Storage devices

Tyler Bletsch
Duke University

Slides include material from Vince Freeh (NCSU)
Basic storage device history

- From https://aaronlimmv.wordpress.com/2013/05/02/types-of-storage-and-basic-advantages-and-disadvantages/
The ancient model of large enterprise storage

- **DASD:** Direct Access Storage Device
  - Starting with the IBM 350 in 1956
  - Your One Big Computer accesses your One Big Drive
  - Evolution: make the One Big Drive bigger and more reliable
  - Result: The One Big Drive became more and more expensive and critical
- **Problem?**

An IBM 350 drive (5 MB) being loaded into a PanAm jet, circa 1956.
DASD problem: single point of failure

- The DASD was a single point of failure with *all* your data
  - Better treat it gently...

Man with amazing fashion sense moves a 250MB disk, circa 1979.
Key trend: consumerization

• A common evolution in IT:
  • Businesses use a fancy expensive “Enterprise Thing”.
  • Normal people get a cheaper version, “Consumer Thing”. It’s cheap and good enough.
  • Consumer Thing gets better and better every year because:
    • There are more consumers than businesses (bigger market)
    • There are more vendors for consumers than for businesses (more competition)
    • The margins are thinner for consumer goods (more cut-throat competition)
  • A Smart Person finds a way to use the Consumer Thing for business.
  • Industry experts call the Smart Person dumb and say that no real business could ever use the Consumer Thing.
  • The Smart Person is immensely successful, and all businesses use the Consumer Thing.
  • Industry experts pretend they knew all along.
Consumerization in servers

- Big business use mainframe computers
- Everyone else uses microcomputers
- Microcomputers beat mainframes
- We start calling them "servers"
- Mainframes almost entirely gone
Consumerization in storage

- Big business use DASDs
- Everyone else eventually gets small hard disks (SCSI)
- Disk arrays invented using "JBOD" and eventually "RAID"
- Storage companies based on disk arrays gain traction
- DASDs are entirely gone
Disk arrays

- **JBOD**: Just a Bunch Of Disks
  - Multiple physical disks in an external cabinet
  - Array is connected to one server only.
  - Provides higher storage capacity with increased number of drives.
  - Effect on performance?
  - Effect on reliability?

- Can we do better?
Disk arrays

- **RAID**: Redundant Array of Inexpensive Disks
  - Academic paper from 1988
  - Revolutionized storage
  - Will discuss in depth later
  - Combine disks in such a way that:
    - Performance is additive
    - Capacity is additive
    - Drive failures can occur without data loss
  - Still directly attached to one server
Next step: intelligent arrays

- Server acts as host for storage, provides access to other servers
  - Dedicated hardware for RAID
  - Optimized for IO performance
  - High speed cache
  - Can add various special features at this layer: access controls, multiple protocols, data compression and deduplication, etc.
Method of Attachment

• How to connect storage array to other systems?
  • DAS: Direct Attached Storage
    • One client, one storage server
  • SAN: Storage Area Network
    • Storage system divides storage into “virtual block devices”
    • Clients make “read block”/“write block” requests just like to a hard drive, but they go to the storage server
  • NAS: Network-Attached Storage
    • Storage system runs a file system to create abstraction of files/directories
    • Clients make open/close/read/write requests just like to the OS’s local file system
DAS: Direct Attached Storage

- One-to-one connection
- Historically: connect via SCSI (“Small Computer Systems Interface”)  
  - Even though actual SCSI cables/drives/systems are gone, the software protocol is still *everywhere* in storage. We’ll see it again very soon*.  
- Modern:  
  - USB: External drives, very fast as of USB 3.0  
  - SATA (or if it’s external, e-SATA): The protocol modern consumer drives use  
  - SAS (Serial Attached SCSI): The protocol modern enterprise drives use

* see, I told you.
SAN: Storage Area Network (1)

- Split the aggregated storage into virtual drives called Logical Units (LUNs)
- Clients make read/write requests for blocks of “their” drive(s)
- Storage server translates request for block 50 of client 2 to actual block 4000 (which in turn is block 1000 of disk 3 of the RAID array)
SAN: Storage Area Network (2)

- Historical protocol: Fibre Channel (FC)
  - A special physical network just for storage
  - Totally unlike Ethernet in almost every way
  - Still popular with very conservative enterprises
  - Actual traffic is SCSI frames
  - Clients and servers have special cards: a Host Bus Adapter (HBA) for FC

- Modern protocols:
  - Fibre Channel over Ethernet (FCoE):
    - Requires FCoE-capable switch
    - SCSI inside of an FC frame inside of an Ethernet frame
    - Clients and servers have special cards: a Converged Network Adapter for FCoE/Ethernet
  - iSCSI:
    - SCSI inside of an IP frame, usually inside of an Ethernet frame (but it’s IP, so it could be inside a bongo drum frame)
    - No special switch or cards needed (though iSCSI HBAs do technically exist)
NAS: Network-Attached Storage (1)

- Put a file system on the storage server so it has the concept of files and directories
- Clients make open/close/read/write requests for files on the remote file system
NAS: Network-Attached Storage (2)

- No special network or cards – works on normal IP/Ethernet

Network File System (NFS):
- Common for UNIX-style systems, invented by Sun in 1984
- Literally just turns the system calls open/close/read/write/etc into “remote procedure calls” (RPCs)
- Many revisions, we’re up to NFS v4 now

Server Message Block (SMB) also known as Common Internet File System (CIFS)
- Microsoft Windows standard for network file sharing, developed around 1990
- Really badly named
- Many revisions, we’re up to SMB 3.1.1 now
- Native on Windows, supported on Linux with Samba (client and server)
How to tell NAS and SAN apart

**NAS** = File

**SAN** = Block
System constraints

- What is a tradeoff?
- Constraints:
  - Cost
  - Physical environment
  - Maintenance & support
  - Compliance (regulatory/legal)
  - HW & SW infrastructure
  - Interoperability/compatibility
Management activities

- Provisioning: allocate storage for use
- Monitoring: ensure proper functioning over time
- Archival/destruction: retire data properly
Provisioning

- Based on workload requirements:
  - **Capacity** – capacity planning
  - **Performance** – workload profiling
  - **Security** – access rule creation, encryption policy
  - **Reliability** – type of redundancy, backup policy
  - **Other** – archival duration, regulatory compliance, etc.
Monitoring

- **Capacity**: watch usage over time, identify workloads at risk of running out, include in report
- **Performance**: collect metrics at storage layer and/or application layer, compare to requirement, alert on violation/deviation, add resources as needed, include in report
- **Security**: verify access control rules, deploy intrusion/anomaly detection, ensure at-rest and in-flight encryption is used where appropriate, include in report
- **Reliability**: receive alerts when failures occur at any layer, continually ensure that availability and backup policies remain satisfied, include in report
- **Other requirements**: keep ‘em satisfied, include in report
- **Report**: Analyze collected statistics over time to assess cost and determine where array growth or configuration changes are needed.
The data lifecycle

Course project discussion
The course project

- Semester long effort in some area of storage
- Several choices (plus choose-your-own)
- Instructor feedback at each stage

- Any stage can result in a need for resubmission (grade withheld pending a second attempt).

- See course site project page for details
Project ideas

- Write-once file system*
- Network file system with caching*
- Deduplication*
- Special-case file system*
- File system performance survey
- Hybrid HDD/SSD system*
- Storage workload characterization
- Cloud storage tiering*

* Likely implemented via FUSE
FUSE overview
• **File System in Userspace:** Write a file system like you would a normal program.

• **You** implement the system calls: open, close, read, write, etc.

Figure from Wikipedia: http://en.wikipedia.org/wiki/Filesystem_in_Userspace
Let’s walk through it:

https://github.com/libfuse/libfuse/blob/master/example/hello.c
Project idea
Write-once file system
Write-once file system (WOFS)

- Normal file system
  - Read/write
  - Starts empty, evolves over time
  - Simplest implementation isn’t simple
    - Fragmentation and indirection

- Write-once file system
  - Read-only
  - Starts “full”, created with a body of data
  - Simple implementation
    - No fragmentation, little indirection
What is a WOFS for?

• CD/DVD images
  • "Master" the image with the content in /mydir
    $ mkiisosfs -o my.iso /home/user/mydir
  
  • Write the disc image directly onto the burner
    $ cdrecord my.iso

• Ramdisk images (e.g. cramfs, squashfs, etc.)
Major parts of a WOFS

- **Mastering program:**
  
  ```
  $ mkwofs myfilesystem.img data/
  ```

- **Mounting program (FUSE):**
  
  ```
  $ wofsmount myfilesystem.img dir/
  ```

- **Mounting program must not “extract” data at load time – data is retrieved from the image as read requests are handled!**
Project idea
Network file system with caching
Network File System without Special Sauce

• Simple idea:
  Put IO system calls over the network

• Complex consequences:
  • Stateful or stateless?
  • Caching? Cache coherency?
  • What server? How many servers?
  • Data compression?
  • Data reduction, e.g. “Low-bandwidth File System”
    (http://pdos.csail.mit.edu/papers/lbfs:sosp01/lbfs.pdf)
An *interesting* network file system

- A basic network filesystem is basic OS stuff
- Yours must could also optionally have:
  - Read caching and write-behind caching
  - Read caching and read-ahead optimization
  - Distributed storage over multiple servers
  - Compression
  - “Low-bandwidth file system” features
    - (Persistent disk cache, basically dedupe-on-the-wire)
  - Something else?
Project idea
Deduplication
Deduplication

• Will be covered later, here’s the short version

• Split the file into chunks
• Hash each chunk with a big hash
• If hashes match, data matches:
  • Replace this with a reference to the matching data
• Else:
  • It’s new data, store it.

Figure from http://www.eweek.com/c/a/Data-Storage/How-to-Leverage-Data-Deduplication-to-Green-Your-Data-Center/
Common deduplication data structures

- Metadata:
  - Directory structure, permissions, size, date, etc.
  - Each file’s contents are stored as a list of hashes

- Data pool:
  - A flat table of hashes and the data they belong to
  - Must keep a reference count to know when to free an entry
Design decisions

- **Eager** or **lazy**?

- **Fixed**- or **variable-sized** blocks?
  - Variable size via Rabin-Karp Fingerprinting
Project idea
Special-case file system
Special-case file system

- Sometimes “general purpose” is too general

- Example motivations:
  - Can we exploit a workload’s peculiar access pattern?
  - Can we examine the data to present new organizational structures?
  - Can we map non-filesystem information into the file system?
Tips to keep in mind

• Performance: Disk seeks are the enemy!
  • Often, “Minimize seeks” = “Optimize performance”

• Metadata: Many files have metadata not usually exposed to the file system, such as JPEG EXIF tags, MP3 ID3 tags, DOC/DOCX author tags, etc.

• Anything can be a filesystem. You can have a file system represent:
  • A git server
  • An email account
  • A web server
  • A physical system (e.g. “Internet of Things”*)
  • A database (e.g. via the Duke registration system public API**)  
  • More!

* This term is really dumb, and I’m sorry for using it.
Project idea
File system performance survey
File system performance survey

- Storage systems are enormously complex with many pieces affecting overall performance
  - Filesystem (ext3, ntfs, etc.)
  - Filesystem configuration (journaling, alignment, etc.)
  - Workload (benchmarks)
  - Underlying devices (SSD, HDD, and also RAID)
- It is useful to characterize how different configurations perform under different workloads
How to approach the problem

• Get hardware
  • Such as your course server!!

• Define your test variables

• Build a test harness
  • Automate all testing, it will run for days!
  • Automate data collation – don’t scrape numbers by hand!
  • Get it all into a giant spreadsheet

• Data mining – find knowledge in the data

• Detailed write up of interesting conclusions
Project idea
Hybrid HDD/SSD system
Hybrid storage

- SSD is expensive per GB, cheap for random IO performance
- HDD is the opposite

- Can develop a software that gets best of both worlds

- Examples:
  - SSD as cache for HDD
  - SSD as write buffer for HDD
  - Auto-migrate “hot” data to SSD, “cold” data to HDD
  - Identify random workloads, migrate to SSD

- Mechanism:
  - File system (e.g. with FUSE)
  - Virtual block device (e.g. via BUSE)
Evaluation

- Must include:
  - Benchmark of your system against pure HDD and pure SSD systems.
  - Measurement of FUSE overhead
  - Cost/benefit analysis based on HDD and SSD costs
  - All of the above must be conducted against a good cross-section of workloads
Project idea
Storage workload characterization
Storage workload capture

- In storage sizing, need to characterize workload
- Workload may be confidential or too complex to migrate

- Project: Use a technique to *record* a storage workload
  - Example 1: take a trace of read/write ops; need to *anonymize*, then be able to replay operations with equivalent performance
  - Example 2: monitor I/O ops, characterize nature of workload, then be able to simulate a request stream with similar characteristics

- Will need to prove the accuracy of your technique with statistical analysis across variety of workloads
Project idea
Cloud storage tiering
Cloud storage tier

- Cloud storage (e.g. Amazon S3) is useful, generally pretty cheap
- Downside: internet latency and bandwidth

- Can develop a storage system which migrates “cold” or otherwise lower-priority data out to a cloud service, brings it back live on demand without user interaction
  - Optional enhancements:
    - Intelligent prediction algorithm for migration
    - Encryption for cloud-exported data
    - Compression for cloud-exported data
  - Can be implemented at block level or file system level
Questions?