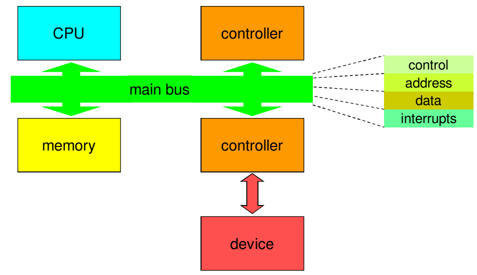
Device I/O

- 10A I/O Architectures
- 10B I/O Mechanisms
- 10C Disks
- 10D Low-Level I/O Techniques
- 10E Higher Level I/O Techniques
- 10I Polled and non-blocking I/O
- 10J User-Mode Asynchronous I/O
- 10U User-Mode Device Drivers

I/O architectures: busses



Memory type busses

- Initially back-plane memory-to-CPU interconnects
  - a few “bus masters”, and many “slave devices”
  - arbitrated multi-cycle bus transactions
    - request, grant, address, respond, transfer, ack
    - operations: read, write, read/modify/write, interrupt
- originally most busses were of this sort
  - ISA, EISA, PCMCIA, PCI, cPCI, video busses, ...
  - distinguished by
    - form-factor, speed, data width, hot-plug, maximum length, ...
    - bridging, self identifying, dynamic resource allocation, …

TERMS: Bus Arbitration & Mastery

- bus master
  - any device (or CPU) that can request the bus
  - one can also speak of the “current bus master”
- bus slave
  - a device that can only respond to bus requests
- bus arbitration
  - process of deciding to whom to grant the bus
    - may be based on time, geography or priority
    - may also clock/choreograph steps of bus cycles
    - bus arbitrator may be part of CPU or separate

Network type busses

- evolved as peripheral device interconnects
  - SCSI, USB, 1394 (firewire), Infiniband, ...
  - cables and connectors rather than back-planes
  - designed for easy and dynamic extensibility
  - originally slower than back-plane, but no longer
- much more similar to a general purpose network
  - packet switched, topology, routing, node identity
  - may be master/slave (USB) or peer-to-peer (1394)
  - may be implemented by controller or by host

I/O architectures: devices & controllers

- I/O devices
  - peripheral devices that interface between the computer and other media (disks, tapes, networks, serial ports, keyboards, displays, pointing devices, etc.)
- device controllers connect a device to a bus
  - communicate control operations to device
  - relay status information back to the bus
  - manage DMA transfers for the device
  - generate interrupts for the device
- controller usually specific to a device <u>and</u> a bus

Device Controller Registers

- device controllers export registers to the bus
  - registers in controller can be addressed from bus
  - writing into registers controls device or sends data
  - reading from registers obtains data/status
- register access method varies with CPU type
  - may require special instructions (e.g. x86 IN/OUT)
    - privileged instructions restricted to supervisor mode
  - may be mapped onto bus like memory
    - accessed with normal (load/store) instructions
    - I/O address space not accessible to most processes

A simple device: 16550 UART

offset				*contents*					*Register*
0	x	x	x	x	x	x	x	x	Data Register
1					MDM	STS	XMT	RCV	Interrupt Enable Register
2					MDM	STS	XMT	RCV	Interrupt Register
3	speed	BRK		PARITY		STOP	WORDLEN		Line Control Register
4							DTR	RTS	Modem Control Register
5	RCV	EMT	XMT	BRK	FER	PER	OVR	RER	Line Status Register
6					DCD	RI	DSR	CTS	Modem Status Register

A 16550 presents seven 8-bit registers to the bus.

All communication between the bus and the device (send data, receive data, status and control) is performed by reading from, and writing to these registers.

(16550 UART registers)

- 0: data – read received byte, write to transmit a byte
  - (or LSB of speed divisor when speed set is enabled)
- 1: interrupt enables – for transmit done, data received, cd/ring
  - (or MSB of speed divisor when speed set is enabled)
- 2: interrupt registers – currently pending interrupt conditions
- 3: line control register – character length, parity and speed
- 4: modem control register – control signals sent by computer
- 5: line status register – xmt/rcv completion and error conditions
- 6: modem status registers – received modem control signals

Scenario: direct I/O with polling

```
uart_write_char( char c ) {
    while( (inb(UART_LSR) & TR_DONE) == 0);
    outb( UART_DATA, c );
}
char uart_read_char() {
    while( (inb(UART_LSR) & RX_READY) == 0);
    return( inb(UART_DATA) );
}
```


(mechanisms: direct polled I/O)

- all transfers happen under direct control of CPU
  - CPU transfers data to/from device controller registers
  - transfers are typically one byte or word at a time
  - may be accomplished with normal or I/O instructions
- CPU polls device until it is ready for data transfer
  - received data is available to be read
  - previously initiated write operations are completed
- advantages
  - very easy to implement (both hardware and software)

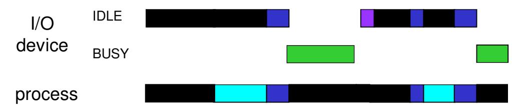
performance of direct I/O

- CPU intensive data transfers
  - each byte/word requires mutiple instructions
- CPU wasted while awaiting completion
  - busy-wait polling ties up CPU until I/O is completed
- devices are idle while we are running other tasks
  - I/O can only happen when an I/O task is running
- how can these problems be dealt with
  - let controller transfer data without attention from CPU
  - let application block pending I/O completion
  - let controller interrupt CPU when I/O is finally done

importance of good device utilization

- 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

Poor I/O device Utilization



1. process waits to run
2. process does computation in preparation for I/O operation
3. process issues read system call, blocks awaiting completion
4. device performs requested operation
5. completion interrupt awakens blocked process
6. process runs again, finishes read system call
7. process does more computation
8. Process issues read system call, blocks awaiting completion

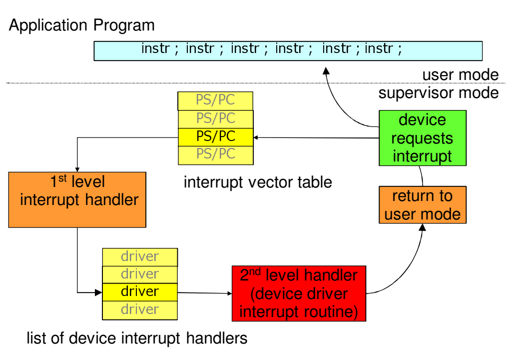
Direct Memory Access

- bus facilitates data flow in all directions between
  - CPU, memory, and device controllers
- CPU can be the bus-master
  - initiating data transfers w/memory, device controllers
- device controllers can also master the bus
  - CPU instructs controller what transfer is desired
    - what data to move to/from what part of memory
  - controller does transfer w/o CPU assistance
  - controller generates interrupt at end of transfer

I/O Interrupts

- device controllers, busses, and interrupts
  - busses have ability to send interrupts to the CPU
  - devices signal controller when they are done/ready
  - when device finishes, controller puts interrupt on bus
- CPUs and interrupts
  - interrupts look very much like traps
    - traps come from CPU, interrupts are caused externally
  - unlike traps, interrupts can be enabled/disabled
    - a device can be told it can or cannot generate interrupts
    - special instructions can enable/disable interrupts to CPU
    - interrupt may be held *pending* until s/w is ready for it

Interrupt Handling



Keeping Key Devices Busy

- allow multiple requests pending 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
  - <u>interrupt handler selects and initiates next transfer</u>

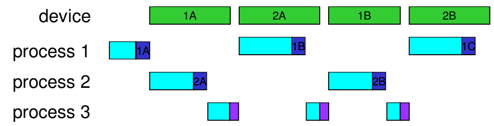
Interrupt Driven Chain Scheduled I/O

```
xx_read/write() {
    allocate a new request descriptor
    fill in type, address, count, location
    insert request into service queue
    if (device is idle) {
        disable_device_interrupt();
        xx_start();
        enable_device_interrupt();
    }
    await completion of request
    extract completion info for caller
}

xx_start() {
    get next request from queue
    get address, count, disk address
    load request parameters into controller
    start the DMA operation
    mark device busy
}

xx_intr() {
    extract completion info from controller
    update completion info in current req
    wakeup current request
    if (more requests in queue)
        xx_start()
    else
        mark device idle
}
```


Multi-Tasking & Interrupt Driven I/O



1. P_1 runs, requests a read, and blocks
2. P_2 runs, requests a read, and blocks
3. P_3 runs until interrupted
4. Awaken P_1 and start next read operation
5. P_1 runs, requests a read, and blocks
6. P_3 runs until interrupted
7. Awaken P_2 and start next read operation
8. P_2 runs, requests a read, and blocks
9. P_3 runs until interrupted
10. Awaken P_1 and start next read operation
11. P_1 runs, requests a read, and blocks

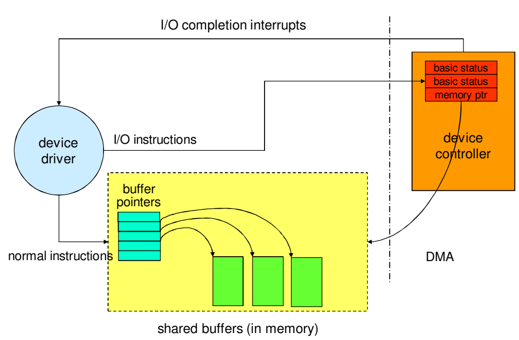
mechanisms: memory mapped I/O

- DMA may not be the best way to do I/O
  - designed for large contiguous transfers
  - some devices have many small sparse transfers
    - e.g. consider a video game display adaptor
- implement as a bit-mapped display adaptor
  - 1Mpixel display controller, on the CPU memory bus
  - each word of memory corresponds to one pixel
  - application uses ordinary stores to update display
- low overhead per update, no interrupts to service
- relatively easy to program

Trade-off: memory mapped vs. DMA

- DMA performs large transfers efficiently
  - better utilization of both the devices and the CPU
    - device doesn't have to wait for CPU to do transfers
  - but there is considerable per transfer overhead
    - setting up the operation, processing completion interrupt
- memory-mapped I/O has no per-op overhead
  - but every byte is transferred by a CPU instruction
    - no waiting because device accepts data at memory speed
- DMA better for occasional large transfers
- memory-mapped better frequent small transfers
- memory-mapped devices more difficult to share

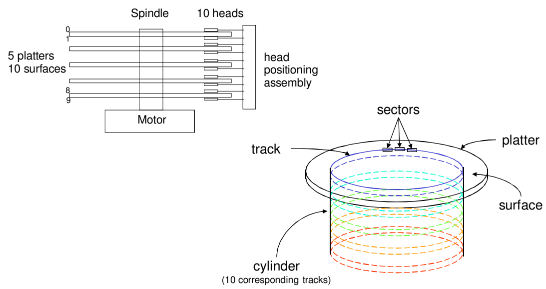
Smart Device Controller



(I/O Mechanisms: smart controllers)

- Smarter controlers can improve on basic DMA
- they can queue multiple input/output requests
  - when one finishes, automatically start next one
  - reduce completion/start-up delays
  - eliminate need for CPU to service interrupts
- they can relieve CPU of other I/O responsibilities
  - request scheduling to improve perormance
  - they can do automatic error handling & retries
- abstract away details of underlying devices

Disk Drives and Geometry



(Disk drive geometry)

- spindle
  - a mounted assembly of circular platters
- head assembly
  - read/write head per surface, all moving in unison
- track
  - ring of data readable by one head in one position
- cylinder
  - corresponding tracks on all platters
- sector
  - logical records written within tracks
- disk address = <cylinder / head / sector >

Disks have Dominated File Systems

- fast swap, file system, database access
- minimize seek overhead
  - organize file systems into cylinder clusters
  - write-back caches and deep request queues
- minimize rotational latency delays
  - maximum transfer sizes
  - buffer data for full-track reads and writes
- we accepted poor latency in return for IOPS

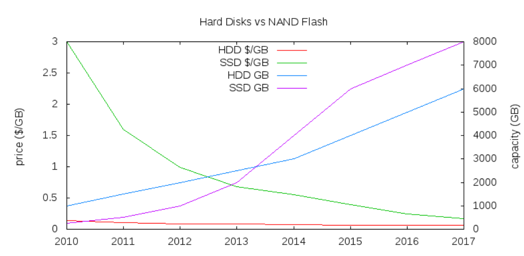
(Optimizing disk performance)

- don't start I/O until disk is on-cyl/near sector
  - I/O ties up the controller, locking out other operations
  - other drives seek while one drive is doing I/O
- minimize head motion
  - do all possible reads in current cylinder before moving
  - make minimum number of trips in small increments
- encourage efficient data requests
  - have lots of requests to choose from
  - encourage cylinder locality
  - encourage largest possible block sizes

Disk vs SSD Performance

	Cheeta (archival)	Barracuda (high perf)	Extreme/Pro (SSD)
RPM	7,000	15,000	n/a
average latency	4.3ms	2ms	n/a
average seek	9ms	4ms	n/a
transfer speed	105MB/s	125MB/s	540MB/s
sequential 4KB read	39us	33us	10us
sequential 4KB write	39us	33us	11us
random 4KB read	13.2ms	6ms	10us
random 4KB write	13.2ms	6ms	11us

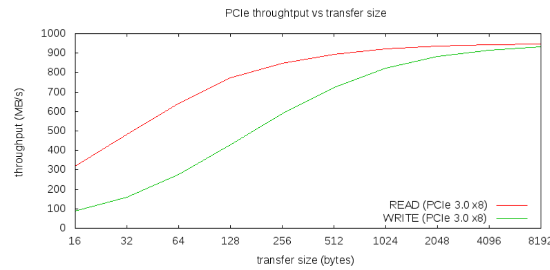
Random Access: Game Over



The Changing I/O Landscape

- Storage paradigms
  - old: swapping, paging, file systems, data bases
  - new: NAS, distributed object/key-value stores
- I/O traffic
  - old: most I/O was disk I/O
  - new: network and video dominate many systems
- Performance goals:
  - old: maximize throughput, IOPS
  - new: low latency, scalability, reliability, availability

Bigger Transfers are Better



(Bigger Transfers are Better)

- disks have high seek/rotation overheads
  - larger transfers amortize down the cost/byte
- all transfers have per-operation overhead
  - instructions to set up operation
  - device time to start new operation
  - time and cycles to service completion interrupt
- larger transfers have lower overhead/byte
  - this is not limited to s/w implementations

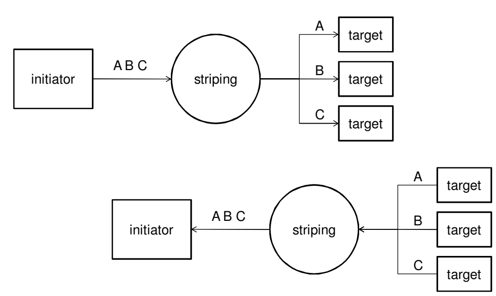
Input/Output Buffering

- Fewer/larger transfers are more efficient
  - they may not be convenient for applications
  - natural record sizes tend to be relatively small
- Operating system can buffer process I/O
  - maintain a cache of recently used disk blocks
  - accumulate small writes, flush out as blocks fill
  - read whole blocks, deliver data as requested
- Enables read-ahead
  - OS reads/caches blocks not yet requested

Deep Request Queues

- Having many I/O operations queued is good
  - maintains high device utilization (little idle time)
  - reduces mean seek distance/rotational delay
  - may be possible to combine adjacent requests
- Ways to achieve deep queues:
  - many processes making requests
  - individual processes making parallel requests
  - read-ahead for expected data requests
  - write-back cache flushing

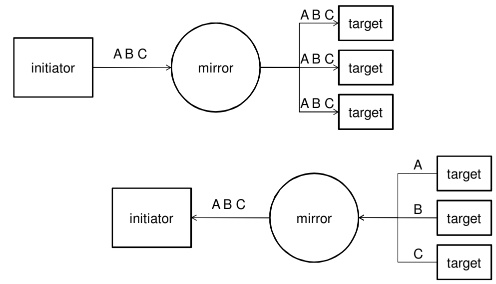
Data Striping for Bandwidth



(Data Striping for Bandwidth)

- spread requests across multiple targets
  - increased aggregate throughput
  - fewer operations per second per target
- used for many types of devices
  - disk or server striping
  - NIC bonding
- potential issues
  - more/shorter requests may be less efficient
  - source can generate many parallel requests
  - striping agent throughput is the bottleneck

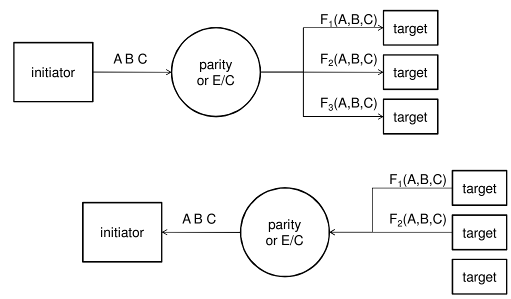
Data Mirroring for Reliability



(Data Mirroring for Reliability)

- mirror writes to multiple targets
  - redundancy in case a target fails
  - spread reads across multiple targets
    - increased aggregate throughput, reduced ops/target
- used for all types of persistent storage
  - disks, NAS, distributed key/value stores
- potential issues
  - added write traffic on the source
  - 2x-3x storage requirements on targets
  - deciding which (conflicting) copy is correct

Parity/Erasure Coding for Efficiency



(Parity/Erasure Coding for Efficiency)

- N out of M encoding (with M/N overhead)
  - accumulate N writes from source
  - compute M versions of that collection
  - send a version to each of M targets
- Advantages
  - reduced overhead for higher redundancy
  - rotating parity reduces bottleneck
- Potential issues
  - greatly increased source computational load
  - <u>deferred writes</u> for parity block accumulation
  - expensive updates, recovery (and EC reads)
  - choosing the right ratio

Error Detection/Correction Terms

- Parity
  - typically one bit per byte, detect single-bit errors
  - used as redundancy, it can recover one lost bit/block
- Cyclical Redundancy Check (CRC)
  - multiple bits per record, detect multi-bit burst errors
- Error Correcting Coding (ECC)
  - fixed ratio, capable of detection and correction
  - e.g. Reed-Soloman (204,188) can correct 8 bad bits
- Erasure Coding (distributed Reed-Soloman)
  - transforms K blocks into N (>K)
  - all can be recovered from <u>any K</u> (of those N) blocks

Parallel I/O Paradigms

- Busy, but periodic checking just in case
  - new input might cause a change of plans
- Multiple semi-independent streams
  - each requiring relatively simple processing
- Multiple semi-independent operations
  - each requiring multiple, potentially blocking steps
- Many balls in the air at all times
  - numerous parallel requests from many clients
  - keeping I/O queues full to improve throughput

Enabling Parallel Operations

- Threads are an obvious solution
  - one thread per-stream or per-request
  - streams or requests are handled in parallel
  - when one thread blocks, others can continue
- There are other parallel I/O mechanisms
  - non-blocking I/O
  - multi-channel poll/select operations
  - asynchronous I/O

Non-Blocking I/O

- check to see if data/room is available
  - but do not block to wait for it
  - this enables parallelism, prevents deadlocks
- a file can be opened in a non-blocking mode
  - open(name, flags | O_NONBLOCK)
  - fcntl(fd, F_SETFL, flags | O_NONBLOCK)
- if data is available, *read(2)* will return it
  - otherwise it fails with EWOULDBLOCK
- can also be used with *write(2)* and *open(2)*

Multi-Channel Poll/Select

- there are multiple possible input sources
  - parallel streams (e.g. ssh input/output)
  - multiple request generating clients
- *poll(2)*/*select(2)* wait for first interesting event
  - a list of file descriptors to be checked
  - a list of interesting events (input, output, error)
  - a maximum time to wait
  - a signal mask (to use while waiting)
- do read/write on indicated file descriptor(s)

Worker Threads

- Consider a web or remote file system server
  - it receives thousands of requests/second
  - each requires multiple (blocking) operations
  - create a thread to serve each new request
- Thread creation is relatively expensive
  - continuous creation/destruction seems wasteful
  - solution: recycle the worker threads
    - thread blocks when its operation finishes
    - it is awakened when a new operation needs servicing
- we still have switching and synchronization

NBIO vs. Poll/Select vs. Threads

- NBIO … very simple
  - occasional checks for unlikely input
  - cost of wasted spins is not a concern
- Poll/Select … efficient multi-stream processing
  - multiple sources of interesting input/event
  - wait for the first available, serve one at a time
- Parallel Threads … for complex operations
  - all can operations proceed in parallel, not just I/O
  - blocking operation does not block other threads
- None are practical for massive parallelism

Asynchronous I/O

- Huge numbers of parallel I/O operations
  - many parallel clients w/many parallel requests
  - deep I/O queues to improve throughput
  - make sure completions processed correctly
- thread per operation is too expensive
- we want to queue many parallel operations
  - receive asynchronous completion notifications
  - OS has always handled high traffic I/O this way
  - increasingly many applications now do as well

Scheduling Asynchronous I/O

int aio_read(struct aiocb *)

```
struct aiocb {
   int  aio_filedes;   // file descriptor
   off_t   aio_offset;   // file offset
   void   *aio_buf;  // local buffer
   int  aio_nbytes;   // byte count
   int  aio_reqprio;  // request priority
   sigevent aio_sigevent;   // notification method
}
```

- if successful, operation has been queued
  - it will complete at some time in the future
- a very large number of ops can be outstanding

Asynchronous Completion

- we can poll the status of any operation
  int aio_error(struct aiocb *)
  int aio_return(struct aiocb *)
  - returns 0, EINPROGRESS, or completion error
- we can await completion of some opeations
  int aio_suspend(struct aiocb *, items, timeout)
  - returns when one or more complete (or timeout)
- we can cancel or force any operations
  int aio_cancel(struct aiocb *)
  int aio_fsync(fd)

Completion Notifications

```
struct sigevent {
   int sigev_notify;   // by signal or thread
   int sigev_signo;   // notification signal #
   int sigev_value;   // param to signal handler
   void (*handler)(int);  // handler to invoke
   …
```

- user-mode analog of completion interrupts
  - completion generates a specified signal
  - completion creates a specified thread

Signals for Event Notifications

- Signals were originally designed for exceptions
  - infrequent events, most often fatal
  - multiple race conditions in handling/disabling
  - bad semantics were “good enough”
- Now they are used for event notifications
  - continuous events in normal operation
  - loss of even a single event is unacceptable
  - they need to be safe and reliable
- We have long known how to do this properly
  - make them more like h/w interrupts

sigaction(2)

int sigaction (int signum, sigaction *new, sigaction *old)

```
struct sigaction {
   void (*handler)(int);      // handler
   void (*action)(int, siginfo); // handler
   sigset_t  mask;        // signals to block
   int     flags;     // handling options
```

- mask eliminates reentrancy races
- siginfo passes much info about cause of signal
- *sigreturn(2)* controls return from handler

Asynchronous I/O: Back to the Future

- OS I/O always asynchronous, interrupt driven
  - necessary to achieve throughput and efficiency
  - apps were given comforting synchronous illusion
    until they needed major throughput and efficiency
- simpler, more s/w-like mechanisms were tried
  - they were much less efficient
  - they proved race-prone under heavy use
- h/w interrupt model is refined, well proven
  - if there was a simpler way, we would be using it
  - the same model works well for s/w too

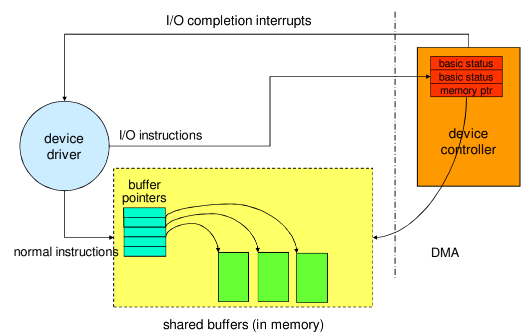
User-Mode Drivers: Why?

- Kernel-mode code is brittle
  - if it crashes, it takes the OS with it
- Kernel-mode code is hard to build and test
  - correctness rules are extremely complex
  - debugging tools are relatively crude
- Kernel-mode code is hard to upgrade
  - often necessary to reboot the system
- Kernel-mode code is not necessarily fast
  - system calls and interrupts are very expensive
  - processes can be pinned to memory and cores

User-Mode Drivers: How?

- Doesn't I/O require privileged instructions?
  - many ISAs allow user-mode I/O to limited ports
  - I/O space may be mapped into user address space
- Doesn't I/O require access to DMA controller?
  - some devices (e.g. graphics) don't need DMA
  - smart devices have on-board DMA controllers
    all DMA is done to/from device-owned memory
- Doesn't I/O require interrupt handling?
  - smart devices have request queues, polled status

Smart Device Controller



User-Mode Drivers: Security?

- There is lots of trusted user-mode code
  - init, login, mail delivery, network protocols, …
  - there are even user-mode file systems
- Accessing I/O space is a privileged operation
  - it can be restricted to specific (privileged) UIDs
  - only a few programs can run w/those UIDs
  - file system security protects those programs
- Privileged User-mode code can be trusted
  - and safer than loadable kernel modules

User-Mode Drivers: Limitations

- They cannot use kernel services or data
  - they are ordinary user-mode programs
  - they do not execute in kernel mode
  - they do not run in kernel address space
- They open a driver to access the device
  - driver maps I/O device into process address space
  - driver handles configuration, interrupts, errors
- They cannot service interrupts
  - they must poll for asynchronous completions
  - but they may get signals for asynchronous errors

Assignments

- For Next Lecture
  - AD 39 Files
  - AD 40 File Systems
  - File Types
  - Key-Value Stores (intro, types)
  - Object Storage (history, architectures)
  - FAT File Systems
  - FUSE (intro)
- Project 4B … talk to your sensors ASAP

Supplementary Slides

Device Drivers: where they fit in

- They meet the requirements for kernel code:
  - privileged instructions, kernel structures, trust
- Not entirely part of the Operating System
  - most OS code is device-independent
  - although the OS does depend on some devices
- Drivers are often after-market additions
  - built by device manufacturers
  - down-loaded when new devices are added

Drivers – plug-in modules

- each driver supports a particular device
  - automatic discovery and configuration
  - implements a standard set of operations
- they can be dynamically loaded/unloaded
  - making them easy to add and upgrade
  - they tend to be highly compartmentalized
  - using only a small number of kernel services
- when loaded, they become part of the OS
  - making correctness/security a key consideration
  - some run drivers in a “sand-box” or user-mode

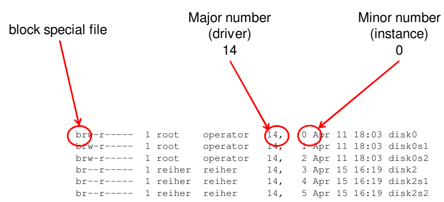
Drivers – simplifying abstractions

- encapsulate knowledge of how to use 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
- encapsulation of fault handling
  - knowledge of how to handle recoverable faults
  - prevent device faults from becoming OS faults

Drivers – generalizing abstractions

- 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
- software analog to h/w device controllers
  - device drivers connect a device controller to an OS

Special Files



(UNIX: special files)

- how does one open an instance of a device
  - like everything else, by opening some named file
- 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
- opening special file opens the associated device
  - open/close/read/write/etc calls map into calls to the appropriate DDI entry-points of the selected driver

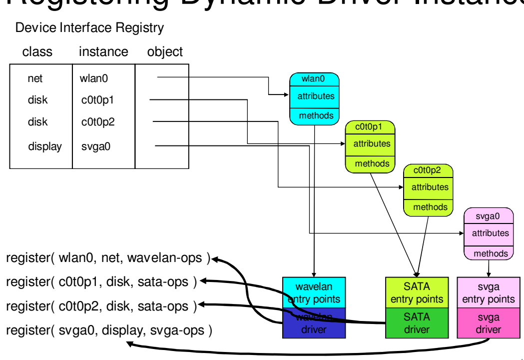
UNIX: block and character Devices

- block devices ... used for file systems
  - random access devices, accessible block at a time
  - support queued, asynchronous reads and writes
  - accessed through an LRU buffer cache
- character devices ... anything else
  - may be either stream or record structured
  - may be sequential or random access
  - support direct, synchronous reads and writes
- all other device sub-classes derive from these

UNIX: device instances

- minor device # is an instance under a driver
  - meaning of minor number is entirely driver-specific
- instances may be physically distinct
  - e.g. different serial ports, different disk drives
- instances may refer to multiplexed sub-devices
  - e.g. one of four FDISK partitions on a hard disk
  - e.g. a sub-channel on a communications interface
- instances may merely select different options
  - e.g. enable rewind-on-close for a tape drive
  - e.g. different densities for diskettes

Registering Dynamic Driver Instances



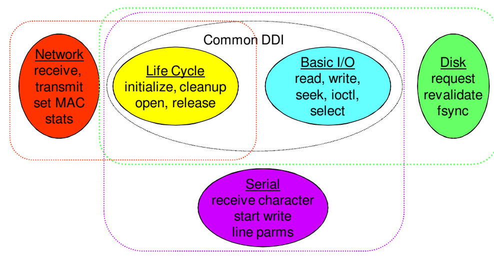
(driver instance/interface registration)

- driver must register each device instance
  - register name, class, and instance # of device
  - so programs will know that instance is available
- register driver methods for accessing that device
  - driver advertises its entrypoints for all methods
    - which methods depend on the class and driver
  - enables other s/w to use device instance/call driver
- OS includes services to register and un-register
  - e.g. register_chrdev(major ID, minor ID, operations)
  - create special file for accessing device instance

Device Driver Interface (DDI)

- standard (top-end) device driver entry-points
  - basis for device independent applications
  - enables system to exploit new devices
  - a critical interface contract for 3rd party developers
- some correspond directly to system calls
  - e.g. open, close, read, write
- some are associated w/OS frameworks
  - disk drivers are meant to be called by block I/O
  - network drivers are meant to be called by protocols

DDIs and sub-DDIs



(General DDI entry points (Linux))

- Standard entry points, supported by 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

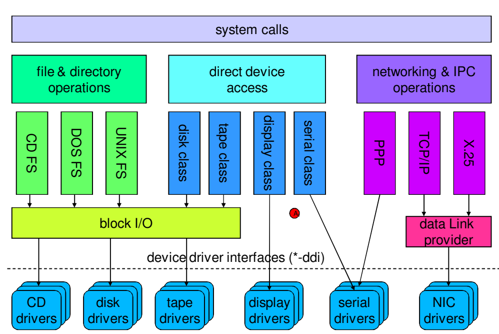
(sub-DDI – block devices (linux))

- 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

(sub-DDI – network devices (linux))

- includes wide range of networking technologies
  - ethernet, token-ring, wireless, infra-red, ...
- drivers provide only basic transport/control
  - protocols are 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

Standard Driver Classes & Clients



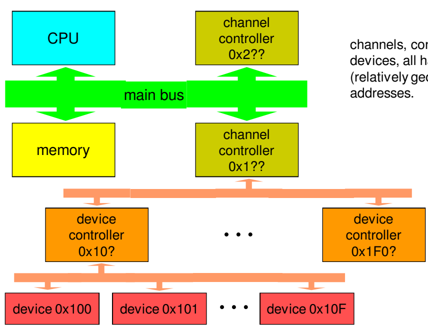
Criticality of Stable Interfaces

- Drivers are independent from the OS
  - they are built by different organizations
  - they are not co-packaged with the OS
- OS and drivers have interface dependencies
  - OS depends on driver implementations of DDI
  - drivers depends on kernel DKI implementations
- These interfaces must be carefully managed
  - well defined and well tested
  - upwards-compatible evolution

Channels – I/O co-processors

- Channels sit between CPU and I/O devices
  - think of them as extremely smart busses
- the include highly specialized CPUs
  - they execute channel I/O programs
    - instructions to read, write and control devices
    - instructions to generate progress interrupts
- once started, I/O pgms execute w/o CPU attention
  - command chaining, from one command to the next
  - data chaining, from one buffer to the next

Typical Channel Architecture



channels, controllers, and devices, all have assigned (relatively geographic) addresses.

Typical Channel Program

Main CPU Program	Channel Program (can execute one per controller)
Device driver	
SIO 0x1C2 iopgm	iopgm: SEEK cyl=1020 hd=5 rec=10
…	READ buf=xxx, cnt=4096
	READX buf=yyy, cnt=4096, IR
Interrupt handler	TIC next
TIO 0x1C2	
	next: SEEK cyl=1050, hd=0, rec=2
…	WRITE buf=zzz, cnt=8192, IR
	END intr

Devices and Busses

- Devices are not connected directly to the CPU
- Both CPU and devices are connected to a bus
- Sometimes the same bus, sometimes a different bus
- Devices communicate with CPU across the bus
- Bus used both to send/receive interrupts and to transfer data and commands
  - Devices signal controller when they are done/ready
  - When device finishes, controller puts interrupt on bus
  - Bus then transfers interrupt to the CPU
  - Perhaps leading to movement of data

Devices and Interrupts

- Devices are primarily interrupt-driven
  - Drivers aren't schedulable processes
- They work at different speed than the CPU
  - Typically slower
- They can do their own work while CPU does something else
- They use interrupts to get the CPU's attention

Head Travel w/various algorithms

First Come First Served

76	124	17	269	201	29	137	12
48	107	252	68	172	108	125	

total head motion: 880 cylinders

Shortest Seek First

76	29	17	12	124	137	201	269
47	12	5	112	13	64	68	

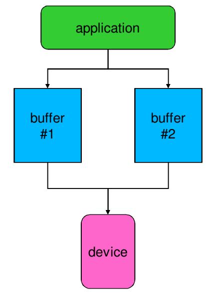
total head motion: 321 cylinders

Scan/Look (elevator algorithm)

76	124	137	201	269	29	17	12
48	13	64	68	240	12	5	

total head motion: 450 cylinders

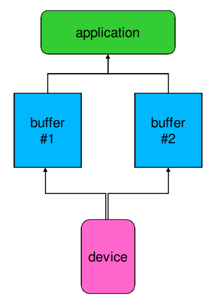
Double-Buffered Output



(double-buffered output)

- multiple buffers queued up, ready to write
  - each write completion interrupt starts 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 Input



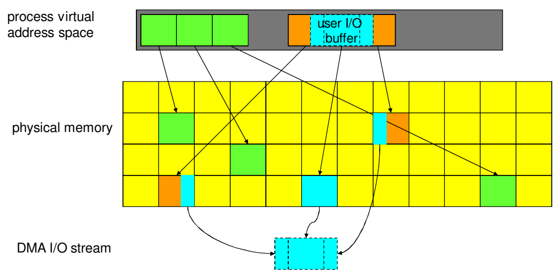
(double buffered input)

- 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
- when can we do chain-scheduled reads?
  - 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

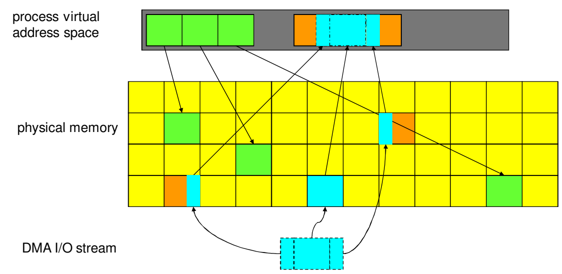
Scatter/Gather I/O

- many controllers support DMA transfers
  - entire transfer must be contiguous in physical memory
- user buffers are in paged virtual memory
  - user buffer may be spread all over physical memory
  - *scatter*: read from device to multiple pages
  - *gather*: writing from multiple pages to device
- three basic approaches apply
  - copy all user data into contiguous physical buffer
  - split logical req into chain-scheduled page requests
  - I/O MMU may automatically handle scatter/gather

"gather" writes from paged memory



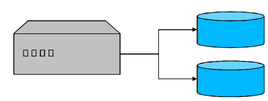
"scatter" reads into paged memory



RAID

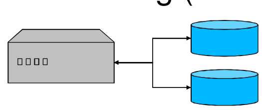
- disks are the weak point of any computer system
  - reliability: disk drives are subject to mechanical wear
    - mis-seeks: resulting in corrupted or unreadable data
    - head crashes: resulting in catastrophic data loss
  - performance: limited seek and transfer speeds
- these limitations are inherent in the technology
  - moving heads and rotating media
- don't try to build super-fast or reliable disks
  - build Redundant Array of Independent Disks
  - combine multiple cheap disks for better performance

Striping (RAID-0)



- combine them to get a larger virtual drive
  - striping: alternate tracks are on alternate physical drives
  - concatenation: 1st 500 cylinders on drive 1, 2nd 500 on drive 2
- benefits
  - increased capacity (file systems larger than a physical disk)
  - read/write throughput (spread traffic out over multiple drives)
- cost
  - increased susceptibility to failure

Mirroring (RAID-1)



- two copies of everything
  - all writes are sent to both disks
  - reads can be satisfied from either disk
- benefits
  - redundancy (data survives failure of one disk)
  - read throughput (can be doubled)
- cost
  - requires twice as much disk

Block-wise Striping w/Parity (RAID-5)

disk 1	disk 2	disk 3	disk 4
1A	1B	1C	XOR 1A-1C
2A	2B	XOR 2A-2C	2C
3A	XOR 3A-3C	3B	3C

- dedicate 1/N[th] of the space to parity
  - write data on N-1 corresponding blocks
  - N[th] block contains XOR of the N-1 data blocks
- benefits
  - data can survive loss of any one drive
  - much more space efficient than mirroring
- cost
  - slower and more complex write performance

RAID implementation

- RAID is implemented in many different ways
  - as part of the disk driver
    - these were the original implementations
  - between block I/O and the disk drivers (e.g. Veritas)
    - making it independent of disks and controllers
  - absorbed into the file system (e.g. zfs)
    - permitting smarter implementation
  - built into disk controllers
    - potentially more reliable
    - significantly off-loads the host OS
    - exploit powerful Storage Area Networking (SAN) fabric

select(2)

int pselect(int nfds, fd_set *readfds, fd_set *writefds, fd_set *exceptfds, struct timeval *timeout, sigset_t *sigmask)

- fd_set is a bit-map of interesting file descriptors
- returns when event, timeout, or signal
- parameters updated to reflect what happened

- Created in 4.2BSD (1983)
  - older, more widely adopted

poll(2)

```
int ppoll( stuct pollfd *fds, int nfds, struct timespec *,
     sigset_t *)
struct pollfd {
     int fd;
     short events;        // requested events
     short revents;    // returned events
}
```

- returns when event, timeout, or signal
- revents reflect what happened

- Created in UNIX SVR3 (1986)
  - newer, perhaps a little better thought out