Slides Credit: Matthias Boehm

Data Integration and Large Scale Analysis
09 Distributed Data Storage

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Announcements/Org

- **Course Evaluation and Exam**
  - Exercise submission deadline **Jan 12**
  - Evaluation period: **Dec 01 – Feb 15**
  - Exam date: **Feb 02, 3:00pm** (90 min written exam)
    - Second Exam data: **TBA** (probably after 2 weeks of first exam)

Course Outline Part B:
Large-Scale Data Management and Analysis

12 Distributed Stream Processing

13 Distributed Machine Learning Systems

Compute/ Storage

- 11 Distributed Data-Parallel Computation
- 10 Distributed Data Storage

Infra

- 09 Cloud Resource Management and Scheduling
- 08 Cloud Computing Fundamentals

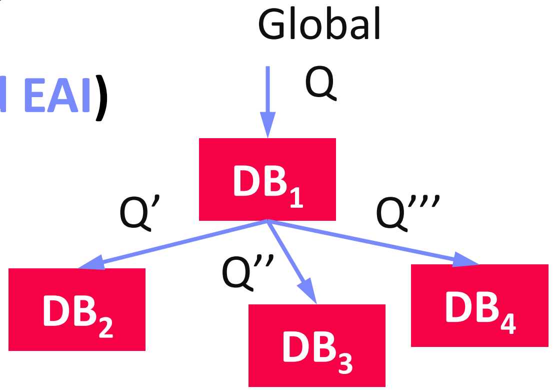
Agenda

- **Motivation and Terminology**
- **Object Stores and Distributed File Systems**
- **Key-Value Stores and Cloud DBMS**

Motivation and Terminology

Overview Distributed Data Storage

- **Recap: Distributed DBS (03 Replication, MoM, and EAI)**
  - **Distributed DB:** Virtual (logical) DB, appears like a local DB but consists of multiple physical DBs
  - Components for global query processing
  - **Virtual DBS** (homo.) vs **federated DBS** (hetero.)



- **Cloud and Distributed Data Storage**
  - **Motivation: size** (large-scale), **semi-structured**/nested , **fault tolerance**
  - **#1 Cloud and Distributed Storage**
    - **Block storage:** files split into blocks, read/write (e.g., SAN, AWS EBS)
    - **Object storage:** objects of limited size (e.g., 5TB), get/put (e.g., AWS S3)
    - **Distributed file systems:** file system on block/object stores (NFS, HDFS)
  - **#2 Database as a Service**
    - **NoSQL stores:** Key-value stores, document stores
    - **Cloud DBMSs** (SQL, for OLTP and OLAP workloads)

Central Data Abstractions

- **#1 Files and Objects**
  - **File:** Arbitrarily large sequential data in specific file format (CSV, binary, etc)
  - **Object:** binary large object, with certain meta data

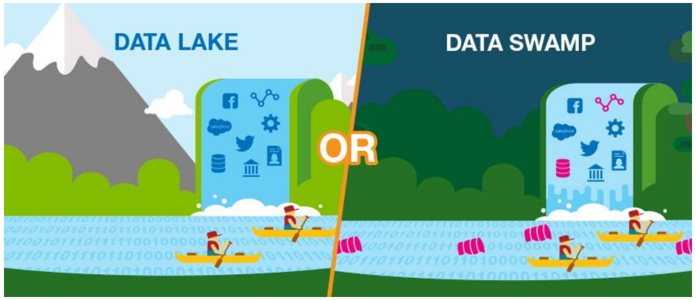
- **#2 Distributed Collections**
  - Logical multi-set (**bag**) of **key-value pairs** (**unsorted collection**)
  - Different physical representations
  - **Easy distribution** of pairs via horizontal partitioning (aka shards, partitions)
  - Can be created from single file, or directory of files (unsorted)

Key	Value
4	Delta
2	Bravo
1	Alfa
3	Charlie
5	Echo
6	Foxtrot
7	Golf
1	Alfa

Data Lakes

- **Concept "Data Lake"**
  - **Store massive amounts of un/semi-structured, and structured data** (append only, no update in place)
  - **No need for architected schema** or upfront costs (unknown analysis)
  - Typically: file storage in open, raw formats (inputs and intermediates)
  - ➔ **Distributed storage and analytics** for scalability and agility

- **Criticism: Data Swamp**
  - Low data quality (lack of schema, integrity constraints, validation)
  - Missing meta data (context) and data catalog for search
  - ➔ **Requires proper data curation / tools** According to priorities (data governance)



[**Credit:** www.collibra.com]

Catalogs of Data and Artefacts

- **Data Catalogs**
  - Data curation in repositories for finding relevant datasets in data lakes
  - Augment data with open and linked data sources

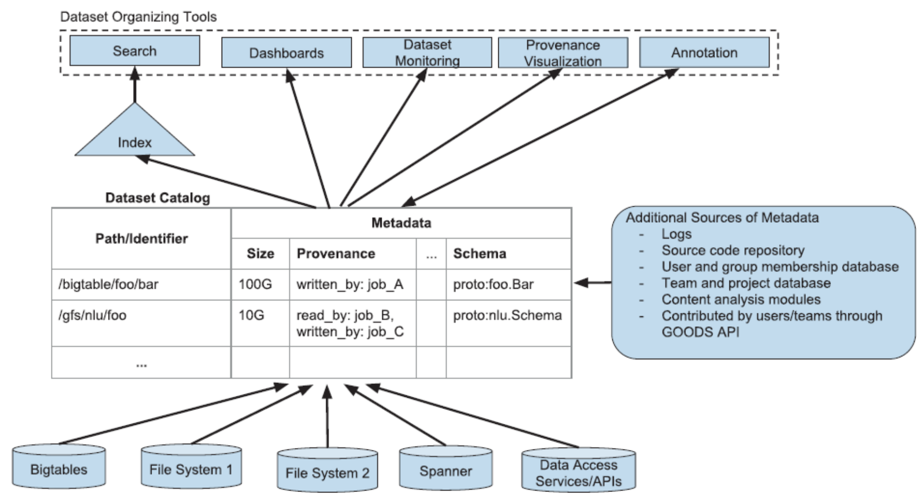
- **Examples**

[Alon Y. Halevy et al: Goods: Organizing Google's Datasets. **SIGMOD 2016**]

SAP Data Hub

[SAP Sapphire Now 2019]

Google Data Search



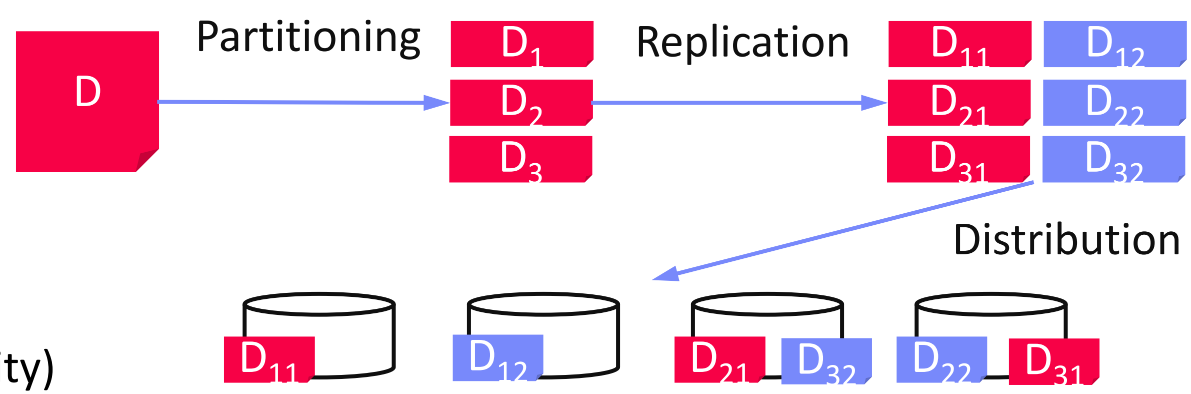
Object Stores and Distributed File Systems

Object Storage

- **Recap: Key-Value Stores**
  - **Key**-**value** mapping, where values can be of a variety of data types
  - APIs for CRUD operations; scalability via sharding (**objects** or object segments)

- **Object Store**
  - Similar to key-value stores, but: **optimized for large objects in GBs and TBs**
  - Object identifier (**key**), **meta data**, and object as binary large object (**BLOB**)
  - APIs: often REST APIs, SDKs, sometimes implementation of DFS APIs

- **Key Techniques**
  - Partitioning
  - Replication & Distribution
  - Erasure Coding (partitioning + parity)



Object Storage, cont.

- **Example Object Stores / Protocols**
  - Amazon Simple Storage Service (S3)
  - OpenStack Object Storage (Swift)
  - IBM Object Storage
  - Microsoft Azure Blob Storage

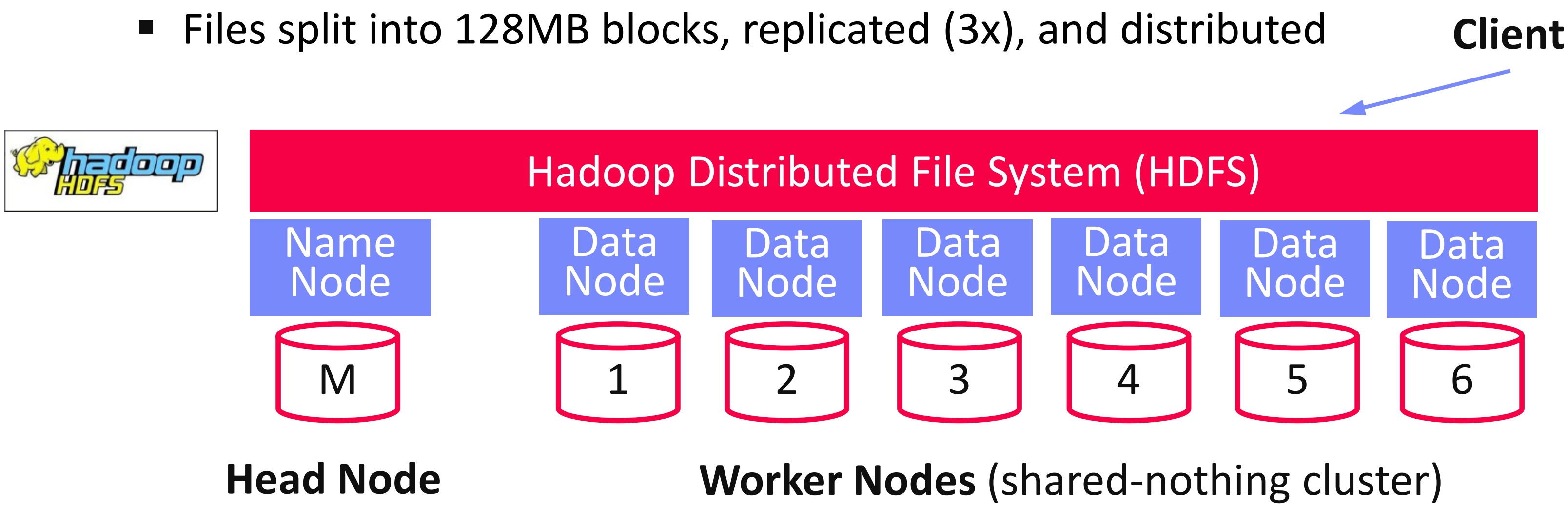
- **Example Amazon S3**
  - Reliable object store for photos, videos, documents or any binary data
  - **Bucket:** Uniquely named, static data container
    http://s3.aws-eu-central-1.amazonaws.com/<identifier>
  - **Object:** key, version ID, value, metadata, access control
  - Single (5GB)/multi-part (5TB) upload and direct/BitTorrent download
  - **Storage classes:** STANDARD, STANDARD_IA, GLACIER, DEEP_ARCHIVE
  - **Operations:** GET/PUT/LIST/DEL, and SQL over CSV/JSON objects

Hadoop Distributed File System (HDFS)

- **Brief Hadoop History**
  - Google's GFS + MapReduce [ODSI'04]
    → Apache Hadoop (2006)
  - Apache Hive (SQL), Pig (ETL), Mahout/SystemML (ML), Giraph (Graph)

[Sanjay Ghemawat, Howard Gobioff, Shun-Tak Leung: The Google file system. **SOSP 2003**]

- **HDFS Overview**
  - Hadoop's distributed file system, for large clusters and datasets
  - Implemented in Java, w/ native libraries for compression, I/O, CRC32
  - Files split into 128MB blocks, replicated (3x), and distributed



HDFS Daemon Processes

- **HDFS NameNode**
  - Master daemon that manages file system namespace and access by clients
  - Metadata for all files (e.g., replication, permissions, sizes, block ids, etc)
  - **FSImage:** checkpoint of FS namespace
  - **EditLog:** **write-ahead-log (WAL)** of file write operations (merged on startup)

```
hadoop fs -ls ./data/mnist1m.bin
```

```
-rw-r--r--   3 mboehm hdfs  104510159 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00000
-rw-r--r--   3 mboehm hdfs  137887319 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00001
-rw-r--r--   3 mboehm hdfs  139012247 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00002
-rw-r--r--   3 mboehm hdfs  139123247 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00003
-rw-r--r--   3 mboehm hdfs  139053743 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00004
-rw-r--r--   3 mboehm hdfs  138928955 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00005
-rw-r--r--   3 mboehm hdfs  139016375 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00006
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-rw-r--r--   3 mboehm hdfs  139042307 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00008
-rw-r--r--   3 mboehm hdfs  139068143 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00009
-rw-r--r--   3 mboehm hdfs  139029875 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00010
-rw-r--r--   3 mboehm hdfs  138901043 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00011
-rw-r--r--   3 mboehm hdfs  139042763 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00012
-rw-r--r--   3 mboehm hdfs  139030751 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00013
-rw-r--r--   3 mboehm hdfs  139172051 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00014
-rw-r--r--   3 mboehm hdfs  138962735 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00015
-rw-r--r--   3 mboehm hdfs  139079495 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00016
-rw-r--r--   3 mboehm hdfs   63417008 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00017
```

- **HDFS DataNode**
  - Worker daemon per cluster node that manages block storage (list of disks)
  - Block creation, deletion, replication as individual files in local FS
  - On startup: scan local blocks and send **block report** to name node
  - Serving block read and write requests
  - Send heartbeats to NameNode (capacity, current transfers) and receives replies (replication, removal of block replicas)

HDFS InputFormats and RecordReaders

- **Overview InputFormats**
  - **InputFormat:** implements access to distributed collections in files
  - **Split:** record-aligned block of file (aligned with HDFS block size)
  - **RecordReader:** API for reading key-value pairs from file splits
  - Examples: FileInputFormat, TextInputFormat, SequenceFileInputFormat

- **Example Text Read**

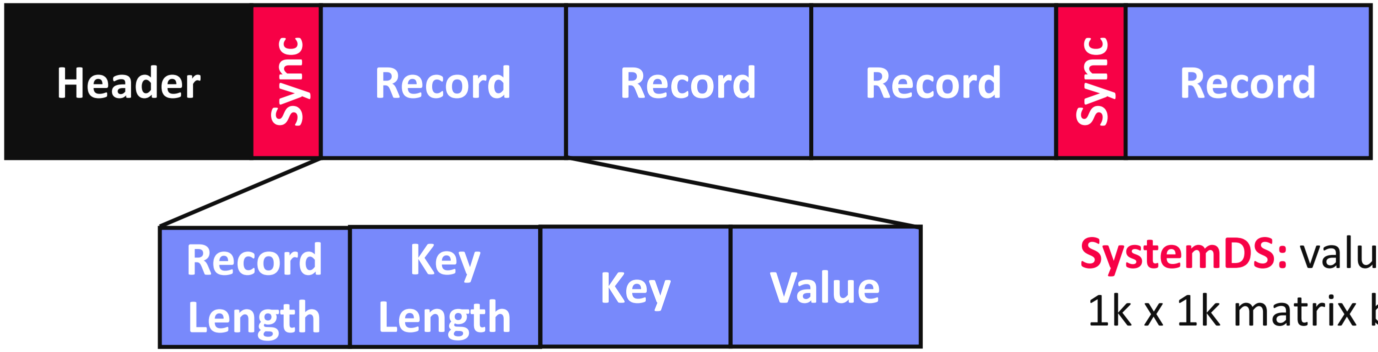
```
FileInputFormat.addInputPath(job, path); # path: dir/file
TextInputFormat informat = new TextInputFormat();
InputSplit[] splits = informat.getSplits(job, numSplits);

LongWritable key = new LongWritable();
Text value = new Text();
for(InputSplit split : splits) {
  RecordReader<LongWritable,Text> reader = informat
    .getRecordReader(split, job, Reporter.NULL);
  while( reader.next(key, value) )
    ... //process individual text lines
}
```

HDFS InputFormats and RecordReaders, cont.

- **Sequence Files**
  - **Binary files for key/value pairs**, w/ optional compression (MapReduce/Spark inputs/outputs, MapReduce intermediates)
  - InputFormat with readers, writers, and sorters

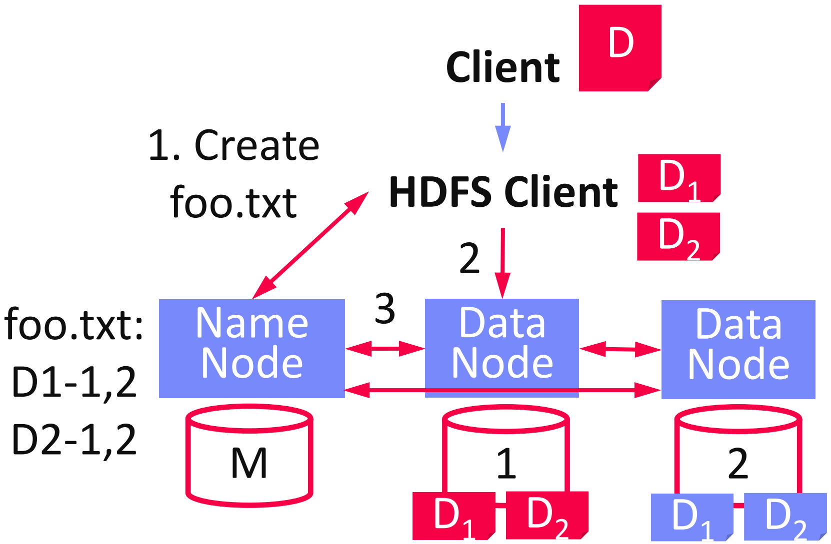
- **Example Uncompressed SequenceFile**
  - **Header:** SEQ+version (4 bytes), keyClassName, valueClassName, compression, blockCompression, compressor class (codec), meta data
  - Splittable binary representation of key-value pair collection



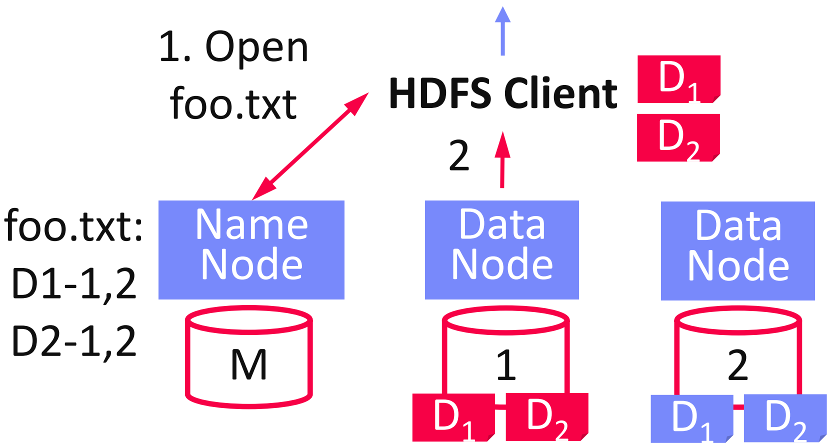
SystemDS: values are 1k x 1k matrix blocks

HDFS Write and Read

- **HDFS Write**
  - #1 Client RPC to NameNode to create file → lease/replica DNs
  - #2 Write blocks to DNs, pipelined replication to other DNs
  - #3 DNs report to NN via heartbeat



- **HDFS Read**
  - #1 Client RPC to NameNode to open file → DNs for blocks
  - #2 Read blocks sequentially from closest DN w/ block
  - InputFormats and RecordReaders as abstraction for multi-part files (incl. compression/encryption)



HDFS Data Locality

- **Data Locality**
  - HDFS is generally rack-aware (node-local, rack-local, other)
  - Schedule reads from closest data node
  - Replica placement (rep 3): local DN, other-rack DN, same-rack DN
  - MapReduce/Spark: locality-aware execution (**function vs data shipping**)

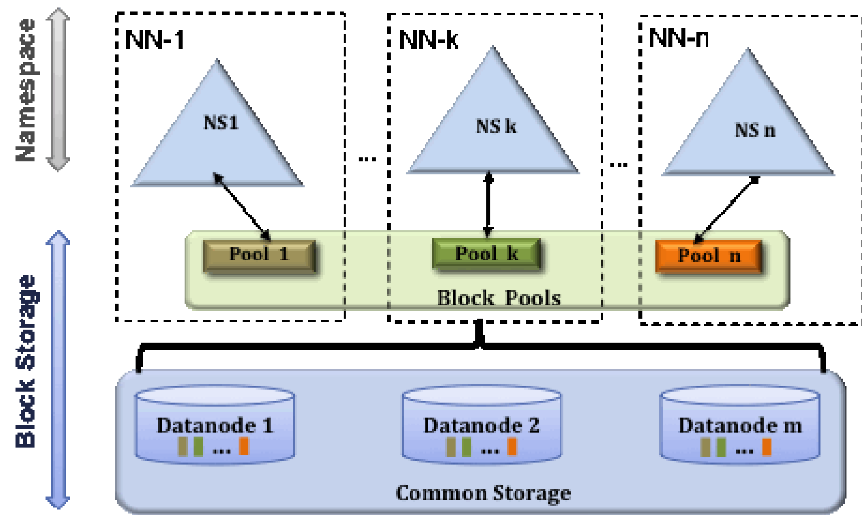
- **Custom Locality Information**
  - Custom **InputFormat** and **FileSplit** implementations
  - Return customized mapping of locations on getLocations()
  - Can use block locations of arbitrary files

```
public class MyFileSplit extends FileSplit
{
  public MyFileSplit(FileSplit x, ...) {}
  @Override
  public String[] getLocations() {
    return new String[]{"node1","node7"};
  }
}
```

```
FileStatus st = fs.getFileStatus(new Path(fname));
BlockLocation[] tmp1 = fs.getFileBlockLocations(st, 0, st.getLen());
```

HDFS Federated NameNodes

- **HDFS Federation**
  - Eliminate NameNode as namespace scalability bottleneck
  - Independent NameNodes, responsible for name spaces
  - DataNodes store blocks of all NameNodes
  - Client-side mount tables



[**Credit:** https://hadoop.apache.org/docs/current/hadoop-project-dist/hadoop-hdfs/Federation.html]

- **GFS Multiple Cells**
  - *"We also ended up doing what we call a "multi-cell" approach, which basically made it possible to put multiple GFS masters on top of a pool of chunkservers."* -- Sean Quinlan

[Kirk McKusick, Sean Quinlan: GFS: evolution on fast-forward. Commun. **ACM 53(3) 2010**]

Other DFS

- **HDFS FileSystem Implementations (subset)**
  - LocalFileSystem (**file**), DistributedFileSystem (**hdfs**)
  - FTPFileSystem, HttpFileSystem, ViewFilesystem (ViewFs – mount table)
  - NativeS3FileSystem (**s3**, **s3a**), NativeSwiftFileSystem, NativeAzureFileSystem
  - Other proprietary: IBM **GPFS**, Databricks FS (DBFS)
- **Google Colossus**
  - More fine-grained accesses, Google Cloud Storage

[WIRED: Google Remakes Online Empire With 'Colossus', https://www.wired.com/2012/07/google-colossus/]

- **High-Performance Computing**
  - **Scope:** Focus on high IOPs (instead of bandwidth) with block write
  - IBM **GPFS** (General Parallel File System) / Spectrum Scale
  - **BeeGFS** (Fraunhofer GFS) – focus on usability, storage/metadata servers
  - **Lustre** (Linux + Cluster) – GPL license, LNET protocol / metadata / object storage
  - RedHat **GFS2** (Global File System) – Linux cluster file system, close to local
  - **NAS** (Network Attached Storage), **SAN** (Storage Area Network)
  - **GekkoFS** (Uni Mainz / Barcelona SC) – data-intensive HPC applications

Key-Value Stores and Cloud DBMS

Motivation and Terminology

- **Motivation**
  - **Basic key-value mapping via simple API** (more complex data models can be mapped to key-value representations)
  - **Reliability at massive scale on commodity HW** (cloud computing)

- **System Architecture**
  - **Key**-value maps, where values can be of a variety of data types
  - APIs for CRUD operations (create, read, update, delete)
  - Scalability via sharding (horizontal partitioning)

Key	Value
users:1:a	“Inffeldgasse 13, Graz”
users:1:b	“[12, 34, 45, 67, 89]”
users:2:a	“Mandellstraße 12, Graz”
users:2:b	“[12, 212, 3212, 43212]”

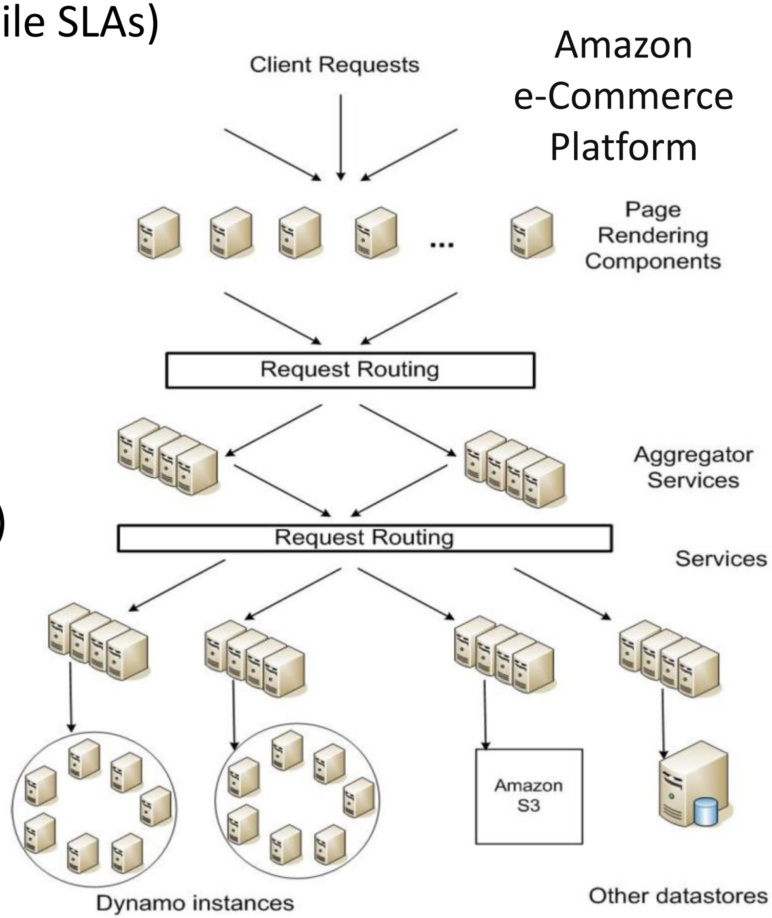
- **Example Systems**
  - **Dynamo** (2007, AP) → **Amazon DynamoDB** (2012)
  - **Redis** (2009, CP/AP)

[Giuseppe DeCandia et al: Dynamo: amazon's highly available **key-value store**. **SOSP 2007**]

Example Systems: Dynamo

[Giuseppe DeCandia et al: Dynamo: amazon's highly available **key-value store**. **SOSP 2007**]

- **Motivation**
  - **Simple**, **highly-available** data storage for small objects in ~1MB range
  - Aim for **good load balance** (99.9th percentile SLAs)
- **#1 System Interface**
  - Simple get(k, ctx) and put(k, ctx) ops
- **#2 Partitioning**
  - **Consistent hashing** of nodes and keys on circular ring for **incremental scaling**
  - Nodes hold **multiple virtual nodes** for **load balance** (add/rm, heterogeneous)
- **#3 Replication**
  - Each data item **replicated N times** (at coord node and N-1 successors)
  - Eventual consistency with async update propagation based on **vector clocks**
  - Replica synchronization via **Merkle trees**

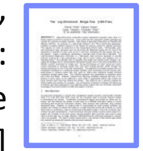


Example Systems, cont.

- **Redis Data Types**
  - Redis is not a plain KV-store, but "data structure server" with persistent log (**appendfsync no/everysec/always**)
  - **Key:** ASCII string (max 512MB, common key schemes: comment:1234:reply.to)
  - **Values:** strings, lists, sets, sorted sets, hashes (map of string-string), etc
- **Redis APIs**
  - **SET/GET/DEL:** insert a key-value pair, lookup value by key, or delete by key
  - **MSET/MGET:** insert or lookup multiple keys at once
  - **INCRBY/DECBY:** increment/decrement counters
  - Others: EXISTS, LPUSH, LPOP, LRANGE, LTRIM, LLEN, etc
- **Other systems**
  - Classic KV stores (AP): **Riak**, **Aerospike**, **Voldemort**, **LevelDB**, **RocksDB**, **FoundationDB**, **Memcached**
  - Wide-column stores: **Google BigTable** (CP), **Apache HBase** (CP), **Apache Cassandra** (AP)

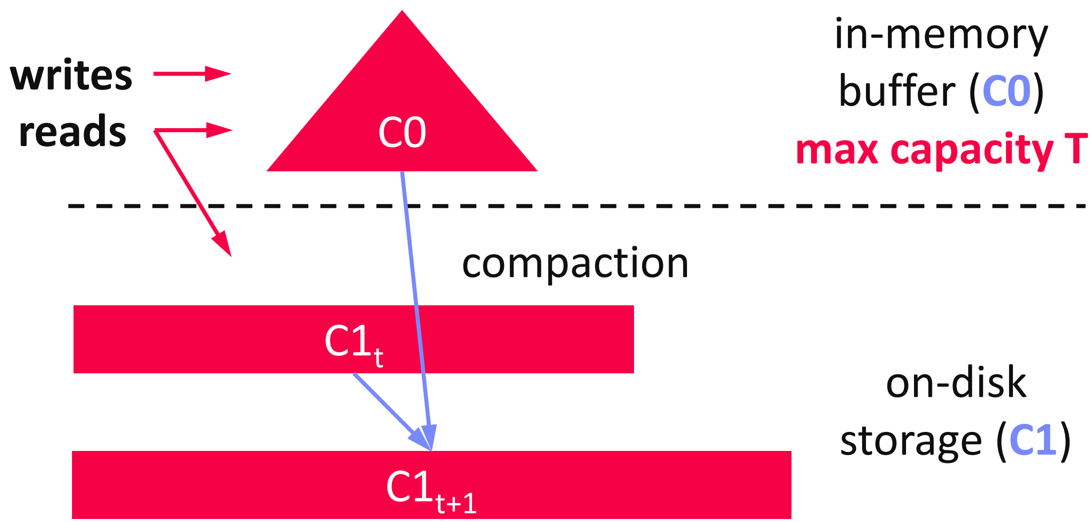
Log-structured Merge Trees

[Patrick E. O'Neil, Edward Cheng, Dieter Gawlick, Elizabeth J. O'Neil: The Log-Structured Merge-Tree (LSM-Tree). **Acta Inf. 1996**]



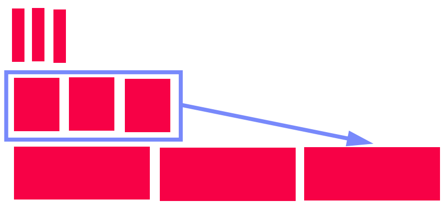
- **LSM Overview**
  - Many KV-stores rely on LSM-trees as their storage engine (e.g., **BigTable**, **DynamoDB**, **LevelDB**, **Riak**, **RocksDB**, **Cassandra**, **HBase**)
  - **Approach:** Buffers writes in memory, flushes data as sorted runs to storage, merges runs into larger runs of next level (compaction)

- **System Architecture**
  - Writes in C0
  - Reads against C0 and C1 (w/ buffer for C1)
  - Compaction (rolling merge): sort, merge, including **deduplication**

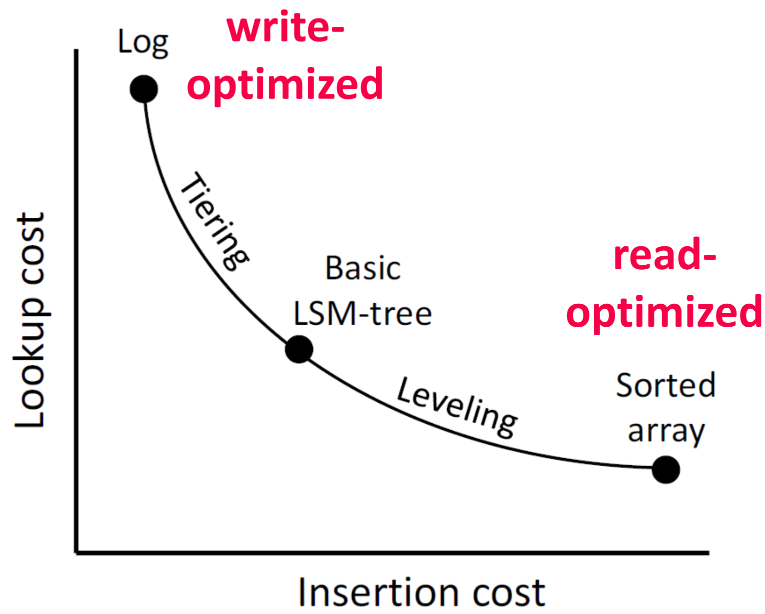


Log-structured Merge Trees, cont.

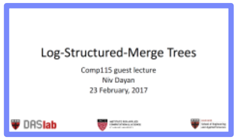
- **LSM Tiering (write optimized)**
  - Keep up to T-1 runs per level L
  - Merge all runs of L_i into 1 run of L_{i+1}
    - L1
    - L2
    - L3



- **LSM Leveling (read optimized)**
  - Keep 1 run per level L
  - Merge run of Li with Li+1
    - L1
    - L2
    - L3



[Niv Dayan: Log-Structured-Merge Trees, **Comp115 guest lecture, 2017**]



[Stratos Idreos, Mark Callaghan: Key-Value Storage Engines (Tutorial), **SIGMOD 2020**]

Cloud Databases (DBaaS)

- **Motivation DBaaS**
  - Simplified setup, maintenance, tuning and auto scaling
  - Multi-tenant systems (scalability, learning opportunities)
  - Different types based on workload (OLTP vs OLAP)

Microsoft

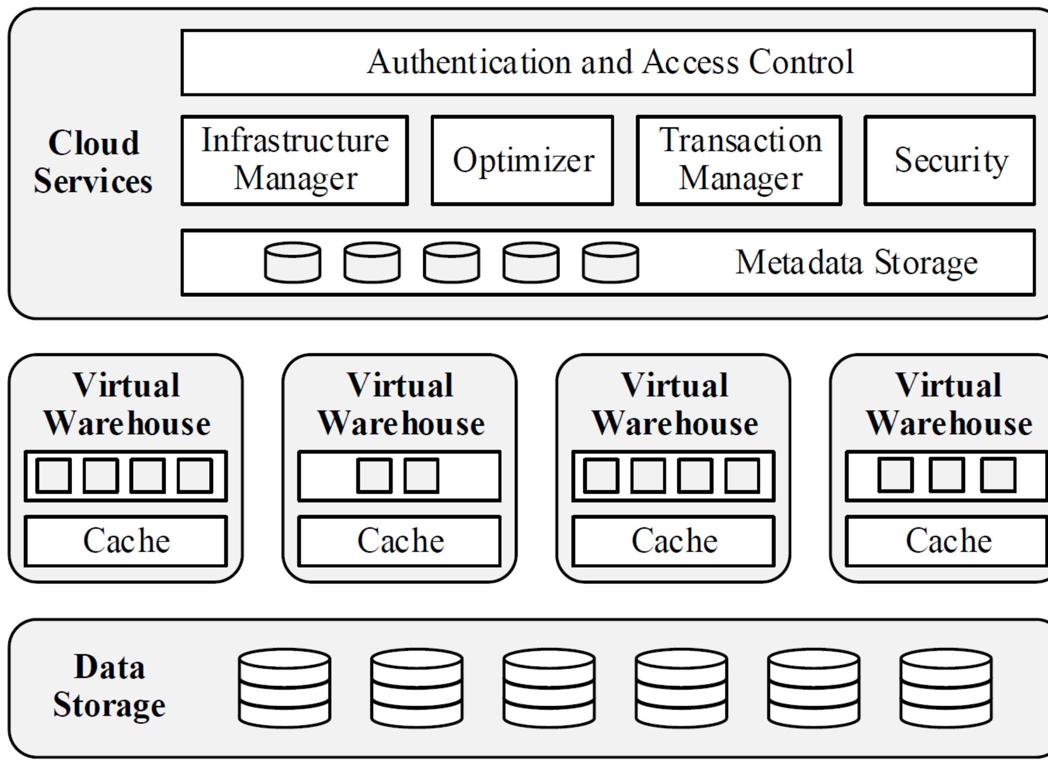
- **Elastic Data Warehouses**
  - Motivation: Intersection of data warehousing (**02 DWH, ETL, SQL/OLAP**), cloud computing (**07/08 Cloud Computing**), Distributed Storage (**09 today**)
  - Example Systems
    - **#1** Snowflake
    - **#2** Google BigQuery (Dremel)
    - **#3** Amazon Redshift
    - Azure SQL Data Warehouse

Commonalities:
SQL, **column stores**,
data on **object store / DFS**,
elastic cloud scaling

Example Snowflake

[Benoît Dageville et al.: The Snowflake Elastic Data Warehouse. **SIGMOD 2016**]

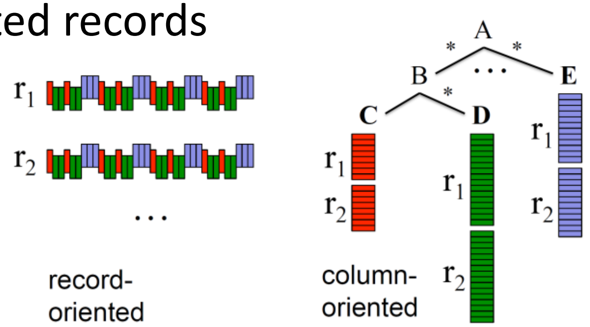
- **Motivation** (impl started late 2012)
  - **Enterprise-ready DWH solution for the cloud** (elasticity, semi-structured)
  - Pure SaaS experience, high availability, cost efficient
- **Cloud Services**
  - Manage virtual DHWs, TXs, and queries
  - Meta data and catalogs
- **Virtual Warehouses**
  - Query execution in EC2
  - Caching/intermediates
- **Data Storage**
  - **Storage in AWS S3**
  - PAX / hybrid **columnar**
  - **Min-max pruning**



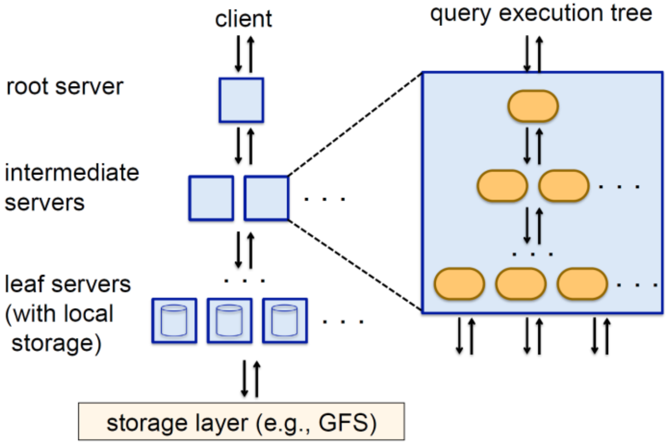
Example Google BigQuery

[Sergey Melnik et al.: Dremel: Interactive Analysis of Web-Scale Datasets. **PVLDB 3(1) 2010**]

- **Background Dremel**
  - Scalable and fast **in-situ analysis of read-only nested data** (DFS, BigTable)
  - **Data model:** protocol buffers - strongly-typed nested records
  - **Storage model: columnar storage of nested data** (efficient splitting and assembly records)
  - Query execution via **multi-level serving tree**



- **BigQuery System Architecture**
  - Public impl of internal Dremel system (2012)
  - SQL over structured, nested data (OLAP, BI)
  - **Extensions:** web Uis, REST APIs and ML
  - **Data storage:** Colossus (**NextGen GFS**)



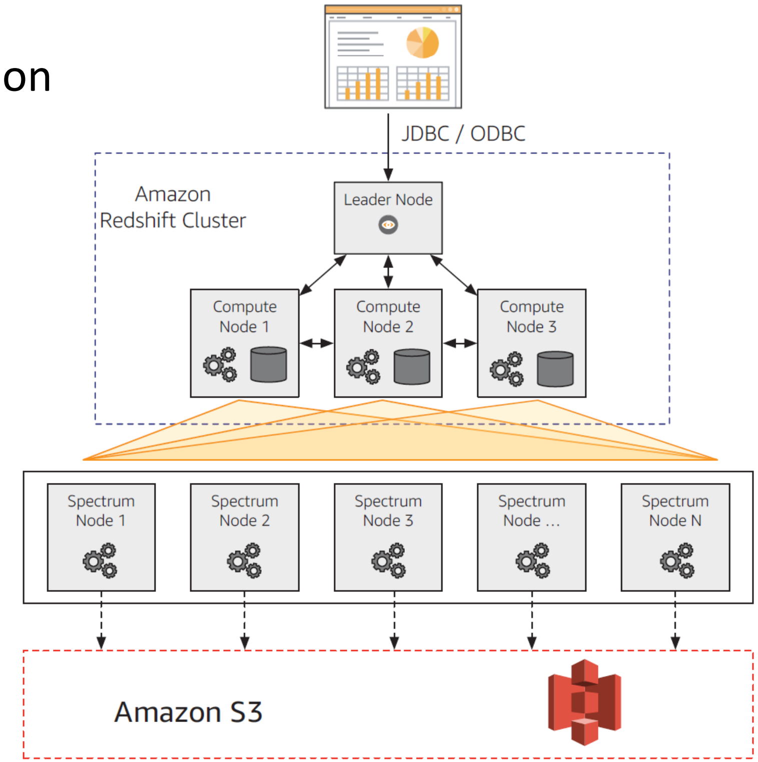
[Kazunori Sato: An Inside Look at Google BigQuery, Google BigQuery White Paper 2012.]

Example Amazon Redshift

[Anurag Gupta et al.: Amazon Redshift and the Case for Simpler Data Warehouses. **SIGMOD 2015**]

[Mengchu Cai et al.: Integrated Querying of SQL database data and S3 data in Amazon Redshift. **IEEE Data Eng. Bull. 41(2) 2018**]

- **Motivation** (release 02/2013)
  - **Simplicity and cost-effectiveness** (fully-managed DWH at petabyte scale)
- **System Architecture**
  - **Data plane:** data storage and SQL execution
  - **Control plane:** workflows for monitoring, and managing databases, AWS services
- **Data Plane**
  - Initial engine licensed from ParAccel
  - Leader node + sliced compute nodes in **EC2** (with **local storage**)
  - Replication across nodes + **S3 backup**
  - **Query compilation** in C++ code
  - Support for **flat and nested files**



Lakehouse

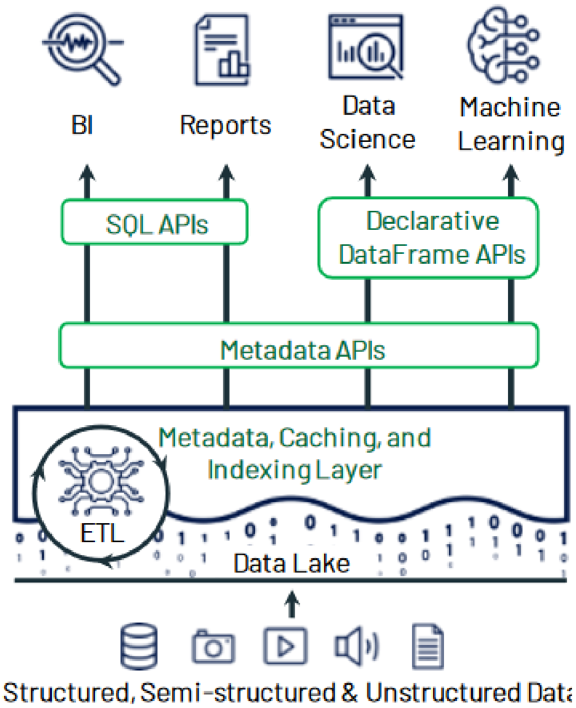
[Matei Zahari et. al, Lakehouse: A New Generation of Open Platforms that Unify Data Warehousing and Advanced Analytics. **CIDR 2021**]

[Alkis Simitsis et. al., The History, Present, and Future of ETL Technology, **DOLAP 2023]**

- **Data Lake**
  - Collection of structured, semi and unstructured data, **schema-on-read**
- **Delta Lake**
  - A storage layer sits on top of data lake
  - **ACID transactions**, schema enforcement schema evolution, meta handling, time travel
- **Lakehouse**
  - Extends delta lake for BI & ML workloads
  - Hybrid architecture for structured and semi-structured data processing

Delta lake (open source project)

Databricks Lakehouse platform, MS Azure Synapse



Summary and Q&A

- **Motivation and Terminology**
- **Object Stores and Distributed File Systems**
- **Key-Value Stores and Cloud DBMS**

- **Next Lectures**
  - **11 Distributed, Data-Parallel Computation** [Jan 12]
  - **12 Distributed Stream Processing** [Jan 19]
  - **13 Distributed Machine Learning Systems** [Jan 19]