Database Systems
11 Distributed Storage

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SCIENCE
PASSION
TECHNOLOGY

Last update: Jan 10, 2020

Announcements/Org

- **#1 Video Recording**
  - Link in TeachCenter & Tube (lectures will be public)
- **#2 Exercises**
  - Exercise 1 graded, feedback in TC, office hours
  - Exercise 2 graded, feedback in TC, office hours
  - **Exercise 3 in progress of being graded**
- **#3 Exam Dates**
  - **Jan 30, 5.30pm, HS i13**
  - **Jan 31, 5.30pm, HS i13**
  - **Feb 3, 7.30pm, HS i13**
  - **Feb 6, 4.00pm, HS i13**
  - **Feb 7, 4.00pm, HS i13**
- **#4 Course Evaluation**
  - Evaluation period: **Jan 14 – Feb 14**
  - Please, participate w/ honest feedback (pos/neg)

56.4%

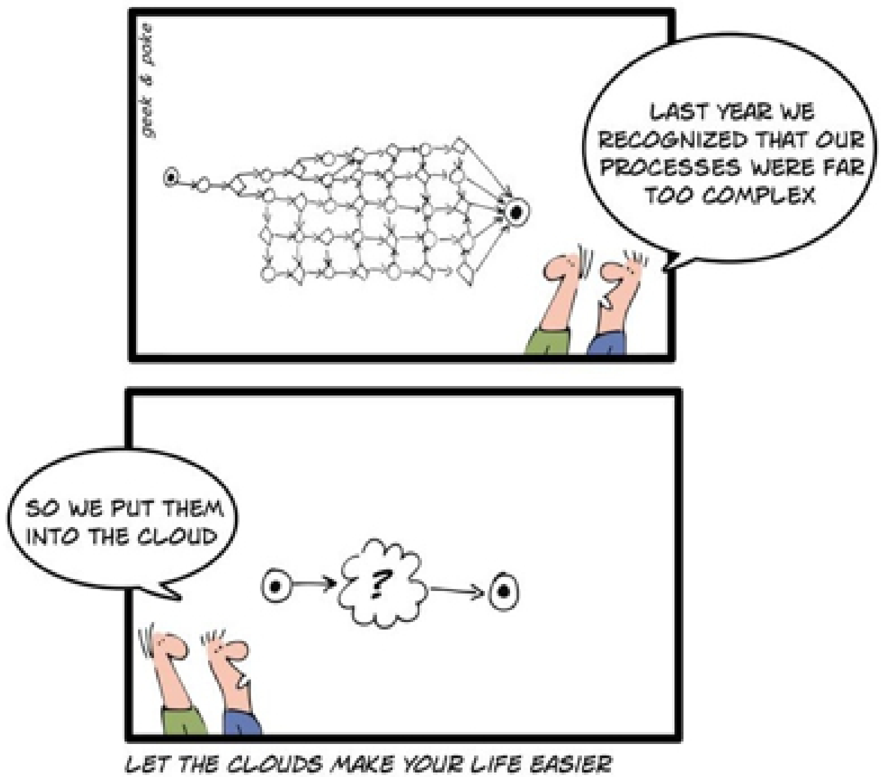
All draft modes accepted

Exam starts +10min, working time: 90min
(no lecture materials)

Agenda

- **Cloud Computing Overview**
- **Distributed Data Storage**
- **Distributed Data Analysis**
- **Exercise 4: Large-Scale Data Analysis**

Data Integration and Large-Scale Analysis (DIA)
(bachelor/master)



Cloud Computing Overview

Motivation Cloud Computing

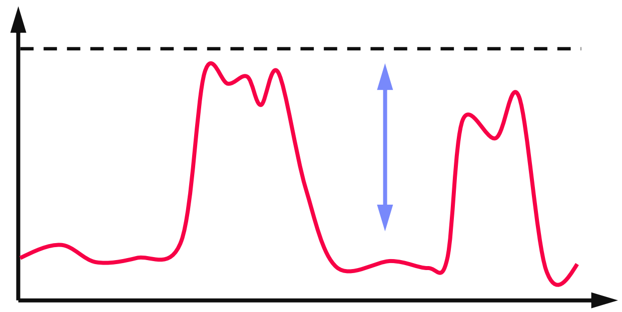
- **Definition Cloud Computing**
  - **On-demand, remote storage and compute resources, or services**
  - **User:** computing as a utility (similar to energy, water, internet services)
  - **Cloud provider:** computation in data centers / multi-tenancy

- **Service Models**
  - **IaaS: Infrastructure as a service** (e.g., storage/compute nodes)
  - **PaaS: Platform as a service** (e.g., distributed systems/frameworks)
  - **SaaS: Software as a Service** (e.g., email, databases, office, github)

→ Transforming IT Industry/Landscape
  - Since ~2010 increasing move from on-prem to cloud resources
  - System software licenses become increasingly irrelevant
  - Few cloud providers dominate IaaS/PaaS/SaaS markets (w/ 2018 revenue): **Microsoft Azure Cloud** ($ 32.2B), **Amazon AWS** ($ 25.7B), **Google Cloud** (N/A), **IBM Cloud** ($ 19.2B), **Oracle Cloud** ($ 5.3B), **Alibaba Cloud** ($ 2.1B)

Motivation Cloud Computing, cont.

- **Argument #1: Pay as you go**
  - No upfront cost for infrastructure
  - Variable utilization ➔ over-provisioning
  - **Pay per use or acquired resources**



- **Argument #2: Economies of Scale**
  - Purchasing and managing IT infrastructure at scale ➔ **lower cost** (applies to both HW resources and IT infrastructure/system experts)
  - Focus on **scale-out on commodity HW** over scale-up ➔ **lower cost**

- **Argument #3: Elasticity**
  - Assuming perfect scalability, work done in **constant time * resources**
  - Given virtually unlimited resources allows to reduce time as necessary

100 days @ 1 node

≈

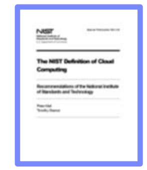
1 day @ 100 nodes

(but beware Amdahl's law: max speedup **sp = 1/s**)

Characteristics and Deployment Models

- **Extended Definition**
  - ANSI recommended definitions for service types, characteristics, deployment models

[Peter Mell and Timothy Grance: The NIST Definition of Cloud Computing, **NIST 2011**]

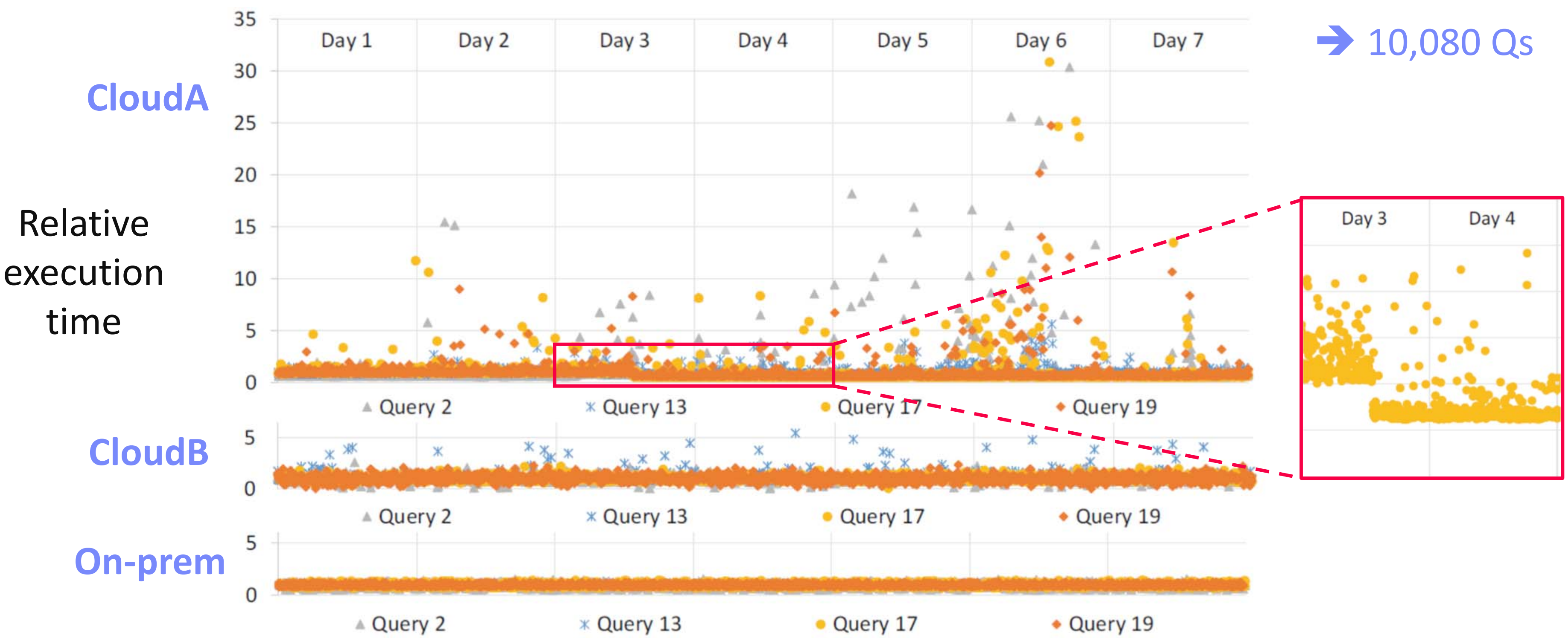


- **Characteristics**
  - **On-demand self service:** unilateral resource provision
  - **Broad network access:** network accessibility
  - **Resource pooling:** resource virtualization / multi-tenancy
  - **Rapid elasticity:** scale out/in on demand
  - **Measured service:** utilization monitoring/reporting
- **Deployment Models**
  - **Private cloud:** single org, on/off premises
  - **Community cloud:** single community (one or more orgs)
  - **Public cloud:** general public, on premise of cloud provider
  - **Hybrid cloud:** combination of two or more of the above

Excursus: 1 Query/Minute for 1 Week

- **Experimental Setup**
  - 1GB TPC-H database, 4 queries on 2 cloud DBs / 1 on-prem DB

[Tim Kiefer, Hendrik Schön, Dirk Habich, Wolfgang Lehner: **A Query, a Minute**: Evaluating Performance Isolation in Cloud Databases. TPCTC 2014]



Anatomy of a Data Center

Commodity CPU:
Xeon E5-2440: 6/12 cores
Xeon Gold 6148: 20/40 cores

Server:
Multiple sockets,
RAM, disks

Rack:
16-64 servers +
top-of-rack switch

Cluster:
Multiple racks + cluster switch

Data Center:
>100,000 servers

[Google Data Center, Eemshaven, Netherlands]

Fault Tolerance

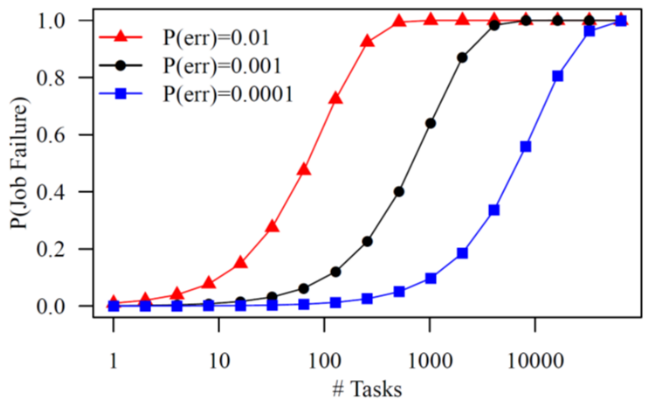
[Christos Kozyrakis and Matei Zaharia: CS349D: Cloud Computing Technology, lecture, **Stanford 2018**]

- **Yearly Data Center Failures**
  - ~0.5 overheating (power down most machines in <5 mins, ~1-2 days)
  - ~1 PDU failure (~500-1000 machines suddenly disappear, ~6 hrs)
  - ~1 rack-move (plenty of warning, ~500-1000 machines powered down, ~6 hrs)
  - ~1 network rewiring (rolling ~5% of machines down over 2-day span)
  - ~20 rack failures (40-80 machines instantly disappear, 1-6 hrs)
  - ~5 racks go wonky (40-80 machines see 50% packet loss)
  - ~8 network maintenances (~30-minute random connectivity losses)
  - ~12 router reloads (takes out DNS and external vIPs for a couple minutes)
  - ~3 router failures (immediately pull traffic for an hour)
  - ~dozens of minor 30-second blips for dns
  - ~1000 individual machine failures (2-4% failure rate, at least twice)
  - ~thousands of hard drive failures (1-5% of all disks will die)

Fault Tolerance, cont.

- **Other Common Issues**
  - **Configuration issues**, partial SW updates, SW bugs
  - **Transient errors:** no space left on device, memory corruption, stragglers

- **Recap: Error Rates at Scale**
  - Cost-effective commodity hardware
  - Error rate increases with increasing scale
  - Fault Tolerance for distributed/cloud storage and data analysis



➔ Cost-effective Fault Tolerance
  - **BASE** (basically **available**, soft state, **eventual consistency**)
  - Effective techniques
    - ECC (error correction codes), CRC (cyclic redundancy check) for detection
    - **Resilient storage:** replication/erasure coding, checkpointing, and lineage
    - **Resilient compute:** task re-execution / speculative execution

Containerization

- **Docker Containers**
  - **Shipping container analogy**
    - Arbitrary, self-contained goods, standardized units
    - Containers reduced loading times ➔ efficient international trade
  - **#1 Self-contained package** of necessary SW and data (read-only image)
  - **#2 Lightweight virtualization** w/ resource isolation via cgroups

- **Cluster Schedulers**
  - Container orchestration: scheduling, deployment, and management
  - Resource negotiation with clients
  - Typical resource bundles (CPU, memory, device)
  - Examples: **Kubernetes**, **Mesos**, (**YARN**), **Amazon ECS**, **Microsoft ACS**, **Docker Swarm**

[Brendan Burns, Brian Grant, David Oppenheimer, Eric Brewer, John Wilkes: Borg, Omega, and Kubernetes. **CACM 2016**]

➔ **from machine- to application-oriented scheduling**

Example Amazon Services – Pricing (current gen)

- **Amazon EC2 (Elastic Compute Cloud)**
  - IaaS offering of different node types and generations
  - **On-demand**, **reserved**, and **spot** instances

	vCores		Mem		
m4.large	2	6.5	8 GiB	EBS Only	$0.12 per Hour
m4.xlarge	4	13	16 GiB	EBS Only	$0.24 per Hour
m4.2xlarge	8	26	32 GiB	EBS Only	$0.48 per Hour
m4.4xlarge	16	53.5	64 GiB	EBS Only	$0.96 per Hour
m4.10xlarge	40	124.5	160 GiB	EBS Only	$2.40 per Hour
m4.16xlarge	64	188	256 GiB	EBS Only	$3.84 per Hour

- **Amazon ECS (Elastic Container Service)**
  - PaaS offering for Docker containers
  - Automatic setup of Docker environment

Pricing according to EC2
(in EC2 launch mode)

- **Amazon EMR (Elastic Map Reduce)**
  - PaaS offering for Hadoop workloads
  - Automatic setup of YARN, HDFS, and specialized frameworks like Spark
  - **Prices in addition to EC2 prices**

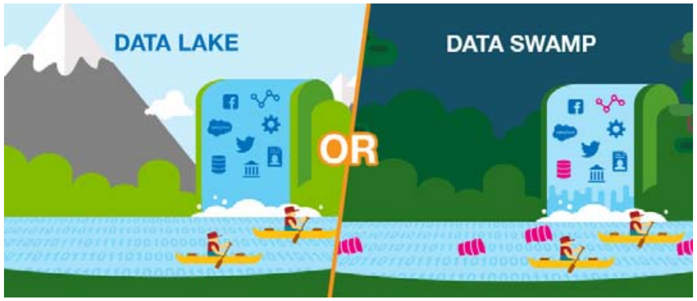
m4.large	$0.117 per Hour	$0.03 per Hour
m4.xlarge	$0.234 per Hour	$0.06 per Hour
m4.2xlarge	$0.468 per Hour	$0.12 per Hour
m4.4xlarge	$0.936 per Hour	$0.24 per Hour
m4.10xlarge	$2.34 per Hour	$0.27 per Hour
m4.16xlarge	$3.744 per Hour	$0.27 per Hour

Distributed Data Storage

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]

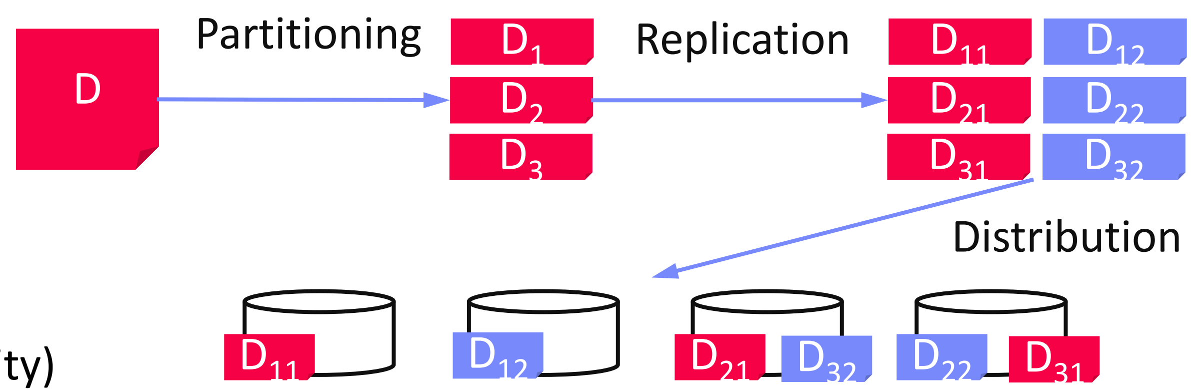
- **Excursus: Research Data Management**
  - FAIR data principles: findable, accessible, interoperable, re-usable

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 + **eventual consistency**

- **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)



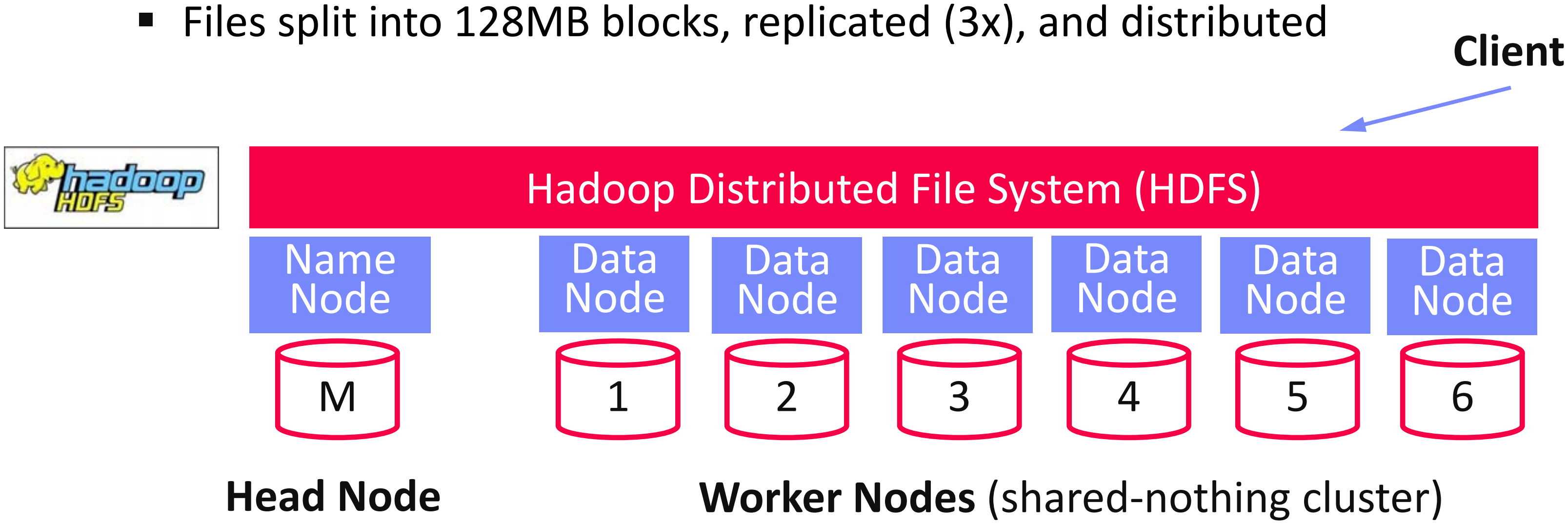
Object Storage, cont.

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

- **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/mboehm-b1`
  - **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 [SOSP'03] + MapReduce [ODSI'04] → Apache Hadoop (2006)
  - Apache Hive (SQL), Pig (ETL), Mahout (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



Hadoop Distributed File System, cont.

- **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)

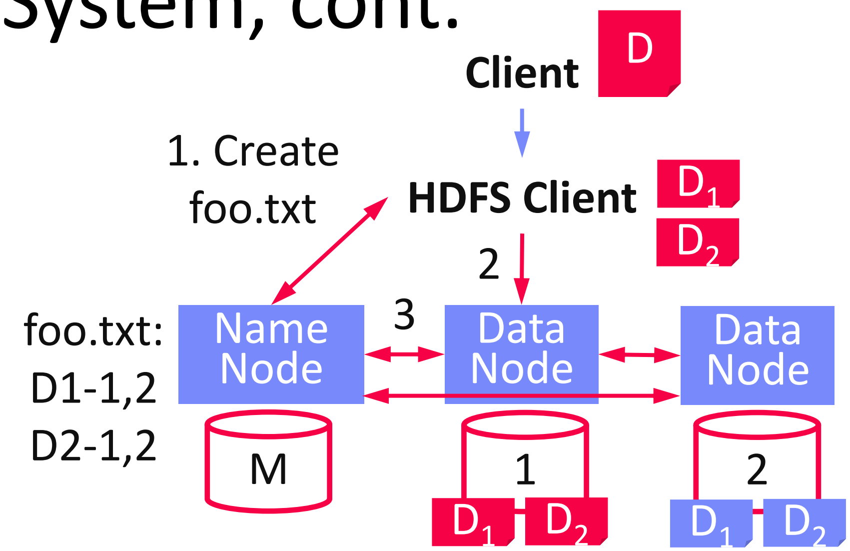
```
hadoop fs -ls ./data/mnist1m.bin
```

```
-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
```

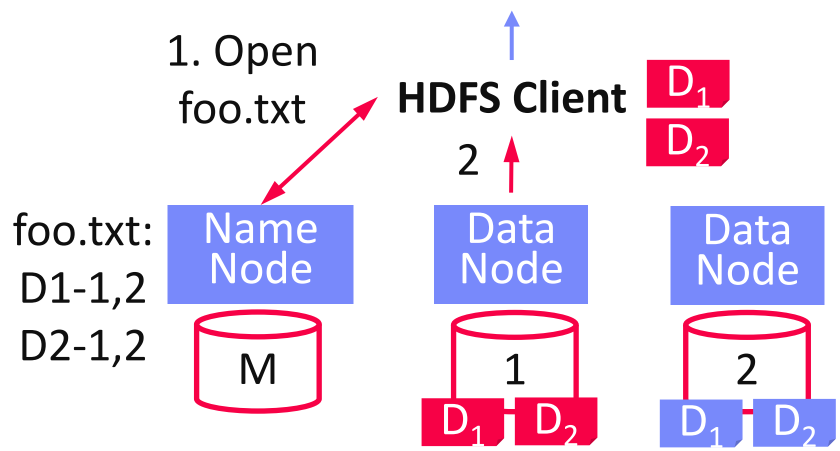
- **HDFS DataNode**
  - Worker daemon per cluster node that manages block storage (list of disks)
  - Block creation, deletion, replication as individual files in local FS
  - On startup: scan local blocks and send **block report** to name node
  - Serving block read and write requests
  - Send heartbeats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

Hadoop Distributed File System, cont.

- **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



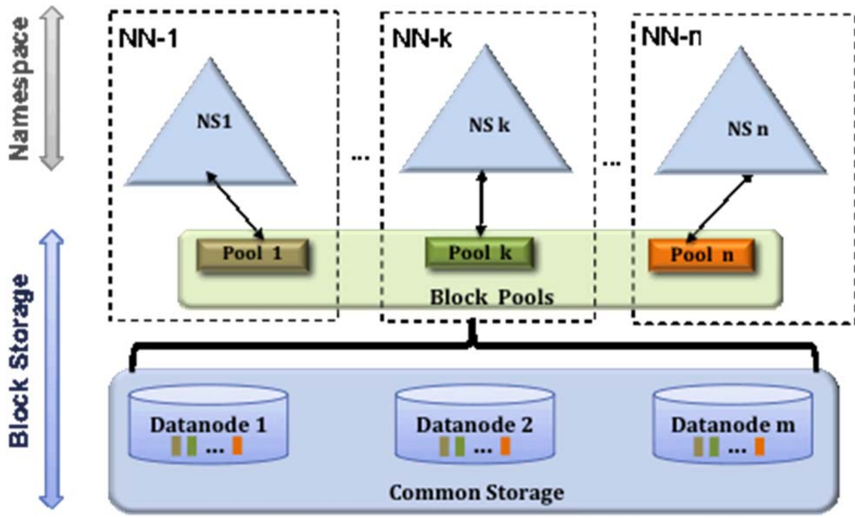
- **HDFS Read**
  - #1 Client RPC to NameNode to open file → DNs for blocks
  - #2 Read blocks sequentially from closest DN w/ block
  - InputFormats and RecordReaders as abstraction for multi-part files (incl. compression/encryption)



Hadoop Distributed File System, cont.

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

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

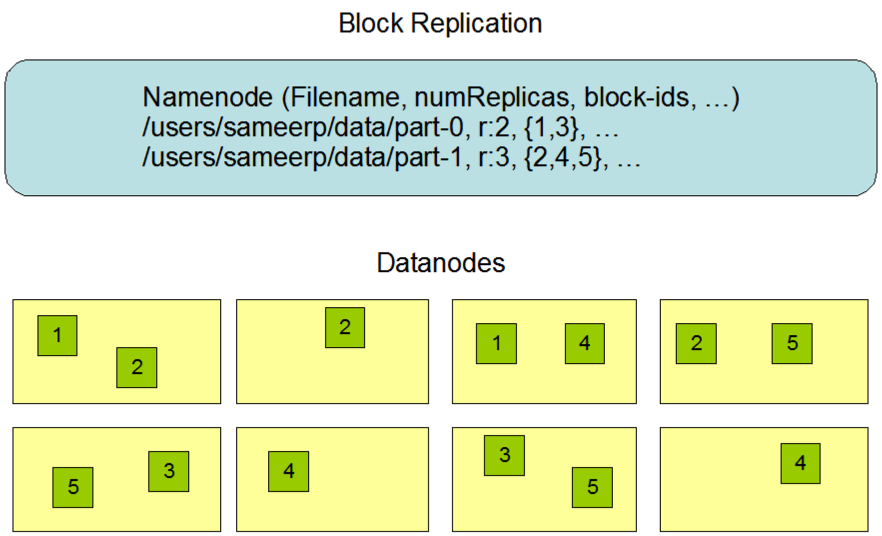


[**Credit:** https://hadoop.apache.org/docs/current/hadoop-project-dist/hadoop-hdfs/Federation.html]

BREAK (and Test Yourself)

- **Large-Scale Analysis** (6/100 points)
  - Describe means (i.e., techniques) of ensuring fault tolerance in distributed storage systems (like Hadoop Distributed File System) and distributed analysis frameworks (like Apache MapReduce or Apache Spark).

- **Solution of 1st part**
  - Data replication in HDFS [3]
  - Replica Placement Policy (node-local, rack-local, other)



[**Credit**: https://hadoop.apache.org/docs/stable/hadoop-project-dist/hadoop-hdfs/HdfsDesign.html#Data_Replication]