Chapter 13: I/O Systems
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- I/O Hardware
- Application I/O Interface
- Kernel I/O Subsystem
- Transforming I/O Requests to Hardware Operations
- Streams
- 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
A Typical PC Bus Structure
## Device I/O Port Locations on PCs (partial)

<table>
<thead>
<tr>
<th>I/O address range (hexadecimal)</th>
<th>device</th>
</tr>
</thead>
<tbody>
<tr>
<td>000–00F</td>
<td>DMA controller</td>
</tr>
<tr>
<td>020–021</td>
<td>interrupt controller</td>
</tr>
<tr>
<td>040–043</td>
<td>timer</td>
</tr>
<tr>
<td>200–20F</td>
<td>game controller</td>
</tr>
<tr>
<td>2F8–2FF</td>
<td>serial port (secondary)</td>
</tr>
<tr>
<td>320–32F</td>
<td>hard-disk controller</td>
</tr>
<tr>
<td>378–37F</td>
<td>parallel port</td>
</tr>
<tr>
<td>3D0–3DF</td>
<td>graphics controller</td>
</tr>
<tr>
<td>3F0–3F7</td>
<td>diskette-drive controller</td>
</tr>
<tr>
<td>3F8–3FF</td>
<td>serial port (primary)</td>
</tr>
</tbody>
</table>
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 **nonmaskable**
- Interrupt mechanism also used for exceptions
Interrupt-Driven I/O Cycle

1. CPU
   - device driver initiates I/O
   - CPU executing checks for interrupts between instructions
   - CPU receiving interrupt, transfers control to interrupt handler
   - interrupt handler processes data, returns from interrupt
   - CPU resumes processing of interrupted task

2. I/O controller
   - initiates I/O

3. input ready, output complete, or error generates interrupt signal

4. CPU resumes processing of interrupted task
## Intel Pentium Processor Event-Vector Table

<table>
<thead>
<tr>
<th>vector number</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>divide error</td>
</tr>
<tr>
<td>1</td>
<td>debug exception</td>
</tr>
<tr>
<td>2</td>
<td>null interrupt</td>
</tr>
<tr>
<td>3</td>
<td>breakpoint</td>
</tr>
<tr>
<td>4</td>
<td>INTO-detected overflow</td>
</tr>
<tr>
<td>5</td>
<td>bound range exception</td>
</tr>
<tr>
<td>6</td>
<td>invalid opcode</td>
</tr>
<tr>
<td>7</td>
<td>device not available</td>
</tr>
<tr>
<td>8</td>
<td>double fault</td>
</tr>
<tr>
<td>9</td>
<td>coprocessor segment overrun (reserved)</td>
</tr>
<tr>
<td>10</td>
<td>invalid task state segment</td>
</tr>
<tr>
<td>11</td>
<td>segment not present</td>
</tr>
<tr>
<td>12</td>
<td>stack fault</td>
</tr>
<tr>
<td>13</td>
<td>general protection</td>
</tr>
<tr>
<td>14</td>
<td>page fault</td>
</tr>
<tr>
<td>15</td>
<td>(Intel reserved, do not use)</td>
</tr>
<tr>
<td>16</td>
<td>floating-point error</td>
</tr>
<tr>
<td>17</td>
<td>alignment check</td>
</tr>
<tr>
<td>18</td>
<td>machine check</td>
</tr>
<tr>
<td>19–31</td>
<td>(Intel reserved, do not use)</td>
</tr>
<tr>
<td>32–255</td>
<td>maskable interrupts</td>
</tr>
</tbody>
</table>
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. The device driver is told to transfer disk data to buffer at address X.
2. The device driver tells the disk controller to transfer C bytes from disk to buffer at address X.
3. The disk controller initiates the DMA transfer.
4. The disk controller sends each byte to the DMA controller.
5. The DMA controller transfers bytes to buffer X, increasing memory address and decreasing C until C = 0.
6. When C = 0, DMA interrupts the CPU to signal transfer completion.
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

<table>
<thead>
<tr>
<th>hardware</th>
<th></th>
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<tbody>
<tr>
<td>SCSI devices</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PCI bus</td>
<td></td>
<td>floppy disk drives</td>
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<tr>
<td>keyboard</td>
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<td></td>
<td></td>
<td>device controller</td>
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<tr>
<td>mouse</td>
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<td></td>
<td></td>
<td></td>
<td>device controller</td>
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<td></td>
<td>device controller</td>
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</table>

<table>
<thead>
<tr>
<th>software</th>
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<tbody>
<tr>
<td>kernel I/O subsystem</td>
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<td></td>
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</tr>
<tr>
<td>SCSI device driver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PCI bus device driver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>keyboard device driver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>floppy device driver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mouse device driver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ATAPI device driver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| kernel             |   |   |   |   |   |   |   |   |   |   |   |
## Characteristics of I/O Devices

<table>
<thead>
<tr>
<th>aspect</th>
<th>variation</th>
<th>example</th>
</tr>
</thead>
<tbody>
<tr>
<td>data-transfer mode</td>
<td>character block</td>
<td>terminal disk</td>
</tr>
<tr>
<td>access method</td>
<td>sequential</td>
<td>modem</td>
</tr>
<tr>
<td></td>
<td>random</td>
<td>CD-ROM</td>
</tr>
<tr>
<td>transfer schedule</td>
<td>synchronous</td>
<td>tape</td>
</tr>
<tr>
<td></td>
<td>asynchronous</td>
<td>keyboard</td>
</tr>
<tr>
<td>sharing</td>
<td>dedicated</td>
<td>tape</td>
</tr>
<tr>
<td></td>
<td>sharable</td>
<td>keyboard</td>
</tr>
<tr>
<td>device speed</td>
<td>latency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>seek time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>transfer rate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>delay between operations</td>
<td></td>
</tr>
<tr>
<td>I/O direction</td>
<td>read only</td>
<td>CD-ROM</td>
</tr>
<tr>
<td></td>
<td>write only</td>
<td>graphics controller</td>
</tr>
<tr>
<td></td>
<td>read–write</td>
<td>disk</td>
</tr>
</tbody>
</table>
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/9x/2000 include socket interface
  ◆ Separates network protocol from network operation
  ◆ Includes select functionality

■ Approaches vary widely (pipes, FIFOs, streams, queues, mailboxes)
Clocks and Timers

- Provide current time, elapsed time, timer

- **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
Blocking and Nonblocking I/O

- **Asynchronous** - process runs while I/O executes
  - Difficult to use
  - I/O subsystem signals process when I/O completed
Two I/O Methods

(a) Synchronous

(b) Asynchronous
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”
## Device-status Table

<table>
<thead>
<tr>
<th>Device</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keyboard</td>
<td>idle</td>
</tr>
<tr>
<td>Laser Printer</td>
<td>busy</td>
</tr>
<tr>
<td>Mouse</td>
<td>idle</td>
</tr>
<tr>
<td>Disk Unit 1</td>
<td>idle</td>
</tr>
<tr>
<td>Disk Unit 2</td>
<td>busy</td>
</tr>
</tbody>
</table>

- **Request for Laser Printer**
  - Address: 38546
  - Length: 1372

- **Request for Disk Unit 2**
  - File: xxx
  - Operation: read
  - Address: 43046
  - Length: 20000

- **Request for Disk Unit 2**
  - File: yyy
  - Operation: write
  - Address: 03458
  - Length: 500
Kernel I/O Subsystem

- **Caching** - fast memory holding copy of data
  - Always just a copy
  - Key to performance

- **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
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
I/O Protection

- User process may accidentally or purposefully attempt to disrupt normal operation via illegal I/O instructions
  - All I/O instructions defined to be privileged
  - I/O must be performed via system calls
    - Memory-mapped and I/O port memory locations must be protected too
Use of a System Call to Perform I/O

1. Trap to monitor
2. Perform I/O
3. Return to user
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

- 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
  - 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

- per-process open-file table
- file descriptor
- user-process memory
- kernel memory
- active_inode table
- network_information table
I/O Requests to Hardware Operations

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

2. can already satisfy request?
   - yes
     - user process
     - I/O completed, input data available, or output completed
     - return from system call
   - no
     - 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

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

5. receive interrupt, store data in device-driver buffer if input, signal to unblock device driver
   - interrupt handler

6. determine which I/O completed, indicate state change to I/O subsystem
   - device driver

7. I/O completed, generate interrupt
   - device controller

8. time

College of Software Engineering, Southeast University
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
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
Device-Functionality Progression

- Increased time (generations)
- Increased efficiency
- Increased development cost
- Increased abstraction

- New algorithm
- Application code
- Kernel code
- Device-driver code
- Device-controller code (hardware)
- Device code (hardware)

Increased flexibility