Input/Output

Today

- Principles of I/O hardware & software
- I/O software layers
- Secondary storage

Next

- File systems

Operating systems and I/O

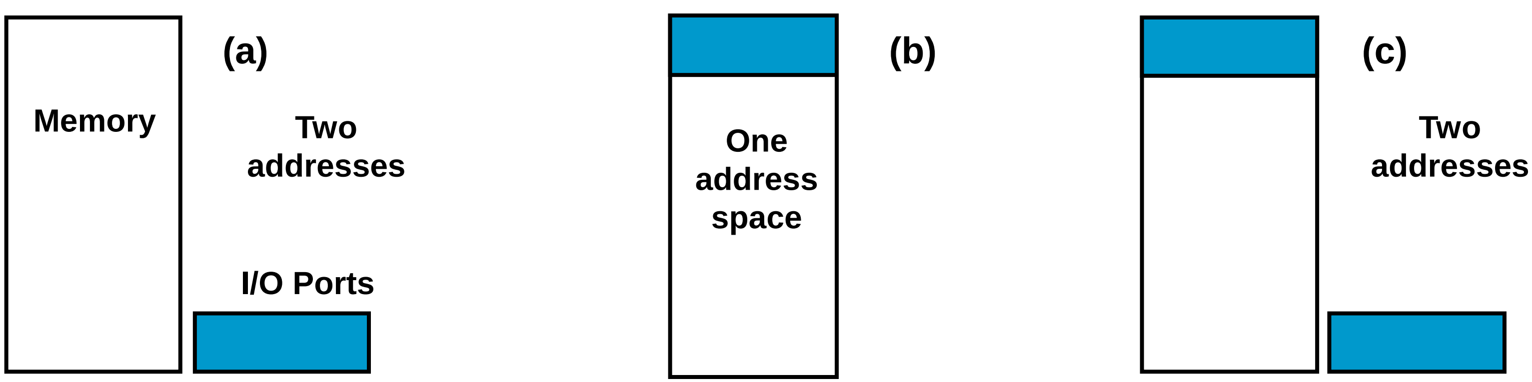
- Two key operating system goals
  - Control I/O devices
  - Provide a simple, easy-to-use, interface to devices
- Problem – large variety
  - Data rates – from 10B/sec (keyboard) 125MB/sec (Gigabit Ethernet)
  - Applications – what the device is used for
  - Complexity of control – a printer (simple) or a disk
  - Units of transfer – streams of bytes or larger blocks
  - Data representation – character codes, parity
  - Error condition – nature of errors, how they are reported, their consequences, …
- Makes a uniform & consistent approach difficult to get

I/O hardware - I/O devices

- I/O devices – roughly divided as
  - Block devices – stored info in fixed-size, addressable blocks (e.g. 512 – 32KB), read/write in blocks (e.g. disk, CD-ROMs)
  - Character devices – I/O stream of non-addressable characters (e.g. printers, network interfaces)
  - Of course, some devices don't fit in here (e.g. clocks)
- I/O devices components
  - Device itself – mechanical component
  - Device controller or adapter – electronic component
- Device controller
  - Maybe more than one device per controller
  - Some standard i/f between controller and devices: IDE, ATA, SATA, SCSI, FireWire, …
  - Converts serial bit stream to block of bytes
  - Performs error correction as necessary
  - Makes data available in main memory

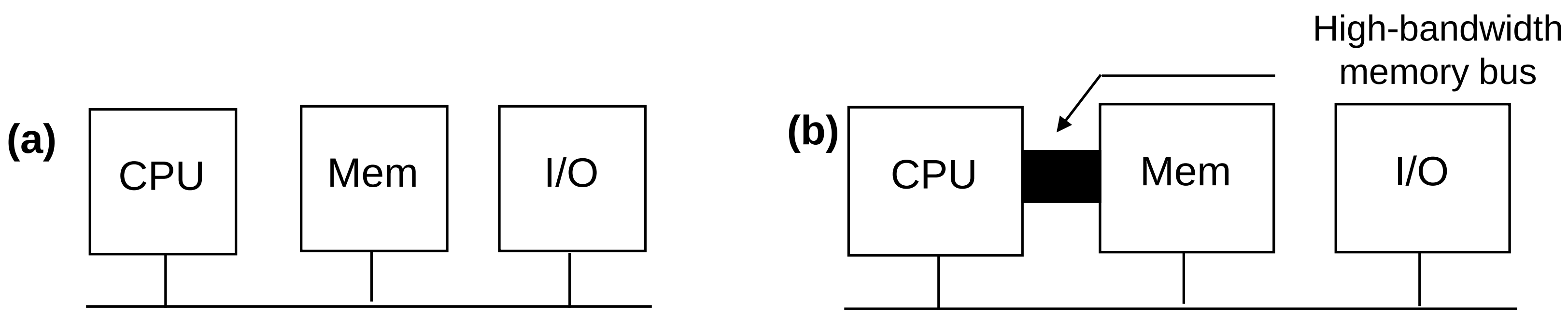
I/O controller & CPU communication

- Device controllers have
  - A few registers for communication with CPU
    - Typically: data-in, data-out, status, control, …
  - A data buffer that OS can read/write (e.g. video RAM)
- How does the CPU use that?
  - Separate I/O and memory space, each control register assigned an I/O port (a) – IBM 360 (`IN REG,PORT`)
  - Memory-mapped I/O – first in PDP-11 (b)
  - Hybrid – Pentium (c) (graphic controller is a good example)



Memory-mapped I/O

- Pros and cons
  - ☆ No special instructions or protection mechanism needed
  - ☆ Driver can be entirely written in C (how to do IN/OUT in C?)
  - ✖ What do you do with caching? Disable it on a per-page basis
  - ✖ Only one AS, so all mem modules must check all references
    - Easy with single bus (a) but harder with dual-bus (b) arch
    - Possible solutions
      - Send all references to memory first, if fails try bus
      - Snoop in the memory bus
      - Filter addresses in the PCI bridge (Pentium config.) (preloaded with range registers at boot time)



I/O software – goals & issues

- Device independence
  - Programs can access any I/O device w/o specifying it in advance
- Uniform naming, closely related
  - Name independent of device
- Error handling
  - As close to the hardware as possible (first the controller should try, then the device driver, …)
- Buffering for better performance
  - Check what to do with packets, for example
  - Decouple production/consumption
- Deal with dedicated (tape) & shared devices (disks)

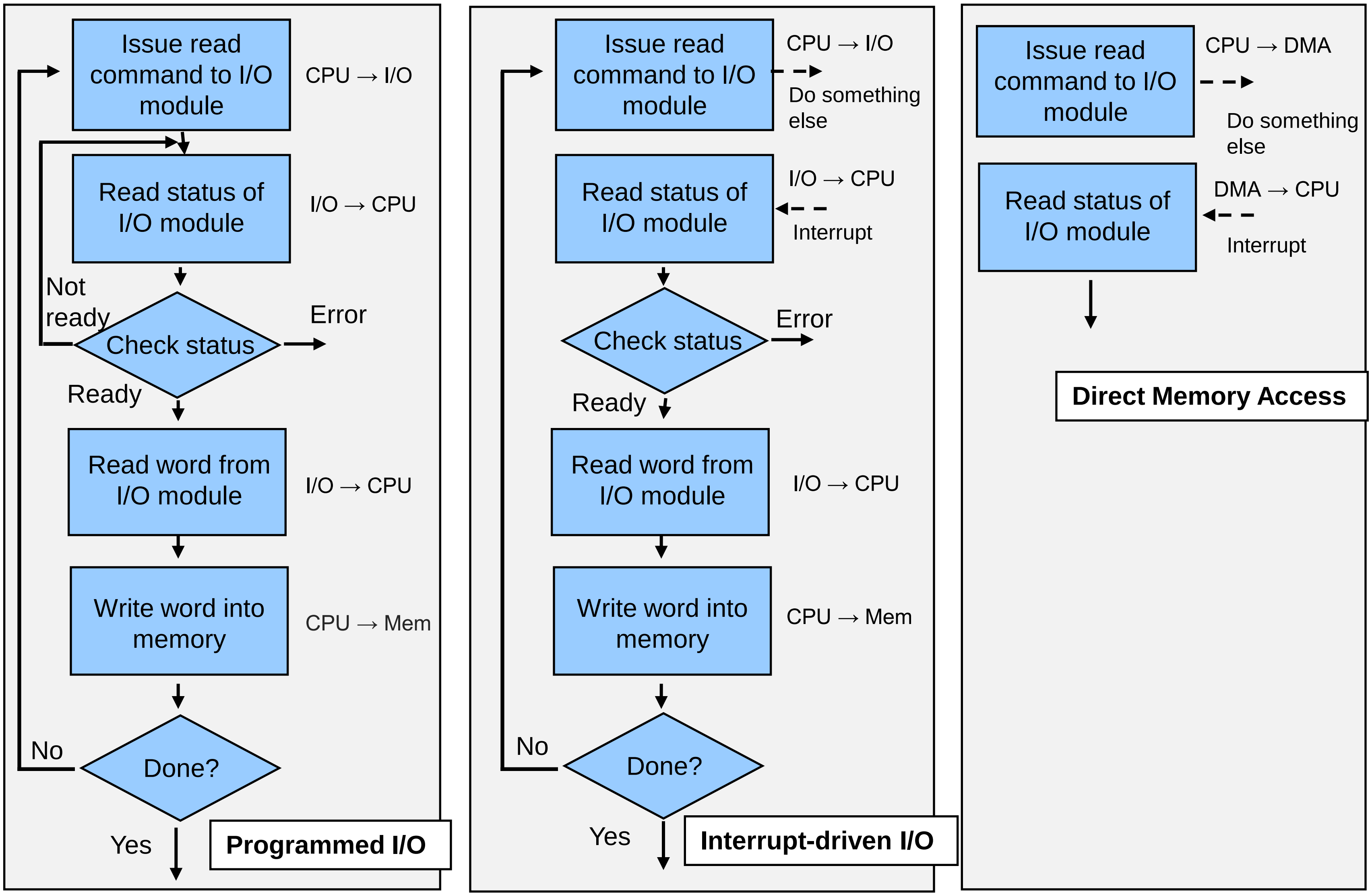
  Dedicated devices bring their own problems – deadlock?

Ways I/O can be done (OS take)

- Programmed I/O
  - Simplest – CPU does all the work
  - CPU basically polls the device
  - … and it is tied up until I/O completes
- Interrupt-driven I/O
  - Instead of waiting for I/O, context switch to another process & use interrupts
- Direct Memory Access
  - Obvious disadvantage of interrupt-driven I/O?

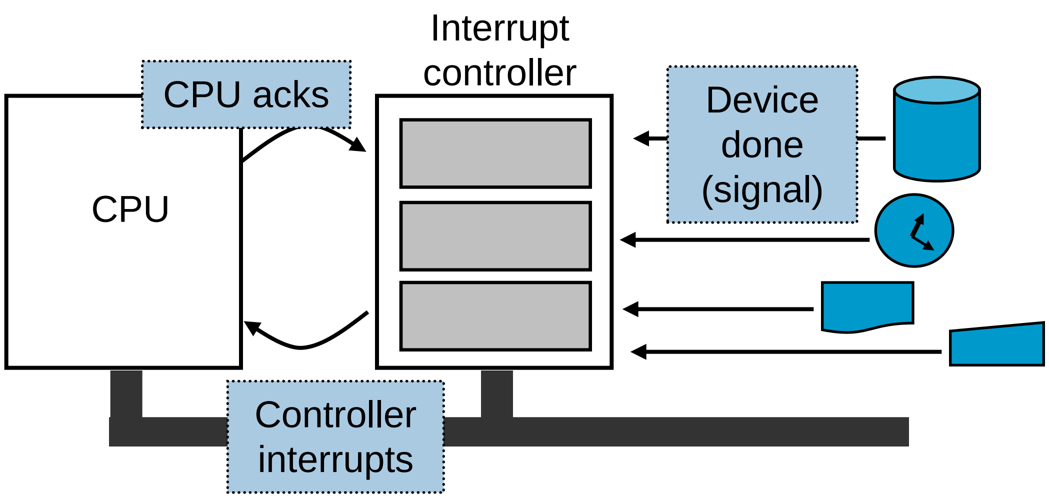
    An interrupt for every character
  - Solution: DMA - Basically programmed I/O done by somebody else

Three techniques for I/O



Interrupts revisited

- When I/O is done – interrupt by asserting a signal on a bus line
- Interrupt controller puts a # on address lines – index into interrupt vector (PC to interrupt service procedure)
- Interrupt service procedure ACK the controller
- Before serving interrupt, save context …



Interrupts revisited

Not that simple …

- Where do you save the state?
  - Internal registers? Hold your ACK (avoid overwriting internal regs.)
  - In stack? You can get a page fault … pinned page?
  - In kernel stack? Change to kernel mode $$$
- Besides: pipelining, superscalar architectures, …

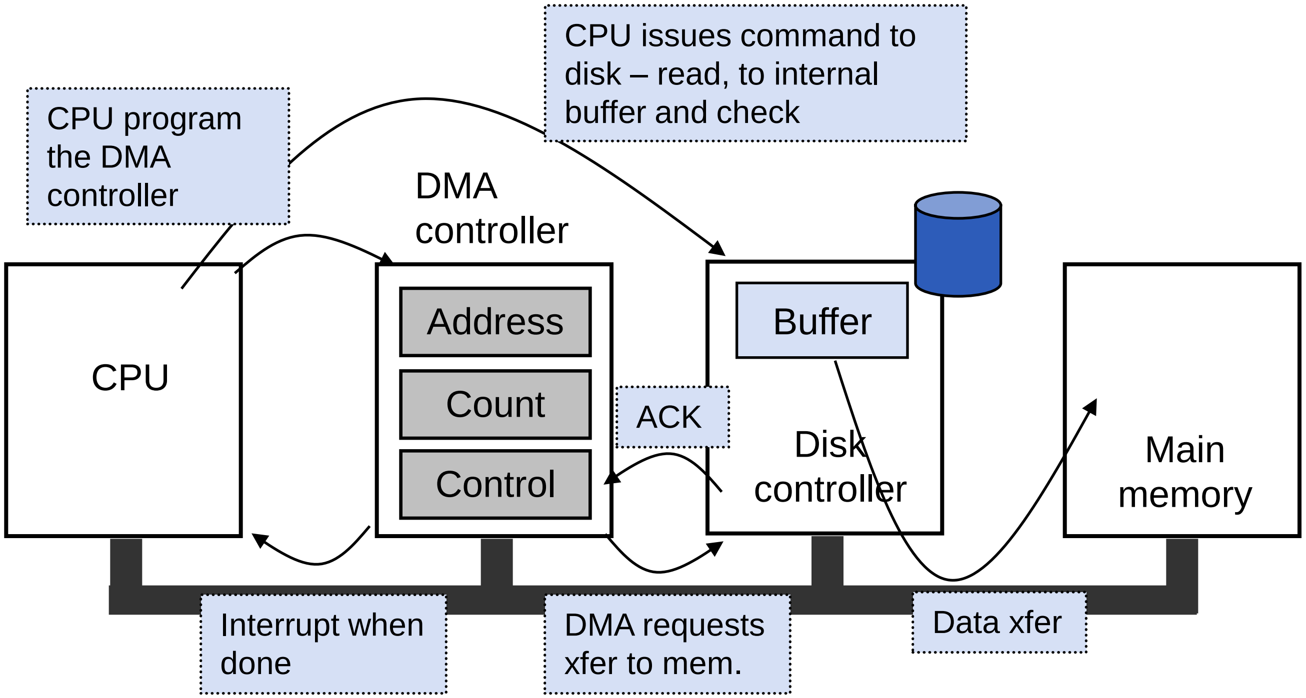
Ideally - a precise interrupt, leaves the machine in a well-defined state

- PC is saved in a known place
- All previous instructions have been fully executed
- All following ones have not
- The execution state of the instruction pointed by PC is known

The tradeoff – complex OS or really complex interrupt logic within the CPU (design complexity & chip area)

Direct Memory Access

- Clearly OS can use it only if HW has DMA controller
  - Either on the devices (controller) or on the parentboard
- DMA has access to system bus, independent of CPU
- DMA operation



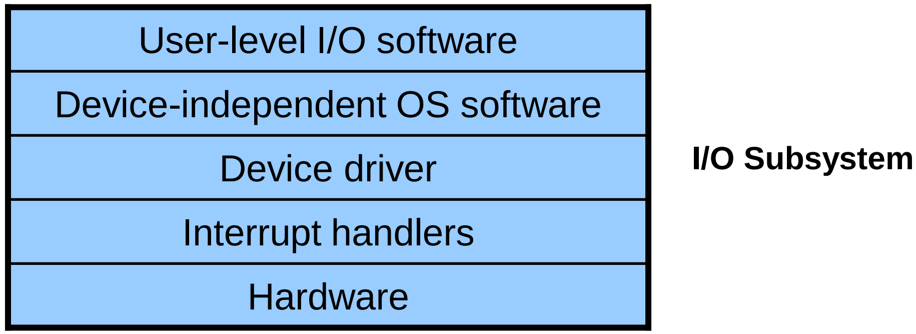
Some details on DMA

- One or more transfers at a time
  - Need multiple set of registers for the multiple channels
  - DMA has to schedule itself over devices served
- Buses and DMA can operate on one of two modes
  - Cycle stealing – device controller occasionally steals the bus
  - Burst mode (block) – DMA tells the device to take the bus for a while
- Two approaches to data transfer
  - Fly-by mode – just discussed, direct transfer to memory
  - Two steps – transfer via DMA; it requires extra bus cycle, but now you can do device-to-device transfers
- Physical (common) or virtual address for DMA transfer
- *Why you may not want a DMA?*

  If the CPU is fast and there's not much else to do anyway

I/O software layers

- I/O normally implemented in layers



- Interrupt handlers
  - Interrupts – an unpleasant fact of life – hide them!
  - Best way
    - Driver blocks (semaphores?) until I/O completes
    - Upon an interrupt, interrupt procedure handles it before unblocking driver

Layers - Device drivers

- Different device controllers – different registers, commands, etc → each I/O device needs a device driver
- Device driver – device specific code
  - Written by device manufacturer
  - Better if we have specs
  - Clearly, it needs to be reentrant (I/O device may complete while the driver is running, interrupting the driver and maybe making it run …)
  - Must be included in the kernel (as it needs to access the device's hardware) - How do you include it?
    - *Is there another option?*
  - Problem with plug & play

Layers - Device-independent SW

Some part of the I/O SW can be device independent

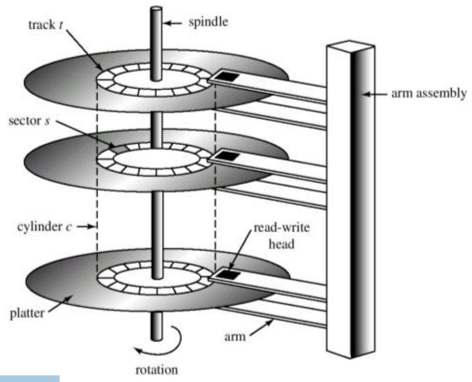
- Uniform interfacing with drivers
  - Fewer modifications to the OS with each new device
  - Easier naming (`/dev/disk0`) – major & minor device #s in UNIX, driver + unit, (kept by the i-node of the device's file)
  - Device driver writers know what's expected of them
- Buffering
  - Unbuffered, user space, kernel, …
- Error reporting
  - Some errors are transient – keep them low
  - Actual I/O errors – reporting up when in doubt
- Allocating & releasing dedicated devices
- Providing a device-independent block size

User-space I/O software

- Small portion of I/O software runs in user-space
- Libraries that linked together with user programs
  - E.g., stdio in C
  - Mostly parameter checking and some formatting (printf)
- Beyond libraries, e.g. spooling
  - Handling dedicated devices (printers) in a multiprogramming system
  - Daemon plus spooling directory

Disk – a concrete I/O device

- Magnetic disk hardware - organization
  - Cylinders – made of vertical tracks
  - Tracks – divided into sectors
  - Sectors – minimum transfer unit



20 years

Parameter	IBM 360KB floopy	WD 18300 HD
Capacity	360KB	18.3GB
Seek time (avg)	77msec	6.9msec
Rotation time	200msec	8.33msec
Motor stop/start	250msec	20msec
Time to transfer 1 sector	22msec	17µsec

Note different rates of improvements on seek time, transfer rate and capacity

- Simplified model - careful with specs
  - Sectors per track are not always the same
  - Zoning – zone, a set of tracks with equal sec/track
- Hide this with a logical disk w/ constant sec/track

RAIDs

- Disk transfer rates are improving, but slower than CPU performance
- Use multiple disks to improve performance
  - Strip content across multiple disks
  - Use parallel I/O to improve performance
- But striping reduces reliability (n*MTBF)
  - Add redundancy for reliability
    - Parity – add a bit to get even number of 1's

1	**0**	**1**	**1**	**0**	**1**	**1**	**0**	**1**
0	**0**	**1**	**1**	**0**	**1**	**1**	0	**0**

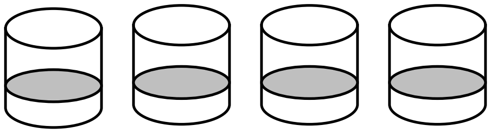
    - Any single missing bit can be reconstructed
    - More complex schemes can detect multiple bit errors and correct single bit errors

RAIDs tradeoffs

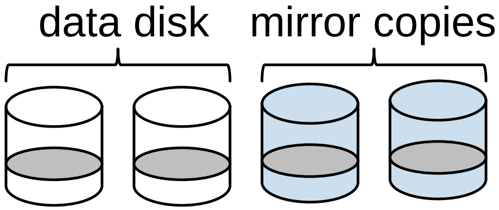
- Granularity
  - Fine-grained – stripe each file over all disks
    - High throughput for the file
    - Limits transfer to one file at a time
  - Course-grained – stripe each file over only a few disks
    - Limit throughput for one file
    - Allows concurrent access to multiple files
- Redundancy
  - Uniformly distribute redundancy information on disks
    - Avoid load-balancing problems
  - Concentrate redundancy information on a small # of disks
    - Partition the disk into data disks and redundancy disks
    - Simpler

RAIDs

- RAID 0 – non-redundant disk array
  - Files are striped across disks, non redundant info
  - High read throughput
  - Best write throughput (nothing extra to write)
  - Worst reliability than with a single disk

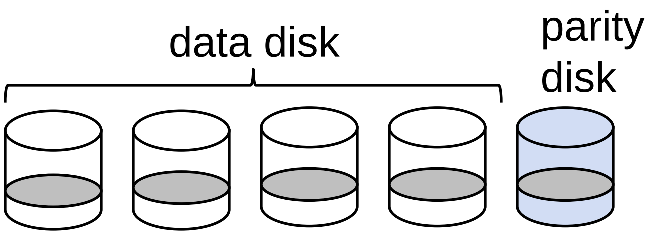


- RAID 1 – mirrored disk
  - Files are striped across half the disks
  - Data is written in two places
  - Read from either copy
  - On failure, just use the surviving one
  - Of course you need 2x space

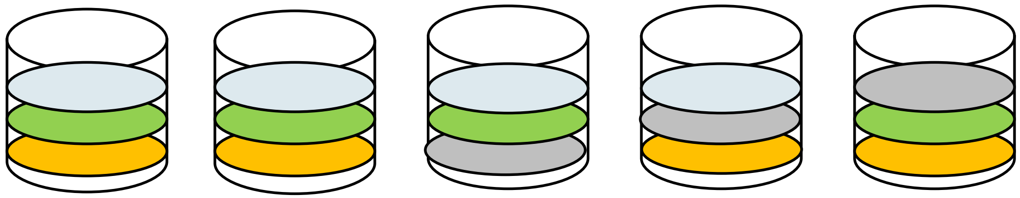


RAIDs

- RAID 2, 3 and 4 uses ECC or parity disks
  - Each byte on the parity disk is a parity function of the corresponding bytes in all other disks
  - Differences are in the EEC used and whether it is bit- (2 & 3) or block-level
  - A read can access all data disks
  - A write updates 1+ data disks and parity disk

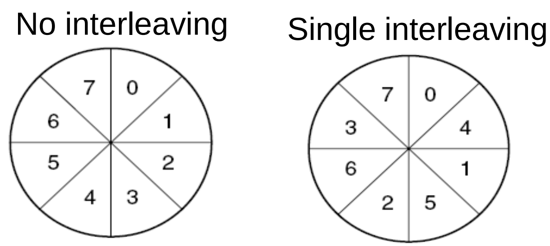


- RAID 5 – block interleaved distributed paritiy
  - Distribute parity info over all disks
  - Much better performance (no hot spot)



Disk formatting

- Low-level formatting ~20% capacity goes with it
  - Set of concentric tracks of sectors with short gaps in between
  - Sectors – [preamble, to recognize the start + data + ecc]
  - Spare sectors for replacements
  - Sectors and head skews (bet/ tracks) to deal with moving head
  - Interleaving to deal with transfer time (space bet/ consecutive sectors)



- After formatting, partitioning – multiple logical disks – sector 0 holds master boot record (boot code + partition table)
- Last step, high-level formatting
  - Boot block, free storage admin, root dir, empty file system

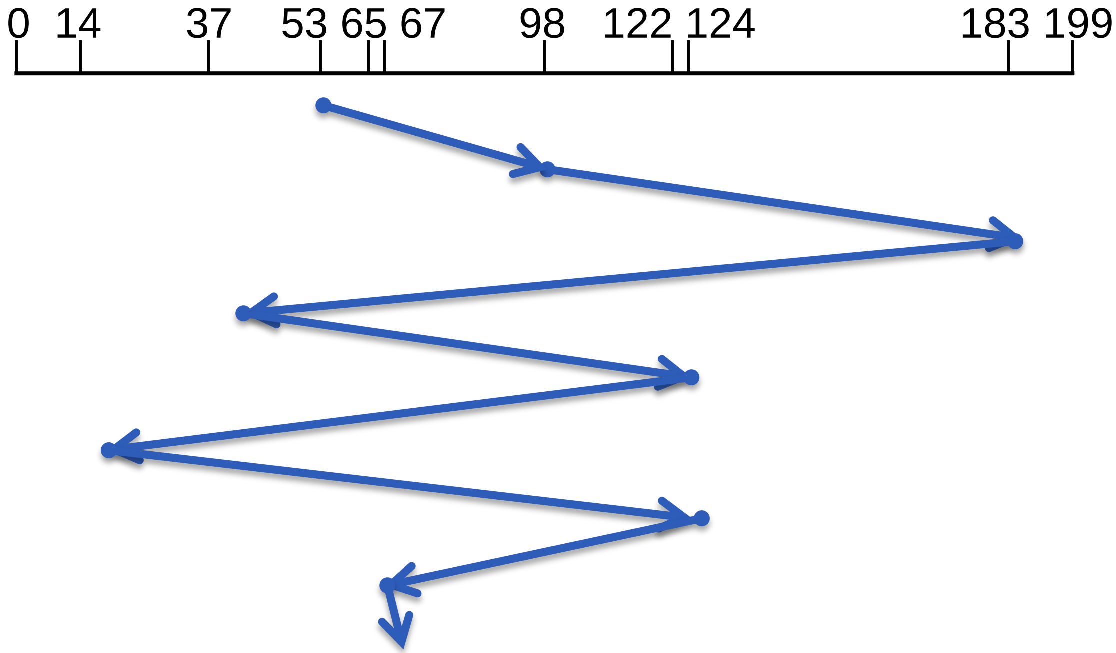
Disk attachment

- Host-attached storage
  – Accessed through local I/O ports
  – Standards interfaces like SATA, SCSI, Fiber Channel
- Network-attached storage
  – Usually implemented as RAID
  – Clients access storage over the network, usually same data LAN, over NSF or CIFS (Windows)
  – Easy to access and share, slower performance
- Storage-area network
  – Private network connecting clients to storage units using storage protocols (rather than networking protocols)
    - Over FC or iSCSI
  – Multiple hosts and storage array can connect to the same SAN; storage can be dynamically allocated

Disk arm scheduling

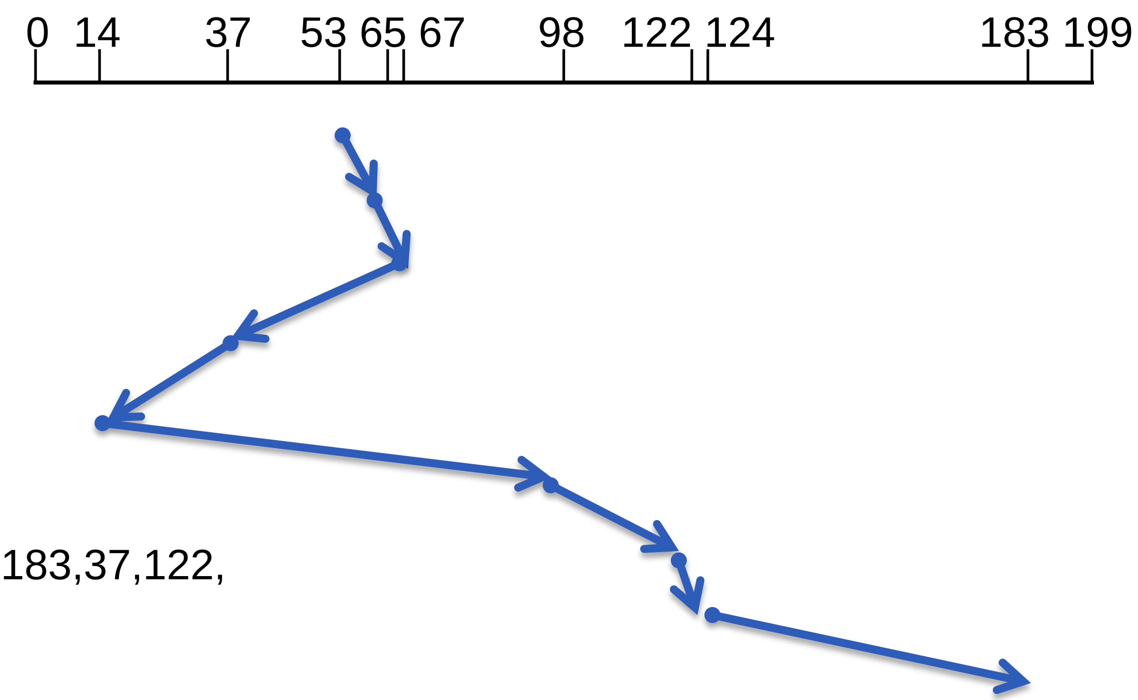
- Time to read/write a disk block determined by
  - Seek time – dominates!
  - Rotational delay
  - Actual transfer time
- If request come one at a time, little you can do - FCFS

Starting at 53
Requests: 98,183,37,122,
14,124,65,67



SSTF

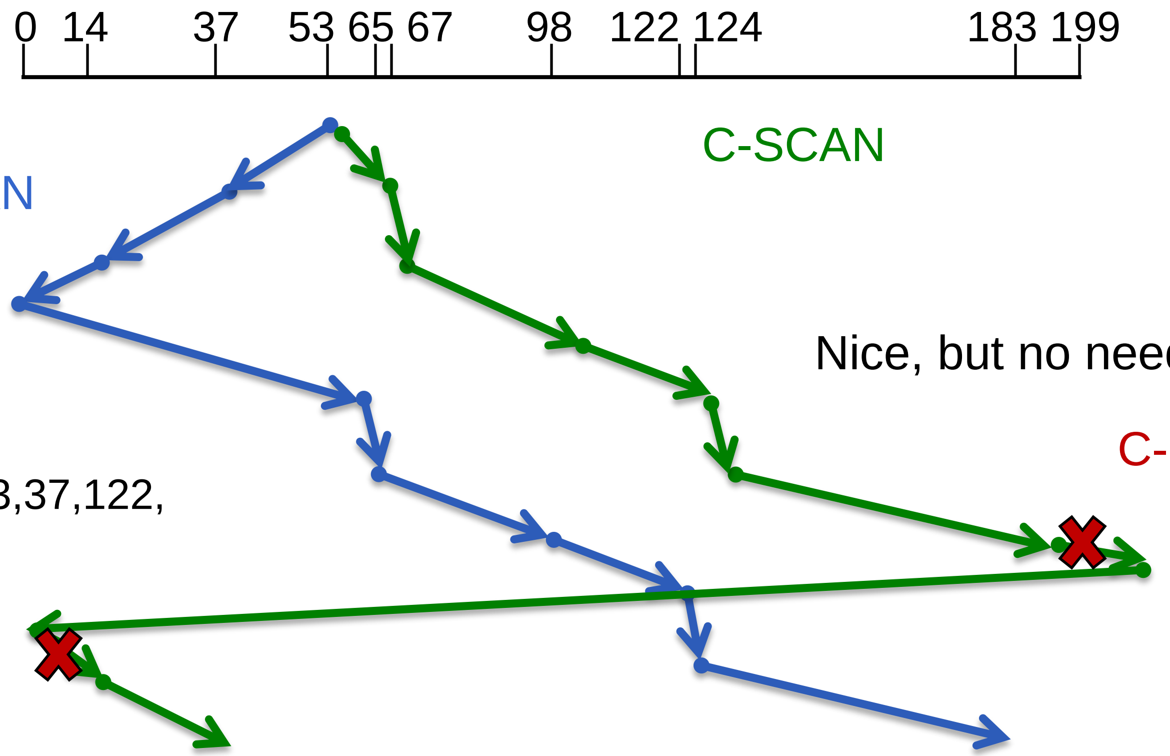
- Given a queue of request for blocks → scheduling to reduce head movement



Starting at 53
Requests: 98,183,37,122, 14,124,65,67

- As SJF, possible starvation

SCAN, C-SCAN and C-LOOK



Nice, but no need to be blind

Starting at 53
Requests: 98,183,37,122,
14,124,65,67

Assuming a uniform distribution of requests, where's the highest density when head is on the left?

Next time

- File systems interface and implementation