I/O Hardware

- Wide variety of ‘devices’ which interact with the computer via I/O:
  - **Human readable**: graphical displays, keyboard, mouse, printers
  - **Machine readable**: disks, tapes, CD, sensors
  - **Communications**: modems, network interfaces

- They differ significantly from one another with regard to:
  - Data rate
  - Complexity of control
  - Unit of transfer
  - Direction of transfer
  - Data representation
  - Error handling

⇒ hard to present a uniform I/O system which masks all complexity

**I/O subsystem is generally the ‘messiest’ part of OS.**
• Programs access virtual devices:
  – terminal streams not terminals
  – windows not frame buffer
  – event stream not raw mouse
  – files not disk blocks
  – printer spooler not parallel port
  – transport protocols not raw ethernet

• OS deals with processor–device interface:
  – I/O instructions versus memory mapped
  – I/O hardware type (e.g. 10’s of serial chips)
  – polled versus interrupt driven
  – processor interrupt mechanism

Polled Mode I/O

• Consider a simple device with three registers: status, data and command.
• (Host can read and write these via bus)
• Then polled mode operation works as follows:
  – Host repeatedly reads device_busy until clear.
  – Host sets e.g. write bit in command register, and puts data into data register.
  – Host sets command_ready bit in status register.
  – Device sees command_ready and sets device_busy.
  – Device performs write operation.
  – Device clears command_ready & then device_busy.
• What’s the problem here?
Interrupts Revisited

Recall: to handle mismatch between CPU and device speeds, processors provide an interrupt mechanism:

- at end of each instruction, processor checks interrupt line(s) for pending interrupt
- if line is asserted then processor:
  - saves program counter,
  - saves processor status,
  - changes processor mode, and
  - jump to a well known address (or its contents)
- after interrupt-handling routine is finished, can use e.g. the `rti` instruction to resume where we left off.

Some more complex processors provide:

- multiple levels of interrupts
- hardware vectoring of interrupts
- mode dependent registers

Interrupt-Driven I/O

Can split implementation into low-level interrupt handler plus per-device interrupt service routine:

- interrupt handler (processor-dependent) may:
  - save more registers
  - establish a language environment (e.g. a C run-time stack)
  - demultiplex interrupt in software.
  - invoke appropriate interrupt service routine (ISR)
- Then interrupt service routine (device-specific but not processor-specific) will:
  1. for programmed I/O device:
     - transfer data.
     - clear interrupt (sometimes a side effect of tx).
  1. for DMA device:
     - acknowledge transfer.
  2. request another transfer if there are any more I/O requests pending on device.
  3. signal any waiting processes.
  4. enter scheduler or return.

Question: who is scheduling who?
Device Classes

Homogenising device API completely not possible

⇒ OS generally splits devices into four classes:

1. **Block devices** (e.g. disk drives, CD):
   - commands include read, write, seek
   - raw I/O or file-system access
   - memory-mapped file access possible

2. **Character devices** (e.g. keyboards, mice, serial ports):
   - commands include get, put
   - libraries layered on top to allow line editing

3. **Network Devices**
   - varying enough from block and character to have own interface
   - Unix and Windows/NT use socket interface

4. **Miscellaneous** (e.g. clocks and timers)
   - provide current time, elapsed time, timer
   - ioctl (on UNIX) covers odd aspects of I/O such as clocks and timers.

I/O Buffering

- Buffering: OS stores (its own copy of) data in memory while transferring to or from devices
  - to cope with device speed mismatch
  - to cope with device transfer size mismatch
  - to maintain “copy semantics”

- OS can use various kinds of buffering:
  1. single buffering — OS assigns a system buffer to the user request
  2. double buffering — process consumes from one buffer while system fills the next
  3. circular buffers — most useful for bursty I/O

- Many aspects of buffering dictated by device type:
  - character devices ⇒ line probably sufficient.
  - network devices ⇒ bursty (time & space).
  - block devices ⇒ lots of fixed size transfers.
  - (last usually major user of buffer memory)
Blocking v. Nonblocking I/O

From the programmer’s point of view, I/O system calls exhibit one of three kinds of behaviour:

1. **Blocking**: process suspended until I/O completed
   - easy to use and understand.
   - insufficient for some needs.

2. **Nonblocking**: I/O call returns as much as available
   - returns almost immediately with count of bytes read or written (possibly 0).
   - can be used by e.g. user interface code.
   - essentially application-level “pollled I/O”.

3. **Asynchronous**: process continues to run while I/O executes
   - I/O subsystem explicitly signals process when its I/O request has completed.
   - most flexible (and potentially efficient).
   - . . . but also most difficult to use.

Most systems provide both blocking and non-blocking I/O interfaces; modern systems (e.g. NT, Linux) also support asynchronous I/O, but used infrequently.

Other I/O Issues

- **Caching**: fast memory holding copy of data
  - can work with both reads and writes
  - key to I/O performance

- **Scheduling**:
  - e.g. ordering I/O requests via per-device queue
  - some operating systems try fairness. . .

- **Spooling**: queue output for a device
  - useful for “single user” devices which can serve only one request at a time (e.g. printer)

- **Device reservation**:
  - system calls for acquiring or releasing exclusive access to a device (careful!)

- **Error handling**:
  - e.g. recover from disk read, device unavailable, transient write failures, etc.
  - most I/O system calls return an error number or code when an I/O request fails
  - system error logs hold problem reports.
I/O and Performance

- I/O is a major factor in overall system performance
  - demands CPU to execute device driver, kernel I/O code, etc.
  - context switches due to interrupts
  - data copying, buffering, etc
  - (network traffic especially stressful)

- Improving performance:
  - reduce number of context switches
  - reduce data copying
  - reduce # interrupts by using large transfers, smart controllers, adaptive polling (e.g. Linux NAPI)
  - use DMA where possible
  - balance CPU, memory, bus and I/O for best throughput.

**Improving I/O performance is a major remaining OS challenge**

File Management

Filing systems have two main components:

1. **Directory Service**
   - maps from names to file identifiers.
   - handles access & existence control

2. **Storage Service**
   - provides mechanism to store data on disk
   - includes means to implement directory service
File Concept

What is a file?

• Basic abstraction for non-volatile storage.
• Typically comprises a single contiguous logical address space.
• Internal structure:
  1. None (e.g. sequence of words, bytes)
  2. Simple record structures
     – lines
     – fixed length
     – variable length
  3. Complex structures
     – formatted document
     – relocatable object file
• Can simulate 2,3 with byte sequence by inserting appropriate control characters.
• All a question of who decides:
     – operating system
     – program(mer).

Naming Files

Files usually have at least two kinds of ‘name’:

1. system file identifier (SFID):
   • (typically) a unique integer value associated with a given file
   • SFIDs are the names used within the filing system itself

2. human-readable name, e.g. hello.java
   • what users like to use
   • mapping from human name to SFID is held in a directory, e.g.

<table>
<thead>
<tr>
<th>Name</th>
<th>SFID</th>
</tr>
</thead>
<tbody>
<tr>
<td>hello.java</td>
<td>12353</td>
</tr>
<tr>
<td>Makefile</td>
<td>23812</td>
</tr>
<tr>
<td>README</td>
<td>9742</td>
</tr>
</tbody>
</table>

• directories also non-volatile ⇒ must be stored on disk along with files.

3. Frequently also get user file identifier (UFID)
   • used to identify open files (see later)
As well as their contents and their name(s), files can have other attributes, e.g.

- **Location**: pointer to file location on device
- **Size**: current file size
- **Type**: needed if system supports different types
- **Protection**: controls who can read, write, etc.
- **Time, date, and user identification**: for protection, security and usage monitoring.

Together this information is called **meta-data**. It is contained in a **file control block**.

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**Directory Name Space (I)**

What are the requirements for our name space?

- **Efficiency**: locating a file quickly.
- **Naming**: user convenience
  - allow two (or more generally *N*) users to have the same name for different files
  - allow one file have several different names
- **Grouping**: logical grouping of files by properties (e.g. all Java programs, all games)

First attempts:

- **Single-level**: one directory shared between all users
  - naming problem
  - grouping problem
- **Two-level directory**: one directory per user
  - access via *pathname* (e.g. `bob:hello.java`)
  - can have same filename for different user
  - but still no grouping capability.
• Get more flexibility with a general hierarchy.
  – directories hold files or [further] directories
  – create/delete files relative to a given directory

• Human name is full path name, but can get long:
  e.g. /usr/groups/X11R5/src/mit/server/os/4.2bsd/utils.c
  – offer relative naming
  – login directory
  – current working directory

• What does it mean to delete a [sub]-directory?

Directory Name Space (III)

• Hierarchy good, but still only one name per file.
  ⇒ extend to directed acyclic graph (DAG) structure:
    – allow shared subdirectories and files.
    – can have multiple aliases for the same thing

• Problem: dangling references

• Solutions:
  – back-references (but require variable size records); or
  – reference counts.

• Problem: cycles...
• Directories are non-volatile ⇒ store as “files” on disk, each with own SFID.
• Must be different types of file (for traversal)
• Explicit directory operations include:
  – create directory
  – delete directory
  – list contents
  – select current working directory
  – insert an entry for a file (a “link”)

File Operations (I)

<table>
<thead>
<tr>
<th>UFID</th>
<th>SFID</th>
<th>File Control Block (Copy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23421</td>
<td>location on disk, size,...</td>
</tr>
<tr>
<td>2</td>
<td>3250</td>
<td>&quot;</td>
</tr>
<tr>
<td>3</td>
<td>10532</td>
<td>&quot;</td>
</tr>
<tr>
<td>4</td>
<td>7122</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

• Opening a file: UFID = open(<pathname>)
  1. directory service recursively searches for components of <pathname>
  2. if all goes well, eventually get SFID of file.
  3. copy file control block into memory.
  4. create new UFID and return to caller.
• Create a new file: UFID = create(<pathname>)
• Once have UFID can read, write, etc.
  – various modes (see next slide)
• Closing a file: status = close(UFID)
  1. copy [new] file control block back to disk.
  2. invalidate UFID
• Associate a cursor or file position with each open file (viz. UFID)
  – initialised at open time to refer to start of file.
• Basic operations: read next or write next, e.g.
  – read(UFID, buf, nbytes), or read(UFID, buf, nrecords)
• Sequential Access: above, plus rewind(UFID).
• Direct Access: read N or write N
  – allow “random” access to any part of file.
  – can implement with seek(UFID, pos)
• Other forms of data access possible, e.g.
  – append-only (may be faster)
  – indexed sequential access mode (ISAM)

Other Filing System Issues

• Access Control: file owner/creator should be able to control what can be done, and by whom.
  – normally a function of directory service ⇒ checks done at file open time
  – various types of access, e.g.
    * read, write, execute, (append?),
    * delete, list, rename
  – more advanced schemes possible (see later)
• Existence Control: what if a user deletes a file?
  – probably want to keep file in existence while there is a valid pathname referencing it
  – plus check entire FS periodically for garbage
  – existence control can also be a factor when a file is renamed/moved.
• Concurrency Control: need some form of locking to handle simultaneous access
  – may be mandatory or advisory
  – locks may be shared or exclusive
  – granularity may be file or subset