Hard disks, SSDs, and the I/O subsystem

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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

^ (these aren’t common any more)
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

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 average seek time for all seeks yields a poor model
Zoning

• Note
  • More linear distance at edges than at center
  • Bits/track $\sim R$ (circumference $= 2\pi R$)
  • To maximize density, bits/inch should be the same

• How many bits per track?
  • Same number for all $\Rightarrow$ simplicity; lowest capacity
  • Different number for each $\Rightarrow$ 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

**Read**
- Host sends command
- Controller decodes it
- Controller disconnects from bus & starts seek
- Seek
- Rotation latency
- Data transfer off mechanism
- Head switch
- SCSI bus
- Disk mechanism

**Write**
- Host sends command
- Controller decodes it
- SCSI bus data transfer from host
- Controller starts seek
- Seek
- Rotation latency
- Data transfer to mechanism
- Head switch
- SCSI bus
- Disk mechanism
## Disk Parameters

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>1.8”</td>
<td>2.5”</td>
<td>3.5”</td>
</tr>
<tr>
<td>Capacity</td>
<td>Improving ☺ 10 GB</td>
<td>73 GB</td>
<td>6 TB</td>
</tr>
<tr>
<td>RPM</td>
<td>4200 RPM</td>
<td>10000 RPM</td>
<td>7200 RPM</td>
</tr>
<tr>
<td>Cache</td>
<td>Improving ☺ 512 KB</td>
<td>8 MB</td>
<td>128 MB</td>
</tr>
<tr>
<td>Platters</td>
<td>1</td>
<td>2</td>
<td>~6</td>
</tr>
<tr>
<td>Average Seek</td>
<td>About equal ☑ 7 ms</td>
<td>4.5 ms</td>
<td>4.16 ms</td>
</tr>
<tr>
<td>Sustained Data Rate</td>
<td>Improving ☺ 16 MB/s</td>
<td>94 MB/s</td>
<td>216 MB/s</td>
</tr>
<tr>
<td>Interface</td>
<td>ATA</td>
<td>SCSI</td>
<td>SAS/SATA</td>
</tr>
<tr>
<td>Use</td>
<td>Ancient iPod</td>
<td>Laptop</td>
<td>Desktop</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Single-level cell (SLC)</th>
<th>Multi-level cell (MLC)</th>
<th>Triple-level cell (TLC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single (bit) level cell</td>
<td>Two (bit) level cell</td>
<td>Three (bit) level cell</td>
</tr>
<tr>
<td>Fast:</td>
<td>Reasonably fast:</td>
<td>Decently fast:</td>
</tr>
<tr>
<td>25us read/100-300 us write</td>
<td>50us read, 600-900us write</td>
<td>75us read, 900-1350 us write</td>
</tr>
<tr>
<td>Write endurance - 100,000 cycles</td>
<td>Write endurance – 10000 cycles</td>
<td>Write endurance – 5000 cycles</td>
</tr>
<tr>
<td>Expensive</td>
<td>Less expensive</td>
<td>Least expensive</td>
</tr>
</tbody>
</table>
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 $\rightarrow$ Serial IO $\rightarrow$ SSD Controller $\rightarrow$ 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
• 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

<table>
<thead>
<tr>
<th>SSD</th>
<th>HDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform seek time</td>
<td>Different seek time for different sectors</td>
</tr>
<tr>
<td>Fast seek time – random read/writes as fast as sequential read/writes</td>
<td>Seek time dependent upon the distance</td>
</tr>
</tbody>
</table>
| 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

<table>
<thead>
<tr>
<th>SSD</th>
<th>HDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 10,000 to &gt; 1 million IOPS</td>
<td>Hundreds of IOPS</td>
</tr>
<tr>
<td>Read/write in microseconds</td>
<td>Read/write in milliseconds</td>
</tr>
<tr>
<td>No mechanical part – no wear and tear</td>
<td>Moving part – wear and tear</td>
</tr>
<tr>
<td>MTBF ~ 2 million hours</td>
<td>MTBF ~ 1.2 million hours</td>
</tr>
<tr>
<td>Faster wear of a memory cell when it is written multiple times</td>
<td>Slower wear of the magnetic bit recording</td>
</tr>
</tbody>
</table>
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? Yes!

Cheaper per gigabyte of capacity.

or

SSD? Yes!

Cheaper per IOPS (performance).

Tradeoff!
## Workloads

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

- 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

Source: Andy Rudoff, Intel
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**
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...
• 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/\texttt{sda}, /dev/\texttt{sdb}, /dev/\texttt{sdc}, … = SCSI Disk A, B, C, …
  • List block devices with \texttt{lsblk}:
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`
  • `dd if=/dev/sdb of=/dev/null bs=1 count=1`
  • 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 blktrace
  ```
- 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 -
    ```

### Sample Trace Output

<table>
<thead>
<tr>
<th>CPU#</th>
<th>Sequence#</th>
<th>Time (s)</th>
<th>PID</th>
<th>“Action”</th>
<th>“RWBS”</th>
<th>Block#</th>
<th>#Blocks</th>
<th>App name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Q</td>
<td>R A</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1,2</td>
<td>2</td>
<td>0.000000001</td>
<td>2</td>
<td>G</td>
<td></td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1,2</td>
<td>3</td>
<td>0.000000002</td>
<td>3</td>
<td>I</td>
<td></td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1,2</td>
<td>4</td>
<td>0.000000004</td>
<td>4</td>
<td>D</td>
<td></td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1,2</td>
<td>5</td>
<td>0.000000005</td>
<td>5</td>
<td>C</td>
<td></td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1,2</td>
<td>6</td>
<td>0.000000006</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,2</td>
<td>7</td>
<td>0.000000007</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Q=Queued
- G=Get request
- P/U= “Plug”/”Unplug”
- I=Insert into device queue
- D=Device command issued
- C=Completed
- R=Read
- W=Write
- N=None (placeholder)
- D=Discard (trim)
- A=readahead
- S=synchronous
- +

See `man blkparse` for 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)

```
root@esaXX:~# hd /dev/sdb
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 |................|

* means “this row repeats for a while"
Living without a filesystem

- So far, no filesystem. Screw it – we don’t need a filesystem!
- I put my taxes at offset 1000
  
  ```bash
  echo "IRS form 1040 …" | dd of=/dev/sdb bs=1 seek=1000
  ```
- I put my dog picture at offset 2000
  
  ```bash
  dd if=dog.jpg of=/dev/sdb bs=1 seek=2000
  ```
- I can retrieve the stuff!
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)
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`

- 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
    • 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 \texttt{mkfs}
  • Let’s pick a simple filesystem: \texttt{vfat}
    (Why? Because ext4 does fancy background stuff that gets noisy to trace)
  • Run \texttt{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!

A cache! Let’s experiment and understand this…

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)

touch file
  • No blktrace output! (Still a hit, just block isn’t dirty in cache)
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)

```bash
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

{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\n1+0 records out") = 31
write(2, "1 byte copied, 0.000672287 s, 1."...) = 38
write(2, "\n", 1 )                         = 1
close(2)                                   = 0
exit_group(0)                              = ?
+++ exited with 0 +++

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

Cache

Memory - I/O Bus

Main Memory

I/O Controller

Disk

I/O Controller

Disk

I/O Controller

Graphics

I/O Controller

Network

interrupts
I/O Interface

Independent I/O Bus

Separate I/O instructions (in, out)

Lines distinguish between I/O and memory transfers
Memory Mapped I/O

Single Memory & I/O Bus
No Separate I/O Instructions

CPU

Memory

Interface

Interface

Peripheral

Peripheral

CPU

L2

Memory Bus

I/O bus

Memory

Bus Adaptor

ROM

RAM

I/O
Programmed I/O (Polling)

Is the data ready?

- yes → read data
- no → busy wait loop

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

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

(1) I/O interrupt
(2) save PC
(3) interrupt service addr
(4) 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!

\[\text{CPU} \rightarrow \text{Bus} \rightarrow \text{DMA} \rightarrow \text{Main Memory} \rightarrow \text{Disk} \rightarrow \text{display} \rightarrow \text{I/O ctrl} \rightarrow \text{NIC}\]
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
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?