Data Integration and Large-scale Analysis (DIA)
10 Distributed Storage

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Last update: Dec 18, 2025

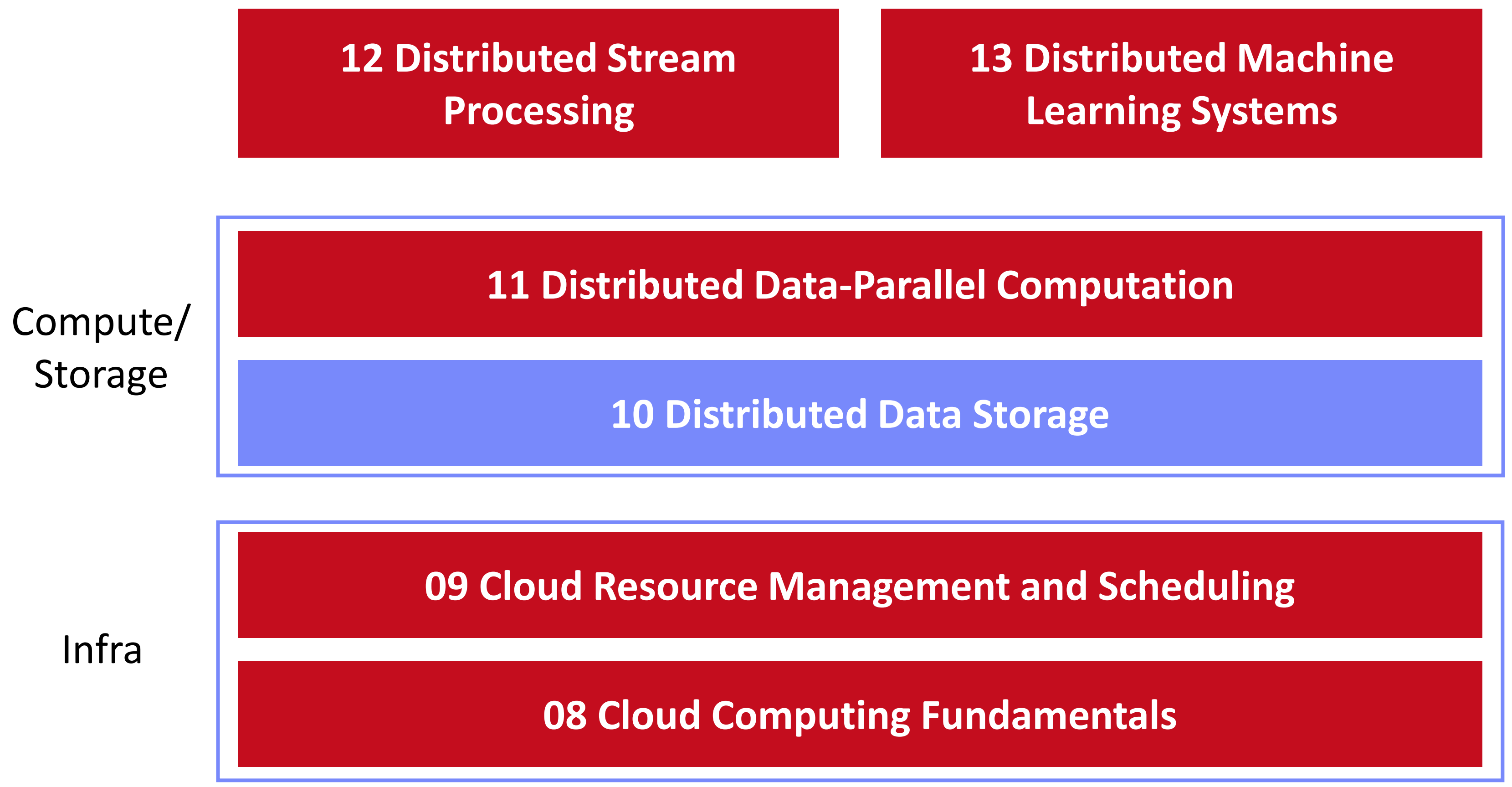
Announcements / Administrative Items

- **#1 Video Recording**
  - Hybrid lectures: in-person BH-N 243, zoom live streaming, video recording
  - https://tu-berlin.zoom.us/j/9529634787?pwd=R1ZsN1M3SC9BOU1OcFdmem9zT202UT09

- **#2 Exercises/Projects**
  - **Reminder:** exercise/project submissions by **Jan 30** (no extensions)
  - Make use of **virtual** / in-person (FR-766) office hours **Wed 5pm-6pm**
  - Docker Setup: https://isis.tu-berlin.de/mod/forum/discuss.php?d=704892

- **#3 Course Evaluation**
  - By default, only mandatory courses and guest lecturers; but **optional evaluation**
  - Joint exercise/lecture evaluation **Jan 12 – 23**

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

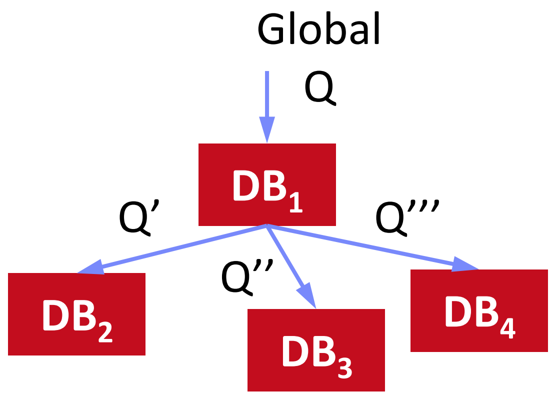
Agenda

- **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

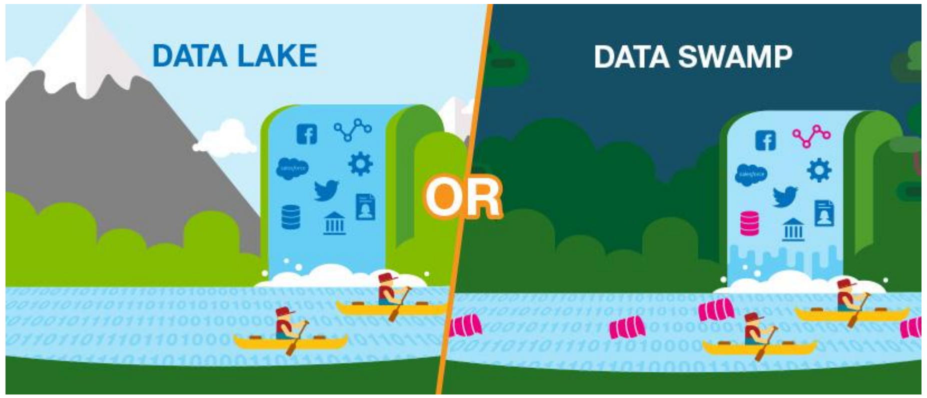
- **#2 Distributed Collections**
  - Logical multi-set (**bag**) of **key-value pairs** (**unsorted collection**)
  - Different physical representations
  - **Easy distribution** of pairs via horizontal partitioning (aka shards, partitions)
  - Can be created from single file, or directory of files (unsorted)

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

Recap FAIR Data Principles
(see 07 Data Provenance)

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

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

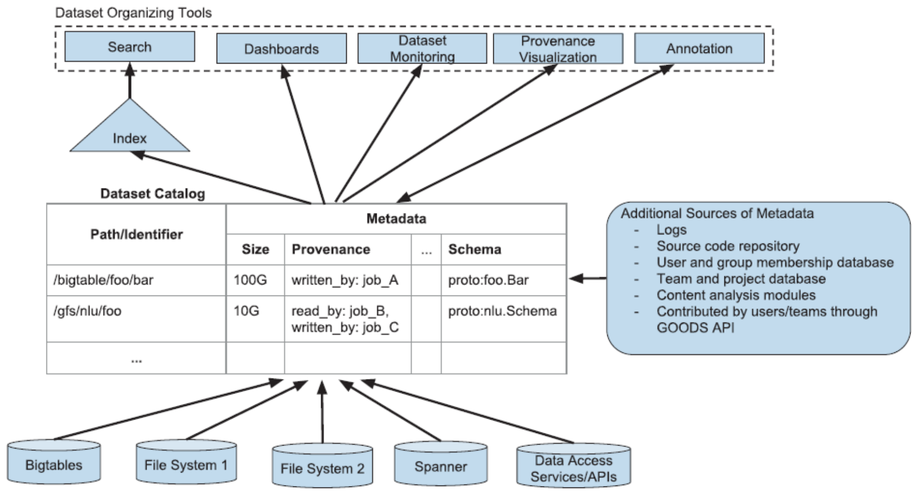
[Dan Brickley, Matthew Burgess, Natasha F. Noy: Google Dataset Search: Building a search engine for datasets in an open Web ecosystem. **WWW 2019**]

[Omar Benjelloun, Shiyu Chen, Natasha Noy: Google Dataset Search by the Numbers, https://arxiv.org/pdf/2006.06894]

SAP Data Hub

[SAP Sapphire Now 2019]

Google Dataset Search



Path/Identifier	Size	Provenance	...	Schema
/bigtable/foo/bar	100G	written_by: job_A		proto:foo.Bar
/gfs/nlu/foo	10G	read_by: job_B, written_by: job_C		proto:nlu.Schema
...				

Additional Sources of Metadata
- Logs
- Source code repository
- User and group membership database
- Team and project database
- Content analysis modules
- Contributed by users/teams through GOODS API

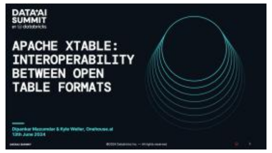
Category	Number of datasets	% of total	Sample formats
Tables	7,822K	37%	CSV, XLS
Structured	6,312K	30%	JSON, XML, OWL, RDF
Documents	2,277K	11%	PDF, DOC, HTML
Images	1,027K	5%	JPEG, PNG, TIFF
Archives	659K	3%	ZIP, TAR, RAR
Text	623K	3%	TXT, ASCII
Geospatial	376K	2%	SHP, GEOJSON, KML
Computational biology	110K	<1%	SBML, BIOPAX2, SBGN
Audio	27K	<1%	WAV, MP3, OGG
Video	9K	<1%	AVI, MPG
Presentations	7K	<1%	PPTX
Medical imaging	4K	<1%	NII, DCM
Other categories	2,245K	11%	

500K → 30M datasets

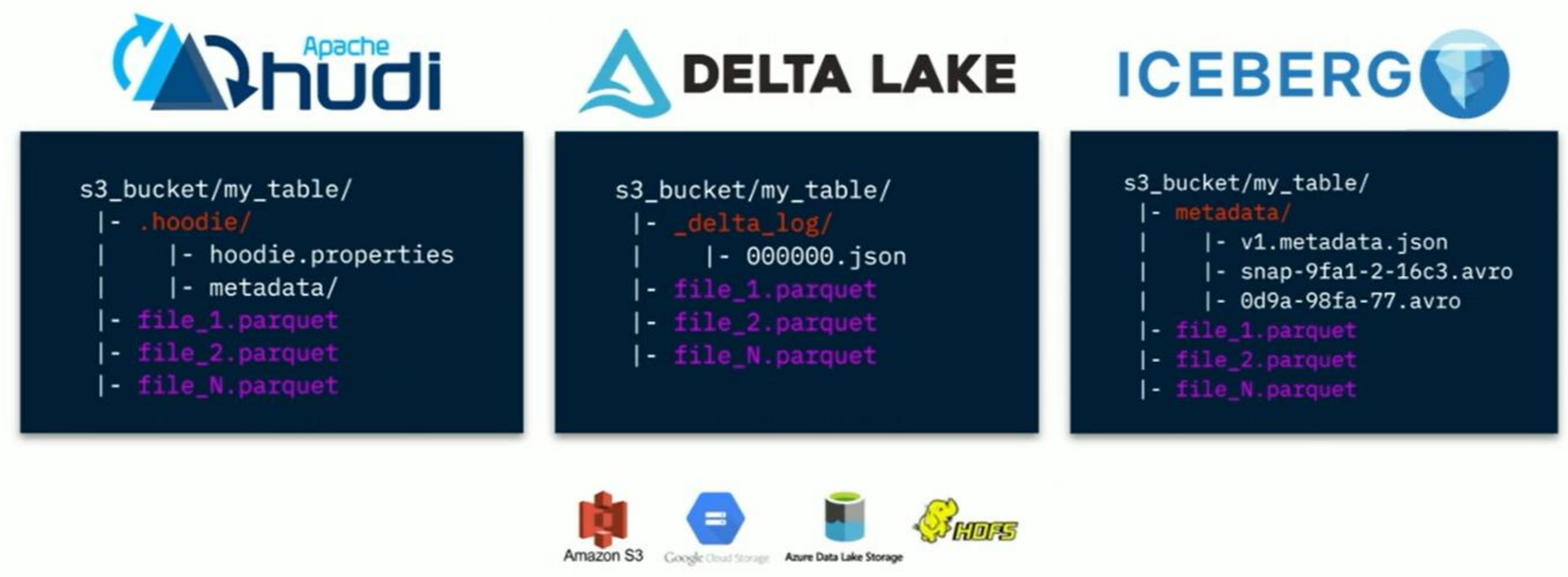
Open Table Formats (File Format + Metadata)

- **Open Table Formats**
  - Data in open formats (e.g., **parquet**, **orc**, **avro**)
  - Meta data (e.g., **schema**, **transaction logs**)
  - **Examples:** **Hudi** (Uber, 2017), **Iceberg** (Netflix/Snowflake, 2018), **Delta Lake** (Databricks, 2019) → **and unfortunately diverging**

[Dipankar Mazumdar, Kyle Weller: Apache XTable (incubating): Interoperability Among Lakehouse Table Formats Databricks, **Data AI Summit 2024**. https://youtu.be/T-ee0xdJ7yM?list=PLTPXxbhUt-YW18S6p5wNu1SJxoF24S_UB]


DATA+AI SUMMIT
APACHE XTABLE: INTEROPERABILITY BETWEEN OPEN TABLE FORMATS

- **Apache XTable**
  - **Cross-table converter for table formats** (lightweight: meta data only)
  - Community contributions by Microsoft, Google, Snowflake, Databricks
  - https://github.com/apache/incubator-xtable



```
s3_bucket/my_table/
 |- .hoodie/
 |     |- hoodie.properties
 |     |- metadata/
 |- file_1.parquet
 |- file_2.parquet
 |- file_N.parquet
```

```
s3_bucket/my_table/
 |- _delta_log/
 |     |- 000000.json
 |- file_1.parquet
 |- file_2.parquet
 |- file_N.parquet
```

```
s3_bucket/my_table/
 |- metadata/
 |     |- v1.metadata.json
 |     |- snap-9fa1-2-16c3.avro
 |     |- 0d9a-98fa-77.avro
 |- file_1.parquet
 |- file_2.parquet
 |- file_N.parquet
```

Excursus: Research Data Management (RDM)

- **Overview**
  - Ensure reproducibility of research results and conclusions
  - **Common problem:**
  - **Create value for others** (compare, reuse, understand, extend)
  - EU Projects: Mandatory proposal section & deliverable on RDM plan

"All code and data was on the student's laptop and the student left / the laptop crashed."

- **RDM @ TU Graz**
  - TU Graz RDM Policy since 12/2019, as well as faculty-specific RDM policies
  - https://www.tugraz.at/sites/rdm/home/

"Ensure that research data, code and any other materials needed to reproduce research findings are appropriately documented, stored and shared in a research data repository in accordance with the FAIR principles (Findable, Accessible, Interoperable and Reusable) for at least 10 years from the end of the research project, unless there are valid reasons not to do so. [...] Develop a written data management strategy for managing research outputs within the first 12 months of the PhD study [...]."

- **RDM @ TU Berlin**
  - TU Berlin RDM Policy since 10/2019
  - https://www.tu.berlin/en/ub/szf/information-tips/what-is-research-data-management
  - https://www.static.tu.berlin/fileadmin/www/10000000/Arbeiten/Wichtige_Dokumente/RDM-Policy_TUBerlin_2023_en.pdf

"The minimum storage period for research data is ten years after either the assignment of a persistent identifier or the publication of the related work following research project completion, whichever is later."

FAIR Data Principles

[https://www.go-fair.org/fair-principles/]

- **#1 Findable**
  - Metadata and data have globally unique **persistent identifiers**
  - Data describes w/ rich **meta data**; registered/indexes and searchable
- **#2 Accessible**
  - Metadata and data retrievable via open, free and universal **communication protocols**
  - Metadata accessible even when data no longer available
- **#3 Interoperable**
  - Metadata and data use a formal, **accessible, and broadly applicable format**
  - Metadata and data use FAIR vocabularies and qualified references
- **#4 Reusable**
  - Metadata and data described with plurality of accurate and relevant attributes
  - Clear license, **associated with provenance**, meets community standards

PUBLIC DOMAIN

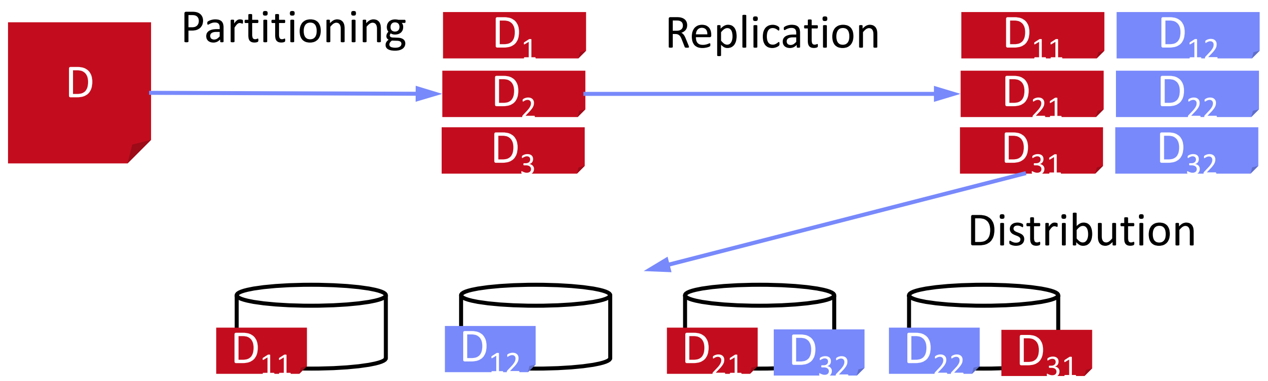
Object Stores and Distributed File Systems

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

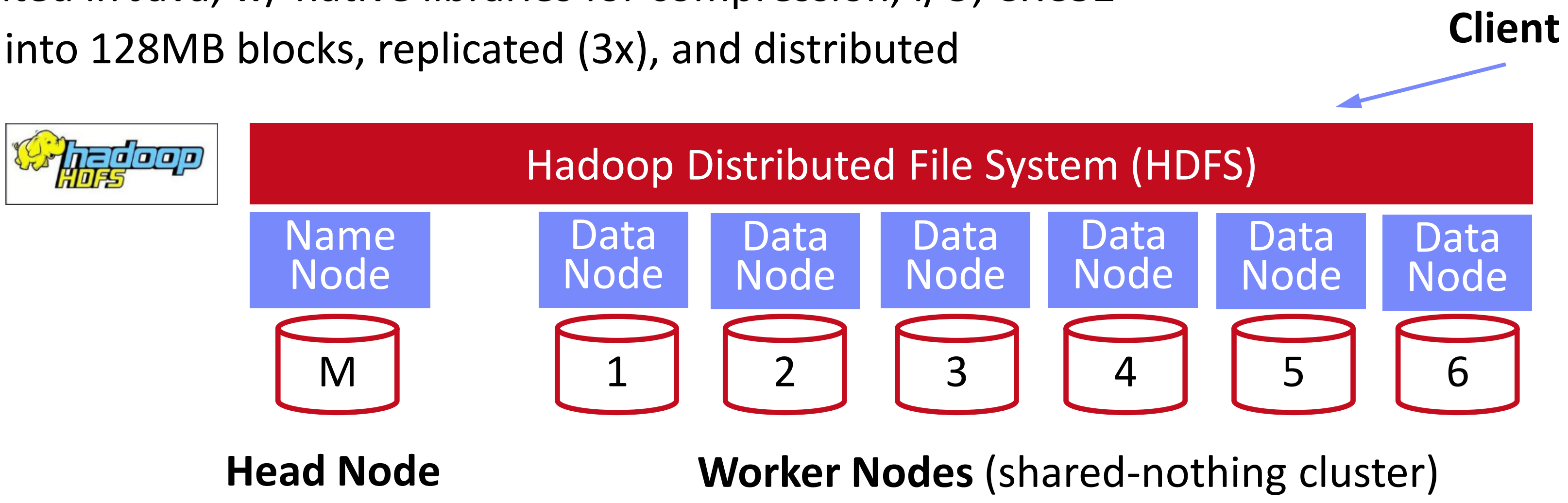
- **Example Amazon S3**
  - Reliable object store for photos, videos, documents or any binary data
  - **Bucket:** Uniquely named, static data container
  - **Object:** key, version ID, value, metadata, access control
  - Single (5GB)/multi-part (5TB) upload and direct/BitTorrent download
  - **Storage classes:** STANDARD, STANDARD_IA, GLACIER, DEEP_ARCHIVE
  - **Operations:** GET/PUT/LIST/DEL, and SQL over CSV/JSON objects
  - Eventual consistency → **Dec 1 2020:** read-after-write and list consistency

```
http://s3.aws-eu-central-1.
amazonaws.com/mboehm7datab
```

Hadoop Distributed File System (HDFS)

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

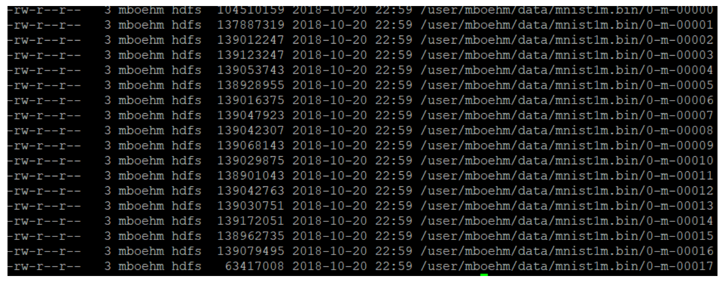
- **Brief Hadoop History**
  - Google's GFS + MapReduce [ODSI'04] → Apache Hadoop (2006)
  - Apache Hive (SQL), Pig (ETL), Mahout/SystemML (ML), Giraph (Graph)
- **HDFS Overview**
  - Hadoop's distributed file system, for large clusters and datasets
  - Implemented in Java, w/ native libraries for compression, 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
-rw-r--r--   3 mboehm hdfs  139047923 2018-10-20 22:59 /user/mboehm/data/mnist1m.bin/0-m-00007
-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

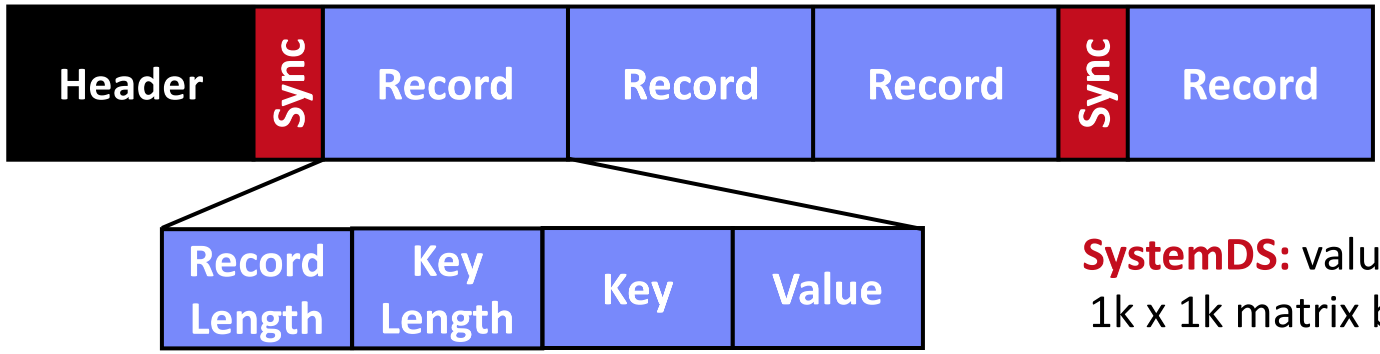
- **Example Text Read**

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

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

HDFS InputFormats and RecordReaders, cont.

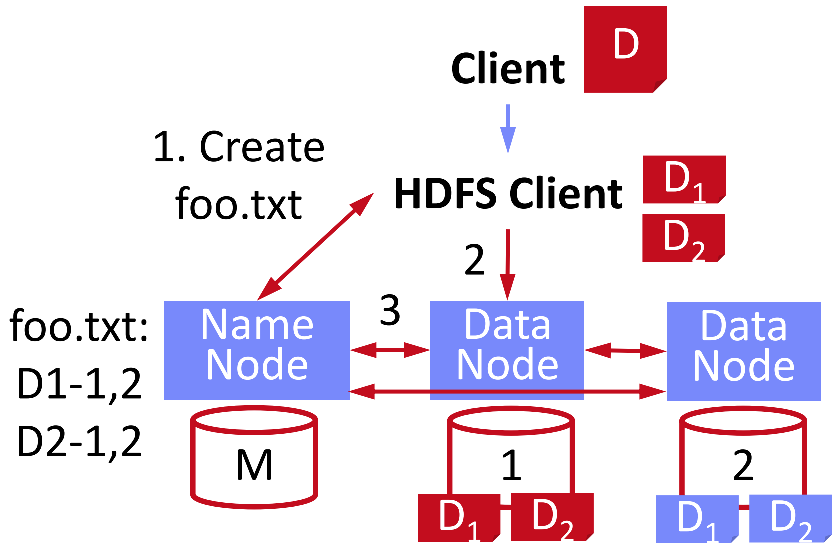
- **Sequence Files**
  - **Binary files for key/value pairs**, w/ optional compression (MR/Spark I/O, MR intermediates)
  - InputFormat with readers, writers, and sorters
- **Example Uncompressed SequenceFile**
  - **Header:** SEQ+version (4 bytes), keyClassName, valueClassName, compression, blockCompression, compressor class (codec), meta data
  - Splittable binary representation of key-value pair collection

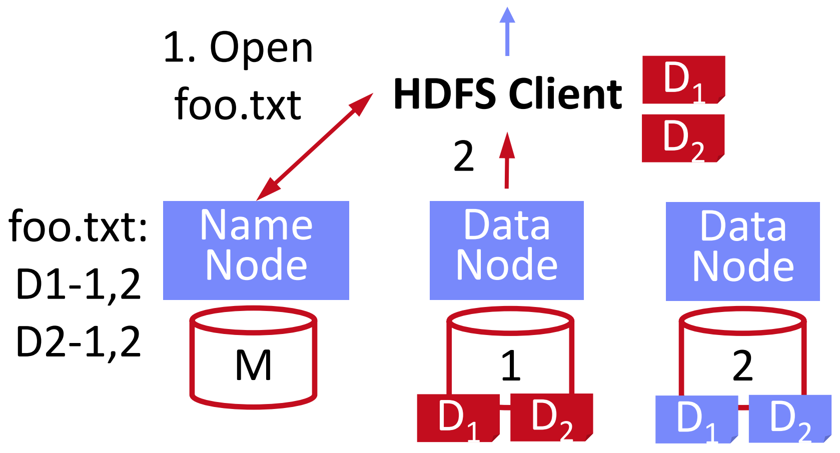


SystemDS: values are 1k x 1k matrix blocks

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**)

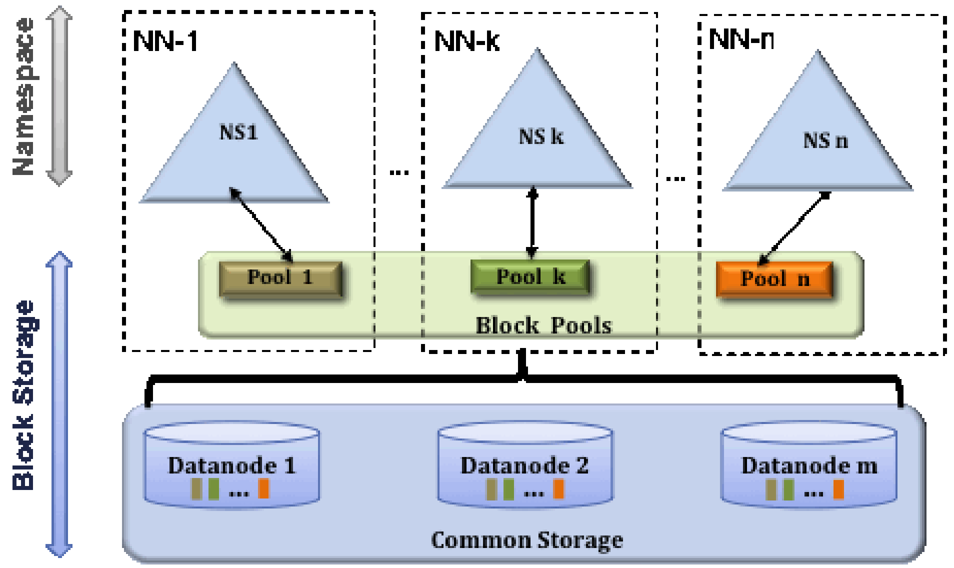
- **Custom Locality Information**
  - Custom **InputFormat** and **FileSplit** implementations
  - Return customized mapping of locations on getLocations()
  - Can use block locations of arbitrary files

```
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

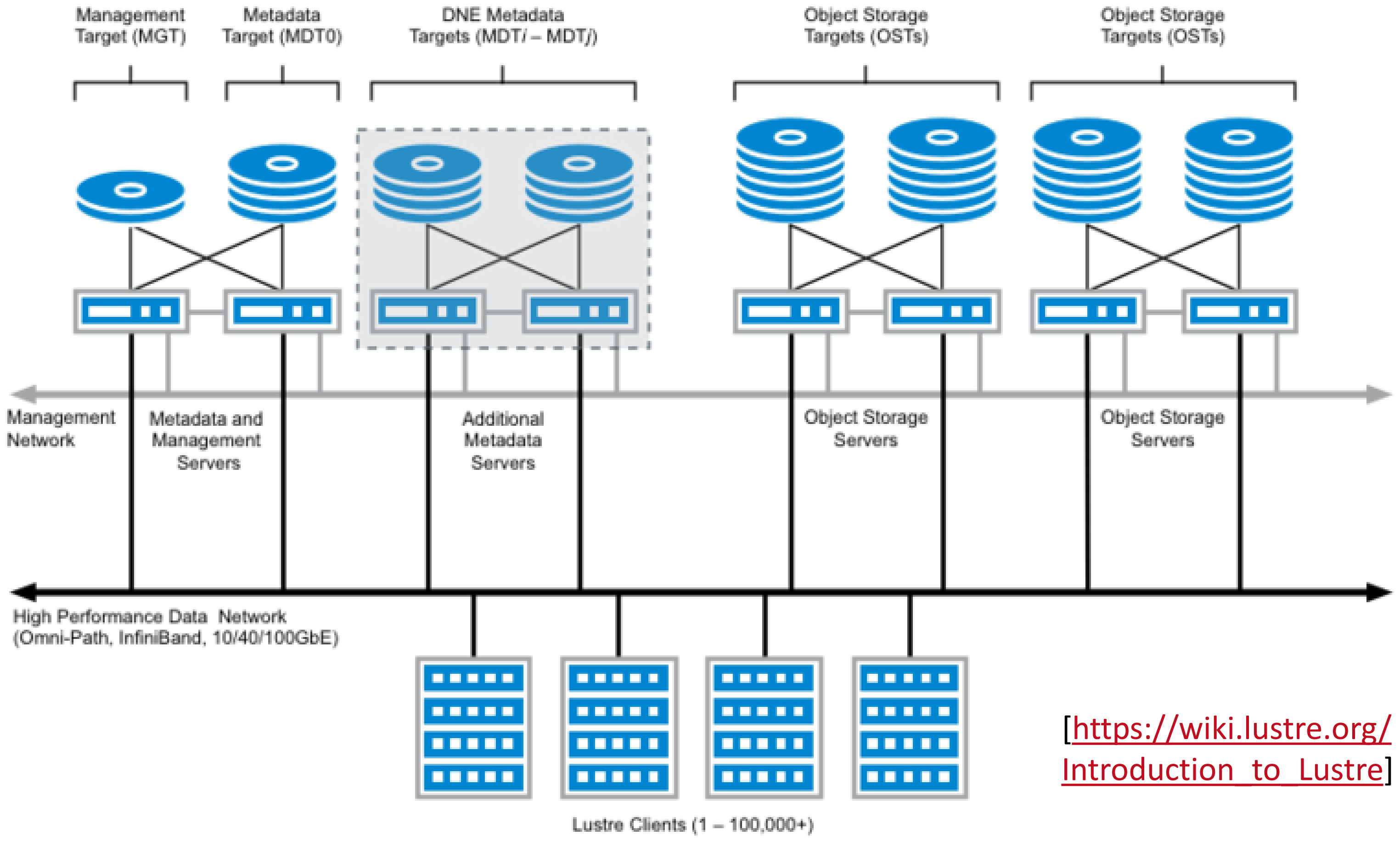
- **HDFS FileSystem Implementations (subset)**
  - LocalFileSystem (**file**), DistributedFileSystem (**hdfs**)
  - FTPFileSystem, HttpFileSystem, ViewFilesystem (ViewFs – mount table)
  - NativeS3FileSystem (**s3**, **s3a**), NativeSwiftFileSystem, NativeAzureFileSystem
  - Other proprietary: IBM **GPFS**,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

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

Scope: Focus on high IOPs (instead of bandwidth) with block write

Lustre Filesystem

- **Overview and System Architecture**
  - Widely used, open-source, POSIX-compliant, distributed parallel file system
  - **Primary domain:** high-performance computing and simulation environments



Management Target (MGT)
Metadata Target (MDT0)
DNE Metadata Targets (MDT*i* – MDT*j*)
Object Storage Targets (OSTs)
Object Storage Targets (OSTs)
Management Network
Metadata and Management Servers
Additional Metadata Servers
Object Storage Servers
Object Storage Servers
High Performance Data Network (Omni-Path, InfiniBand, 10/40/100GbE)
Lustre Clients (1 – 100,000+)

[https://wiki.lustre.org/Introduction_to_Lustre]

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)

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]”`

- **System Architecture**
  - **Key**-value maps, with values of different data types
  - APIs for CRUD operations (create, read, update, delete)
  - Scalability via sharding (horizontal partitioning)

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

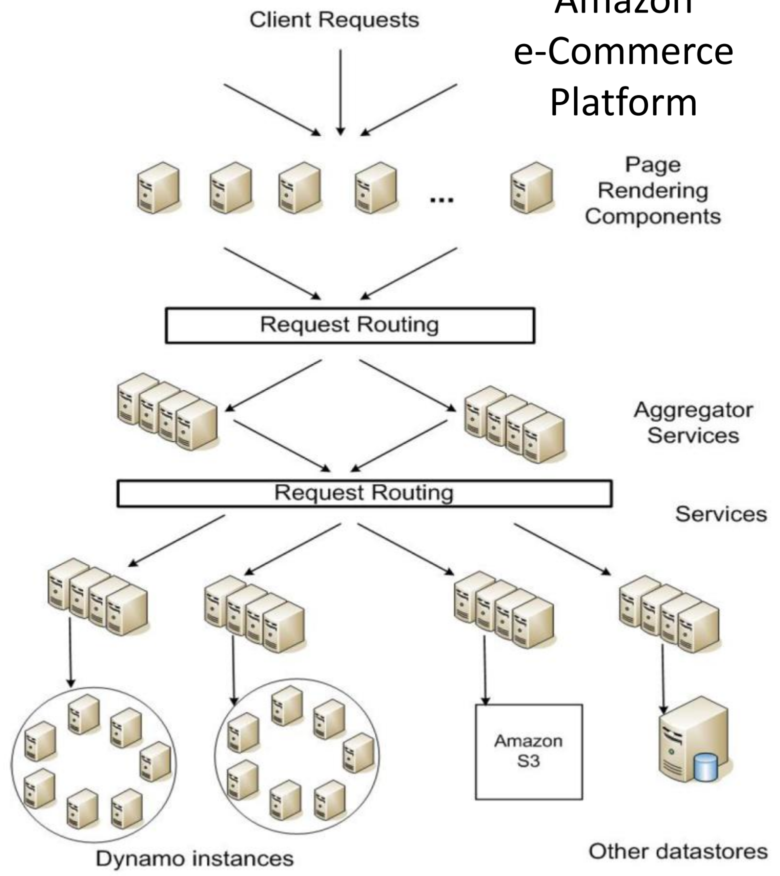
[Giuseppe DeCandia et al: Dynamo: amazon's highly available **key-value store**. **SOSP 2007**]

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 w/ async update propagation via **vector clocks**
  - Replica synchronization via **Merkle trees**

Amazon e-Commerce Platform



Example Systems, cont.

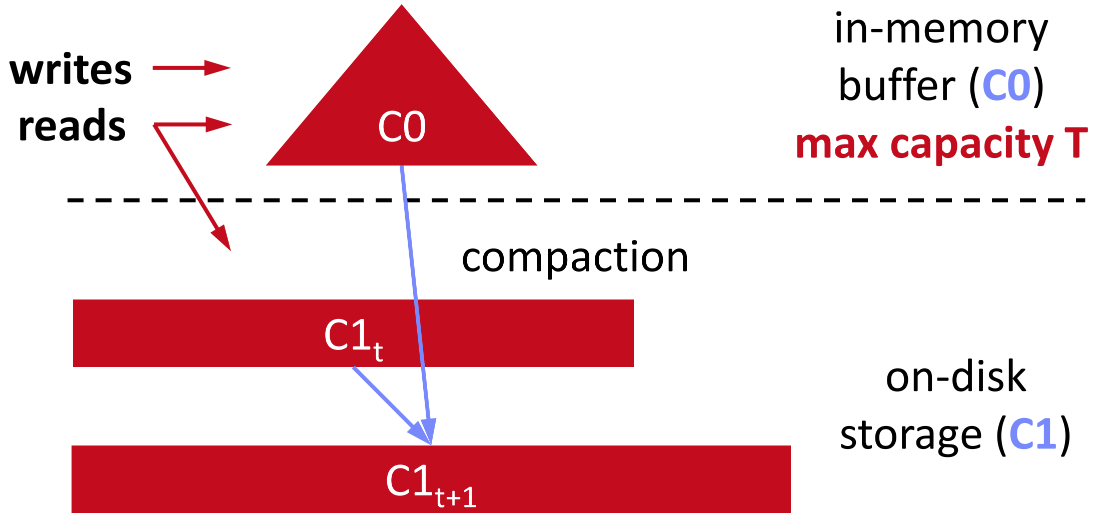
- **Redis Data Types**
  - Redis is not a plain KV-store, but "data structure server" with persistent log (**appendfsync no/everysec/always**)
  - **Key:** ASCII string (max 512MB, common key schemes: comment:1234:reply.to)
  - **Values:** strings, lists, sets, sorted sets, hashes (map of string-string), 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**]

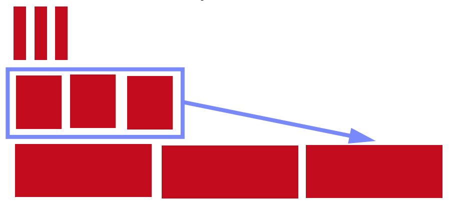
- **LSM Overview**
  - Many KV-stores rely on LSM-trees as their storage engine (e.g., **BigTable**, **DynamoDB**, **LevelDB**, **Riak**, **RocksDB**, **Cassandra**, **HBase**)
  - **Approach:** Buffers writes in memory, flushes data as sorted runs to storage, merges runs into larger runs of next level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

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

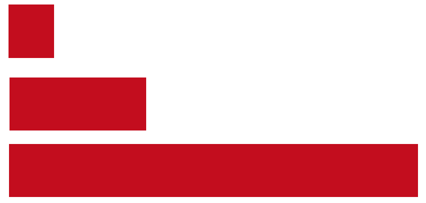


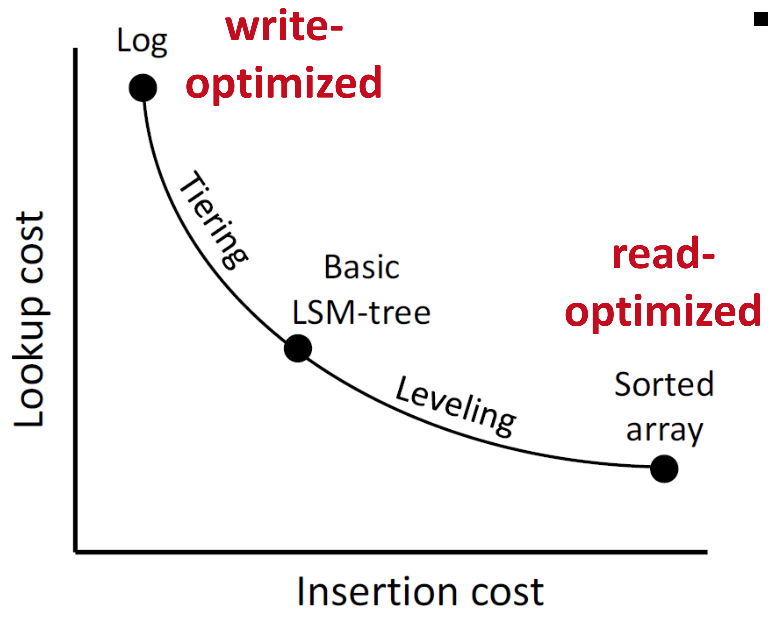
Log-structured Merge Trees, cont.

- **LSM Tiering**
  - 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

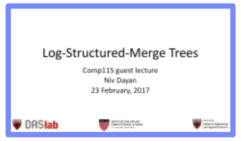


- **LSM Leveling**
  - Keep 1 run per level L
  - Merge run of Li with Li+1
    - L1
    - L2
    - L3





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


Log-Structured-Merge Trees
Comp115 guest lecture
Niv Dayan
23 February, 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, NoSQL)

Microsoft

- **Elastic Data Warehouses**
  - Motivation: Intersection of data warehousing, cloud computing, distributed storage
  - Example Systems
    - **#1** Snowflake
    - **#2** Google BigQuery (Dremel)
    - **#3** Amazon Redshift
    - **#4** ByteDance ByConity
    - Azure SQL Data Warehouse /
      #5 Azure SQL Database Hyperscale (Socrates)

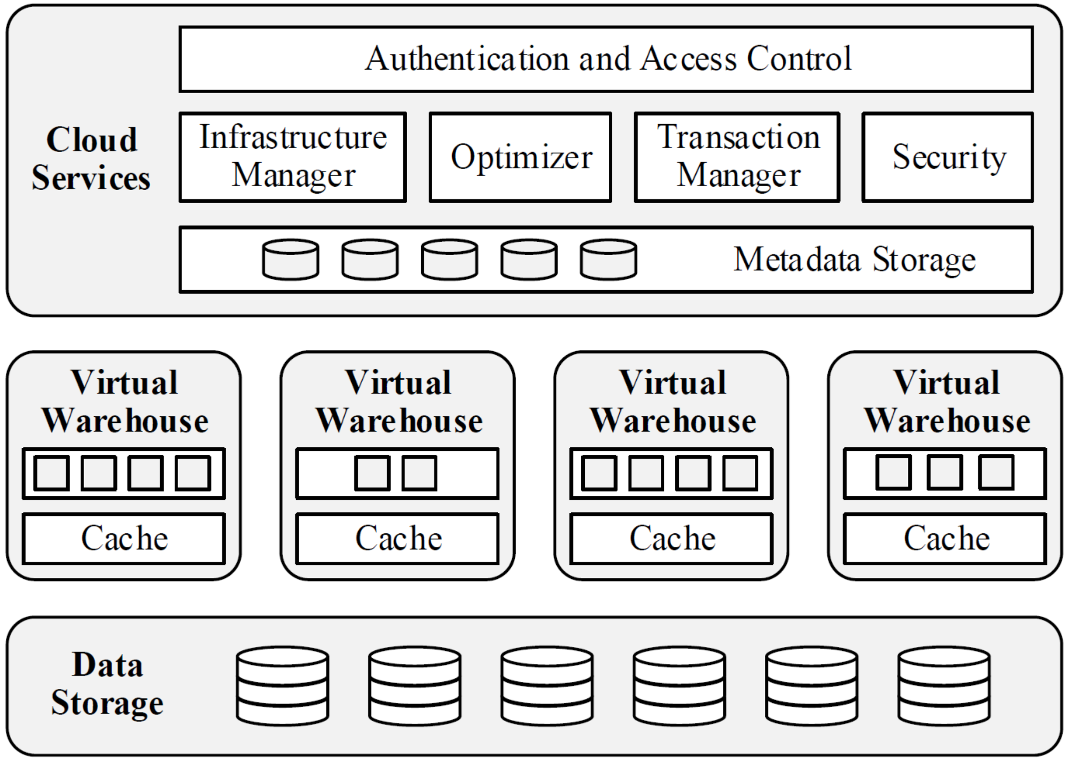
02 Data Warehousing, ETL, and SQL/OLAP

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**]

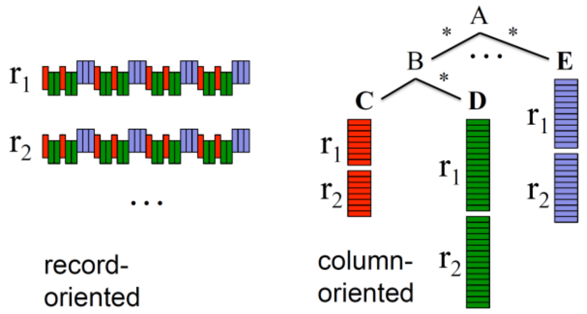
- **Motivation** (impl started late 2012)
  - **Enterprise-ready DWH solution for the cloud** (elasticity, semi-structured)
  - Pure SaaS experience, high availability, cost efficient
- **Cloud Services**
  - Manage virtual DHWs, TXs, and queries
  - Meta data and catalogs
- **Virtual Warehouses**
 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



Example Google BigQuery

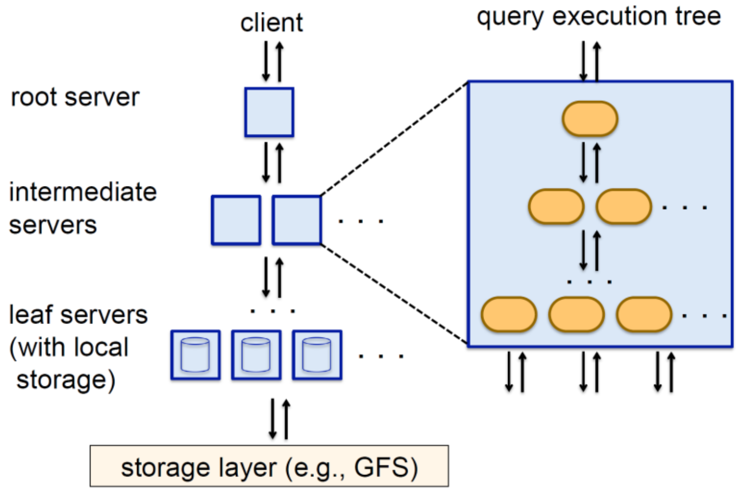
[Sergey Melnik et al.: Dremel: Interactive Analysis of Web-Scale Datasets. **PVLDB 3(1) 2010**]

- **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.]

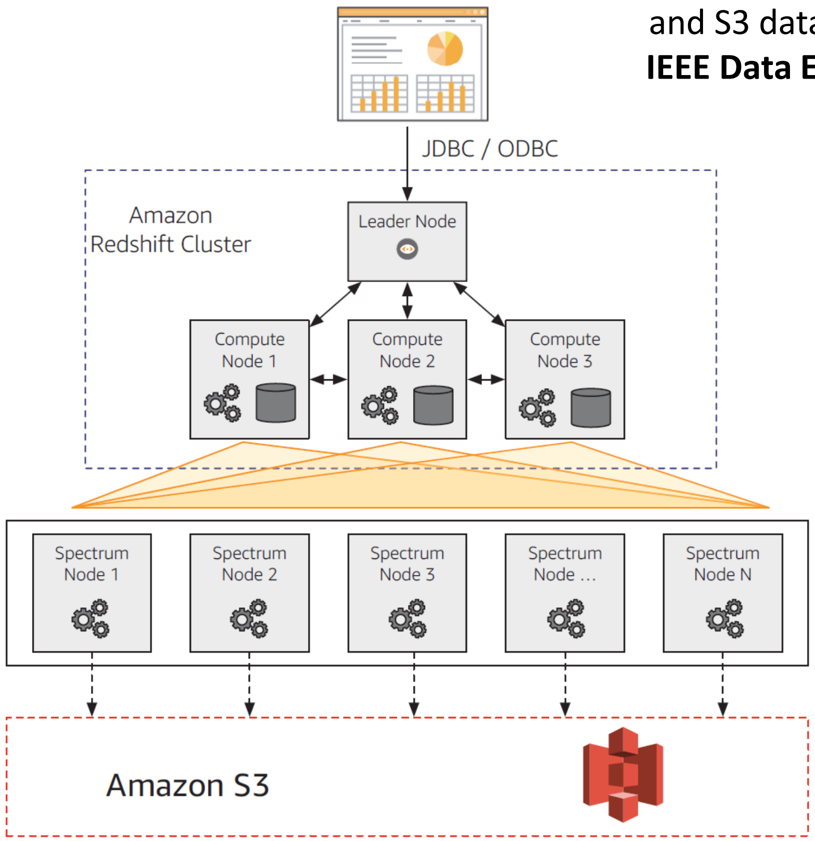


Example Amazon Redshift

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

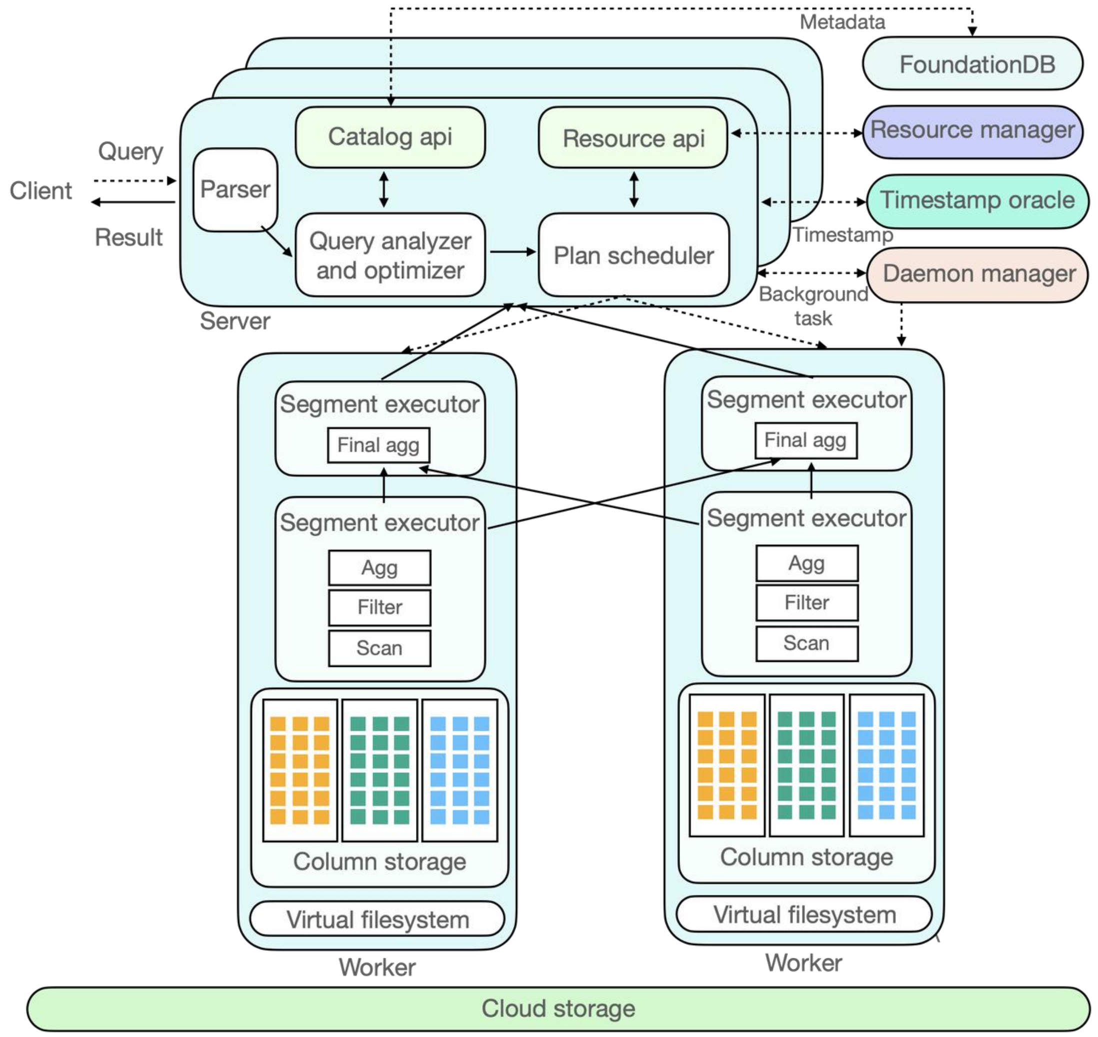
[Mengchu Cai et al.: Integrated Querying of SQL database data and S3 data in Amazon Redshift. **IEEE Data Eng. Bull. 41(2) 2018**]

- **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 + compute nodes in **EC2** (w/ **local storage**)
  - Replication across nodes + **S3 backup**
  - **Query compilation** in C++ code
  - Support for **flat and nested files**



Example ByteDance ByConity

- **System Architecture**
  - Virtual Warehouses (disaggregated storage and compute)
  - On-demand elasticity
  - **Column store** on **object storage** (e.g., S3)
  - Open-source (https://github.com/ByConity/ByConity)



[https://byconity.github.io/blog/2023-05-24-byconity-announcement-opensources-its-cloudnative-data-warehouse]

Summary and Q&A

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

Happy Holidays!

- Next Lectures (Large-scale Data Management and Analysis)
  - 11 Distributed, Data-Parallel Computation [Jan 15]
  - 12 Distributed Stream Processing [Jan 22]
  - 13 Distributed Machine Learning Systems [Jan 29]
  - Exercise/Project Submission [Jan 30]