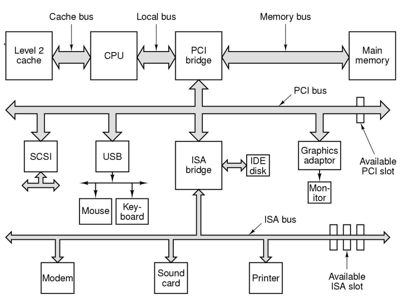
Chapter 13: I/O Systems

- 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)

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)

Example

```
cat /proc/ioports
0000-001f : dma1
0020-003f : pic1
0040-005f : timer
0060-006f : keyboard
0070-007f : rtc
0080-008f : dma page reg
00a0-00bf : pic2
00c0-00df : dma2
00f0-00ff : fpu
0170-0177 : ide1
02f8-02ff : serial(auto)
0376-0376 : ide1
03c0-03df : vga+
03f8-03ff : serial(auto)
```


Example, continued

```
0cf8-0cff : PCI conf1
cd0-ccdf : Intel Corporation 82801AA SMBus
d000-efff : PCI Bus #02
  dc80-dcff : 3Com Corporation 3c905C-TX [Fast Etherlink]
    dc80-dcff : eth0
  e000-efff : PCI Bus #03
    e800-e8ff : Adaptec 7899P (#2)
      e800-e8fe : aic7xxx
    ec00-ecff : Adaptec 7899P
      ec00-ecfe : aic7xxx
ff80-ff9f : Intel Corporation 82801AA USB
  ff80-ff9f : usb-uhci
ffa0-ffaf : Intel Corporation 82801AA IDE
  ffa8-ffaf : ide1
```

I/O Space vs. Memory Space

- I/O space is accessed with I/O instructions:
  - outb %al,$18
- Memory space is accessed with memory instructions:
  movl $0, (%edx)
  movl $3, %eax

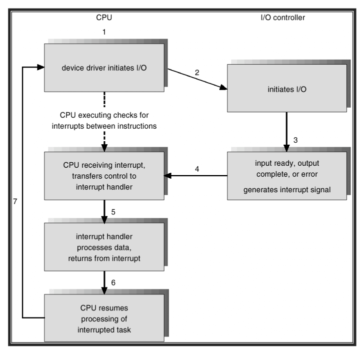
Polling

- 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



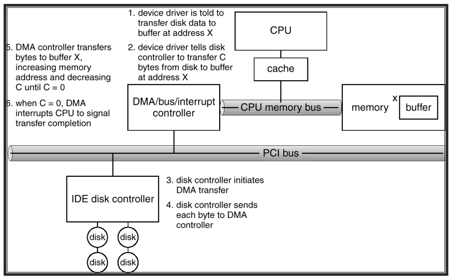
Intel Pentium Processor Event-Vector Table

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
19Ð31	(Intel reserved, do not use)
32Ð255	maskable interrupts

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



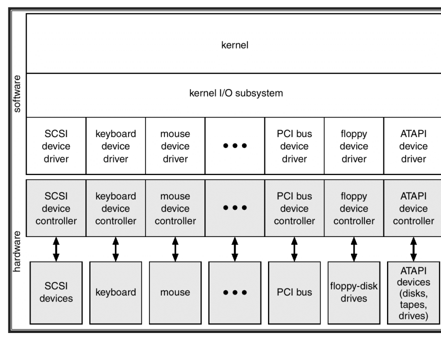
Why is DMA faster?

- Claim: DMA will be able to move data at least twice as fast (and probably three times as fast) as using the CPU
- Why?

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



Characteristics of I/O Devices

aspect	variation	example
data-transfer mode	character block	terminal disk
access method	sequential random	modem CD-ROM
transfer schedule	synchronous asynchronous	tape keyboard
sharing	dedicated sharable	tape keyboard
device speed	latency seek time transfer rate delay between operations	
I/O direction	read only write only readÐwrite	CD-ROM graphics controller disk

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/9*i*/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

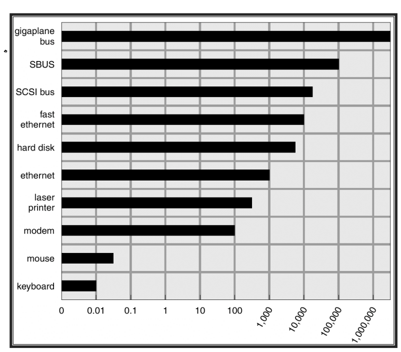
Blocking and Nonblocking I/O

- 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

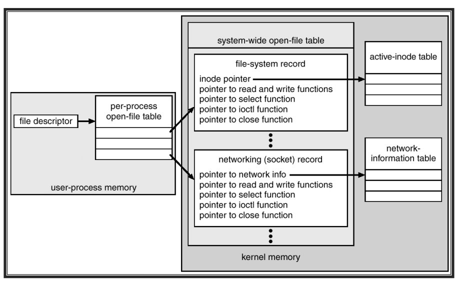
Error Handling

- 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

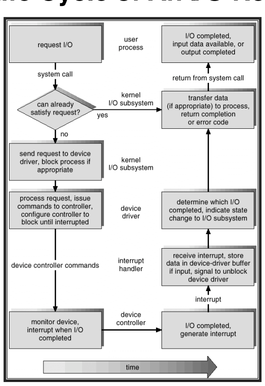
UNIX I/O Kernel Structure



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

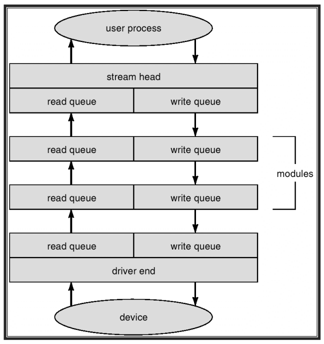
Life Cycle of An I/O Request



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

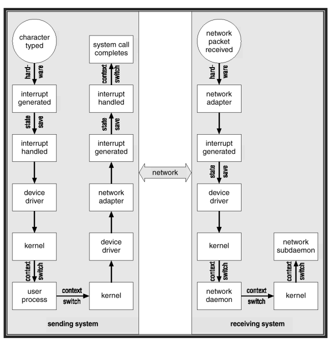
The STREAMS Structure



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