Devices and Device Drivers
CS 111
Operating Systems
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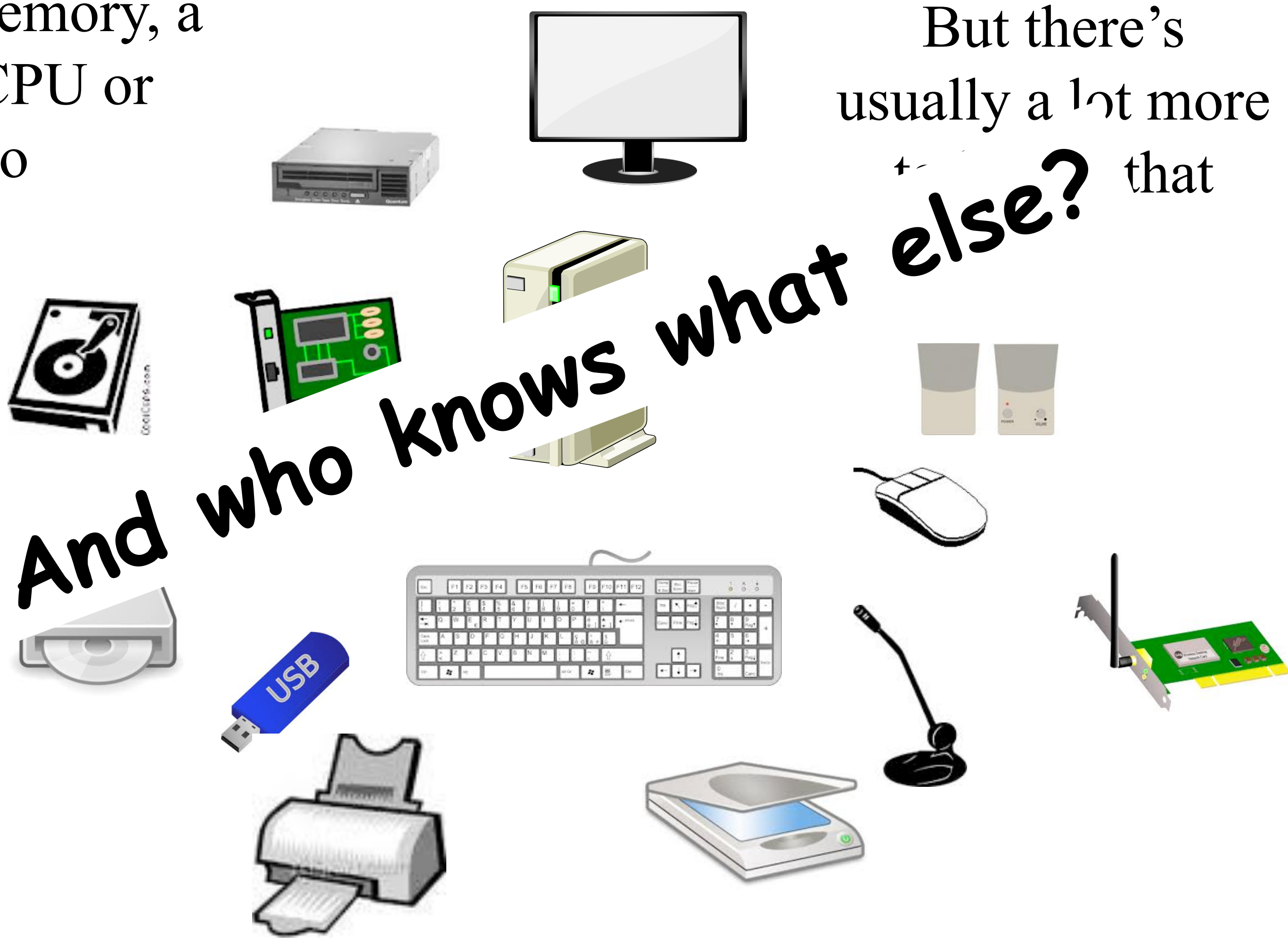
Outline

- The role of devices
- Device drivers
- Classes of device driver

So You've Got Your Computer . . .

It's got memory, a bus, a CPU or two

But there's usually a lot more [illegible] that



And who knows what else?

Welcome to the Wonderful World of Peripheral Devices!

- Our computers typically have lots of devices attached to them
- Each device needs to have some code associated with it
  - To perform whatever operations it does
  - To integrate it with the rest of the system
- In modern commodity OSes, the code that handles these devices dwarfs the rest

Peripheral Device Code and the OS

- Why are peripheral devices the OS' problem, anyway?
- Why can't they be handled in user-level code?
- Maybe they sometimes can, but . . .
- Some of them are critical for system correctness
  - E.g., the disk drive holding swap space
- Some of them must be shared among multiple processes
  - Which is often rather complex
- Some of them are security-sensitive
- Perhaps more appropriate to put the code in the OS

Where the Device Driver Fits in

- At one end you have an application
  - Like a web browser
- At the other end you have a very specific piece of hardware
  - Like an Intel Gigabit CT PCI-E Network Adapter
- In between is the OS
- When the application sends a packet, the OS needs to invoke the proper driver
- Which feeds detailed instructions to the hardware

Connecting Peripherals

- Most peripheral devices don’t connect directly to the processor
  – Or to the main bus
- They connect to a specialized peripheral bus
- Which, in turn, connects to the main bus
- Various types are common
  – PCI
  – USB
  – Several others

Device Drivers

- Generally, the code for these devices is pretty specific to them
- It's basically code that *drives* the device
  - Makes the device perform the operations it's designed for
- So typically each system device is represented by its own piece of code
- The *device driver*
- A Linux 2.6 kernel had over 3200 of them . . .

Typical Properties of Device Drivers

- Highly specific to the particular device
- Inherently modular
- Usually interacts with the rest of the system in limited, well defined ways
- Their correctness is critical
  - At least device behavior correctness
  - Sometimes overall correctness
- Generally written by programmers who understand the device well
  - But are not necessarily experts on systems issues

What About Abstractions?

- Sounds like device drivers don't offer a lot of opportunity to use abstractions
- Since each is specific to one piece of hardware
- But there are some useful similarities at higher levels
- We typically customize each device driver on top of a few powerful abstractions

Using Abstractions for Devices

- OS defines idealized device classes
  - Disk, display, printer, tape, network, serial ports
- Classes define expected interfaces/behavior
  - All drivers in class support standard methods
- Device drivers implement standard behavior
  - Make diverse devices fit into a common mold
  - Protect applications from device eccentricities
- Abstractions regularize and simplify the chaos of the world of devices

What Can Driver Abstractions Help With?

- Encapsulate knowledge of how to use the device
  - Map standard operations into operations on device
  - Map device states into standard object behavior
  - Hide irrelevant behavior from users
  - Correctly coordinate device and application behavior
- Encapsulate knowledge of optimization
  - Efficiently perform standard operations on a device
- Encapsulate fault handling
  - Understanding how to handle recoverable faults
  - Prevent device faults from becoming OS faults

Abstractions on the Other End

- Devices typically connect to some standard type of bus
- Which requires the hardware to conform to that bus standard
- So driver interactions with the physical device are mediated through a standard
- Effectively providing an abstraction on the other side of the OS' role

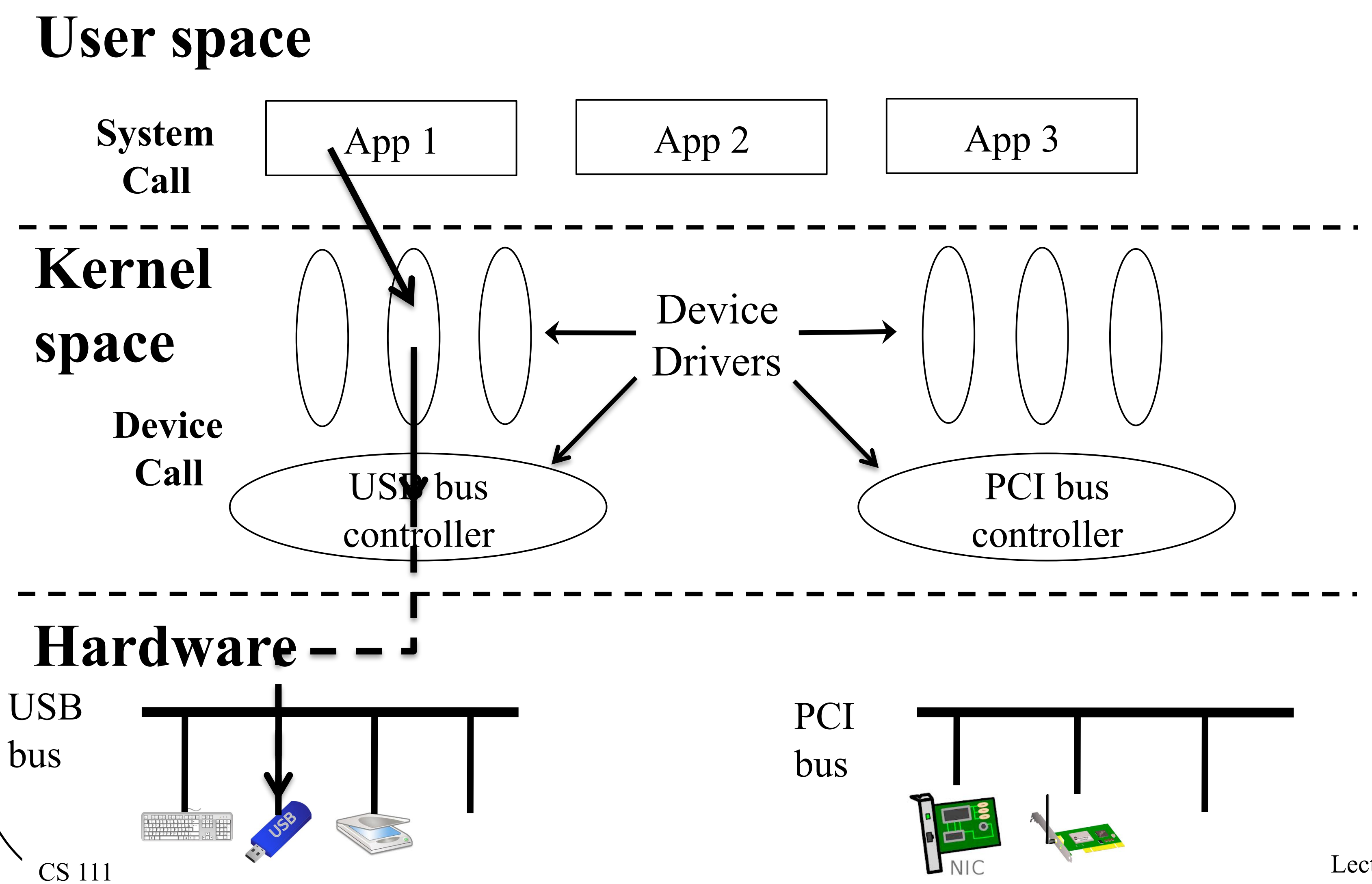
How Do Device Drivers Fit Into a Modern OS?

- There may be a lot of them
- They are each pretty independent
- You may need to add new ones later
- So a pluggable model is typical
- OS provides capabilities to plug in particular drivers in well defined ways
- Then plug in the ones a given machine needs
- Making it easy to change or augment later

Layering Device Drivers

- The interactions with the bus, down at the bottom, are pretty standard
  - How you address devices on the bus, coordination of signaling and data transfers, etc.
  - Not too dependent on the device itself
- The interactions with the applications, up at the top, are also pretty standard
  - Typically using some file-oriented approach
- In between are some very device specific things

A Pictorial View



Device Drivers Vs. Core OS Code

- Device driver code is in the OS, but . . .
- What belongs in core OS vs. a device driver?
- Common functionality belongs in the OS
  - Caching
  - File systems code not tied to a specific device
  - Network protocols above physical/link layers
- Specialized functionality belongs in the drivers
  - Things that differ in different pieces of hardware
  - Things that only pertain to the particular piece of hardware

Linux Device Driver Abstractions

- An example of how an OS handles device drivers
- Basically inherited from earlier Unix systems
- A class-based system
- Several super-classes
  - Block devices
  - Character devices
  - Some regard network devices as a third major class
- Other divisions within each super-class

Why Classes of Drivers?

- Classes provide a good organization for abstraction
- They provide a common framework to reduce amount of code required for each new device
- The framework ensure all devices in class provide certain minimal functionality
- But a lot of driver functionality is very specific to the device
  - Implying that class abstractions don't cover everything

Character Device Superclass

- Devices that read/write one byte at a time
  - "Character" means byte, not ASCII
- May be either stream or record structured
- May be sequential or random access
- Support direct, synchronous reads and writes
- Common examples:
  - Keyboards
  - Monitors
  - Most other devices

Block Device Superclass

- Devices that deal with a block of data at a time
- Usually a fixed size block
- Most common example is a disk drive
- Reads or writes a single sized block (e.g., 4K bytes) of data at a time
- Random access devices, accessible one block at a time
- Support queued, asynchronous reads and writes

Why a Separate Superclass for Block Devices?

- Block devices span all forms of block-addressable random access storage
  - Hard disks, CDs, flash, and even some tapes
- Such devices require some very elaborate services
  - Buffer allocation, LRU management of a buffer cache, data copying services for those buffers, scheduled I/O, asynchronous completion, etc.
- Key system functionality (file systems and swapping/ paging) implemented on top of block I/O
- Block I/O services are designed to provide very high performance for critical functions

Network Device Superclass

- Devices that send/receive data in packets
- Originally treated as character devices
- But sufficiently different from other character devices that some regard as distinct
- Only used in the context of network protocols
  - Unlike other devices
  - Which leads to special characteristics
- Typical examples are Ethernet cards, 802.11 cards, Bluetooth devices

Device Instances

- Can be multiple hardware instances of a device
  - E.g., multiple copies of same kind of disk drive
- One hardware device might be multiplexed into pieces
  - E.g., four partitions on one hard drive
- Or there might be different modes of accessing the same hardware
  - Media writeable at different densities
- The same device driver usable for such cases, but something must distinguish them
- Linux uses *minor device numbers* for this purpose

Accessing Linux Device Drivers

- Done through the file system
- Special files
  - Files that are associated with a device instance
  - UNIX/LINUX uses <block/character, major, minor>
    - Major number corresponds to a particular device driver
    - Minor number identifies an instance under that driver

Major number is 14

Minor number is 0

A block special device

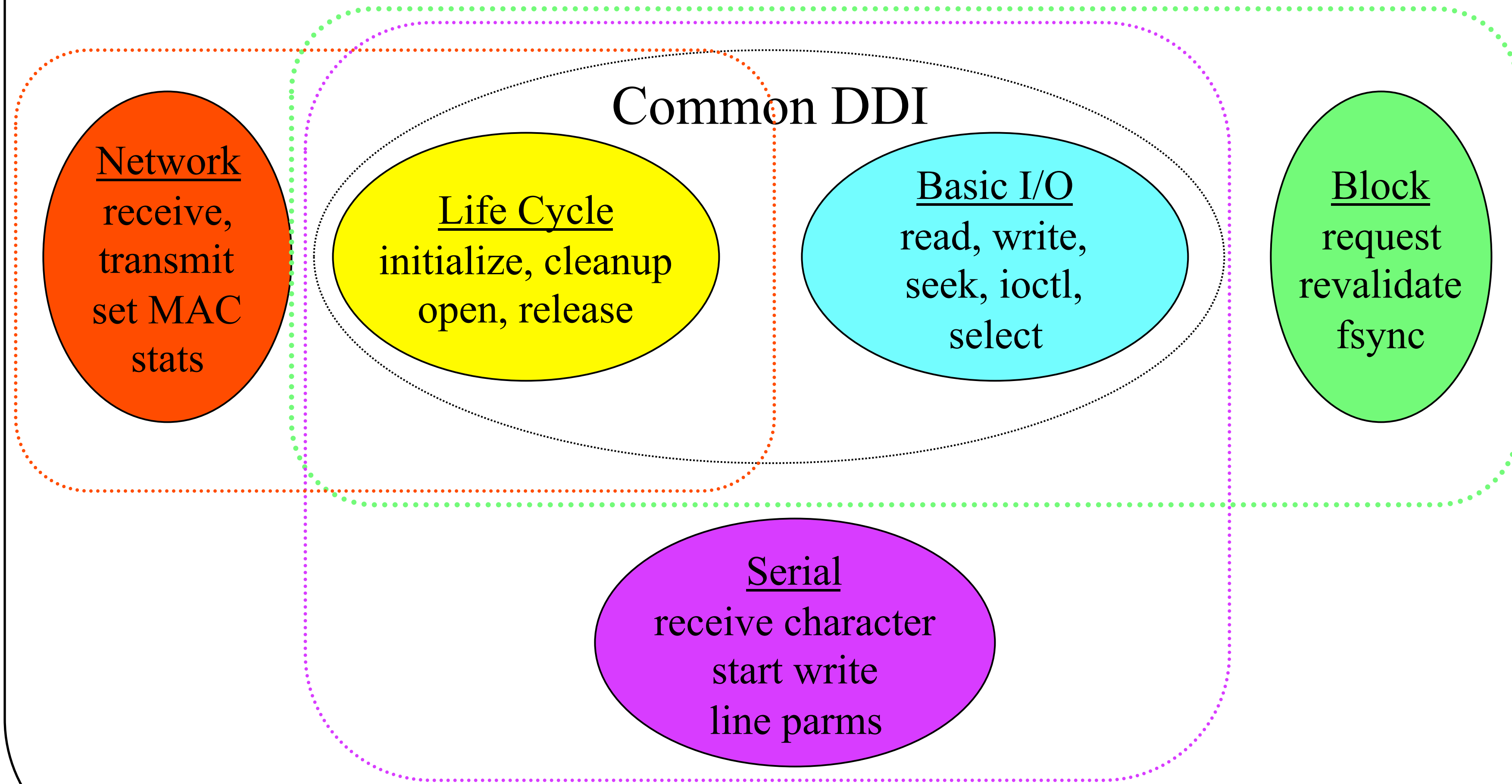
```
brw-r-----  1 root    operator   14,   0 Apr 11 18:03 disk0
brw-r-----  1 root    operator   14,   1 Apr 11 18:03 disk0s1
brw-r-----  1 root    operator   14,   2 Apr 11 18:03 disk0s2
br--r-----  1 reiher  reiher     14,   3 Apr 15 16:19 disk2
br--r-----  1 reiher  reiher     14,   4 Apr 15 16:19 disk2s1
br--r-----  1 reiher  reiher     14,   5 Apr 15 16:19 disk2s2
```

- Opening special file opens the associated device
  - Open/close/read/write/etc. calls map to calls to appropriate entry-points of the selected driver

Linux Device Driver Interface (DDI)

- Standard (top-end) device driver entry-points
  - Basis for device independent applications
  - Enables system to exploit new devices
  - Critical interface contract for 3rd party developers
- Some calls correspond directly to system calls
  - E.g., open, close, read, write
- Some are associated with OS frameworks
  - Disk drivers are meant to be called by block I/O
  - Network drivers meant to be called by protocols

DDIs and Sub-DDIs



General Linux DDI Entry Points

- Standard entry points for most drivers
- House-keeping operations
  - xx_open ... check/initialize hardware and software
  - xx_release ... release one reference, close on last
- Generic I/O operations
  - xx_read, xx_write ... synchronous I/O operations
  - xx_seek ... change target address on device
  - xx_ioctl ... generic & device specific control functions
  - xx_select ... is data currently available?

Linux Block Device DDI

- Includes wide range of random access devices
  - Hard disks, diskettes, CDs, flash-RAM, ...
- Drivers do block reads, writes, and scheduling
  - Caching is implemented in higher level modules
  - File systems implemented in higher level modules
- Standard entry-points
  - xx_request ... queue a read or write operation
  - xx_fsync ... complete all pending operations
  - xx_revalidate ... for dismountable devices

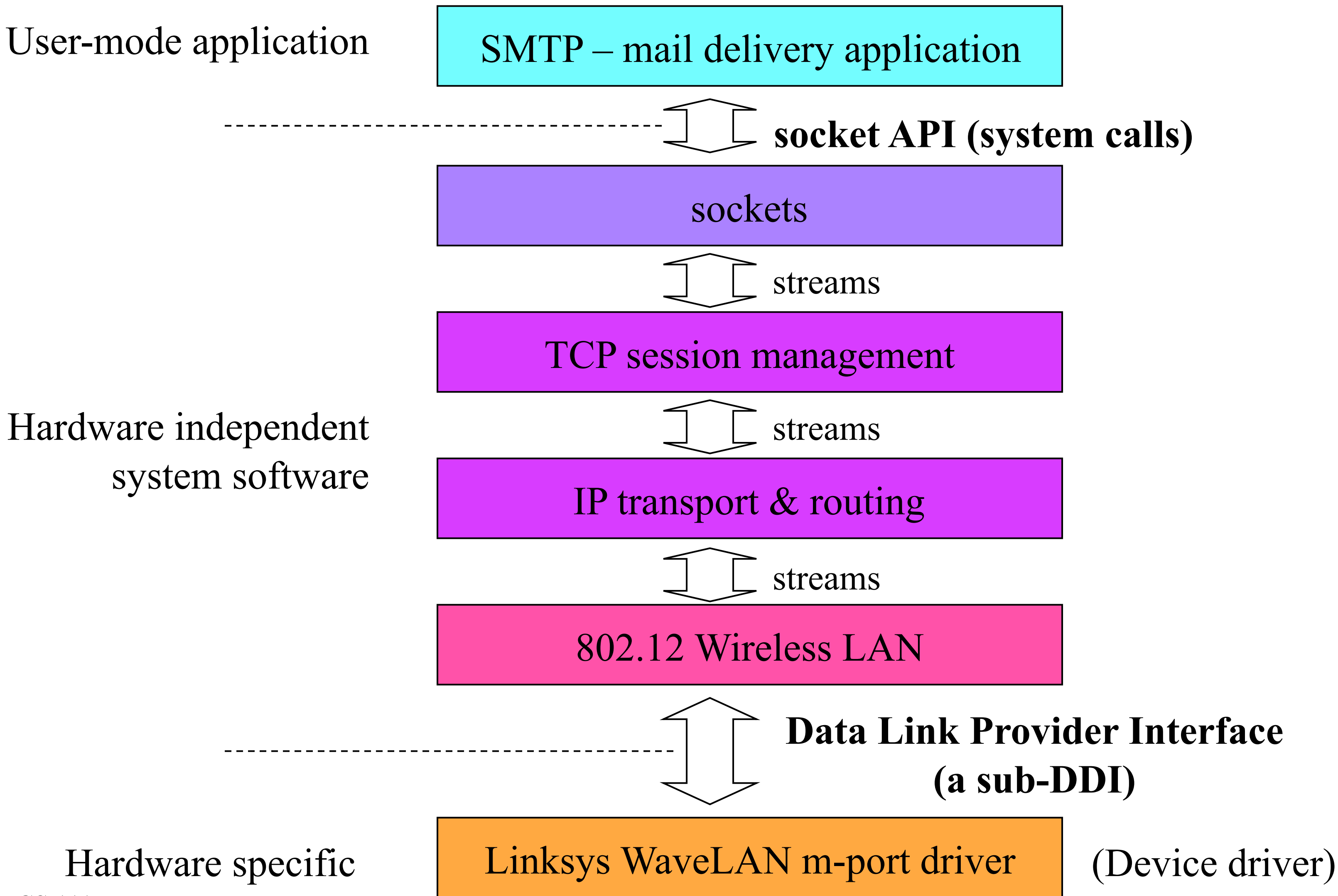
Linux Network Device DDI

- Covers wide range of networking technologies
  - Ethernet, token-ring, wireless, infra-red, ...
- Drivers provide only basic transport/control
  - Protocols implemented by higher level modules
- Standard entry-points
  - xx_transmit ... queue a packet for transmission
  - xx_rcv ... process a received packet
  - xx_statistics ... extract packet, error, retransmit info
  - xx_set_mac/multicast ... address configuration

What About Basic DDI Functionality For Networks?

- Network drivers don't support some pretty basic stuff
  - Like read and write
- Any network device works in the context of a link protocol
  - E.g., 802.11
- You can't just read, you must follow the protocol to get bytes
- So what?
- Well, do you want to implement the link protocol in every device driver for 802.11?
  - No, do that at a higher level so you can reuse it
- That implies doing a read on a network card makes no sense
- You need to work in the context of the protocol

The Role of Drivers in Networking



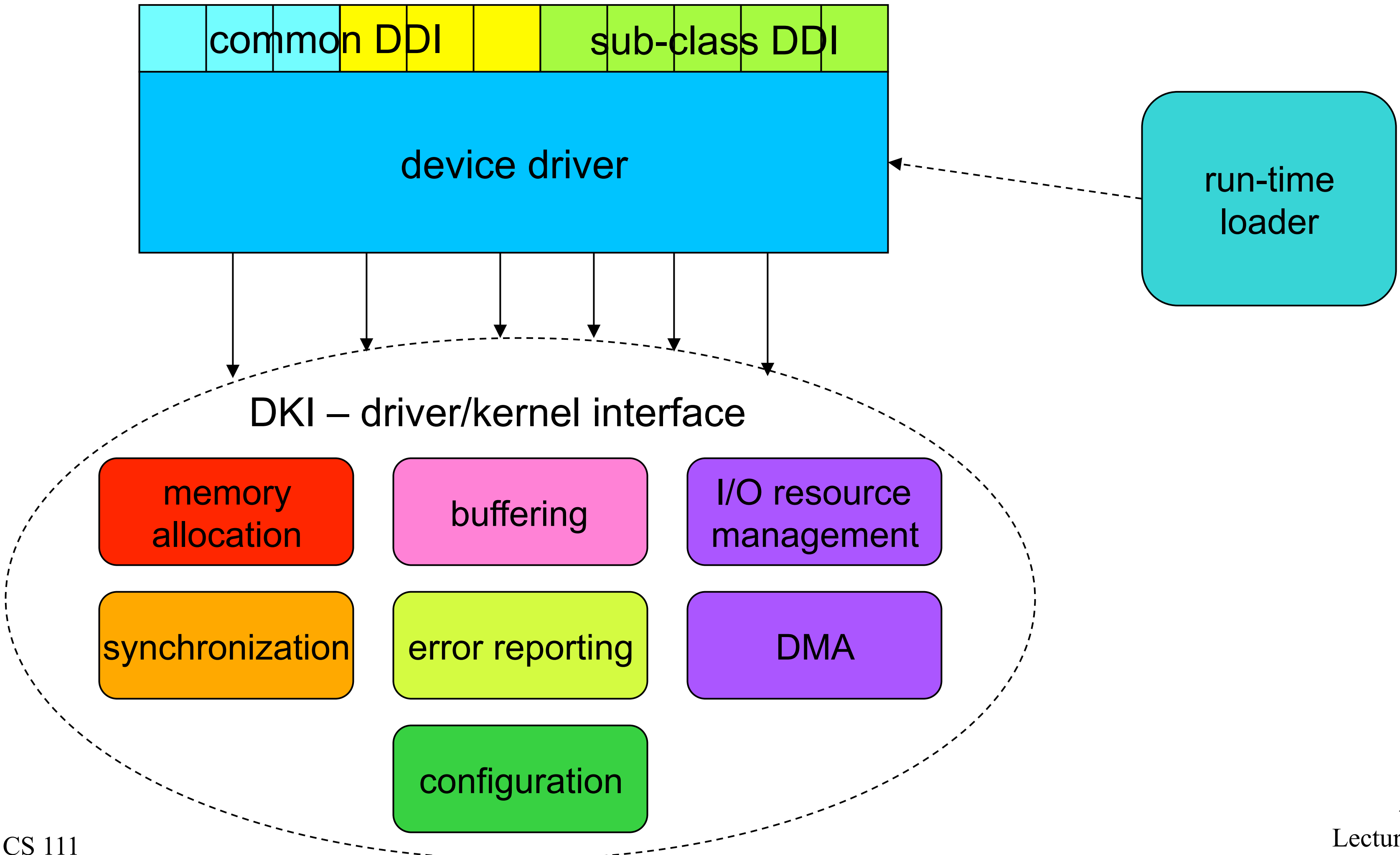
Controlling Devices - ioctl

- Not all device interactions are reading/writing
- Other operations control device behavior
  - Operations supported are device class specific
- Unix/Linux uses *ioctl* calls for many of those
- There are many general ioctl operations
  - Get/release exclusive access to device
  - Blocking and non-blocking opens, reads and writes
- There are also class-specific operations
  - Tape: write file mark, space record, rewind
  - Serial: set line speed, parity, character length
  - Disk: get device geometry

Device Drivers and the Kernel

- Drivers are usually systems code
- But they're not kernel code
- Most drivers are optional
  - Only present if the device they support is there
- They're modular and isolated from the kernel
- But they do make use of kernel services
- Implying they need an interface to the kernel
- Different from application/kernel interface, because driver needs are different

What Kernel Services Do Device Drivers Need?



The Device Driver Writer's Problem

- Device drivers are often written by third parties (not the OS developers)
- There are a lot of drivers and driver authors
- Device drivers require OS services to work
  - All of these services are highly OS specific
  - Drivers must be able to call OS routines to obtain these services
- The horde of driver authors must know how to get the OS services
- Drivers can't be rewritten for each OS release
  - So the services and their interfaces must be stable

The Driver-Kernel Interface

- Bottom-end services OS provides to drivers
- Must be very well-defined and stable
  - To enable third party driver writers to build drivers
  - So old drivers continue to work on new OS versions
- Each OS has its own DKI, but they are all similar
  - Memory allocation, data transfer and buffering
  - I/O resource (e.g., ports and interrupts) management, DMA
  - Synchronization, error reporting
  - Dynamic module support, configuration, plumbing

DKI Memory Management Services

- Heap allocation
  - Allocate and free variable partitions from a kernel heap
- Page allocation
  - Allocate and free physical pages
- Cached file system buffers
  - Allocate and free block-sized buffers in an LRU cache
- Specialized buffers
  - For serial communication, network packets, etc.
- Efficient data transfer between kernel/user space

DKI I/O Resource Management Services

- I/O ports and device memory
  - Reserve, allocate, and free ranges of I/O ports or memory
  - Map device memory in/out of process address space
- Interrupts
  - Allocate and free interrupt request lines
  - Bind an interrupt to a second level handler
  - Enable and disable specific interrupts
- DMA channels
  - Allocate/free DMA channels, set-up DMA operations

DKI Synchronization Services

- Mutual exclusion
  - A wide range of different types of locks
- Asynchronous completion/notifications
  - Sleep/wakeup, wait/signal, P/V
- Timed delays
  - Sleep (block and wake up at a time)
  - Spin (for a brief, calibrated, time)
- Scheduled future processing
  - Delayed Procedure Calls, tasks, software interrupts

DKI Error Management Services

- Logging error messages
  - Print diagnostic information on the console
  - Record information in persistent system log
  - Often supports severity codes, configurable levels
- Event/trace facilities
  - Controllable recording of system calls, interrupts, ...
  - Very useful as audit-trail when diagnosing failures
- High Availability fault management frameworks
  - Rule-based fault diagnosis systems
  - Automated intelligent recovery systems

DKI Configuration Services

- Devices need to be properly configured at boot time
  - Not all configuration can be done at install time
  - Primary display adaptor, default resolution
  - IP address assignment (manual, DHCP)
  - Mouse button mapping
  - Enabling and disabling of devices
- Such information can be kept in a registry
  - Database of nodes, property names and values
  - Available to both applications and kernel software
    - E.g., properties associated with service/device instances
  - May be part of a distributed management system
    - E.g., LDAP, NIS, Active Directory

User Mode Drivers

- Some device drivers don't need to be run in the kernel
- They can be run as applications
- Doing so has advantages and disadvantages
- Sometimes done for display adaptor drivers

Advantages of User Mode Drivers

- Performance and bundling advantages
  - Device driver need not be part of/included in the OS
  - Device I/O can be done without system call overhead
- Device can be mapped into process' user-mode address space
  - Privileged system call maps in memory/ports
  - Process can only use designated memory/ports
  - So protection is still possible

Limitations of User Mode Device Drivers

- Can’t service interrupts
  - Servicing an interrupt usually requires disabling other interrupts
  - Can’t trust user-mode code to do that properly
  - User-mode code might take a long time to execute
- Can’t make use of DKI services
  - These are internal to the kernel
  - Not made available to any applications
  - User mode device drivers look like an application

The Life Cycle of a Device Driver

- Device drivers are part of the OS, but . . .
- They're also pretty different
  - Every machine has its own set of devices
  - It needs device drivers for those specific devices
  - But not for any other devices
  - So a kernel usually doesn't come configured with all possible device drivers
- How drivers are installed and used in an OS is very different than, say, memory management
- More modular and dynamic

Installing and Using Device Drivers

- Loading
  - Load the module, determine device configuration
  - Allocate resources, configure and initialize driver
  - Register interfaces
- Use
  - Open device session (initialize device)
  - Use device (seek/read/write/ioctl/request/...)
  - Process completion interrupts, error handling
  - Close session (clean up device)
- Unloading
  - Free all resources, and unload the driver

Dynamic OS Module Loading and Unloading

- Most OSes can dynamically load and unload their own modules
  - While the OS continues running
- Used to support many plug-in features
  - E.g., file systems, network protocols, device drivers
- The OS includes a run-time linker/loader
  - Linker needed to resolve module-to-OS references
  - There is usually a module initialize entry point
    - That initializes the module and registers its other entry-points
  - There is usually a module finish entry point
    - To free all resources and un-register its entry points

Device Driver Configuration

- Binding a device driver to the hardware it controls
  - May be several devices of that type on the computer
  - Which driver instance operates on which hardware?
- Identifying I/O resources associated with a device
  - What I/O ports, IRQ and DMA channels does it use?
  - Where (in physical space) does its memory reside?
- Assigning I/O resources to the hardware
  - Some are hard-wired for specific I/O resources
  - Most can be programmed for what resources to use
  - Many busses define resource allocation protocols
- Large proportion of driver code is devoted to configuration and initialization

The Static Configuration Option

- We could, instead, build an OS for the specific hardware configuration of its machine
  - Identify which devices use which I/O resources
  - OS can only support pre-configured devices
  - Rebuild to change devices or resource assignments
- Drivers may find resources in system config table
  - Eliminates the need to recompile drivers every time
- This was common many years ago
  - Too cumbersome for a modern commercial OS
  - Still done for some proprietary/micro/real-time OSs

Dynamic Device Discovery

- How does a driver find its hardware?
  - Which is typically sitting somewhere on an I/O bus
- Could use probing (peeking and poking)
  - Driver reserves ports/IRQs and tries talking to them
  - See if they respond like the expected device
  - Error-prone & dangerous (may wedge device/bus)
- Self-identifying busses
  - Many busses define device identification protocols
  - OS selects device by geographic (e.g. slot) address
  - Bus returns description (e.g. type, version) of device
    - May include a description of needed I/O resources
    - May include a list of assigned I/O resources

Configuring I/O Resources

- Driver must obtain I/O resources from the OS
  - OS manages ports, memory, IRQs, DMA channels
  - Some may be assigned exclusively (e.g., I/O ports)
  - Some may be shared (e.g., IRQs, DMA channels)
- Driver may have to program bus and device
  - To associate I/O resources with the device
- Driver must initialize its own code
  - Which I/O ports correspond to which instances
  - Bind appropriate interrupt handlers to assigned IRQs
  - Allocate & initialize device/request status structures

Using Devices and Their Drivers

- Practical use issues
- Achieving good performance in driver use

Device Sessions

- Some devices are serially reusable
  - Processes use them one at a time, in turn
  - Each using process opens and closes a *session* with the device
  - Opener may have to wait until previous process closes
- Each session requires initialization
  - Initialize & test hardware, make sure it is working
  - Initialize session data structures for this instance
  - Increment open reference count on the instance
- Releasing references to a device
  - Shut down instance when last reference closes

Shared Devices and Serialization

- Device drivers often contain sharable resources
  - Device registers, request structures, queues, etc.
  - Code that updates them will contain critical sections
- Use of these resources must be serialized
  - Serialization may be coarse (one open at a time)
  - Serialization may be very fine grained
  - This can be implemented with locks or semaphores
- Serialization is usually implemented within driver
  - Callers needn't understand how locking works

Interrupt Disabling For Device Drivers

- Locking isn't protection against interrupts
  - Remember the sleep/wakeup race?
  - What if interrupt processing requires an unavailable lock?
- Drivers often share data with interrupt handlers
  - Device registers, request structures, queues, etc.
- Some critical sections require interrupt disabling
  - Which is dangerous and can cause serious problems
  - Where possible, do updates with atomic instructions
  - Disable only the interrupts that could conflict
  - Make the disabled period as brief as possible

Performance Issues for Device Drivers

- Device utilization
- Double buffering and queueing I/O requests
- Handling unsolicited input
- I/O and interrupts

Device Utilization

- Devices (and their drivers) are mainly responsive
- They sit idle until someone asks for something
- Then they become active
- Also periods of overhead between when process wants device and it becomes active
- The result is that most devices are likely to be idle most of the time
  - And so are their device drivers

So What?

- Why should I care if devices are being used or not?
- Key system devices limit system performance
  - File system I/O, swapping, network communication
- If device sits idle, its throughput drops
  - This may result in lower system throughput
  - Longer service queues, slower response times
- Delays can disrupt real-time data flows
  - Resulting in unacceptable performance
  - Possible loss of irreplaceable data
- It is very important to keep key devices busy
  - Start request $n+1$ immediately when n finishes

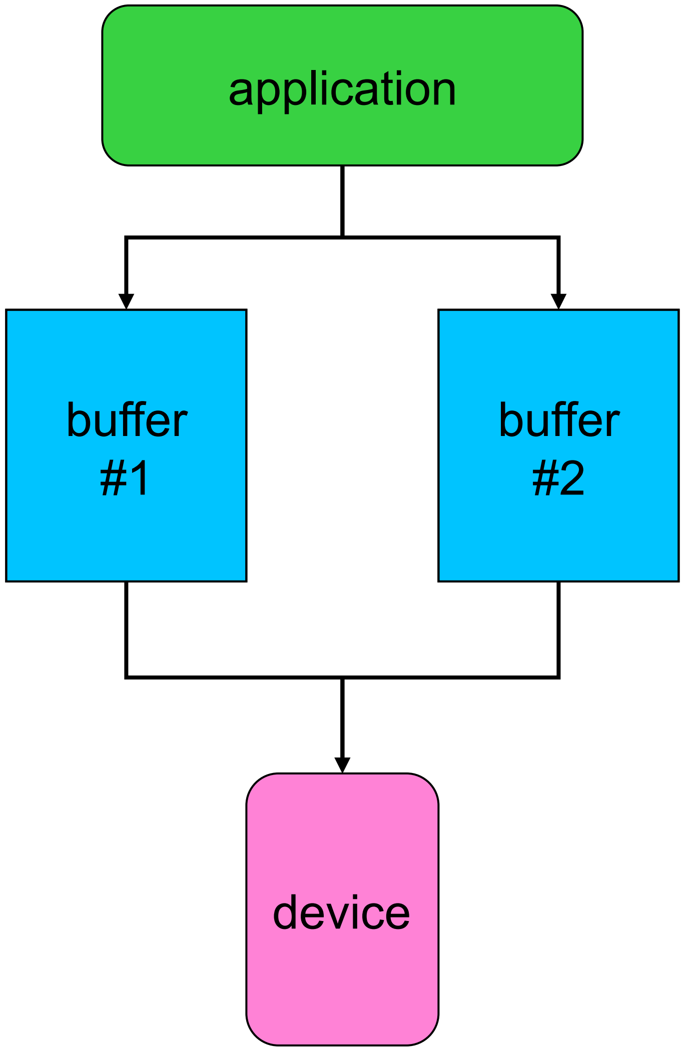
Keeping Key Devices Busy

- Allow multiple pending requests at a time
  - Queue them, just like processes in the ready queue
  - Requesters block to await eventual completions
- Use DMA to perform the actual data transfers
  - Data transferred, with no delay, at device speed
  - Minimal overhead imposed on CPU
- When the currently active request completes
  - Device controller generates a completion interrupt
  - Interrupt handler posts completion to requester
  - Interrupt handler selects and initiates next transfer

Double Buffering For Device Output

- Have multiple buffers queued up, ready to write
  - Each write completion interrupt starts the next write
- Application and device I/O proceed in parallel
  - Application queues successive writes
    - Don’t bother waiting for previous operation to finish
  - Device picks up next buffer as soon as it is ready
- If we're CPU-bound (more CPU than output)
  - Application speeds up because it doesn't wait for I/O
- If we're I/O-bound (more output than CPU)
  - Device is kept busy, which improves throughput
  - But eventually we may have to block the process

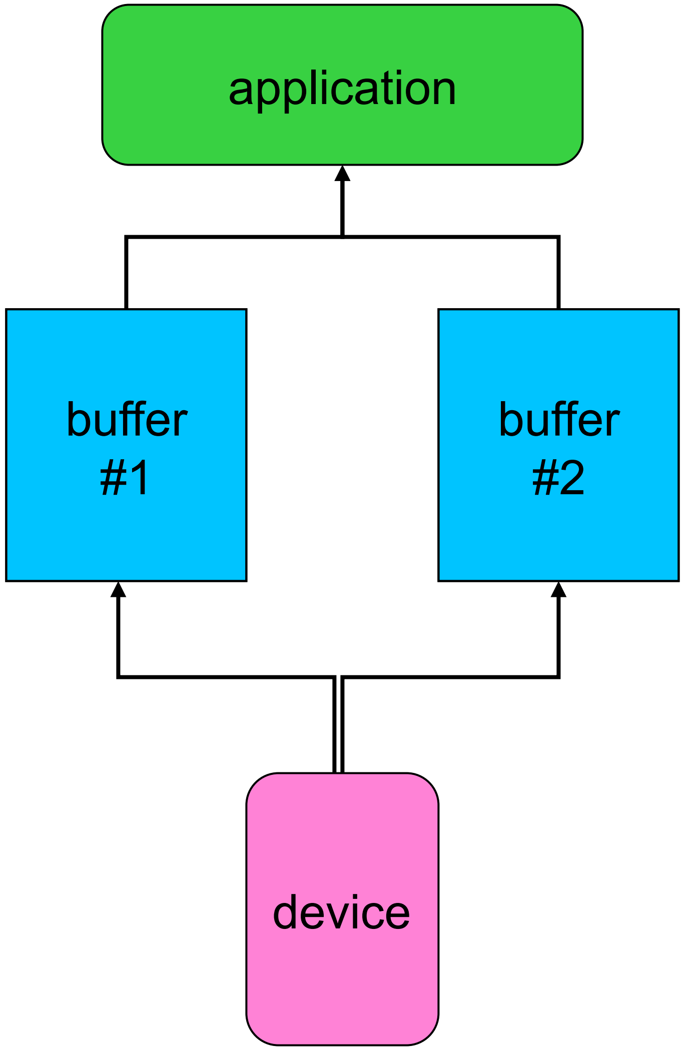
Double-Buffered Output



Double Buffering For Input

- Have multiple reads queued up, ready to go
  - Read completion interrupt starts read into next buffer
- Filled buffers wait until application asks for them
  - Application doesn't have to wait for data to be read
- Can use more than two buffers, of course
- When can we do read queueing?
  - Each app will probably block until its read completes
    - So we won’t get multiple reads from one application
  - We can queue reads from multiple processes
  - We can do predictive read-ahead

Double Buffered Input



Handling I/O Queues

- What if we allow a device to have a queue of requests?
  - Key devices usually have several waiting at all times
  - In what order should we process queued requests?
- Performance based scheduling
  - Elevator algorithm head motion scheduling for disks
- Priority based scheduling
  - Handle requests from higher priority processes first
- Quality-of-service based scheduling
  - Guaranteed bandwidth share
  - Guaranteed response time

Solicited Vs. Unsolicited Input

- In the write case, a buffer is always available
  - The writing application provides it
- Is the same true in the read case?
  - Some data comes only in response to a read request
    - E.g., disks and tapes
  - Some data comes at a time of its own choosing
    - E.g., networks, keyboards, mice
- What to do when unexpected input arrives?
  - Discard it? … probably a mistake
  - Buffer it in anticipation of a future read
  - Can we avoid exceeding the available buffer space?
    - Slow devices (like keyboards) or flow-controlled networks

I/O and Interrupts

- I/O devices work largely asynchronously
- The CPU doesn't know when they will finish their work
  - Or provide new input
- So they make extensive use of interrupts
- But handling interrupts usually involves turning other interrupts off
  - We want limited processing in an interrupt handler
- What if the I/O involves complex stuff, like routing packets, handling queues, etc.?

Top-End/Bottom-End Interrupt Handling

- Divide the work necessary to service the interrupt into two parts
- The top-end does the urgent stuff quickly
  - Hardware-related stuff
  - Then it schedules the bottom-end
- The bottom-end does everything else eventually
  - At lower priority and with interrupts not disabled
  - Essentially, do more work when there's time for it
- But how can we schedule something that isn't a process?

Scheduling Bottom End Processing

- Most OSes support scheduled kernel-mode calls
  - Solaris: soft interrupts, Linux: tasks, NT: DPCs
  - They are just calls, they have no process context
  - They are preemptable, run with interrupts enabled
  - Higher priority than any scheduled process
- They can be scheduled
  - E.g., at a specified time, ASAP, after some event
  - They are used for completion processing
  - They are used for timing out operations
  - They can also be cancelled