Module 12: I/O Systems

- I/O Hardware
- Application I/O Interface
- Kernel I/O Subsystem
- Transforming I/O Requests to Hardware Operations
- Performance
I/O Hardware

- Incredible variety of I/O devices
- Common concepts
  - Port
  - Bus (daisy chain or shared direct access)
  - Controller (host adapter)
- I/O instructions control devices
- Devices have addresses, used by
  - Direct I/O instructions
  - Memory-mapped I/O
Polling

- Determines state of device
  - command-ready
  - busy
  - error
- Busy-wait cycle to wait for I/O from device
Interrupts

- CPU Interrupt request line triggered by I/O device
- Interrupt handler receives interrupts
- Maskable to ignore or delay some interrupts
- Interrupt vector to dispatch interrupt to correct handler
  - Based on priority
  - Some unmaskable
- Interrupt mechanism also used for exceptions
Interrupt-drive I/O Cycle

1. Device driver initiates I/O
2. Initiates I/O
3. Input ready, output complete, or error
4. Generates interrupt signal
5. CPU receiving interrupt, transfers control to interrupt handler
6. Interrupt handler processes data, returns from interrupt
7. CPU resumes processing of interrupted task

CPU executes checks for interrupts between instructions.
Direct Memory Access

- Used to avoid programmed I/O for large data movement
- Requires DMA controller
- Bypasses CPU to transfer data directly between I/O device and memory
Six step process to perform DMA transfer

1. Device driver is told to transfer disk data to buffer at address X
2. Device driver tells disk controller to transfer C bytes from disk to buffer at address X
3. Disk controller initiates DMA transfer
4. Disk controller sends each byte to DMA controller
5. DMA controller transfers bytes to buffer X, increasing memory address and decreasing C until C = 0
6. When C = 0, DMA interrupts CPU to signal transfer completion

IDE disk controller

CPU

Cache

Memory

Buffer

PCI bus

CPU memory bus
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
  - Synchronous or asynchronous
  - Sharable or dedicated
  - Speed of operation
  - read-write, read only, or write only
Block and Character Devices

- 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

- Varying enough from block and character to have own interface
- Unix and Windows/NT include socket interface
  - Separates network protocol from network operations
  - Includes `select` functionality
- Approaches vary widely (pipes, FIFOs, streams, queues, mailboxes)
Clocks and Timers

- Provide current time, elapsed time, timer
- It programmable interval timer used for timings, periodic interrupts
- ioctl (on UNIX) covers odd aspects of I/O such as clocks and timers
Blocking and Nonblocking I/O

- **Blocking** - process suspended until I/O completed
  - Easy to use and understand
  - Insufficient for some needs
- **Nonblocking** - I/O call returns as much as available
  - User interface, data copy (buffered I/O)
  - Implemented via multi-threading
  - Returns quickly with count of bytes read or written
- **Asynchronous** - process runs while I/O executes
  - Difficult to use
  - I/O subsystem signals process when I/O completed
Kernel I/O Subsystem

- 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”
Kernel I/O Subsystem

- Caching - fast memory holding copy of data
  - Always just a copy
  - Key to performance
- Spooling - holds 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
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 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
Consider reading a file from disk for a process

- Determine device holding file
- Translate name to device representation
- Physically read data from disk into buffer
- Make data available to requesting process
- Return control to process
Life Cycle of an I/O Request

1. **request I/O**
   - system call
   - user process
   - can already satisfy request?
     - no
     - yes
     - kernel I/O subsystem

2. **send request to device driver, block process if appropriate**
   - kernel I/O subsystem

3. **process request, issue commands to controller, configure controller to block until interrupted**
   - device controller commands
   - device driver
   - interrupt handler
   - keyboard device controller

4. **monitor device, interrupt when I/O completed**
   - time

5. **I/O completed, input data available, or output completed**
   - transfer data (if appropriate) to process, return completion or error code
   - determine which I/O completed, indicate state change to I/O subsystem
   - receive interrupt, store data in device driver buffer if input, signal to unblock device driver

6. **I/O completed, generate interrupt**
   - interrupt
   - return from system call

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Performance

- I/O a major factor in system performance
  - Demands CPU to execute device driver, kernel I/O code
  - Context switches due to interrupts
  - Data copying
  - Network traffic especially stressful
Intercomputer communications

Sending system:
- Character typed by user process
- Hardware generates interrupt
- Interrupt handled
- Device driver
- Network adapter
- System call completes

Receiving system:
- Network packet received
- Network adapter
- Device driver
- Kernel
- Network subdaemon
- Context switch
- Kernel

Interaction:
- Network packet transferred between systems
- Interrupts and context switches

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Improving Performance

- Reduce number of context switches
- Reduce data copying
- Reduce interrupts by using large transfers, smart controllers, polling
- Use DMA
- Balance CPU, memory, bus, and I/O performance for highest throughput