I/O Management Intro

Chapter 5 - 5.3

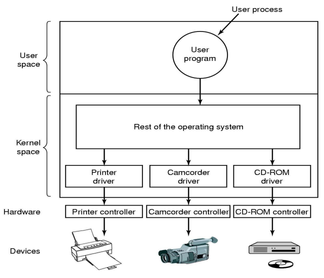
Learning Outcomes

- A high-level understanding of the properties of a variety of I/O devices.
- An understanding of methods of interacting with I/O devices.

I/O Devices

- There exists a large variety of I/O devices:
  - Many of them with different properties
  - They seem to require different interfaces to manipulate and manage them
    - We don't want a new interface for every device
    - Diverse, but similar interfaces leads to code duplication
- Challenge:
  - Uniform and efficient approach to I/O

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**
  - Example: USB *Human Input Device* (HID) class specifications
    - human input devices follow a set of rules making it easier to design a standard interface.

USB Device Classes

Base Class	Descriptor Usage	Description
00h	Device	Use class information in the Interface Descriptors
01h	Interface	Audio
02h	Both	Communications and CDC Control
03h	Interface	HID (Human Interface Device)
05h	Interface	Physical
06h	Interface	Image
07h	Interface	Printer
08h	Interface	Mass Storage
09h	Device	Hub
0Ah	Interface	CDC-Data
0Bh	Interface	Smart Card
0Dh	Interface	Content Security
0Eh	Interface	Video
0Fh	Interface	Personal Healthcare
10h	Interface	Audio/Video Devices
DCh	Both	Diagnostic Device
E0h	Interface	Wireless Controller
EFh	Both	Miscellaneous
FEh	Interface	Application Specific
FFh	Both	Vendor Specific

I/O Device Handling

- Data rate
  - May be differences of several orders of magnitude between the data transfer rates
  - Example: Assume 1000 cycles/byte I/O
    - Keyboard needs 10 KHz processor to keep up
    - Gigabit Ethernet needs 100 GHz processor…..

Sample Data Rates

Device	Data rate
Keyboard	10 bytes/sec
Mouse	100 bytes/sec
56K modem	7 KB/sec
Telephone channel	8 KB/sec
Dual ISDN lines	16 KB/sec
Laser printer	100 KB/sec
Scanner	400 KB/sec
Classic Ethernet	1.25 MB/sec
USB (Universal Serial Bus)	1.5 MB/sec
Digital camcorder	4 MB/sec
IDE disk	5 MB/sec
40x CD-ROM	6 MB/sec
Fast Ethernet	12.5 MB/sec
ISA bus	16.7 MB/sec
EIDE (ATA-2) disk	16.7 MB/sec
FireWire (IEEE 1394)	50 MB/sec
XGA Monitor	60 MB/sec
SONET OC-12 network	78 MB/sec
SCSI Ultra 2 disk	80 MB/sec
Gigabit Ethernet	125 MB/sec
Ultrium tape	320 MB/sec
PCI bus	528 MB/sec
Sun Gigaplane XB backplane	20 GB/sec

USB 3.0 625 MB/s (5 Gb/s)
Thunderbolt 2.5GB/sec (20 Gb/s)
PCIe v3.0 x16 16GB/s

Device Drivers

- **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 thread-safe** as they can be called by another process while a process is already blocked in the driver.
  - Thead-safe: Synchronised…

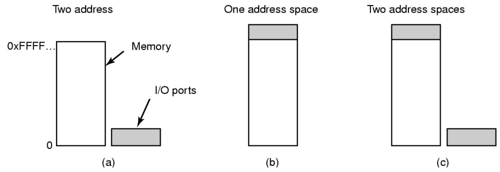
Device-Independent I/O Software

- 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
  - TCP/IP stack
  - Managing access to dedicated devices
  - Error reporting

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
    - Retains compatibility as drivers and kernels change over time.

Accessing I/O Controllers

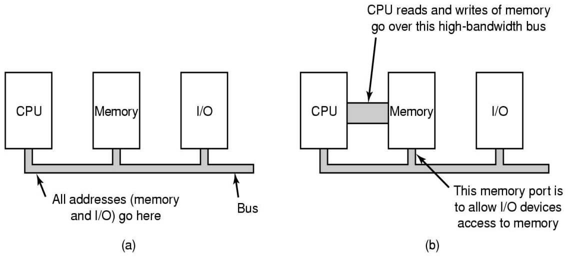


a) **Separate I/O and memory space**
   - I/O controller registers appear as I/O ports
   - Accessed with special I/O instructions

b) **Memory-mapped I/O**
   - Controller registers appear as memory
   - Use normal load/store instructions to access

c) **Hybrid**
   - x86 has both ports and memory mapped I/O

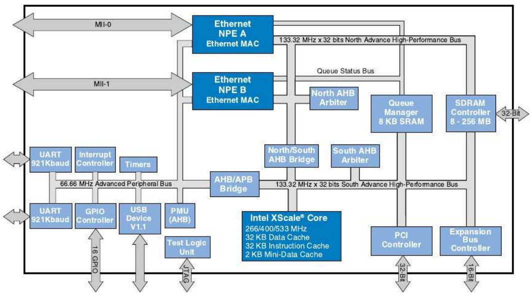
Bus Architectures



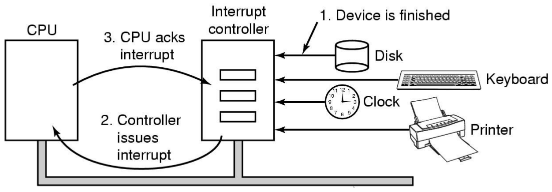
(a) A single-bus architecture

(b) A dual-bus memory architecture

Intel IXP420

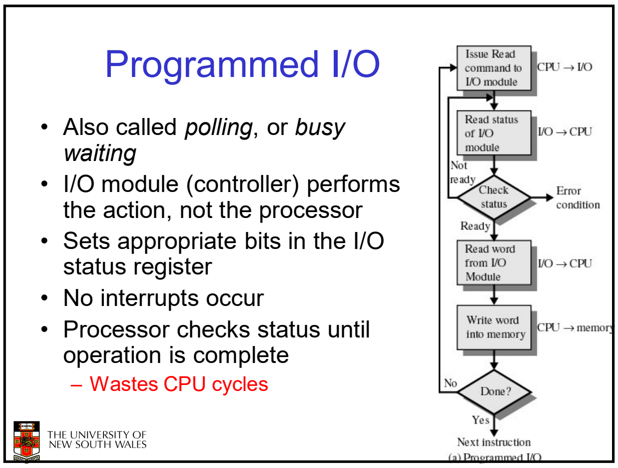


Interrupts



- Devices connected to an *Interrupt Controller* via lines on an I/O bus (e.g. PCI)
- Interrupt Controller signals interrupt to CPU and is eventually acknowledged.
- Exact details are architecture specific.

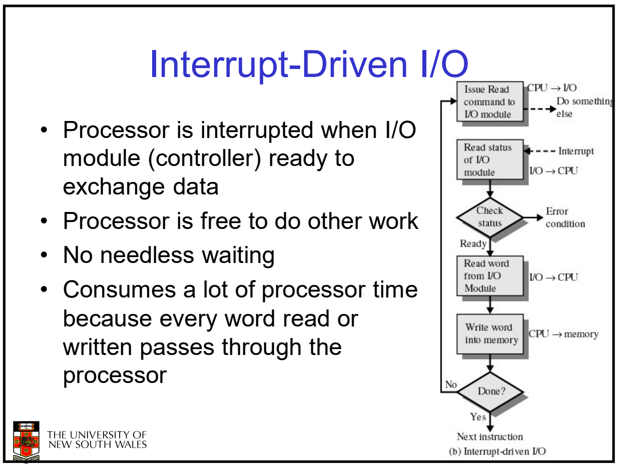
I/O Interaction



Programmed I/O

- Also called *polling*, or *busy waiting*
- I/O module (controller) performs the action, not the processor
- Sets appropriate bits in the I/O status register
- No interrupts occur
- Processor checks status until operation is complete
  - – Wastes CPU cycles

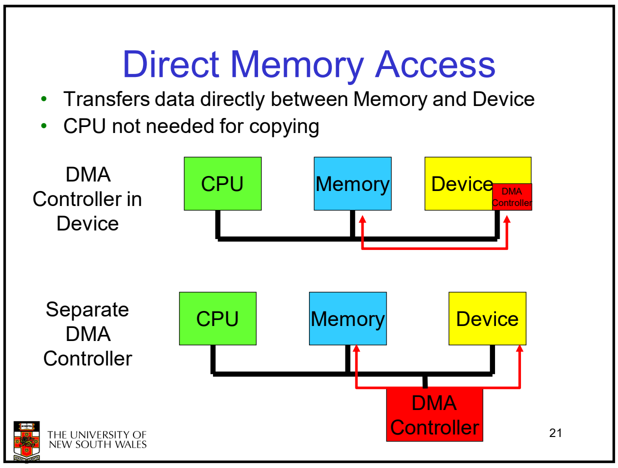
(a) Programmed I/O



Interrupt-Driven I/O

- Processor is interrupted when I/O module (controller) ready to exchange data
- Processor is free to do other work
- No needless waiting
- Consumes a lot of processor time because every word read or written passes through the processor

(b) Interrupt-driven I/O

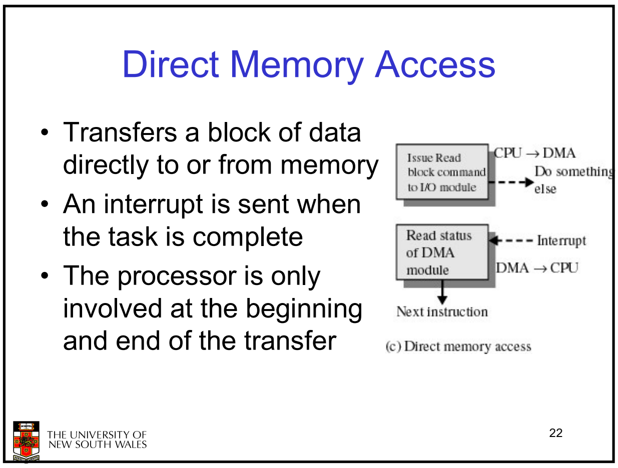


Direct Memory Access

- Transfers data directly between Memory and Device
- CPU not needed for copying

DMA Controller in Device

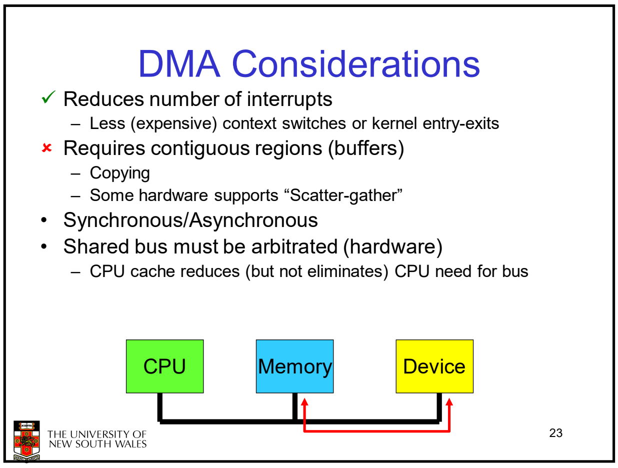
Separate DMA Controller



Direct Memory Access

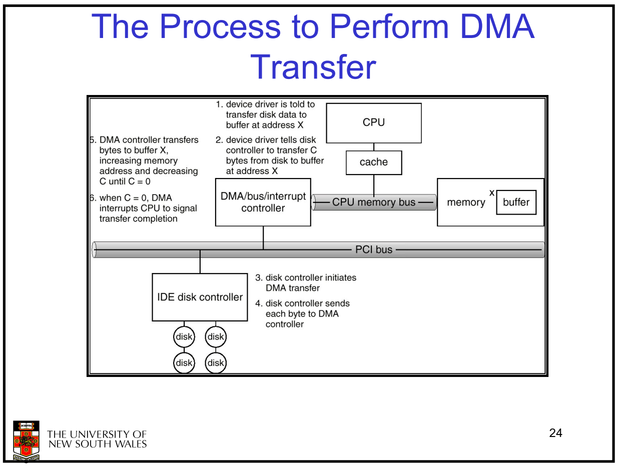
- Transfers a block of data directly to or from memory
- An interrupt is sent when the task is complete
- The processor is only involved at the beginning and end of the transfer

(c) Direct memory access



DMA Considerations

- ✓ Reduces number of interrupts
  - – Less (expensive) context switches or kernel entry-exits
- ✗ Requires contiguous regions (buffers)
  - – Copying
  - – Some hardware supports “Scatter-gather”
- Synchronous/Asynchronous
- Shared bus must be arbitrated (hardware)
  - – CPU cache reduces (but not eliminates) CPU need for bus



The Process to Perform DMA Transfer

1. device driver is told to transfer disk data to buffer at address X
2. device driver tells disk controller to transfer C bytes from disk to buffer at address X
3. disk controller initiates DMA transfer
4. disk controller sends each byte to DMA controller
5. DMA controller transfers bytes to buffer X, increasing memory address and decreasing C until C = 0
6. when C = 0, DMA interrupts CPU to signal transfer completion

I/O Management Software

Chapter 5 – 5.3

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.

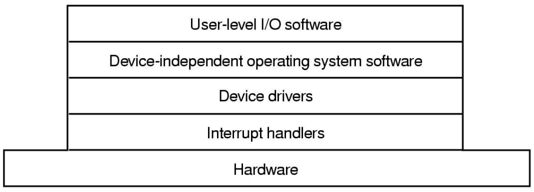
Operating System Design Issues

- **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

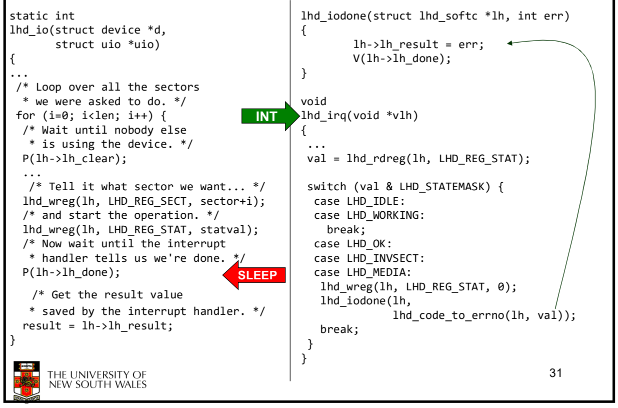


Layers of the I/O Software System

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;
}
```

```
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
  - Or "nests" if already in kernel mode running on kernel stack
- **Ack/Mask interrupt controller**, re-enable other interrupts
  - Implies potential for interrupt nesting.

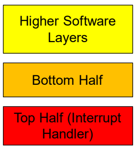
Interrupt Handler Steps

- **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

- An interrupt generally has no **context** (runs on current kernel stack)
  - Unfair to sleep on 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.

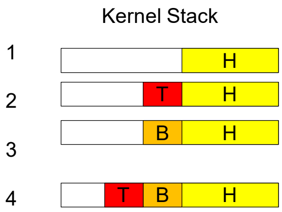
Top/Half Bottom Half



- 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

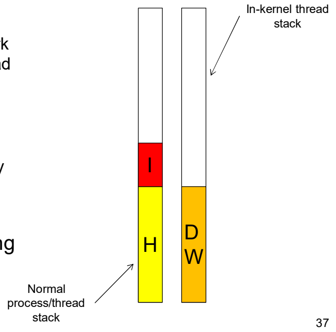
Stack Usage

1. Higher-level software
2. Interrupt processing (interrupts disabled)
3. Deferred processing (interrupt re-enabled)
4. Interrupt while in bottom half



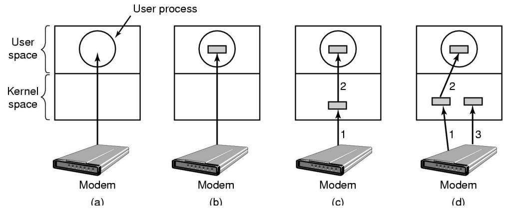
Deferring Work on In-kernel Threads

- 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



Buffering

Device-Independent I/O Software



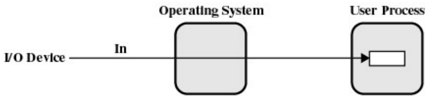
(a) Unbuffered input
(b) Buffering in user space
(c) *Single buffering* in the kernel followed by copying to user space
(d) Double buffering in the kernel

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

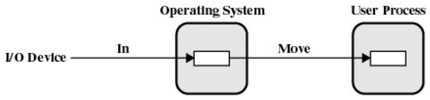


User-level Buffering

- Issues
  - What happens if buffer is paged out to disk
    - Could lose data while unavailable 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

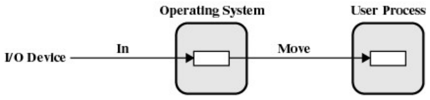
- Operating system assigns a buffer in kernel's memory for an I/O request
- In a stream-oriented scenario
  - Used a line at time
  - User input from a terminal is one line at a time with carriage return signaling the end of the line
  - Output to the terminal is one line at a time



(b) Single buffering

Single Buffer

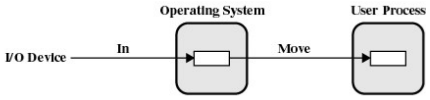
- Block-oriented
  - Input transfers made to buffer
  - Block copied to user space when needed
  - Another block is written into the buffer
    - Read ahead



(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

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

No Buffering Cost

Single Buffering Cost

Single Buffer

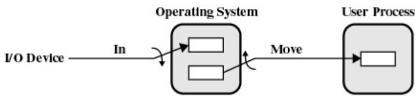
- What happens if kernel buffer is full
  - the user buffer is swapped out, or
  - The application is slow to process previous buffer

  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

No Buffering Cost

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

Double Buffering Cost

- 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

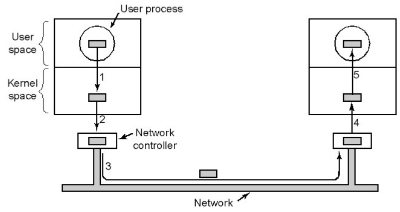
Is Buffering Always Good?

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

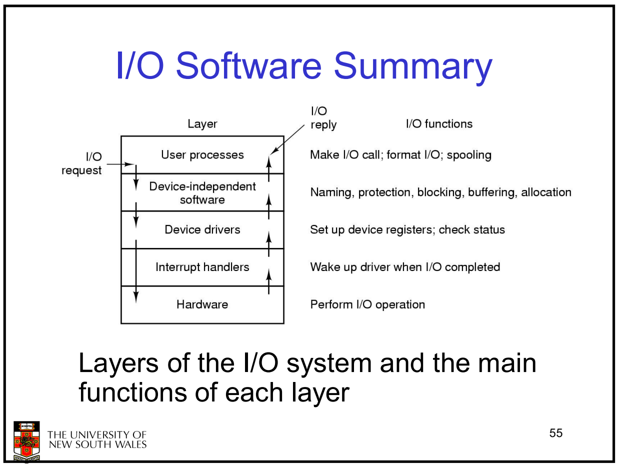
Single Double

- 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

I/O request

I/O reply

Layer	I/O functions
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

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