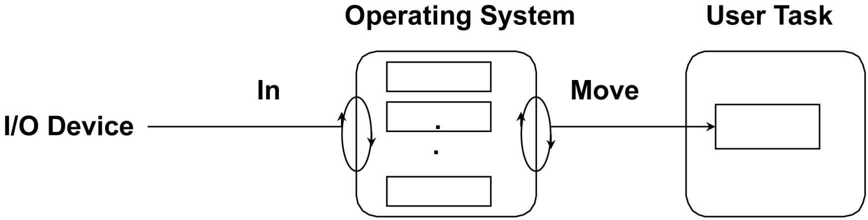
Timing Diagram for Double Buffering



Analysis: The slower I/O-device is busy the whole input-period, thus additional buffers are not needed (in this case).

Circular Buffering

- Double buffering may be insufficient for really bursty traffic situations:
  - Many writes between long periods of computations
  - Long periods of computations while receiving data
  - Might want to read ahead more than just a single block from disk



- Single-, double-, and circular-buffering are all bounded

→ Buffer producer-/consumer problems