ECE566
Enterprise Storage Architecture

Spring 2025

Hard disks, SSDs, and the I/O subsystem

Tyler Bletsch
Duke University

Slides include material from Vince Freeh (NCSU)

Hard Disk Drives (HDD)

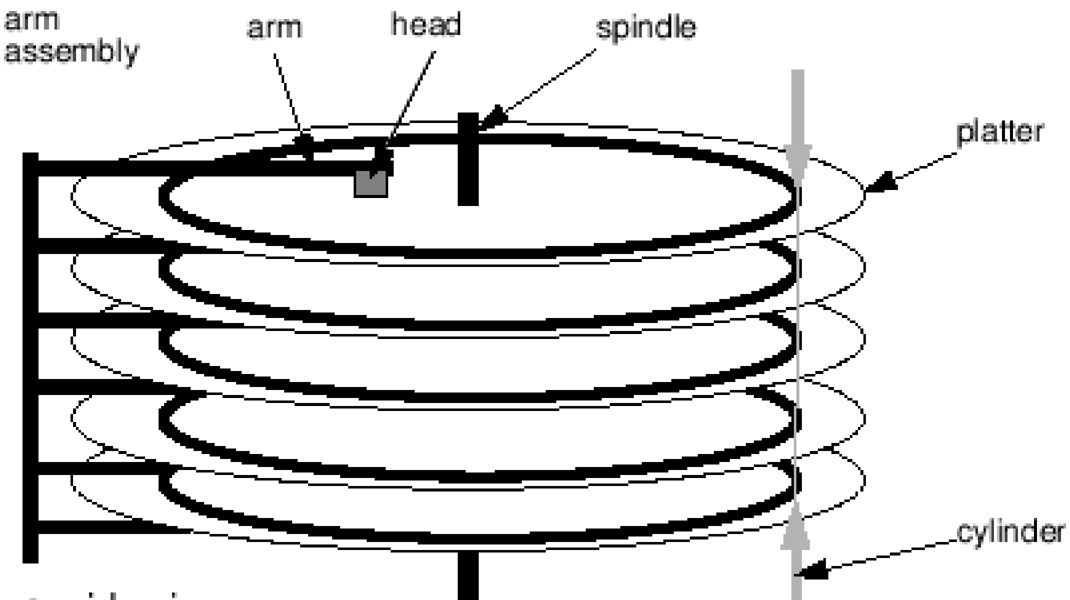
History

- First: IBM 350 (1956)
  - 50 platters (100 surfaces)
  - 100 tracks per surface (10,000 tracks)
  - 500 characters per track
  - 5 million characters
  - 24” disks, 20” high

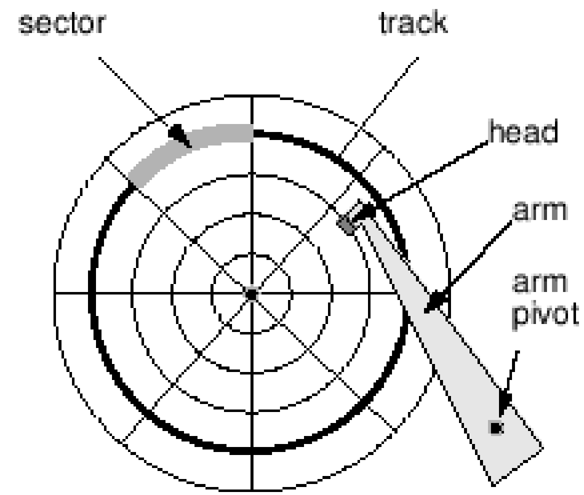
Overview

- Record data by magnetizing ferromagnetic material
- Read data by detecting magnetization
- Typical design
  - 1 or more platters on a spindle
  - Platter of non-magnetic material (glass or aluminum), coated with ferromagnetic material
  - Platters rotate past read/write heads
  - Heads ‘float’ on a cushion of air
  - Landing zones for parking heads

Basic schematic

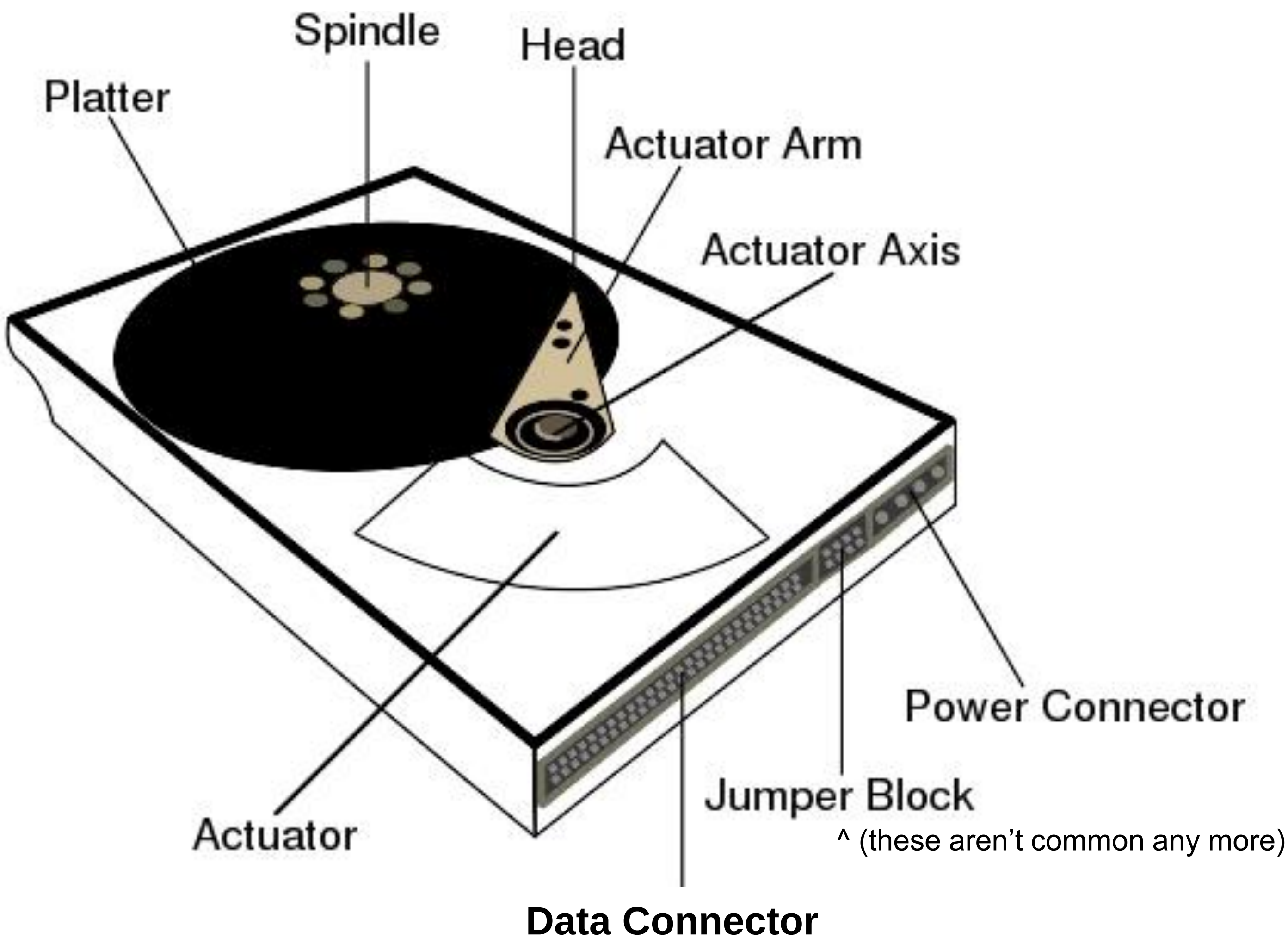


a. side view.



b. top view.

Generic hard drive



Types and connectivity (legacy)

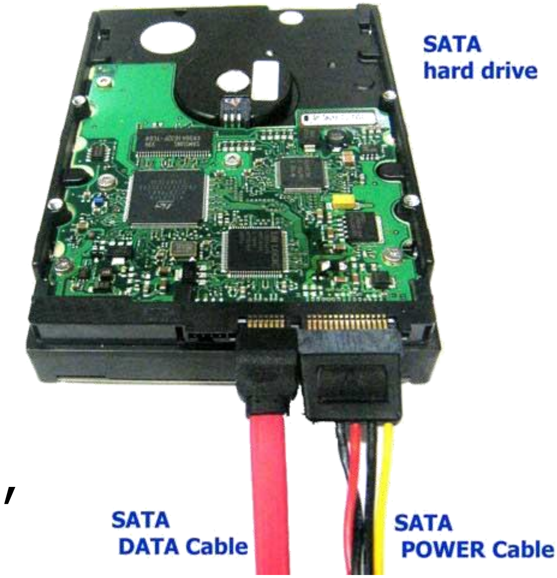
- **SCSI (Small Computer System Interface)**:
  - Pronounced “Scuzzy”
  - One of the earliest small drive protocols
  - The Standard That Will Not Die:
    the drives are gone, but most enterprise
    gear still speaks the SCSI protocol

- **Fibre Channel (FC)**:
  - Used in some Fibre Channel SANs
  - Speaks SCSI on the wire
  - Modern Fibre Channel SANs can
    use any drives: back-end ≠ front-end

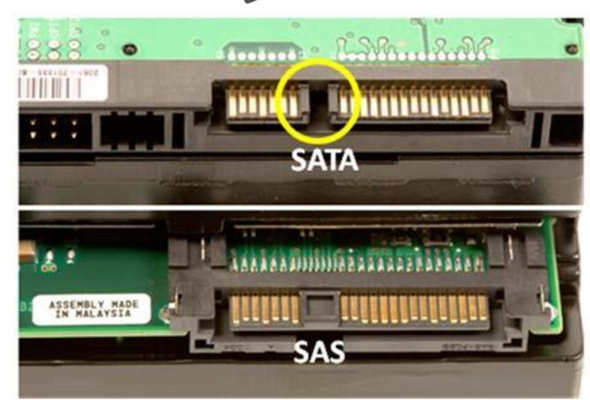
- **IDE / ATA**:
  - Older standard for consumer drives
  - Obsoleted by SATA in 2003

Types and connectivity (modern)

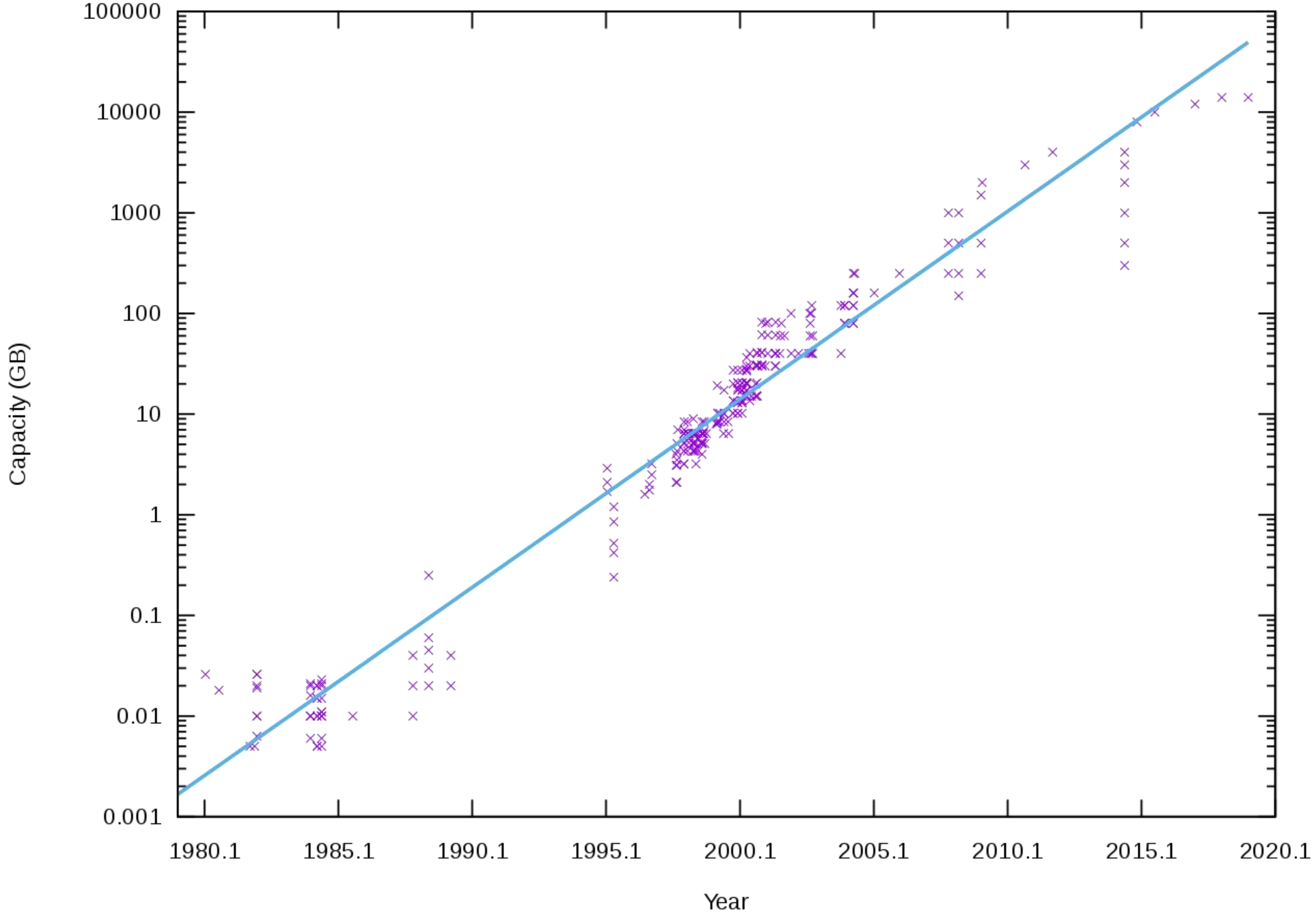
- SATA (Serial ATA):
  - Current consumer standard
  - Series of backward-compatible revisions
    SATA 1 = 1.5 Gbit/s, SATA 2 = 3 Gbit/s,
    SATA 3 = 6.0 Gbit/s, SATA 3.2 = 16 Gbit/s
  - Data and power connectors are hot-swap ready
  - Extensions for external drives/enclosures (eSATA), small all-flash boards (mSATA, M.2), multi-connection cables (SFF-8484), more
  - Usually in 2.5" and 3.5" form factors



- SAS (Serial-Attached-SCSI)
  - SCSI protocol over SATA-style wires
  - (Almost) same connector
  - Can use SATA drives on SAS controller, not vice versa



Hard drive capacity



http://en.wikipedia.org/wiki/File:Hard_drive_capacity_over_time.png

Seeking

- Steps
  - Speedup
  - Coast
  - Slowdown
  - Settle
- Very short seeks (2-4 tracks): dominated by settle time
- Short seeks (<200-400 tracks):
  - Almost all time in constant acceleration phase
  - Time proportional to square root of distance
- Long seeks:
  - Most time in constant speed (coast)
  - Time proportional to distance

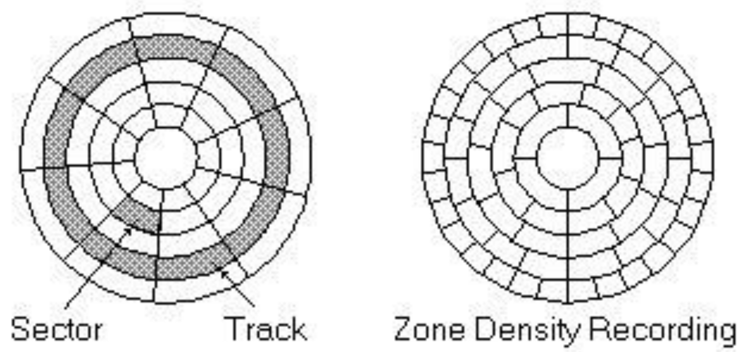
Average seek time

- What is the "average" seek? If
  1. Seeks are fully independent and
  2. All tracks are populated:

  ➔ average seek = 1/3 full stroke
- But seeks are not independent
- Short seeks are common

- Using an <u>average seek time</u> for all seeks yields a poor model

Zoning



- Note
  - More linear distance at edges then at center
  - Bits/track ~ R (circumference = $2\pi R$)
  - To maximize density, bits/inch should be the same
- How many bits per track?
  - Same number for all ➔ simplicity; lowest capacity
  - Different number for each ➔ very complex; greatest capacity
- Zoning
  - Group tracks into zones, with same number of bits
  - Outer zones have more bits than inner zones
  - Compromise between simplicity and capacity

Sparing

- Reserve some sectors in case of defects
- Two mechanisms
  - Mapping
  - Slipping
- Mapping
  - Table that maps requested sector → actual sector
- Slipping
  - Skip over bad sector
- Combinations
  - Skip-track sparing at disk "low level" (factory) format
  - Remapping for defects found during operation

Caching and buffering

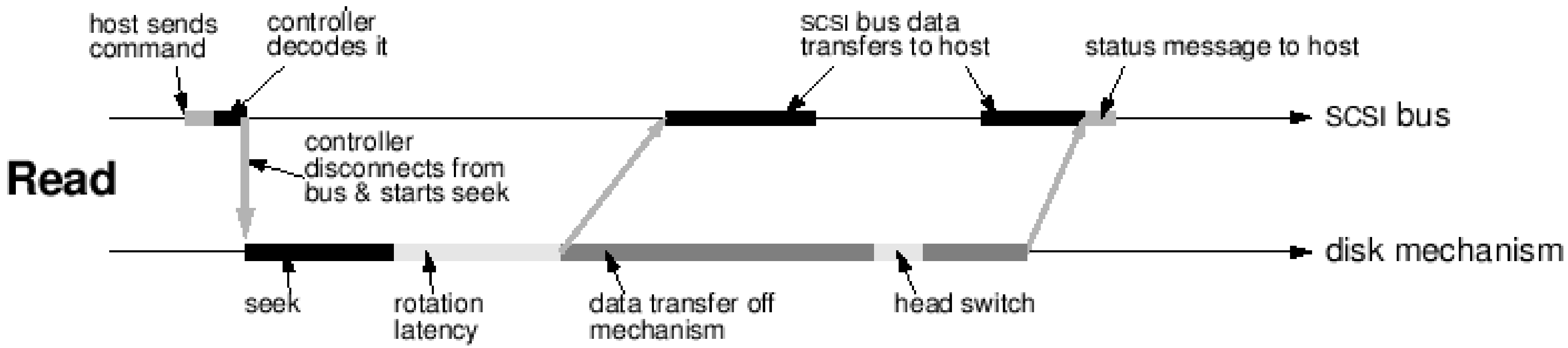
- Disks have caches
  - Caching (eg, optimistic read-ahead)
  - Buffering (eg, accommodate speed differences bus/disk)
- Buffering
  - Accept write from bus into buffer
  - Seek to sector
  - Write buffer
- Read-ahead caching
  - On demand read, fetch requested data and more
  - Upside: subsequent read may hit in cache
  - Downside: may delay next request; complex

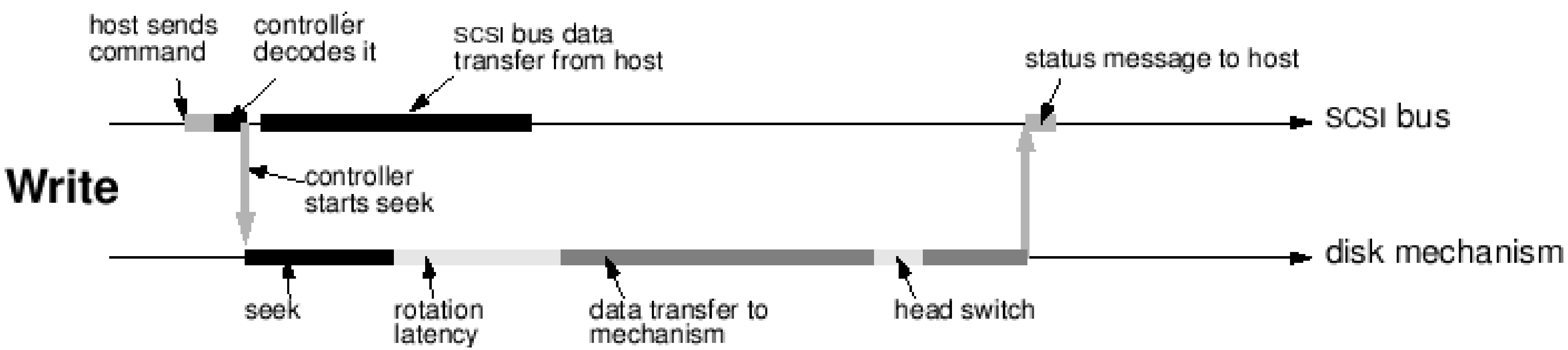
Command queuing

- Send multiple commands (SCSI)
- Disk schedules commands
- Should be “better” because disk “knows” more

- Questions
  - How often are there multiple requests?
  - How does OS maintain priorities with command queuing?

Time line


host sends command
controller decodes it
SCSI bus data transfers to host
status message to host
SCSI bus
Read
controller disconnects from bus & starts seek
disk mechanism
seek
rotation latency
data transfer off mechanism
head switch


host sends command
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Write
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disk mechanism
seek
rotation latency
data transfer to mechanism
head switch

Disk Parameters

		Toshiba MK1003 (early 2000s)	Seagate Savvio (~2005)	Seagate 6TB Enterprise HDD (2016)
Diameter		1.8″	2.5″	3.5″
Capacity	Improving ☺	10 GB	73 GB	6 TB
RPM		4200 RPM	10000 RPM	7200 RPM
Cache	Improving ☺	512 KB	8 MB	128 MB
Platters		1	2	~6
Average Seek	About equal ☹	7 ms	4.5 ms	4.16 ms
Sustained Data Rate	Improving ☺	16 MB/s	94 MB/s	216 MB/s
Interface		ATA	SCSI	SAS/SATA
Use		Ancient iPod	Laptop	Desktop

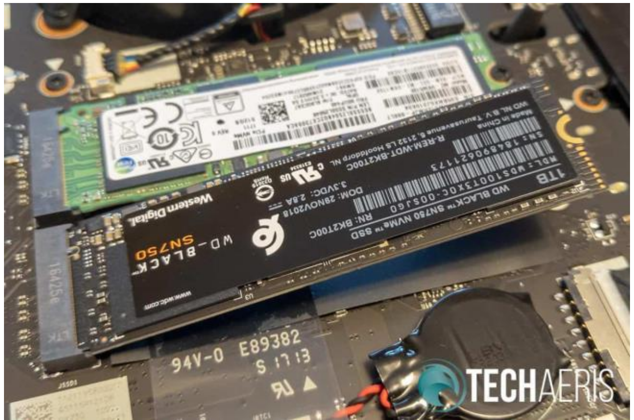
Solid State Disks
(SSD)

Introduction

- Solid state drive (SSD)
  - Storage drives with no mechanical component
  - Available up to 16TB capacity (as of 2019)
  - Classic: 2.5" form factor (card in a box)

Source: wikipedia

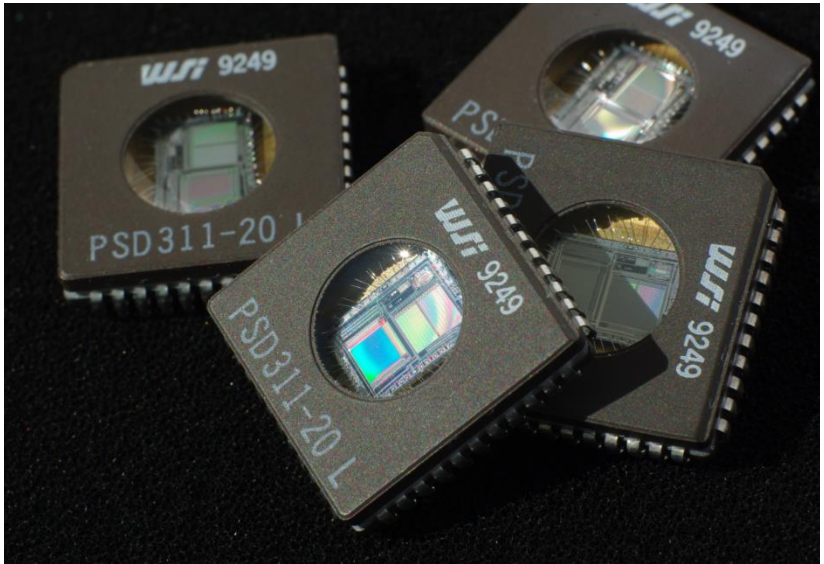
  - Modern: M.2 or newer NVMe (card out of a box)



Evolution of SSDs

- PROM – programmed once, non erasable
- EPROM – erased by UV lighting*, then reprogrammed
- EEPROM – electrically erase entire chip, then reprogram
- Flash – electrically erase and rerecord a single memory cell
- SSD - flash with a block interface emulating controller

* Obsolete, but totally awesome looking because they had a little window:



Flash memory primer

- Types: NAND and NOR
  - NOR allows bit level access
  - NAND allows block level access
    - For SSD, NAND is mostly used, NOR going out of favor
- Flash memory is an array of columns and rows
  - Each intersection contains a memory cell
    - Memory cell = floating gate + control gate
    - 1 cell = 1 bit

Memory cells of NAND flash

Single-level cell (SLC)	Multi-level cell (MLC)	Triple-level cell (TLC)
Single (bit) level cell	Two (bit) level cell	Three (bit) level cell
Fast: 25us read/100-300 us write	Reasonably fast: 50us read, 600-900us write	Decently fast: 75us read, 900-1350 us write
Write endurance - 100,000 cycles	Write endurance – 10000 cycles	Write endurance – 5000 cycles
Expensive	Less expensive	Least expensive

SSD internals

Package contains multiple dies (chips)

↓

Die segmented into multiple planes

↓

A plane with thousands(2048) of blocks + IO buffer pages

↓

A block is around 64 or 128 pages

↓

A page has a 2KB or 4KB data + ECC/additional information

SSD operations

- Read
  - Page level granularity
  - 25us (SLC) to 60us (MLC)

- Write
  - Page level granularity
  - 250us (SLC) to 900us(MLC)
  - 10 x slower than read
- Erase
  - Block level granularity, not page or word level
  - Erase must be done before writes
  - 3.5ms
  - 15 x slower than write

SSD internals

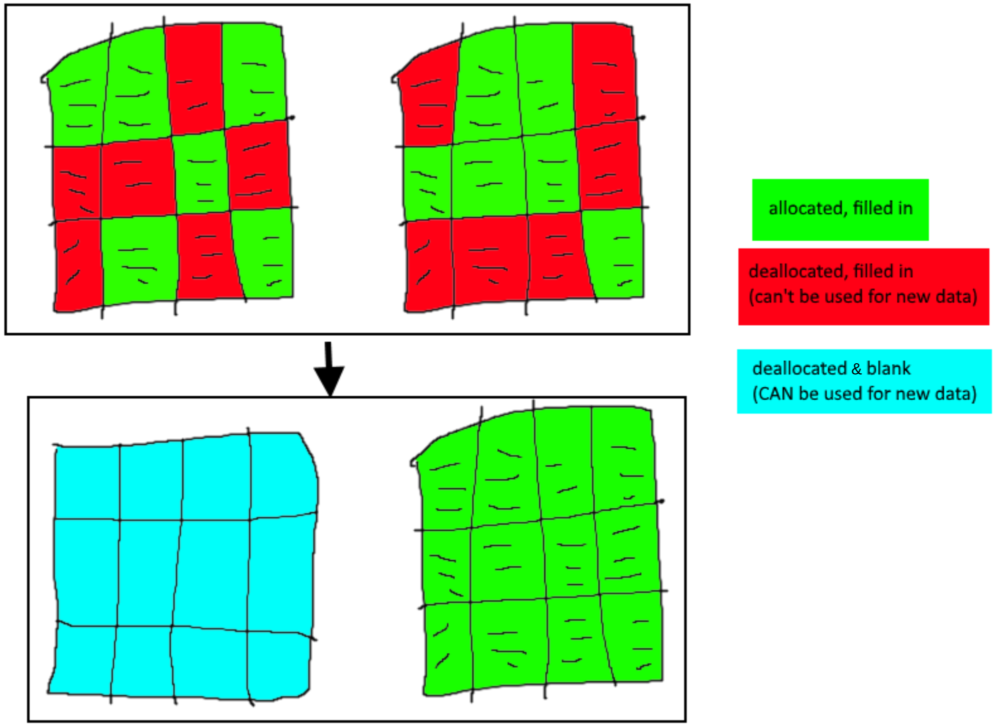
- Logical pages striped over multiple packages
  - A flash memory package provides 40MB/s
  - SSDs use array of flash memory packages
- Interfacing:
  - Flash memory → Serial IO → SSD Controller → disk interface (SATA)
- SSD Controller implements Flash Translation Layer (FTL)
  - Emulates a hard disk
  - Exposes logical blocks to the upper level components
  - Performs additional functionality

SSD controller

- Differences in SSD is due to controller
  - Performance loss if controller not properly implemented
- Has CPU, RAM cache, and may have battery/supercapacitor
- Dynamic logical block mapping

Preemptive erasure

- Preemptive movement of cold data
- Recycle invalidated pages
  - Performed by garbage collector
  - Background operation
  - Triggered when close to having no more unused blocks

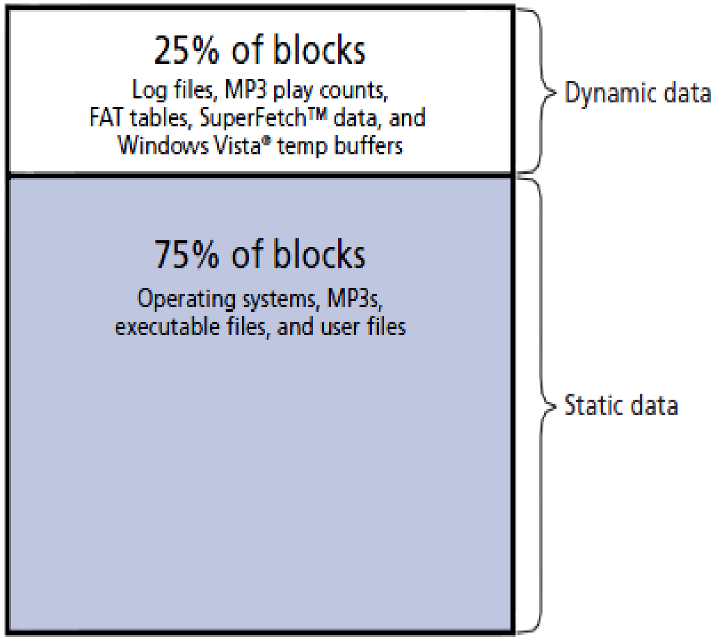


Wear leveling

- SSDs wear out
  - Each memory cell has finite flips
  - All storage systems have finite flips even HDD
  - SSD finite flips < HDD
  - HDD failure modes are larger than SSD
- General method: over-provision unused blocks
  - Write on the unused block
  - Invalidate previous page
  - Remap new page

Dynamic wear leveling

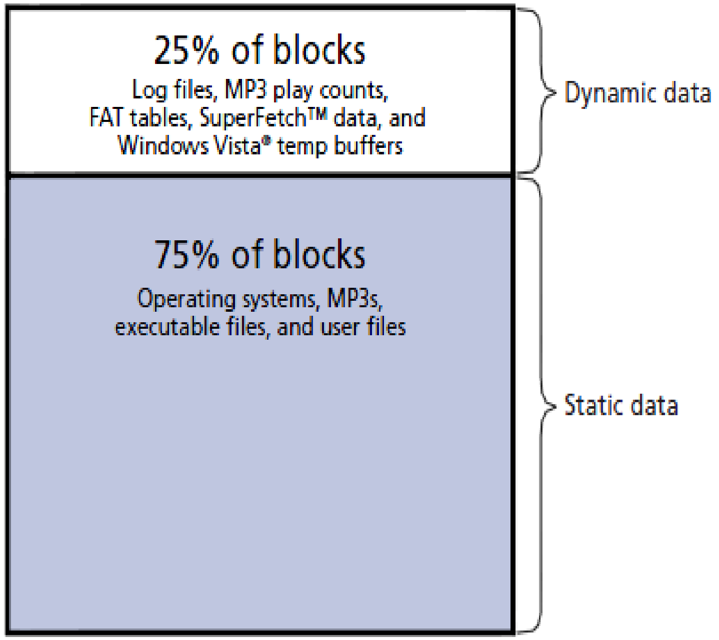
- Only pool unused blocks
- Only non-static portion is wear leveled
- Controller implementation easy
- Example: SSD lifespan dependent on 25% of SSD



Source: micron

Static wear leveling

- Pool all blocks
- All blocks are wear leveled
- Controller complicated
  - needs to track cycle # of all blocks
- Static data moved to blocks with higher cycle #
- Example: SSD lifespan dependent on 100% of SSD



Source: micron

SSD TRIM! Sent from the OS

- TRIM
  - Command to notify SSD controller about deleted blocks
  - Sent by filesystem when a file is deleted
  - Avoids write amplification and improves SSD life

Using SSD (1)

- SSD as main storage device
  - NetApp "All Flash" storage controllers
  - 300,000 read IOPS
  - < 1 ms response time
  - > 6Gbps bandwidth
  - Cost: $big
  - Becoming increasingly common as SSD costs fall

- Hybrid storage (tiering)
  - Server flash
    - Client cache to backend shared storage
    - Accelerates applications
    - Boosts efficiency of backend storage (backend demand decreases by up to 50%)
    - Example: NetApp Flash Accel acts as cache to storage controller
      - Maintains data coherency between the cache and backend storage
      - Supports data persistent for reboots

Using SSD (2)

- Hybrid storage
  - Flash array as cache (PCI-e cards flash arrays)
    - Example: NetApp Flash Cache in storage controller
    - Cache for reads
  - SSDs as cache
    - Example: NetApp Flash Pool in storage controller
    - Hot data tiered between SSDs and HDD backend storage
    - Cache for read and write

NetApp EF540 flash array

- 2U
- Target: transactional apps with high IOPS and low latency
- Equivalent to > 1000 15K RPM HDDs
- 95% reduction in space, power, and cooling
- Capacity: up to 38TB

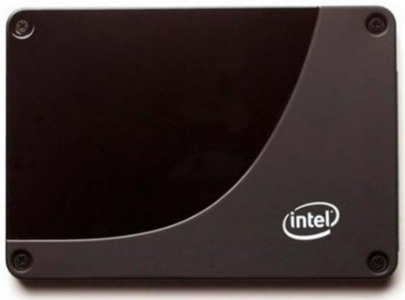
Source: NetApp

Differences between SSD and HDD

SSD	HDD
Uniform seek time	Different seek time for different sectors
Fast seek time – random read/writes as fast as sequential read/writes	Seek time dependent upon the distance
Cost (Intel 530 Series 240GB – $209) • Capacity – $0.87/GB • Rate – $0.005/IOPS • Bandwidth - $0.38/Mbps	Cost (Seagate Constellation 1TB 7200rpm - $116) • Capacity – $0.11/GB • Rate – $0.55/IOPS • Bandwidth - $0.99/Mbps
Power: Active power: 195mW – 2W Idle power: 125mW – 0.5 W Low power consumption, No sleep mode	Power: Average operating power: 5.4W Higher power consumption, sleep mode zero power, higher wake up cost

Differences between SSD and HDD

SSD	HDD
> 10,000 to > 1million IOPS	Hundreds of IOPS
Read/write in microseconds	Read/write in milliseconds
No mechanical part – no wear and tear	Moving part – wear and tear
MTBF ~ 2 million hours	MTBF ~ 1.2 million hours
Faster wear of a memory cell when it is written multiple times	Slower wear of the magnetic bit recording



Intel X-25E - $345
(older)
SLC
32 GB
SATA II
170-250MB/s
Latency 75-85us

Intel 530 - $209
(new)
MLC
240GB
SATA III
up to 540MB/s
Latency 80-85us

Samsung 840 EVO - $499
(new)
TLC
1TB
SATA III
up to 540MB/s

Which is cheaper?

HDD? or **SSD?**

Yes! *Yes!*

Cheaper per gigabyte of capacity.

Cheaper per IOPS (performance).

Tradeoff!

Workloads

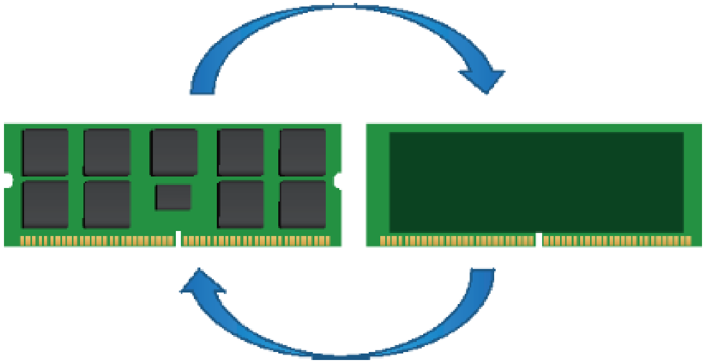
Workloads	SSD	HDD	Why ?
High write		Y	Wear for SSD
Sequential IO (e.g. media files)	Y	Y	Both SSD and HDD do great on sequential
Log files (small writes)	Y		Faster seek time
Database read queries	Y		Faster seek time
Database write queries	Y		Faster seek time
Analytics – HDFS	Y	Y	SSD – Append operation faster HDD – higher capacity
Operating systems	Y		SSD: FAST!!!!

Other Flash technologies - NVDIMMS

- Revisiting NVRAM
- DDR DIMMS + NAND Flash
  - Speed of DIMMS
  - extensive read/write cycles for DIMMS
  - Non volatile nature of NAND Flash
- Support added by BIOS
  - Backup to NAND Flash
  - Triggered by HW SAVE signal
- Stored charge
  - Super capacitors
  - Battery packs

How It Works

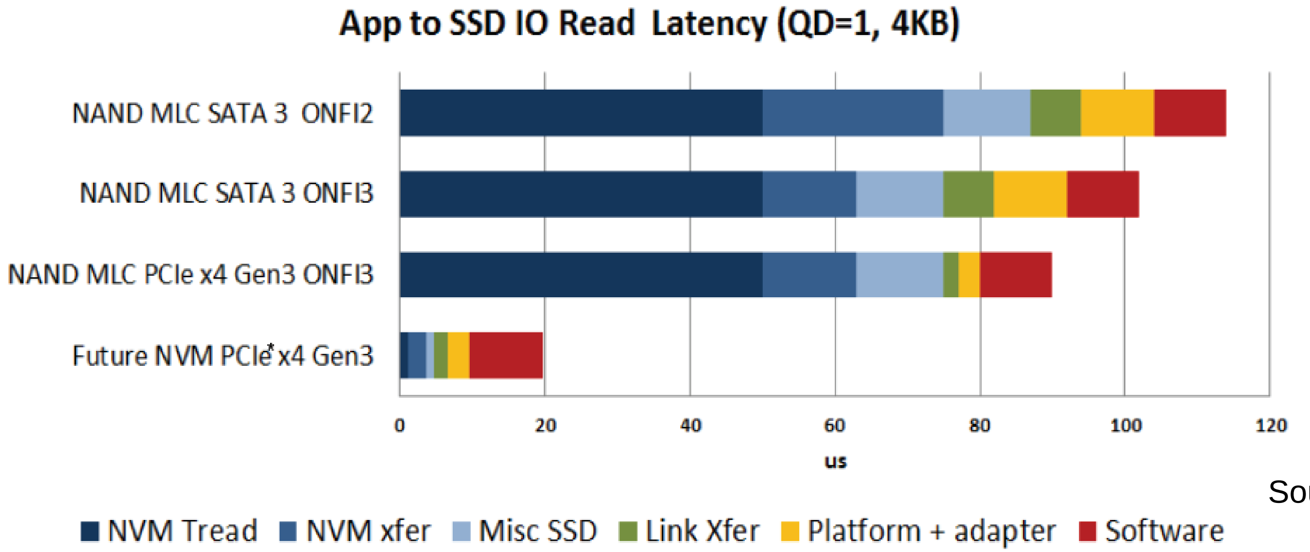
If there is a power failure, the supercap module powers NVDIMM while it copies all data from the DDR-3 to on-module flash



When power is restored NVDIMM copies all data from flash to DDR-3 and normal operation resumes

(SNIA - **NVDIMM Technical Brief**)

In future - persistent memory



Source: Andy Rudoff, Intel

- NVM latency closer to DRAM
- Types
  - Battery-backed DRAM, NVM with caching, Next-gen NVM
- Attributes:
  - Bytes-addressable, LOAD/STORE access, memory-like, DMA
  - Data not persistent until flushed

Basics of IO Performance Measurement

Motivation and basic terminology

- We cover performance measurement in detail later in the semester, but you may need the basics for your project sooner than that...
- The short version:
  - Sequential workload: **MB/s**
    - Even an SSD does better sequential than random because of caching and other locality optimizations
  - Random workload: **IO/s** (commonly written IOPS)
    - You need to indicate the IO size, but it's not part of the metric
  - Don't forget: **latency (ms)**

Measurement methodology

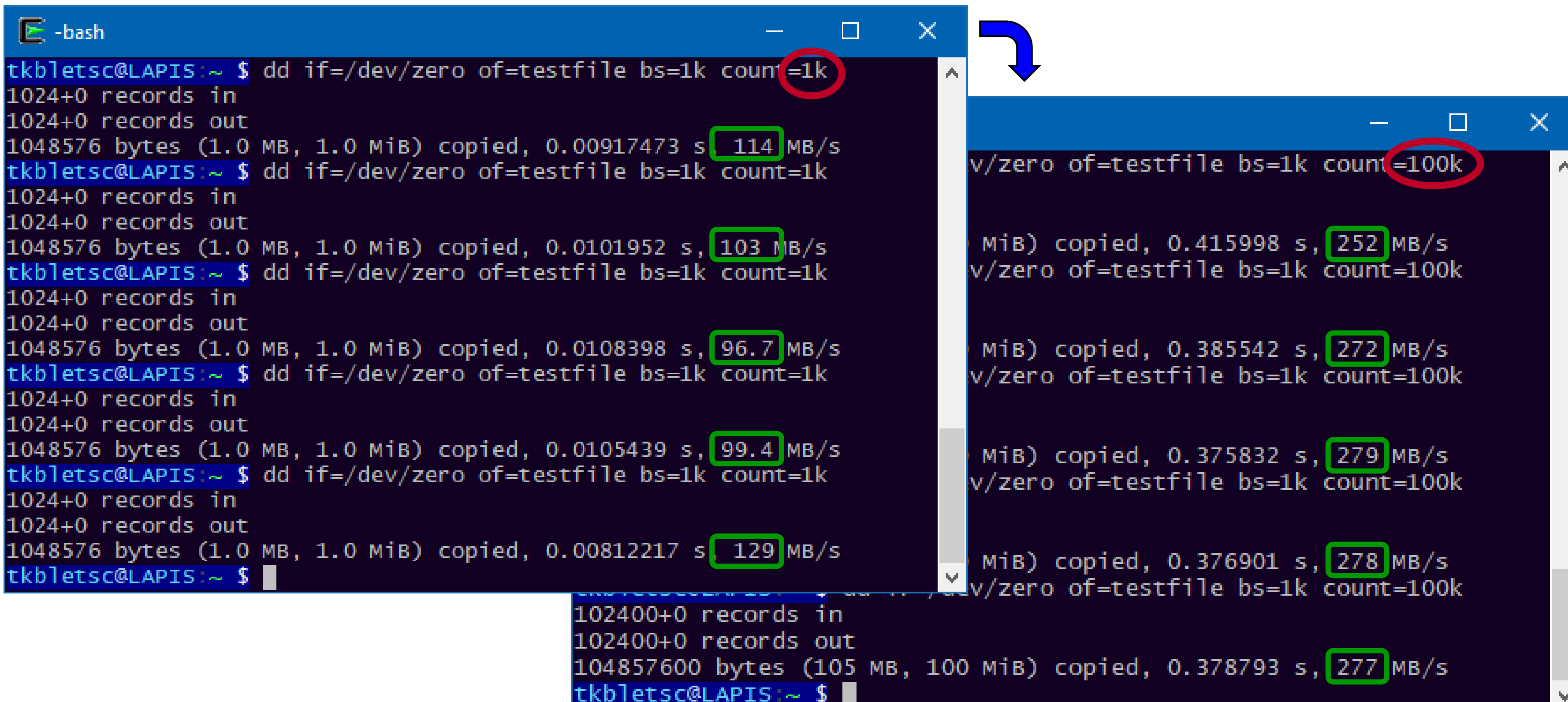
- Basic test: do X amount of IO and divide by time T.
  - Both X and T may be specified or measured
  - Example:
    - Measure time to do 100,000 IOs (X given, T free variable)
    - Write to disk at max rate for 60 seconds, look at file size (T given, X free variable)
- Problem: **measurement variance**

-bash

```
tkbletsc@LAPIS:~ $ dd if=/dev/zero of=testfile bs=1k count=1k
1024+0 records in
1024+0 records out
1048576 bytes (1.0 MB, 1.0 MiB) copied, 0.00917473 s, 114 MB/s
tkbletsc@LAPIS:~ $ dd if=/dev/zero of=testfile bs=1k count=1k
1024+0 records in
1024+0 records out
1048576 bytes (1.0 MB, 1.0 MiB) copied, 0.0101952 s, 103 MB/s
tkbletsc@LAPIS:~ $ dd if=/dev/zero of=testfile bs=1k count=1k
1024+0 records in
1024+0 records out
1048576 bytes (1.0 MB, 1.0 MiB) copied, 0.0108398 s, 96.7 MB/s
tkbletsc@LAPIS:~ $ dd if=/dev/zero of=testfile bs=1k count=1k
1024+0 records in
1024+0 records out
1048576 bytes (1.0 MB, 1.0 MiB) copied, 0.0105439 s, 99.4 MB/s
tkbletsc@LAPIS:~ $ dd if=/dev/zero of=testfile bs=1k count=1k
1024+0 records in
1024+0 records out
1048576 bytes (1.0 MB, 1.0 MiB) copied, 0.00812217 s, 129 MB/s
tkbletsc@LAPIS:~ $
```

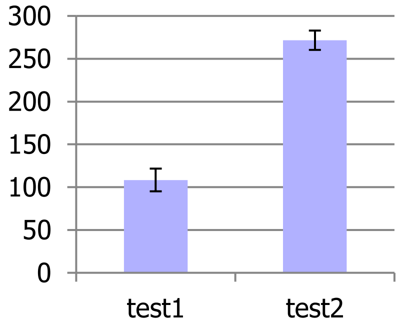
Combating measurement variance (1)

- Measurement varying too much? Make sure your tests are long enough!
  - Otherwise you're testing tiny random effects instead of the actual phenomenon under study...



Combating measurement variance (2)

- Measurement variance never goes away
  - Need to characterize it when presenting results, or you won’t be trusted!
  - How? Take multiple repetitions show average *and* standard deviation (or other variance metric)
- **ALL data requires variance to be characterized!** (not just in this course, but in your life)
  - For your projects, failure to characterize variance is likely an automatic request for resubmission!!
- How to present:
  - In tables, show variance next to average (e.g. “251.2 ± 11.6”)
  - In graphs, show variance with error bars, e.g.:



Hands-on with the Linux storage subsystem

I’m going to **live demo** a lot of command-line tools and concepts:
watching live or reviewing a video recording
may be of more value than just the slides.

Fundamental concepts in UNIX

- UNIX figured out a *lot* of what is smart in OS design.
- One insight: ***Everything is a file***
  - All hardware is represented as special **device files**. Described by "major" and "minor" numbers to tell kernel what device you mean.
  - Devices automatically created in special filesystem "/dev"
  - Includes block devices (e.g., HDDs and SSDs)
    - /dev/**sda**, /dev/**sdb**, /dev/**sdc**, … = **S**CSI **D**isk **A**, **B**, **C**, …
  - List block devices with `lsblk`:

localadmin@esaXX: ~

```
localadmin@esaXX:~$ lsblk
NAME   MAJ:MIN RM  SIZE RO TYPE MOUNTPOINT
sda      8:0    0  120G  0 disk
├─sda1   8:1    0    1M  0 part
├─sda2   8:2    0   40G  0 part /
└─sda3   8:3    0    2G  0 part [SWAP]
sdb      8:16   0  144G  0 disk /mnt/b
sdc      8:32   0  144G  0 disk
sdd      8:48   0  144G  0 disk
sde      8:64   0  144G  0 disk
sr0     11:0    1  908M  0 rom
localadmin@esaXX:~$
```

Doing basic IO manually

- Can open/read/write/close block devices like any other
  - Requires root access by default (e.g. via **`sudo`**)
  - Any program can do this – no special interface!
    - Bash commands, python, etc.
- Useful to have a tool for doing basic IO with lots of options
  - Introducing **`dd`**!
  - Basic usage:
    - **`dd if=INPUTFILE of=OUTPUTFILE bs=1k count=32`**

      `if`: Defaults to stdin if omitted
      `of`: Defaults to stdout if omitted
      `bs`: Defaults to 512 if omitted
      `count`: Defaults to all if omitted

    - **`dd if=/dev/sdb of=/dev/null bs=1 count=1`**

      `if`: Read from disk B
      `of`: Discard result
      `bs`/`count`: 1 byte in total

    - Lots more options, see manpage for details!

Block device tracing

- Kernel can trace the activity to block devices for us
- Install it:

```
sudo apt install --no-install-recommends blktrace
```

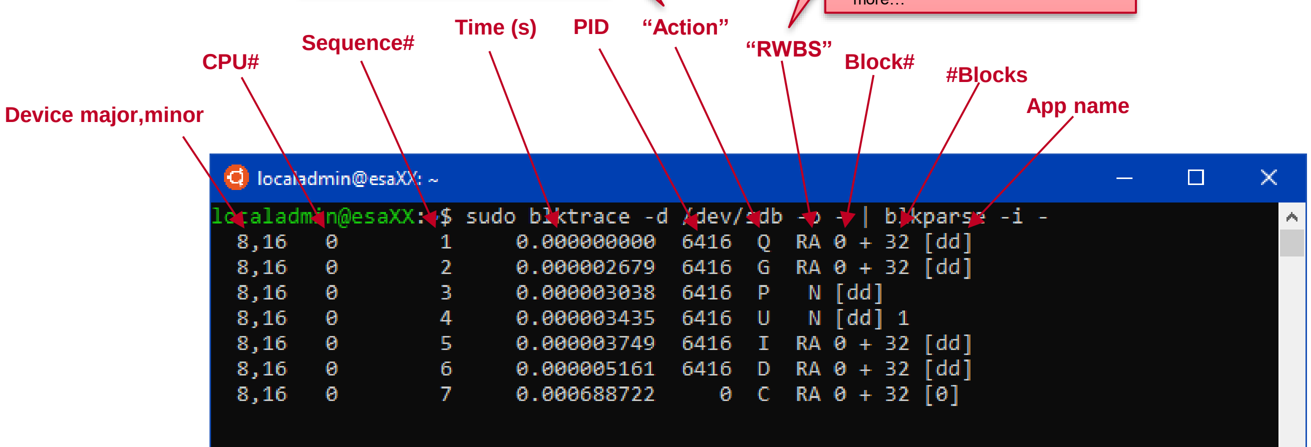
Why --no-install-recommends? Because it recommends a visualizer that depends on ffmpeg, which itself transitively recommends an entire GUI suite we don't need.

- Default: blktrace stores trace in binary format in a file; blkparse used to view it in text
  - Can chain the two to get live trace on screen (as root):

```
blktrace -d /dev/sdb -o - | blkparse -i -
```

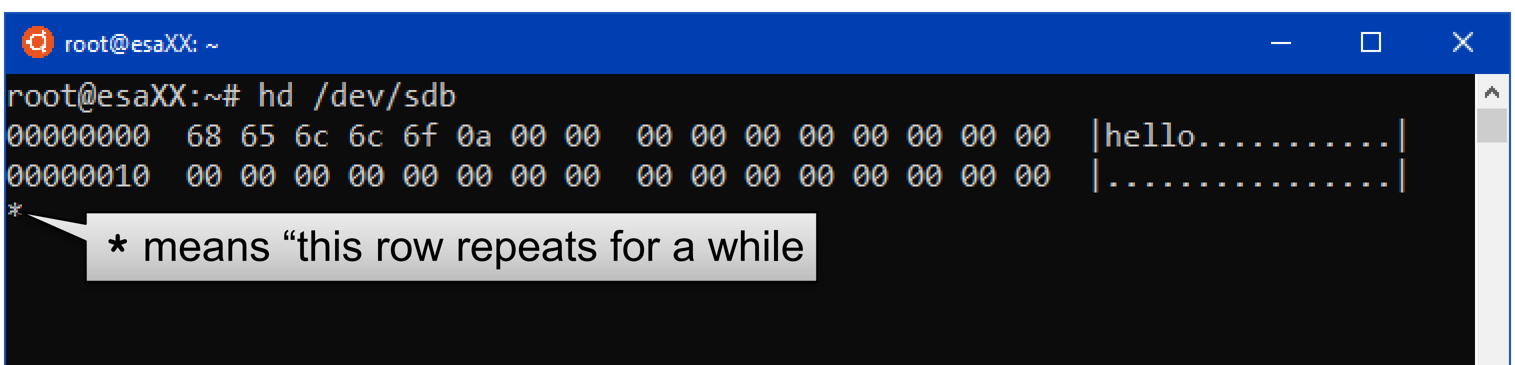
Q=Queued
G=Get request
P/U= "Plug"/"Unplug"
I=Insert into device queue
D=Device command issued
C=Completed
See `man blkparse` for more

R=Read
W=Write
N=None (placeholder)
D=Discard (trim)
+
A=readahead
S=synchronous
more…



Let's directly use this disk!

- Write "hello" to the very front of it? Easy:
  - echo hello > /dev/sdb
- Read the raw bytes of the disk?
  - Could use 'cat', but it will read the whole disk…
  - Can use 'dd', but what about non-text content?
  - Need a way to interpret binary bytes so we can see them onscreen
  - We want a **hex dump**
    - Three flavors:
      - **`hd`**: Gives binary+ascii dump by default (other options available)
      - **`hexdump`**: Get a binary+ascii dump with **`hexdump -C`** (other options available)
      - **`od`**: Gives octal by default (other options available)



Living without a filesystem

- So far, no filesystem. Screw it – we don't need a filesystem!
- I put my taxes at offset 1000

  `echo "IRS form 1040 …" | dd of=/dev/sdb bs=1 seek=1000`
- I put my dog picture at offset 2000

  `dd if=dog.jpg of=/dev/sdb bs=1 seek=2000`
- I can retrieve the stuff!

root@esaXX: ~

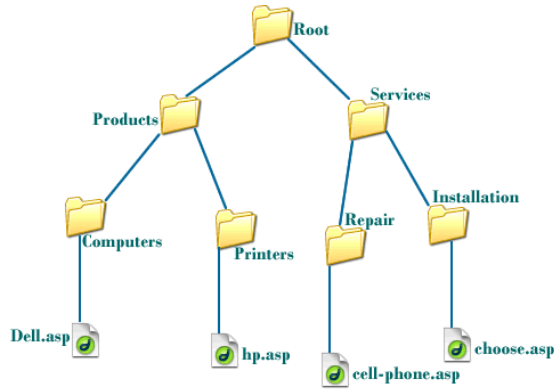
```
root@esaXX:~# hd /dev/sdb | head -n30
00000000  68 65 6c 6c 6f 0a 00 00  00 00 00 00 00 00 00 00  |hello...........|
00000010  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
*
000003e0  00 00 00 00 00 00 00 00  e2 80 9c 49 52 53 20 66  |...........IRS f|
000003f0  6f 72 6d 20 31 30 34 30  20 e2 80 a6 e2 80 9d 0a  |orm 1040 .......|
00000400  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
*
000007d0  ff d8 ff e0 00 10 4a 46  49 46 00 01 01 01 00 48  |......JFIF.....H|
000007e0  00 48 00 00 ff e1 5d 21  45 78 69 66 00 00 4d 4d  |.H....]!Exif..MM|
000007f0  00 2a 00 00 00 08 00 08  01 0f 00 02 00 00 00 04  |.*..............|
00000800  4c 47 45 00 01 10 00 02  00 00 00 08 00 00 00 6e  |LGE............n|
00000810  01 1a 00 05 00 00 00 01  00 00 00 76 01 1b 00 05  |...........v....|
00000820  00 00 00 01 00 00 00 7e  01 28 00 03 00 00 00 01  |.......~.(......|
00000830  00 02 00 00 02 13 00 03  00 00 00 01 00 01 00 00  |................|
00000840  87 69 00 04 00 00 00 01  00 00 00 86 88 25 00 04  |.i...........%..|
00000850  00 00 00 01 00 00 01 72  00 00 01 b4 4e 65 78 75  |.......r....Nexu|
```

Inventing the filesystem

- Wow, remembering these offsets is hard.
  I'll write them down…ON THE DISK!
  - echo "taxes: 1000, dog: 2000, …" > /dev/sdb
- Wow, manually doing the seeks to read/write areas of the disk is hard.
  I'll invent OS functions that do it for me…and update the file locations automatically!!!!!!!
  - I'll call the data containers "files"
  - I'll organize them into hierarchical "directories"
  - I'll give them the concept of "size" so I know when they end
  - I'll keep track of what areas of the disk aren't used and call that "free"
  - I'll call that special info that describes files my "meta-data"
  - To access data, programs will "open" the file (confirm it exists), then "read" and "write" to it, then "close" it – that's a great interface!

Life was good, until….

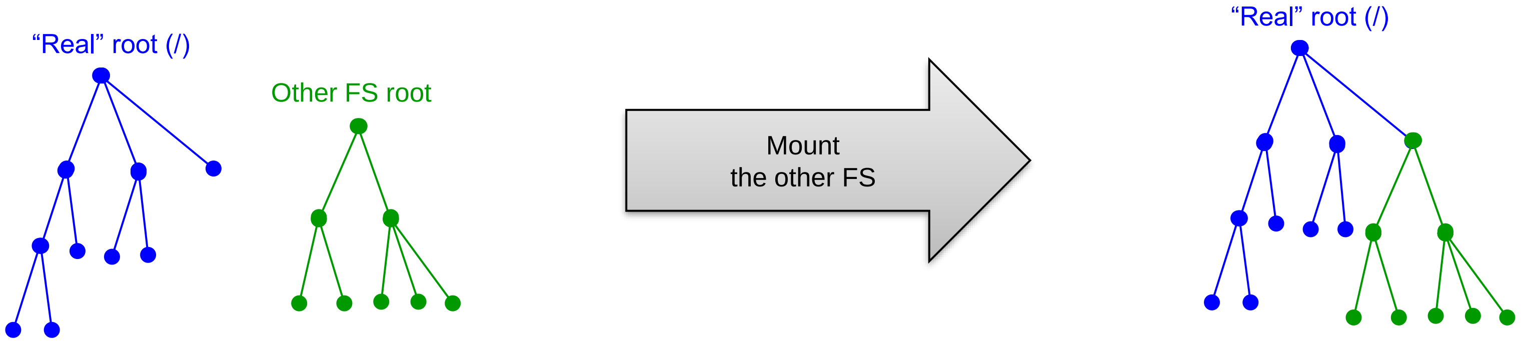
- "I love that my whole hard drive is now organized!"



- But wait, what's this? What if you have ANOTHER DRIVE?????

Filesystem trees in UNIX

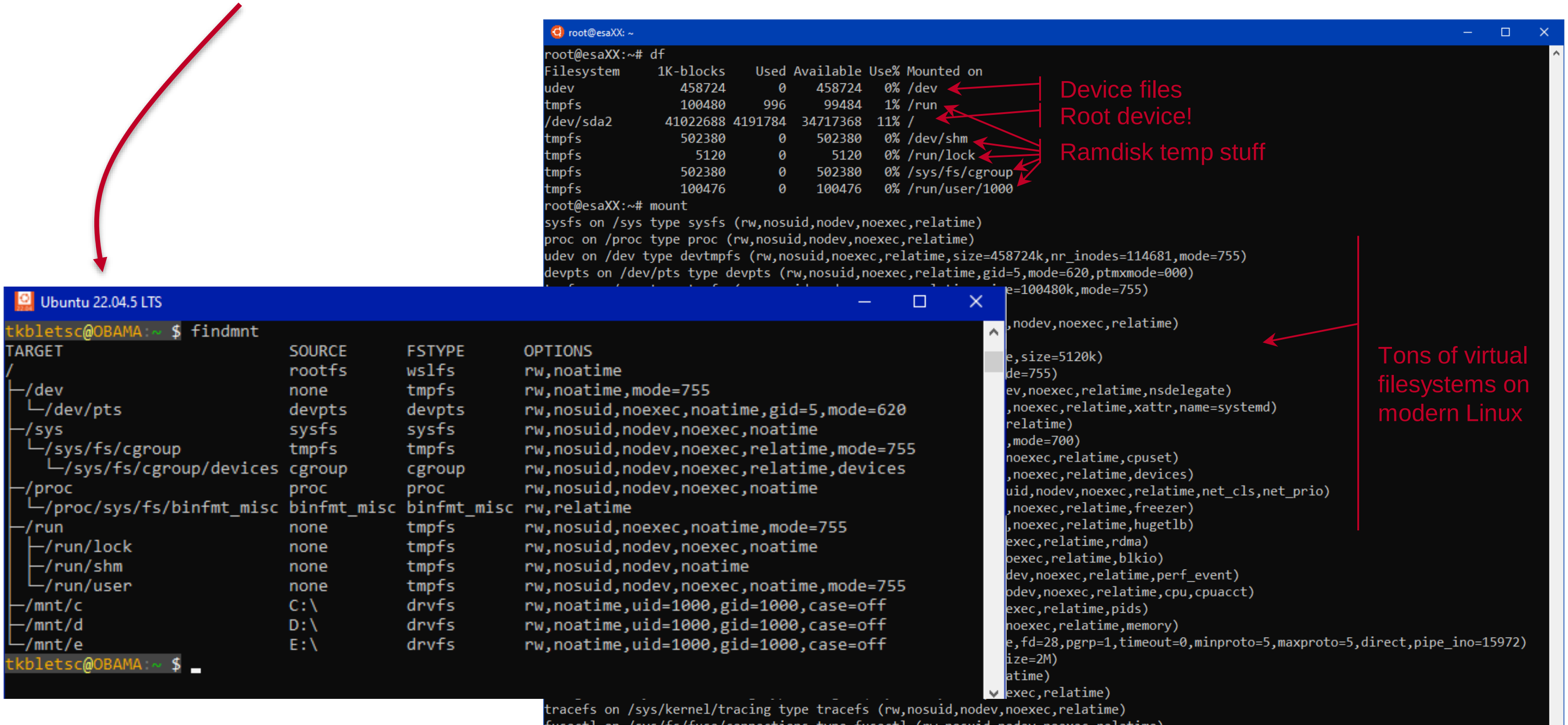
- Another UNIX insight: ***One global hierarchy***
  - A UNIX system has a single root directory with a root file system
  - Other filesystems can be "mounted" in directories under the root



- Also, filesystems don't have to just hold "real" files on "real" storage devices – there are virtual filesystems:
  - /proc – info about processes and basic system info (used by **`top`**)
  - /sys – info about kernel (used by **`blktrace`**)
  - /dev – access to device files themselves (managed by **`udev`**)
  - Ramdisk – files live in memory, wiped on reboot (e.g. **`tmpfs`**)

See what's mounted

- Two commands to see what's mounted:
  - **`mount`** – shows all filesystems (real and virtual)
  - **`df`** – shows disk free space on filesystems that have that concept
    - (Side-effect: shows fewer "fake" filesystems, more concise)
  - **`findmnt`** – newer tool, shows a nice hierarchy



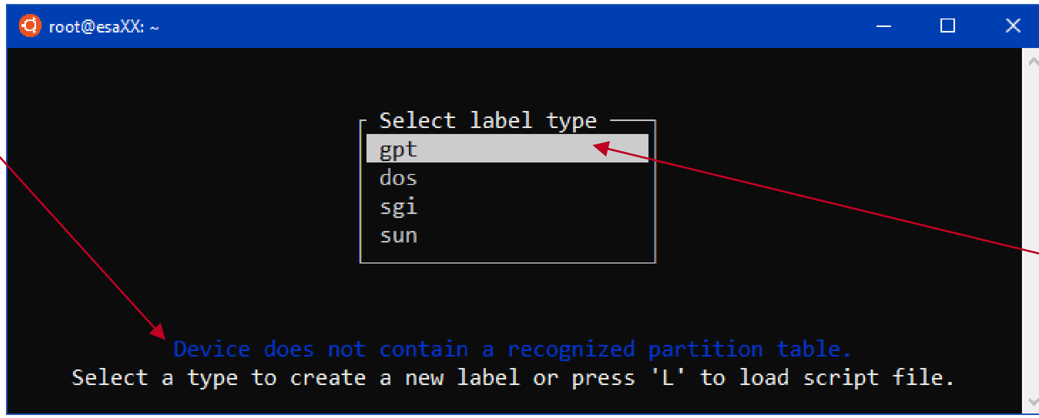
Partitioning

- What if I want to put multiple filesystems on one device?
  - Examples:
    - Multiple operating systems (e.g. Windows and Linux)
    - An area for files and an area for virtual memory swap space
    - Keep the OS separate from user home directories (so user data filling up doesn't affect the OS)
- Solution: **partitioning**
  - Widely supported scheme to divide up a disk; partitions are contiguous and small in number (usually 1-3).
  - Partitions labeled with integer that hints at what type of data is there.
  - Two standards: MBR (deprecated) and GPT (GUID Partition Table).
  - The **partition table** occupies beginning of disk, file systems actually live within partitions. The OS knows about this and gives partitions numbered device files:
    `/dev/sdb` is partitioned into **`/dev/sdb1`**, **`/dev/sdb2`**, etc.

Partitioning with `cfdisk`

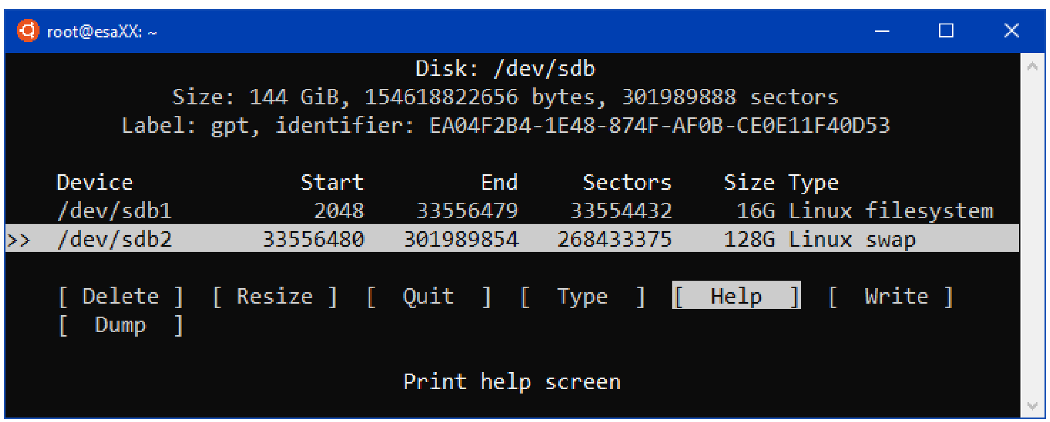
- Run **`cfdisk /dev/sdb`**

New (or erased) disk

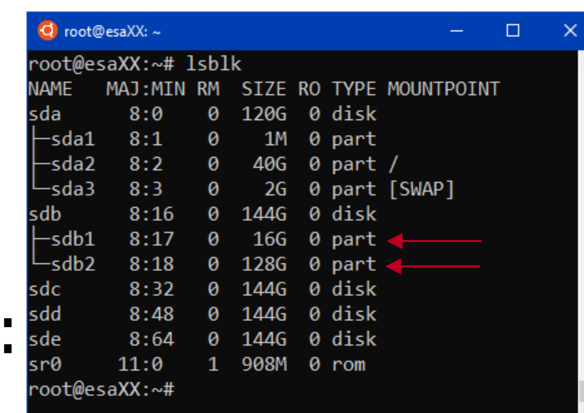


We want this guy

- Follow prompts and we can make partitions, set type, etc.



- Hit “Write” when done. Result in **`lsblk`**:



Filesystem choices

- Let's put a filesystem on, but which one?
  - Common picks:
    - ext4 – common Linux default
    - btrfs – fancy Linux option with lots of special features
    - FAT – classic Windows/DOS filesystem still in use on SD cards; called vfat in Linux
    - exFAT – modern take on FAT, used on large USB/SD cards
    - NTFS – modern Windows filesystem
    - HFS+ - modern Mac OSX filesystem
- Need to initialize a filesystem: write on-disk metadata structures on that represent empty filesystem. Use **`mkfs`**
- Let's pick a simple filesystem: **`vfat`**
  (Why? Because ext4 does fancy background stuff that gets noisy to trace)
- Run **`mkfs.vfat /dev/sdb1`**
  - Watch blktrace as it goes – wheeeee!

Let’s mount it

- Make an empty dir as a mountpoint: **`mkdir /mnt/blah`**
- Mount it: **`mount /dev/sdb1 /mnt/blah`**
    - Kernel will scan partition and auto-detect type of filesystem
    - Will load correct filesystem driver
    - Now, OS calls to paths under there will get handled by that driver
    - Driver satisfies all OS calls by doing readblock/writeblock requests to the underlying block device
    - That’s how filesystems work!

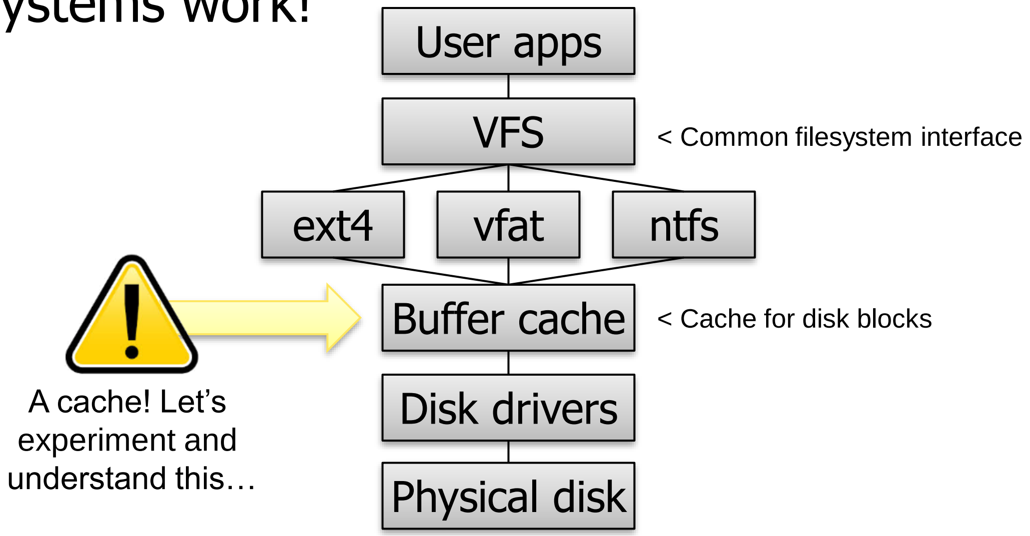


Figure adapted from Gotzon Gregor

Test the block cache (1)

`echo hi > file`

- No blktrace output! (OS cache is writeback by default)

`cat file`

- No blktrace output! (Cache hit)

(Wait about a minute, it posts later to blktrace)

- Yes blktrace output! (Cache being flushed on a timer, see metadata+data changes)

`echo hi > file`

- No blktrace output! (Writeback cache again)

`sync`

- Yes blktrace output! (This command forces OS to flush cache)

`cat file`

- No blktrace output! (Still a hit, just block isn't dirty in cache)

Test the block cache (2)

`echo 3 > /proc/sys/vm/drop_caches`

- Writing to this special file tells kernel to drop caches;
- No blktrace output though, but ramcache was cleared.

`cat file`

- Blktrace output – we miss because we dropped caches

`umount /mnt/blah`

`mount -o sync /dev/sdb1 /mnt/blah`

- Unmount and remount with the 'sync' mount option
- Forces writethrough cache mode!

`echo hi > file`

- Blktrace output immediately! No writeback cache, writethrough instead

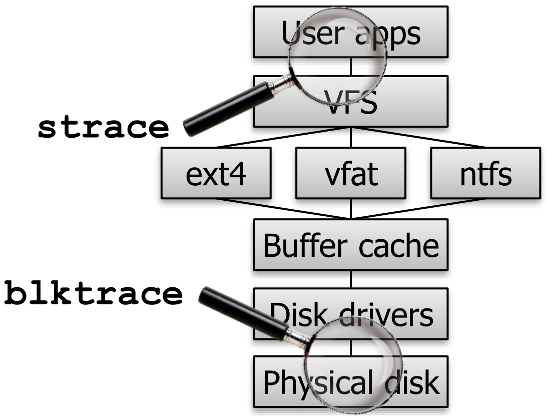
`cat file`

- No blktrace output - it still caches reads

Let's trace from the other side

- We've been tracing the block device
- What about the OS requests?

  strace



- Shows each OS syscall done by a program.
  - Works on a command by default; can attach to already-running program if desired
  - Have to wade through some "noise" (unrelated calls), not hard with a little experience

  - VERY powerful and useful – can determine *behavior* of software without looking at source code or machine instructions!

strace example

```
root@esaXX:/mnt/blah# strace dd if=/dev/sdb bs=1 count=1
execve("/usr/bin/dd", ["dd", "if=/dev/sdb", "bs=1", "count=1"], 0x7ffec5104518 …) = 0
```

{A bunch of openat, pread64, mmap, mprotect, rt_sigaction, brk, etc.: set up dynamic libraries and prep malloc (ignore)}

```
openat(AT_FDCWD, "/dev/sdb", O_RDONLY)  = 3
dup2(3, 0)                              = 0
close(3)                                = 0
lseek(0, 0, SEEK_CUR)                   = 0
```

Open the input device, rename it to file descriptor 0 (dd likes to pretend its input is always stdin, which is 0)

{A bunch of openat and read calls relating to "locale" – language translations (ignore)}

```
read(0, "\0", 1)                        = 1
write(1, "\0", 1 )                      = 1
close(0)                                = 0
close(1)                                = 0
write(2, "1+0 records in\n1+0 records out\n", 311+0 records in
1+0 records out
) = 31
write(2, "1 byte copied, 0.000672287 s, 1."..., 381 byte copied, 0.000672287 s, 1.5 kB/s) = 38
write(2, "\n", 1
)                       = 1
close(2)                                = 0
exit_group(0)                           = ?
+++ exited with 0 +++
```

Read the one requested byte from fd 0 (disk) and write to fd 1 (stdout), then close both.

Report to stderr the statistics. Blue stuff is dd's actual output to stderr; black is strace telling us about it.

Let's play

- Let's try some other strace+dd combos, and let's watch blktrace as we do!
- Things to observe
  - Note how **`bs`** sets the read/write size for OS calls, but a single call could turn into many block IOs
  - Note the effect of read-ahead caching by the OS
  - Note how the cache can be a mix of hits and misses
  - We can use the "-t" option with blkparse to get timing info
    - Observe the correlation between block operations and slower dd results (i.e., cache misses)

Architecture conclusions

- Disks are **block devices**
- All devices in Linux/UNIX are represented by **device files**; can directly interact with
- Disk blocks are cached in RAM by operating system (**buffer cache**)
- Block devices are cumbersome to manually store data, so we invent **filesystems**
- OS handles filesystems – many filesystems can be mounted at once; the **VFS layer** pivots among them, using the right **filesystem driver**
- Filesystem driver will issue read/write requests to **disk driver**

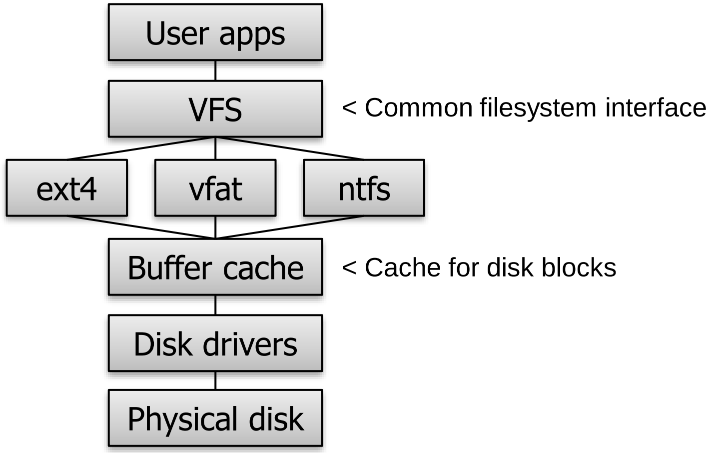


Figure adapted from Gotzon Gregor

Tool conclusions

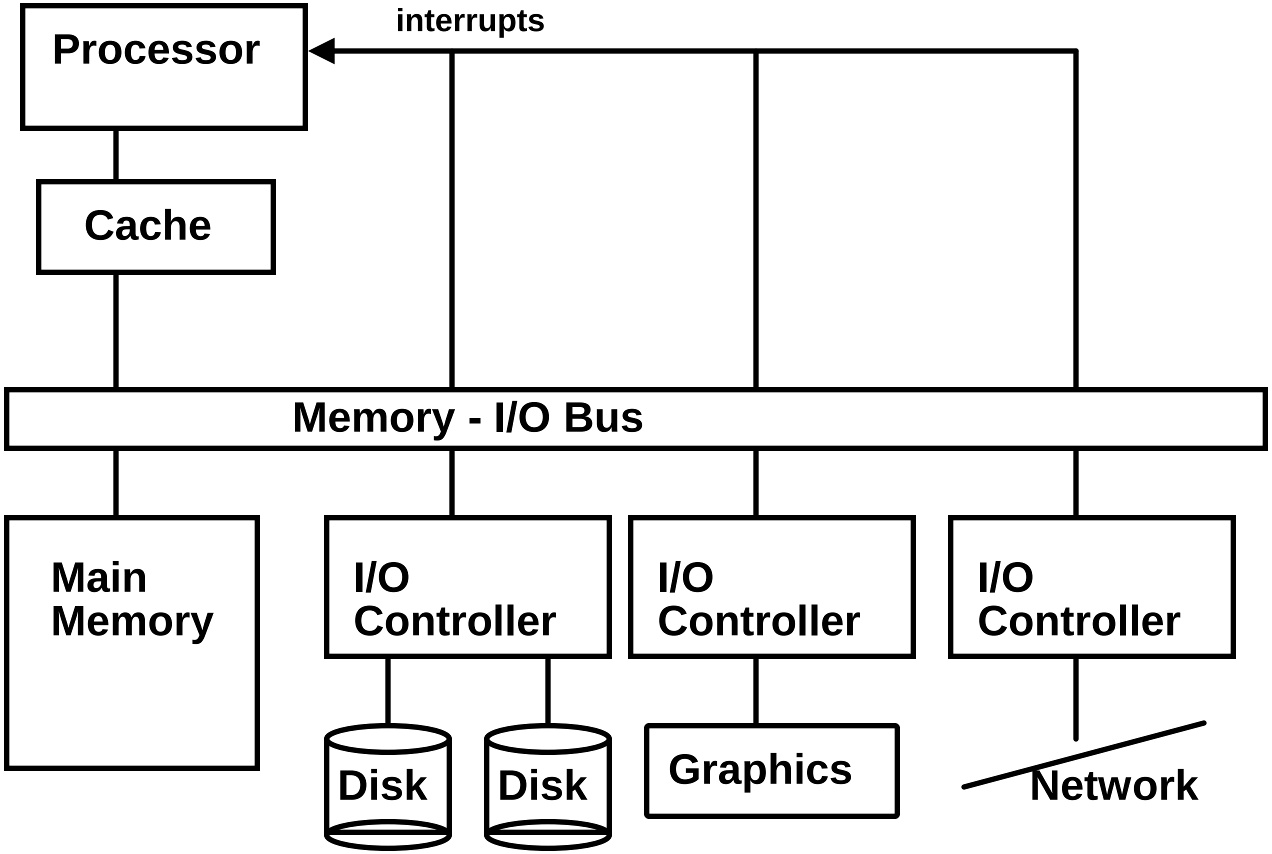
- We learned lots of great tools/commands:
  - `lsblk`: View block devices
  - `df`: View attached "real" filesystems (and free space)
  - `mount`: Without arguments, shows *all* mounted filesystems
  - `dd`: Simple tool to do sequential IO operations
  - `hd` and `hexdump`: View binary data in human-readable way
  - `mount` and `umount`: Mount and unmount filesystems
  - `cfdisk`: Create and manage disk partitions
  - `mkfs.*`: Create various filesystems on a block device
  - `blktrace` and `blkparse`: Trace IO operations to physical block devices
  - `strace`: Trace system calls being made by a program
  - `sync`: Force OS to flush all dirty blocks in writeback cache to disk
  - `echo 3 > /proc/sys/vm/drop_caches`: Force OS to lose entire block cache content

Questions?

Backup slides

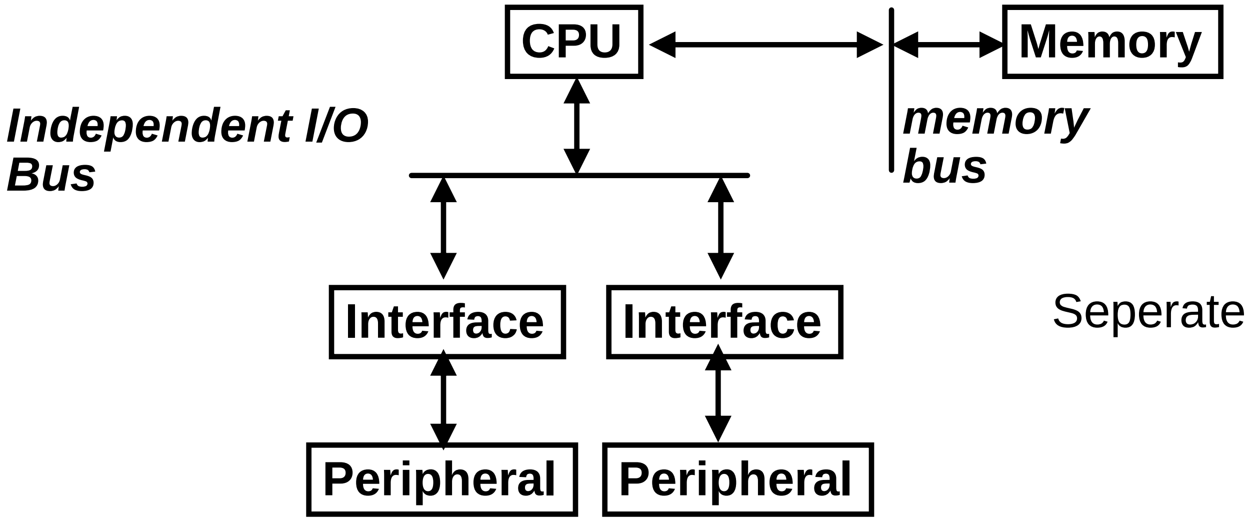
The I/O Subsystem

I/O Systems

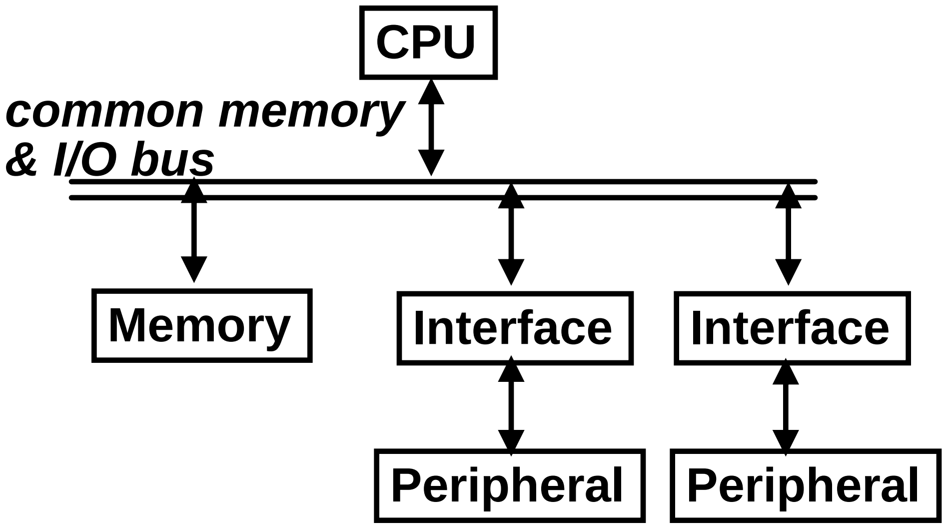


Processor
interrupts
Cache
Memory - I/O Bus
Main Memory
I/O Controller
I/O Controller
I/O Controller
Disk
Disk
Graphics
Network

I/O Interface

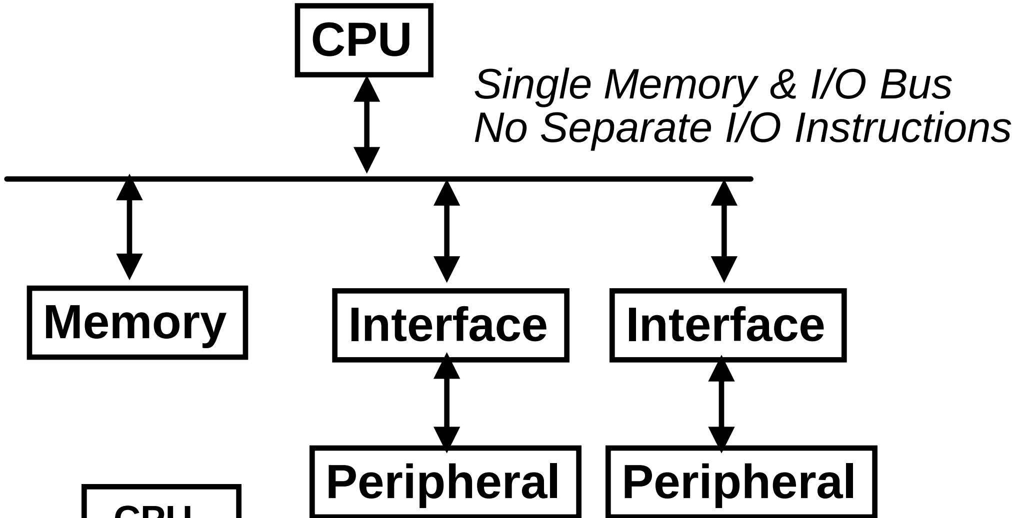


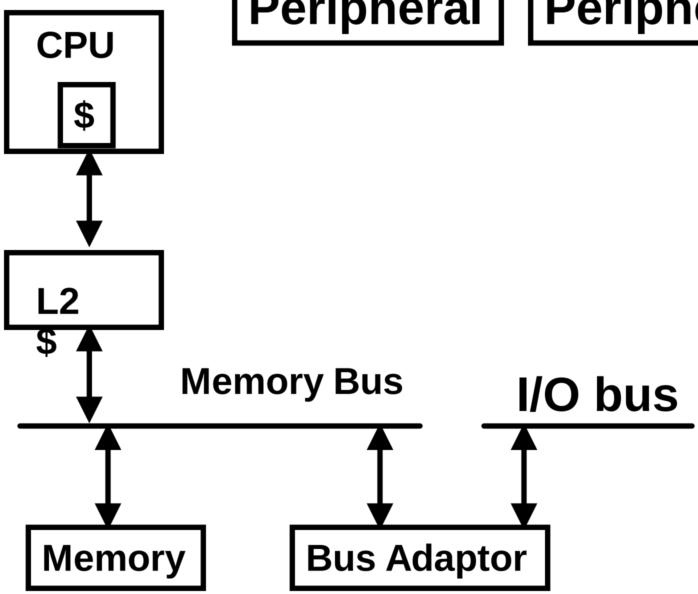
Seperate I/O instructions (in,out)

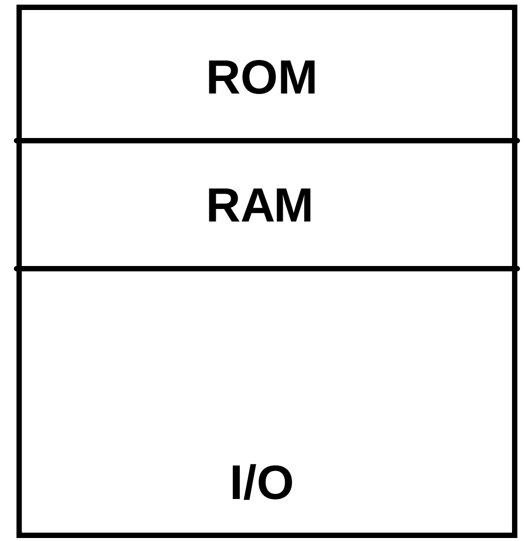


Lines distinguish between
I/O and memory transfers

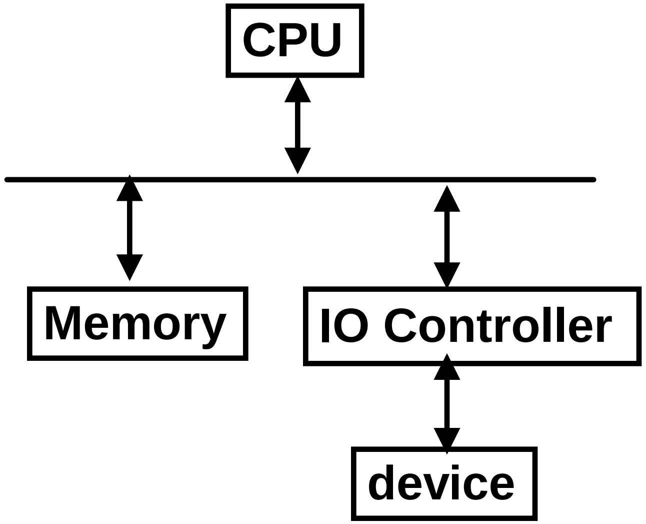
Memory Mapped I/O

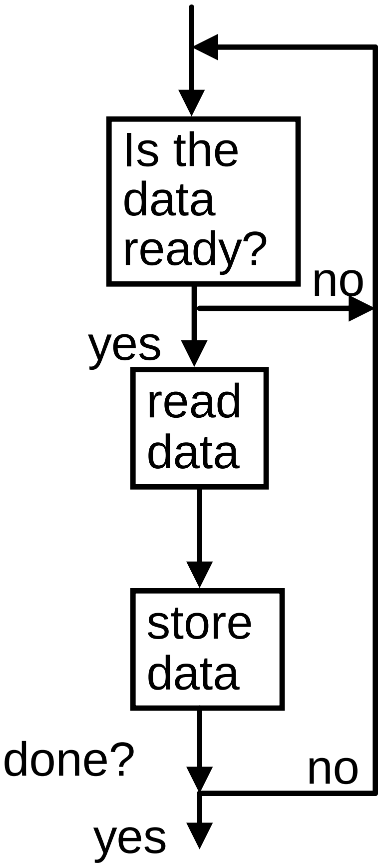






Programmed I/O (Polling)

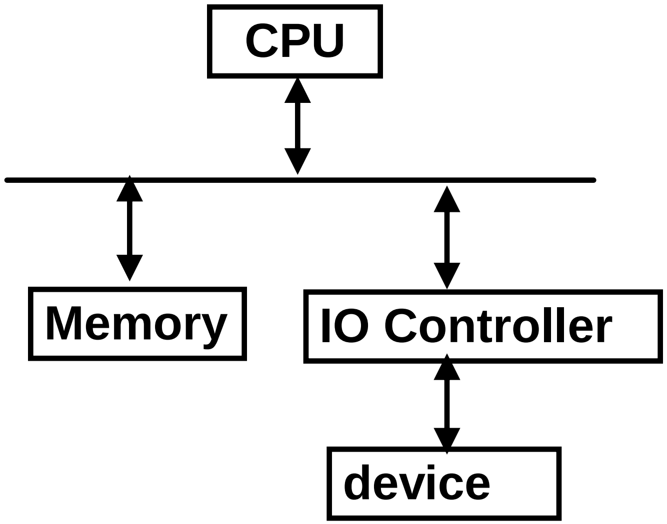


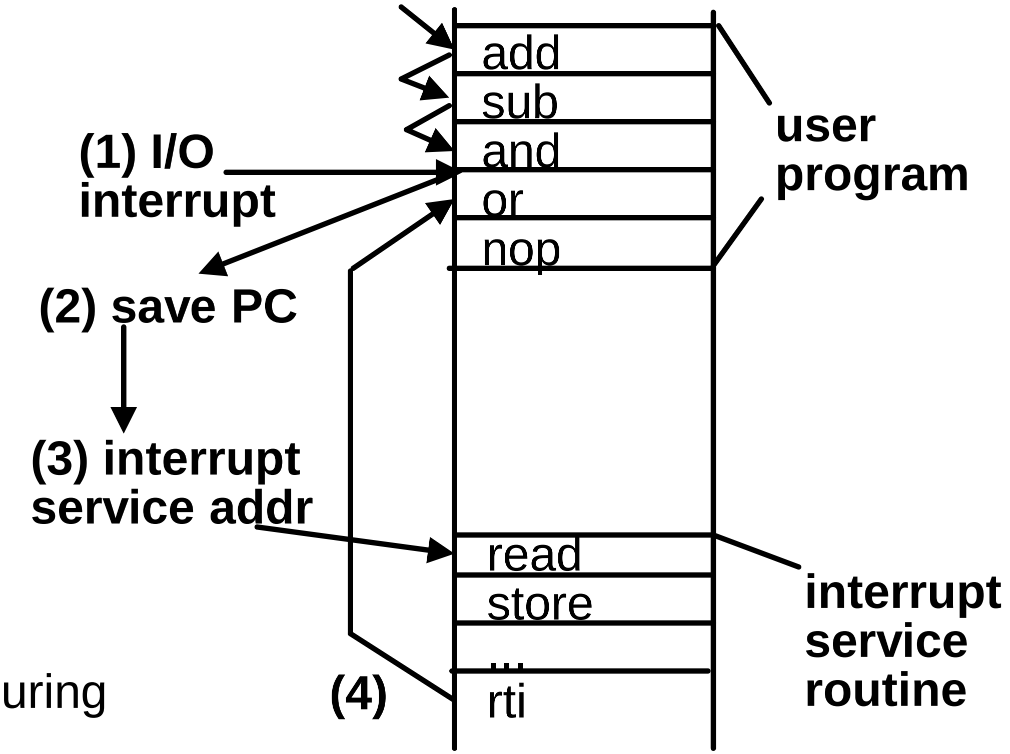


busy wait loop not an efficient way to use the CPU unless the device is very fast!

but checks for I/O completion can be dispersed among computationally intensive code

Interrupt Driven Data Transfer





User program progress only halted during actual transfer

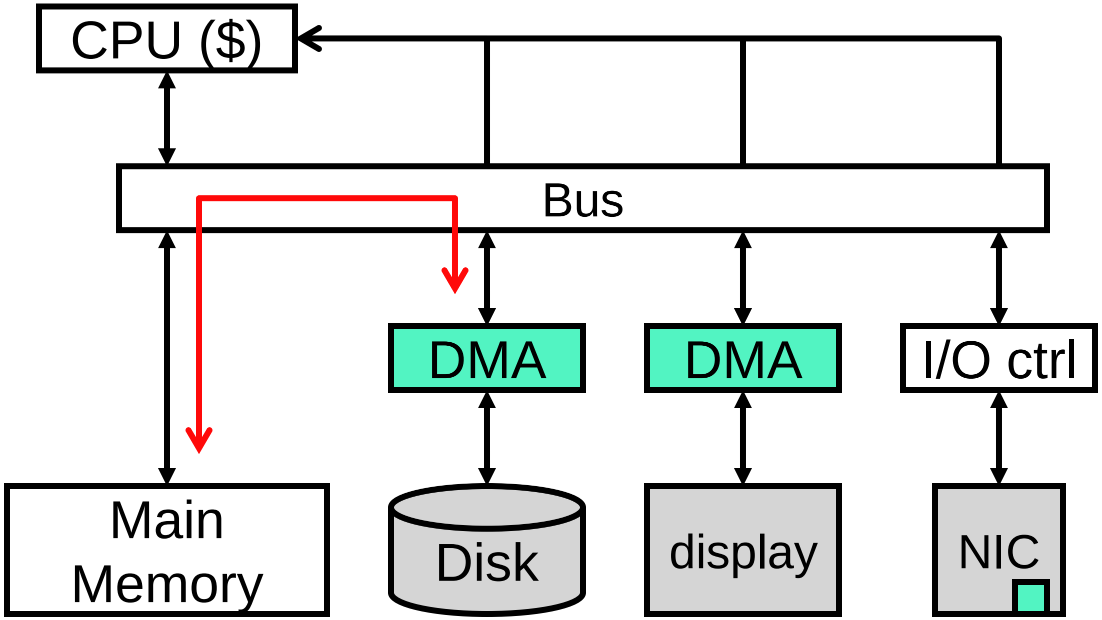
Direct Memory Access (DMA)

- Interrupts remove overhead of polling…
- But still requires OS to transfer data one word at a time
  - OK for low bandwidth I/O devices: mice, microphones, etc.
  - Bad for high bandwidth I/O devices: disks, monitors, etc.

- **Direct Memory Access (DMA)**
  - Transfer data between I/O and memory without processor control
  - Transfers entire blocks (e.g., pages, video frames) at a time
    - Can use bus "burst" transfer mode if available
  - Only interrupts processor when done (or if error occurs)

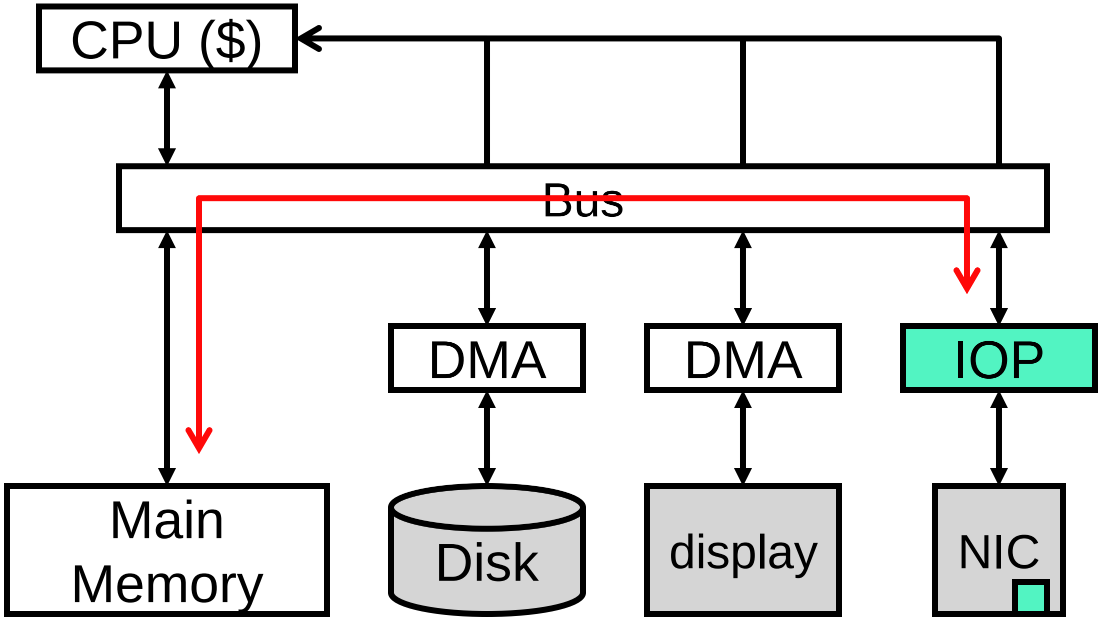
DMA Controllers

- To do DMA, I/O device attached to **DMA controller**
  - Multiple devices can be connected to one DMA controller
  - Controller itself seen as a memory mapped I/O device
    - Processor initializes start memory address, transfer size, etc.
  - DMA controller takes care of bus arbitration and transfer details
    - So that's why buses support arbitration and multiple masters!



I/O Processors

- A DMA controller is a very simple component
  - May be as simple as a FSM with some local memory
- Some I/O requires complicated sequences of transfers
  - **I/O processor**: heavier DMA controller that executes instructions
    - Can be programmed to do complex transfers
    - E.g., programmable network card



Summary: Fundamental properties of I/O systems

Top questions to ask about any I/O system:

- Storage device(s):
  - What kind of device (SSD, HDD, etc.)?
  - Performance characteristics?
- Topology:
  - What's connected to what (buses, IO controller(s), fan-out, etc.)?
  - What protocols in use (SAS, SATA, etc.)?
  - Where are the bottlenecks (PCI-E bus? SATA protocol limit? IO controller bandwidth limit?)
  - Protocol interaction: polled, interrupt, DMA?