Operating System Design

Issues

• Efficiency
  – Most I/O devices slow compared to main memory (and the CPU)
  • Use of multiprogramming allows for some processes to be waiting on I/O while another process executes
  • Often I/O still cannot keep up with processor speed
  • Swapping may used to bring in additional Ready processes
  – More I/O operations

• Optimise I/O efficiency – especially Disk & Network I/O

Operating System Design

Issues

• The quest for generality/uniformity:
  – Ideally, handle all I/O devices in the same way
  • Both in the OS and in user applications
  – Problem:
    • Diversity of I/O devices
    • Especially, different access methods (random access versus stream based) as well as vastly different data rates.
    • Generality often compromises efficiency
  – Hide most of the details of device I/O in lower-level routines so that processes and upper levels see devices in general terms such as read, write, open, close.

I/O Software Layers

User-level I/O software

Device-independent operating system software

Device drivers

Interrupt handlers

Hardware

Layers of the I/O Software System

Interrupt Handlers

• Interrupt handlers are best “hidden”
  • Can execute at almost any time
    – Raise (complex) concurrency issues in the kernel
    – Have similar problems within applications if interrupts are propagated to user-level code (via signals, upcalls).
  – Generally, systems are structured such that drivers starting an I/O operations block until interrupts notify them of completion
    – Example dev_read() waits on semaphore that the interrupt handler signals.
  • Interrupt procedure does its task
    – then unblocks driver waiting on completion

Interrupt Handler Steps

• Steps must be performed in software upon occurrence of an interrupt
  – Save regs not already saved by hardware interrupt mechanism
  – (Optionally) set up context (address space) for interrupt service procedure
    • Typically, handler runs in the context of the currently running process
    – No expensive context switch
  – Set up stack for interrupt service procedure
    • Handler usually runs on the kernel stack of current process
    – Implies handler cannot block as the unlucky current process will also be blocked ⇒ might cause deadlock
  – Ack/Mask interrupt controller, reenable other interrupts
Interrupt Handler Steps

- Run interrupt service procedure
  - Acknowledges interrupt at device level
  - Figures out what caused the interrupt
    - Received a network packet, disk read finished, UART transmit queue empty
  - If needed, it signals blocked device driver
- In some cases, will have woken up a higher priority blocked thread
  - Choose newly woken thread to schedule next.
  - Set up MMU context for process to run next
- Load new/original process' registers
- Re-enable interrupt; Start running the new process

Device Drivers

- Logical position of device drivers is shown here
- Drivers (originally) compiled into the kernel
  - Including OS/161
  - Device installers were technicians
  - Number and types of devices rarely changed
- Nowadays they are dynamically loaded when needed
  - Linux modules
    - Typical users (device installers) can't build kernels
    - Number and types vary greatly
      - Even while OS is running (e.g., hotplug USB devices)

Device Drivers

- Drivers classified into similar categories
  - Block devices and character (stream of data) device
- OS defines a standard (internal) interface to the different classes of devices
- Device drivers job
  - Translate request through the device-independent standard interface (open, close, read, write) into appropriate sequence of commands (register manipulations) for the particular hardware
  - Initialise the hardware at boot time, and shut it down cleanly at shutdown

Device Driver

- After issuing the command to the device, the device either
  - Completes immediately and the driver simply returns to the caller
  - Or, device must process the request and the driver usually blocks waiting for an I/O complete interrupt.
- Drivers are reentrant as they can be called by another process while a process is already blocked in the driver.
  - Reentrant: Code that can be executed by more than one thread (or CPU) at the same time
  - Manages concurrency using synch primitives

Device-Independent I/O Software

- There is commonality between drivers of similar classes
- Divide I/O software into device-dependent and device-independent I/O software
- Device independent software includes
  - Buffer or Buffer-cache management
  - Managing access to dedicated devices
  - Error reporting

Device-Independent I/O Software

(a) Without a standard driver interface
(b) With a standard driver interface
**Driver ⇔ Kernel Interface**

- Major issue is uniform interfaces to devices and kernel
  - Uniform device interface for kernel code
    - Allows different devices to be used the same way
      - No need to rewrite filesystem to switch between SCSI, IDE, or RAM disk
  - Uniform kernel interface for device code
    - Drivers use a defined interface to kernel services (e.g., kmalloc, install IRQ handler, etc.)
    - Allows kernel to evolve without breaking existing drivers
  - Together both uniform interfaces avoid a lot of programming implementing new interfaces

**Device-Independent I/O Software**

- (a) Unbuffered input
- (b) Buffering in user space
- (c) Single buffering in the kernel followed by copying to user space
- (d) Double buffering in the kernel

**No Buffering**

- Process must read/write a device a byte/word at a time
  - Each individual system call adds significant overhead
- Process must wait until each I/O is complete
  - Blocking/interrupt/waking adds to overhead
  - Many short runs of a process is inefficient (poor CPU cache temporal locality)

**User-level Buffering**

- Process specifies a memory buffer that incoming data is placed in until it fills
  - Filling can be done by interrupt service routine
  - Only a single system call, and block/wakeup per data buffer
    - Much more efficient

**User-level Buffering**

- Issues
  - What happens if buffer is paged out to disk
    - Could lose data while buffer is paged in
    - Could lock buffer in memory (needed for DMA), however many processes doing I/O reduce RAM available for paging. Can cause deadlock as RAM is limited resource
  - Consider write case
    - When is buffer available for re-use?
      - Either process must block until potential slow device drains buffer
      - or deal with asynchronous signals indicating buffer drained

**Single Buffer**

- Operating system assigns a buffer in main memory for an I/O request
- Stream-oriented
  - Used a line at time
  - User input from a terminal is one line at a time
  - with carriage return signaling the end of the line
  - Output to the terminal is one line at a time
**Single Buffer**

- Block-oriented
  - Input transfers made to buffer
  - Block moved to user space when needed
  - Another block is moved into the buffer
- Read ahead

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**Single Buffer**

- User process can process one block of data while next block is read in
- Swapping can occur since input is taking place in system memory, not user memory
- Operating system keeps track of assignment of system buffers to user processes

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**Single Buffer Speed Up**

- Assume
  - \( T \) is transfer time from device
  - \( C \) is computation time to process incoming packet
  - \( M \) is time to copy kernel buffer to user buffer
- Computation and transfer can be done in parallel
- Speed up with buffering

\[
\frac{T + C}{\max(T, C) + M}
\]

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**Single Buffer**

- What happens if kernel buffer is full, the user buffer is swapped out, and more data is received???
  - We start to lose characters or drop network packets

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**Double Buffer**

- Use two system buffers instead of one
- A process can transfer data to or from one buffer while the operating system empties or fills the other buffer

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**Double Buffer Speed Up**

- Computation and Memory copy can be done in parallel with transfer
- Speed up with double buffering

\[
\frac{T + C}{\max(T, C + M)}
\]

- Usually \( M \) is much less than \( T \) giving a favourable result
Double Buffer

- May be insufficient for really bursty traffic
  - Lots of application writes between long periods of computation
  - Long periods of application computation while receiving data
  - Might want to read-ahead more than a single block for disk

Circular Buffer

- More than two buffers are used
- Each individual buffer is one unit in a circular buffer
- Used when I/O operation must keep up with process

Important Note

- Notice that buffering, double buffering, and circular buffering are all Bounded-Buffer Producer-Consumer Problems

Is Buffering Always Good?

\[
\frac{T + C}{\max(T, C) + M} \quad \text{Single}
\]

\[
\frac{T + C}{\max(T, C + M)} \quad \text{Double}
\]

- Can \( M \) be similar or greater than \( C \) or \( T \)?

Buffering in Fast Networks

- Networking may involve many copies
- Copying reduces performance
  - Especially if copy costs are similar to or greater than computation or transfer costs
- Super-fast networks put significant effort into achieving zero-copy
- Buffering also increases latency

I/O Software Summary

Layers of the I/O system and the main functions of each layer