CSMC 412
Operating Systems
Prof. Ashok K Agrawala

© 2004 Ashok Agrawala
Set 13

I/O Systems
- 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>2FB-2FF</td>
<td>serial port (secondary)</td>
</tr>
<tr>
<td>320-32F</td>
<td>hard-disk controller</td>
</tr>
<tr>
<td>379-37F</td>
<td>parallel port</td>
</tr>
<tr>
<td>3D0-3DF</td>
<td>graphics controller</td>
</tr>
<tr>
<td>3FD-3F7</td>
<td>diskette-drive controller</td>
</tr>
<tr>
<td>3FB-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 unmaskable
- 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
2. CPU receiving interrupt, transfers control to interrupt handler
3. CPU resumes processing of interrupted task
4. I/O controller
   - Input ready, output complete, or error generates interrupt signal
   - Initiates I/O
   - 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 opcodes</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 overun (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>19D31</td>
<td>(Intel reserved, do not use)</td>
</tr>
<tr>
<td>3292555</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. 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 interrupt signal to 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

A diagram illustrating the software and hardware layers of a kernel I/O structure, including:
- SCSI device
- keyboard device
- mouse device
- PCI bus device
- floppy device
- ATAPI device

### 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</td>
<td>terminal</td>
</tr>
<tr>
<td></td>
<td>block</td>
<td>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</td>
<td></td>
</tr>
<tr>
<td></td>
<td>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</td>
</tr>
<tr>
<td></td>
<td>read/write</td>
<td>controller</td>
</tr>
<tr>
<td></td>
<td></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/9i/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
- If programmable interval time 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”

---

Sun Enterprise 6000 Device-Transfer Rates
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
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
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
STREAMS

- STREAM – a full-duplex communication channel between a user-level process and a device

- 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
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
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 efficiency
- Increased development cost
- Increased abstraction
- Increased flexibility