I/O Management

Chapter 5
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

Layers of the I/O Software System

- User-level I/O software
- Device-independent operating system software
- Device drivers
- Interrupt handlers
- Hardware
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
• 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. hot-plug 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
    - Allows internal changes to device driver with fear of breaking kernel code
  - 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
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
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

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

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

• 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

- **User processes**: Make I/O call; format I/O; spooling
- **Device-independent software**: Naming, protection, blocking, buffering, allocation
- **Device drivers**: Set up device registers; check status
- **Interrupt handlers**: Wake up driver when I/O completed
- **Hardware**: Perform I/O operation