I/O Management Software

Chapter 5

Learning Outcomes

- An understanding of the structure of I/O related software, including interrupt handers.
- An appreciation of the issues surrounding long running interrupt handlers, blocking, and deferred interrupt handling.
- An understanding of I/O buffering and buffering's relationship to a producer-consumer problem.

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**
  - Can execute at (almost) any time
    - Raise (complex) concurrency issues in the kernel
    - Can propagate to userspace (signals, upcalls), causing similar issues
    - Generally structured so I/O operations block until interrupts notify them of completion
      - `kern/dev/lamebus/lhd.c`

Interrupt Handler Example

```
static int
lhd_io(struct device *d,
       struct uio *uio)
{
...
 /* Loop over all the sectors
  * we were asked to do. */
 for (i=0; i<len; i++) {
  /* Wait until nobody else
   * is using the device. */
  P(lh->lh_clear);
  ...
  /* Tell it what sector we want... */
  lhd_wreg(lh, LHD_REG_SECT, sector+i);
  /* and start the operation. */
  lhd_wreg(lh, LHD_REG_STAT, statval);
  /* Now wait until the interrupt
   * handler tells us we're done. */
  P(lh->lh_done);

  /* Get the result value
   * saved by the interrupt handler. */
  result = lh->lh_result;
}
```

INT

SLEEP

```
lhd_iodone(struct lhd_softc *lh, int err)
{
        lh->lh_result = err;
        V(lh->lh_done);
}

void
lhd_irq(void *vlh)
{
 ...
 val = lhd_rdreg(lh, LHD_REG_STAT);

 switch (val & LHD_STATEMASK) {
  case LHD_IDLE:
  case LHD_WORKING:
    break;
  case LHD_OK:
  case LHD_INVSECT:
  case LHD_MEDIA:
   lhd_wreg(lh, LHD_REG_STAT, 0);
   lhd_iodone(lh,
             lhd_code_to_errno(lh, val));
   break;
 }
}
```


Interrupt Handler Steps

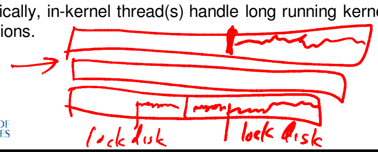
- **Save Registers** not already saved by hardware interrupt mechanism
- (Optionally) **set up context** for interrupt service procedure
  - Typically, handler runs in the context of the currently running process
    - No expensive context switch
- **Set up stack** for interrupt service procedure
  - Handler usually runs on the kernel stack of current process
- **Ack/Mask interrupt controller**, re-enable other interrupts
  - What does this imply?

Interrupt Handler Steps

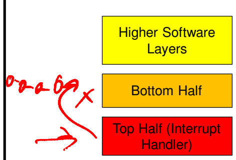
- **Run interrupt service procedure**
  - Acknowledges interrupt at device level
  - Figures out what caused the interrupt
    - Received a network packet, disk read finished, UART transmit queue empty
  - If needed, it signals blocked device driver
- **In some cases, will have woken up a higher priority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

Sleeping in Interrupts

- Interrupt generally has no **context** (runs on current kernel stack)
  - Unfair to sleep interrupted process (deadlock possible)
  - Where to get context for long running operation?
  - What goes into the ready queue?
- What to do?
  - Top and Bottom Half
  - Linux implements with `tasklets` and `workqueues`
  - Generically, in-kernel thread(s) handle long running kernel operations.



Top/Half Bottom Half

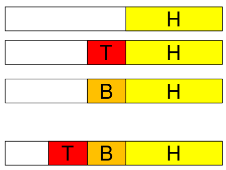


- Top Half
  - Interrupt handler
  - remains short
- Bottom half
  - Is preemptable by top half (interrupts)
  - performs deferred work (e.g. IP stack processing)
  - Is checked prior to every kernel exit
  - signals blocked processes/threads to continue
- Enables low interrupt latency
- Bottom half can't block

Stack Usage

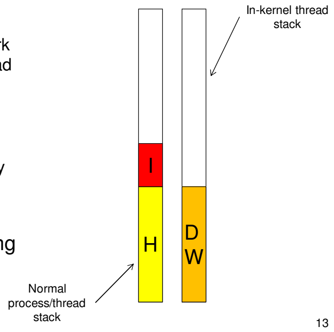
Kernel Stack

- Upper software
- Interrupt (interrupts disabled)
- Deferred processing (interrupt re-enabled)
- Interrupt while in bottom half



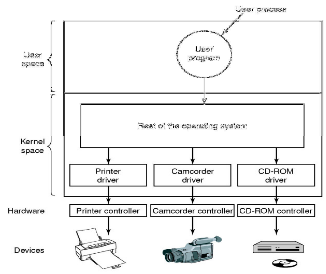
Deferring Work on In-kernel Threads

- Interrupt
  - handler defers work onto in-kernel thread
- In-kernel thread handles deferred work (DW)
  - Scheduled normally
  - Can block
- Both low interrupt latency and blocking operations



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 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 specs often help, e.g. USB
- **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

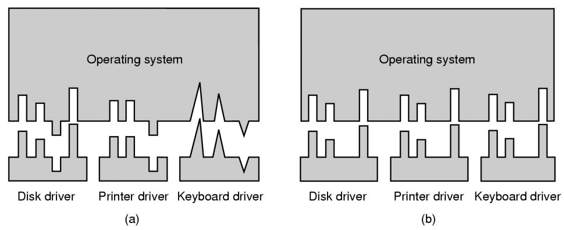
Device Driver

- **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 re-entrant (or thread-safe)** as they can be called by another process while a process is already blocked in the driver.
  - Re-entrant: Mainly no static (global) non-constant data.

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

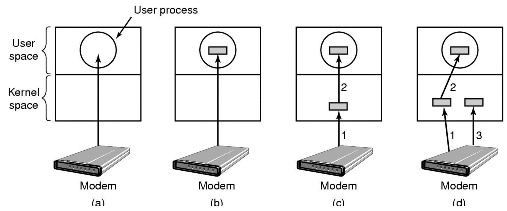
(b) With a standard driver interface

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 file-system 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

Buffering

Device-Independent I/O Software



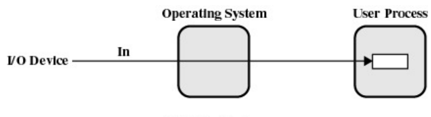
(a) Unbuffered input
(b) Buffering in user space
(c) *Single buffering* in the kernel followed by copying to user space
(d) Double buffering in the kernel

No Buffering

- Process must read/write a device a byte/word at a time
  - Each individual system call adds significant overhead
  - Process must what 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

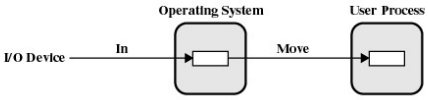


User-level Buffering

- 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

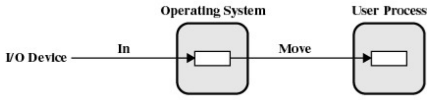
- Operating system assigns a buffer in kernel's memory for an I/O request
- Stream-oriented
  - Used a line at time
  - User input from a terminal is one line at a time with carriage return signaling the end of the line
  - Output to the terminal is one line at a time



(b) Single buffering

Single Buffer

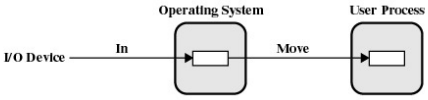
- Block-oriented
  - Input transfers made to buffer
  - Block moved to user space when needed
  - Another block is moved into the buffer
    - Read ahead



(b) Single buffering

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



(b) Single buffering

Single Buffer Speed Up

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

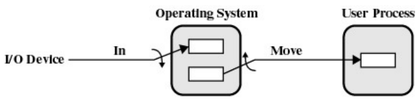
$$\frac{T+C}{\max(T,C)+M}$$

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



(c) Double buffering

Double Buffer Speed Up

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

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

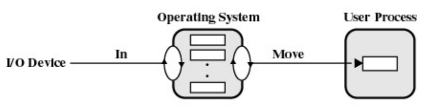
- Usually *M* is much less than *T* giving a favourable result

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



(d) Circular buffering

Important Note

- Notice that buffering, double buffering, and circular buffering are all

Bounded-Buffer Producer-Consumer Problems

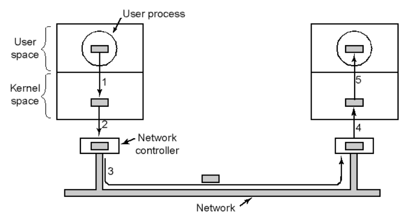
Is Buffering Always Good?

$$\frac{T+C}{\max(T,C)+M} \qquad \frac{T+C}{\max(T,C+M)}$$

Single   Double

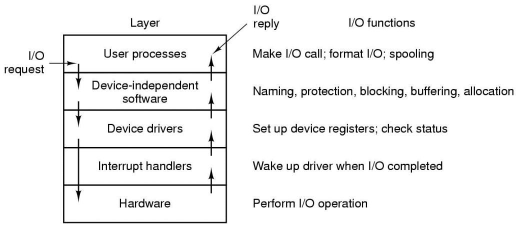
- Can *M* be similar or greater than *C* or *T*?

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