Data Management
11 Distributed Storage & Analysis

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TU Graz
SCIENCE
PASSION
TECHNOLOGY

Last update: Jan 16, 2021

ISDS

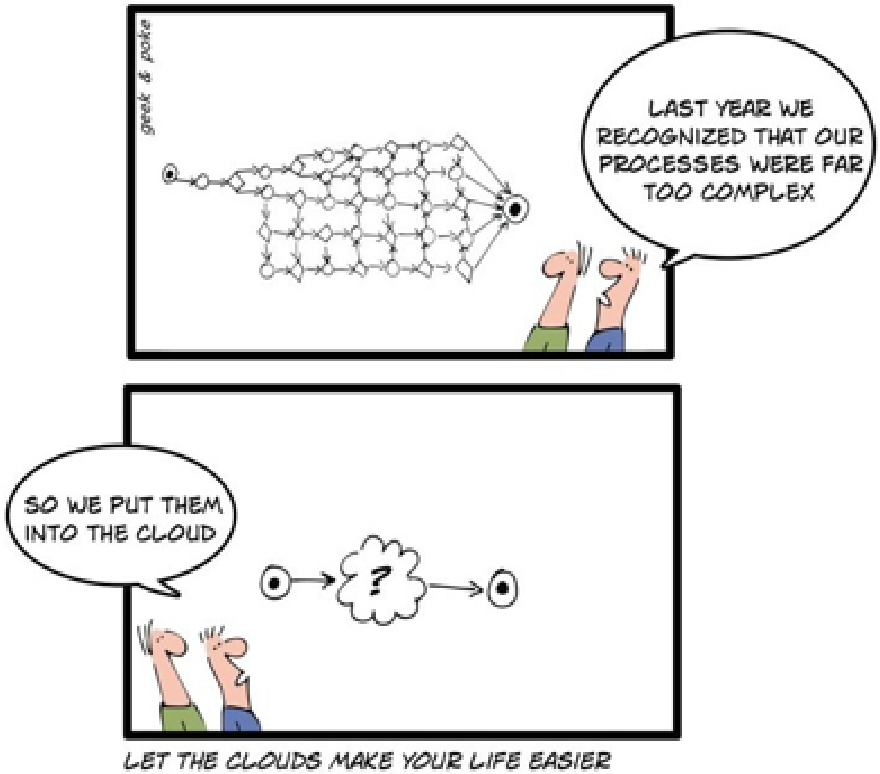
Announcements/Org

- **#1 Video Recording**
  - Link in TeachCenter & TUbe (lectures will be public)
  - Optional attendance (independent of COVID)
- **#2 COVID-19 Restrictions**
  - Corona Traffic Light: **RED**
  - Webex lectures until end of semester
- **#3 Exercise Submissions**
  - **Exercise 1/2:** grading done, **Exercise 3:** in process
  - **Exercise 4:** published Jan 05, deadline: **Jan 26 11.59pm**
- **#4 Course Evaluation and Exam**
  - Evaluation period: **Dec 15 – Jan 31**
  - Exam date: **Feb 12** (i13), 12.30-2.30pm, 3.30-5.30pm, 6.30-8.30pm

Agenda

- **Cloud Computing Overview**
- **Distributed Data Storage**
- **Distributed Data Analysis**

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



Cloud Computing Overview

Motivation Cloud Computing

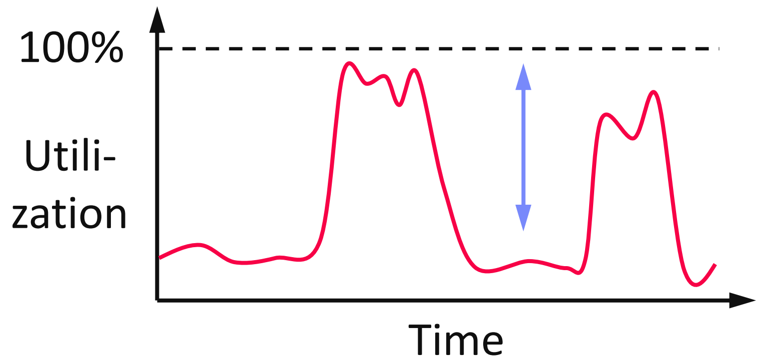
- **Definition Cloud Computing**
  - **On-demand, remote storage and compute resources, or services**
  - **User:** computing as a utility (similar to energy, water, internet services)
  - **Cloud provider:** computation in data centers / multi-tenancy
- **Service Models**
  - **IaaS: Infrastructure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

≈

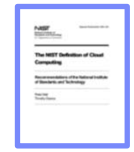
1 day @ 100 nodes

(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**
  - **Public cloud:** general public, on premise of cloud provider
  - **Hybrid cloud:** combination of two or more of the above
  - **Community cloud:** single community (one or more orgs)
  - **Private cloud:** single org, on/off premises

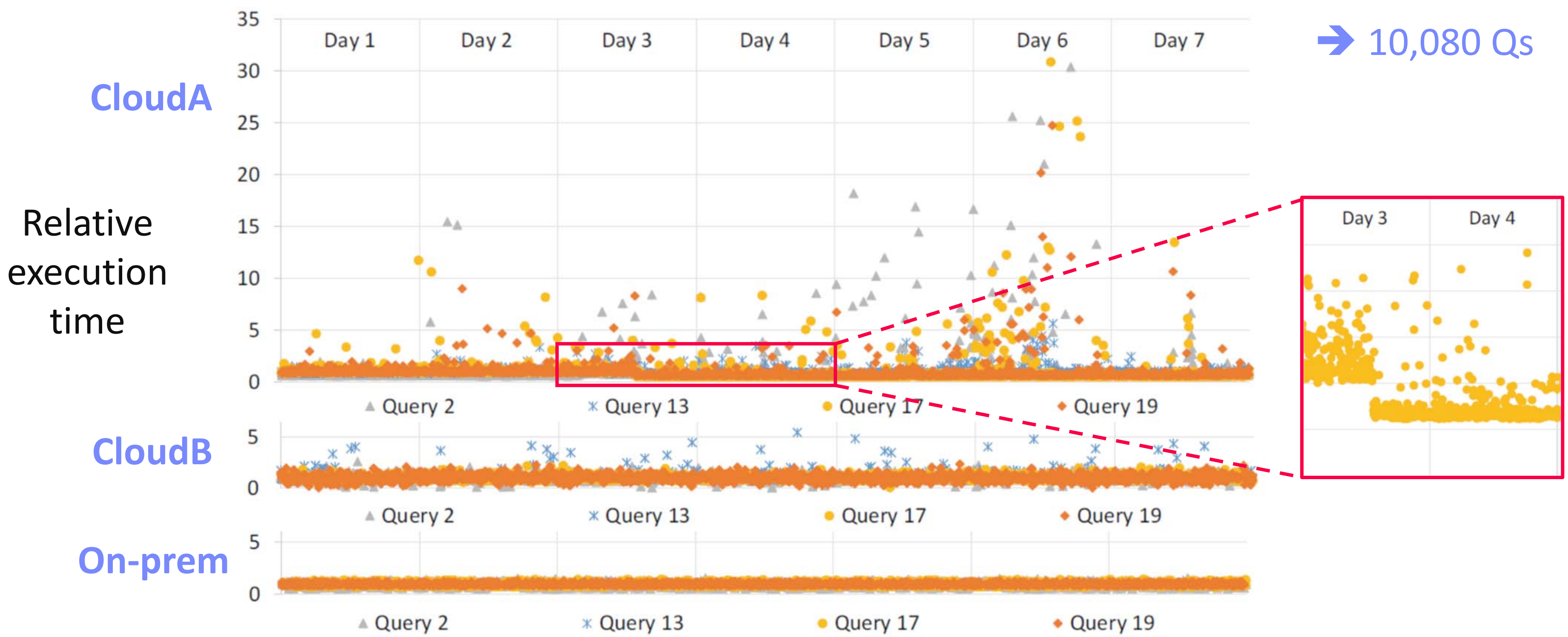
MS Azure Private Cloud

IBM Cloud Private

Excursus: 1 Query/Minute for 1 Week

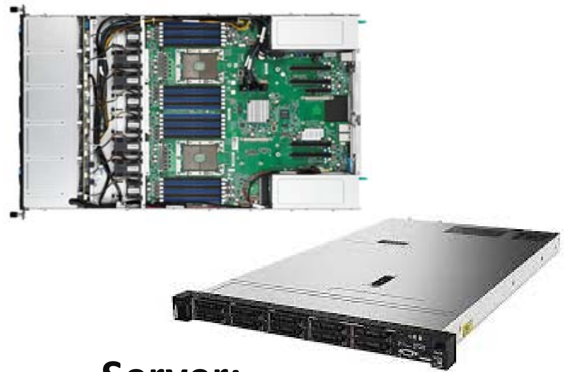
- **Experimental Setup**
  - 1GB TPC-H database, 4 queries on 2 cloud DBs / 1 on-prem DB

[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]

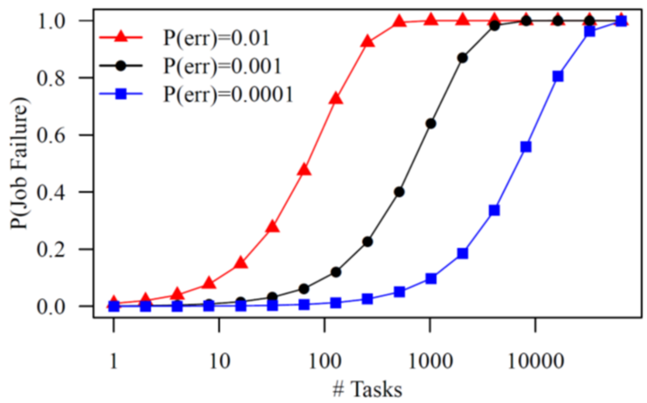
Fault Tolerance

[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/ shared OS and 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

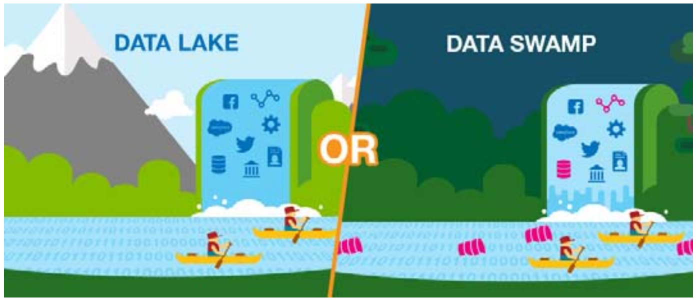
Distributed Data Storage

Cloud Object Storage

Distributed File Systems

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]

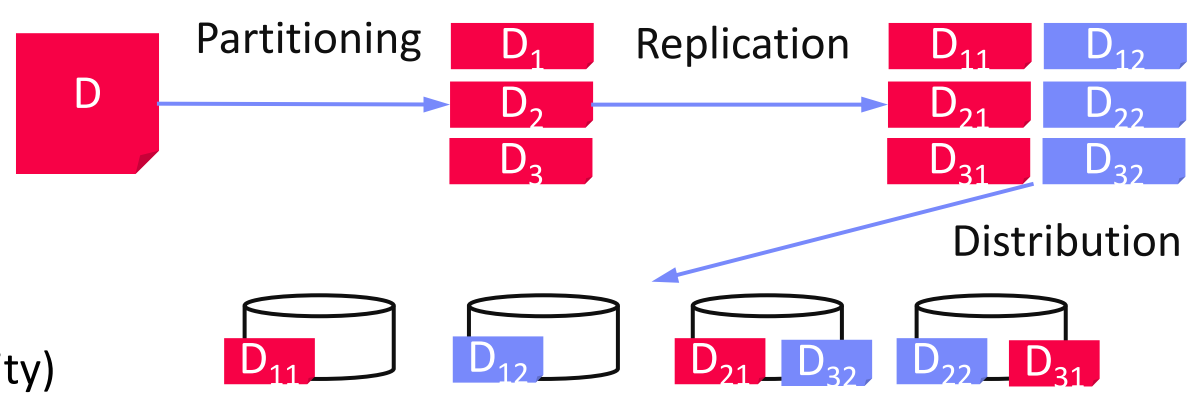
- **Excursus: Research Data Management**
  - FAIR data principles: findable, accessible, interoperable, re-usable

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 (**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

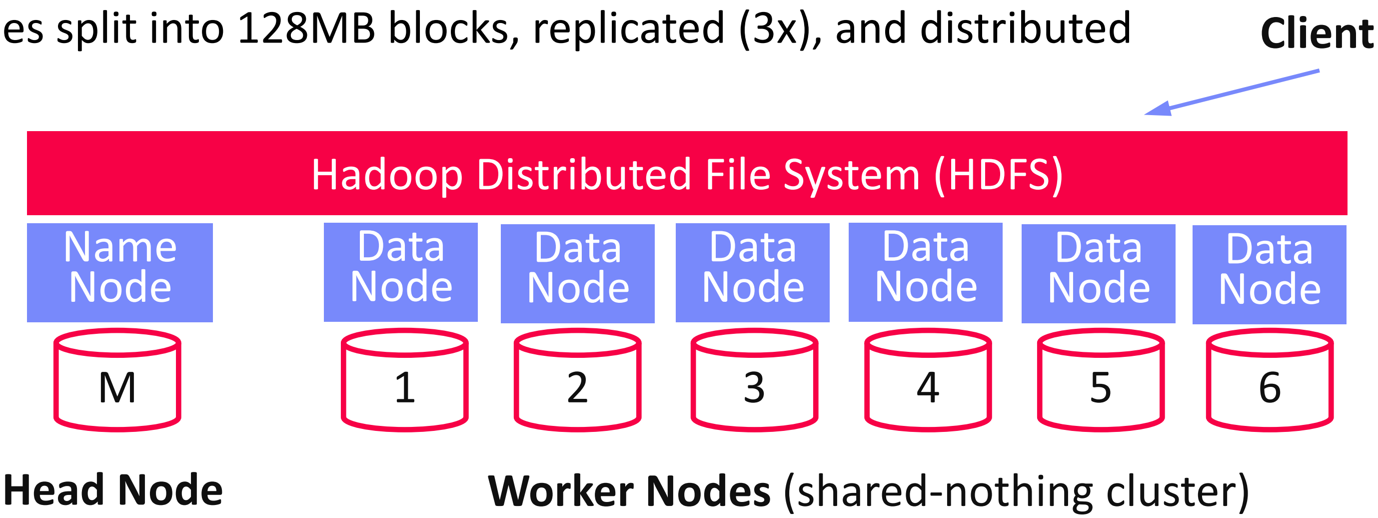
- **Amazon S3**
  - Reliable object store for photos, videos, documents or any binary data
  - **Bucket:** Uniquely named, static data container
    `http://s3.aws-eu-central-1.amazonaws.com/mboehm-b1`
  - **Object:** key, version ID, value, metadata, access control
  - Single (5GB)/multi-part (5TB) 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 + 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



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)

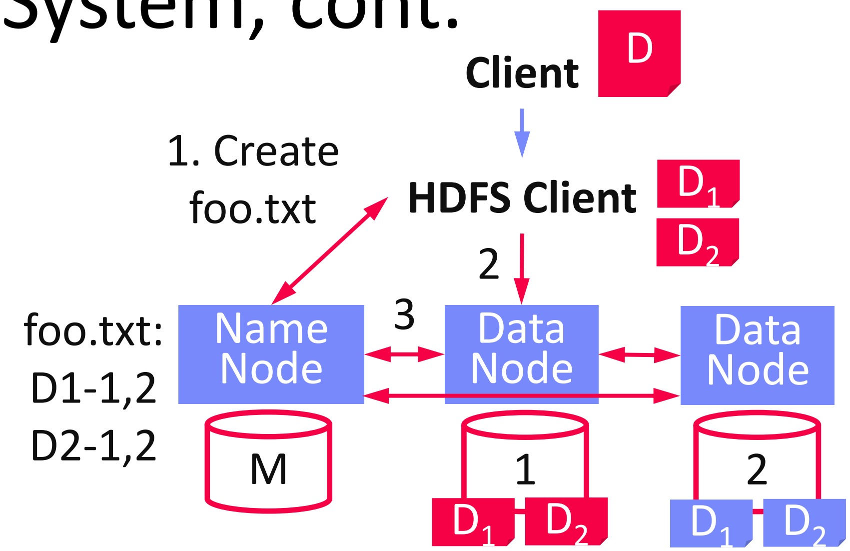
```
hadoop fs -ls ./data/mnist1m.bin
```

```
-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
```

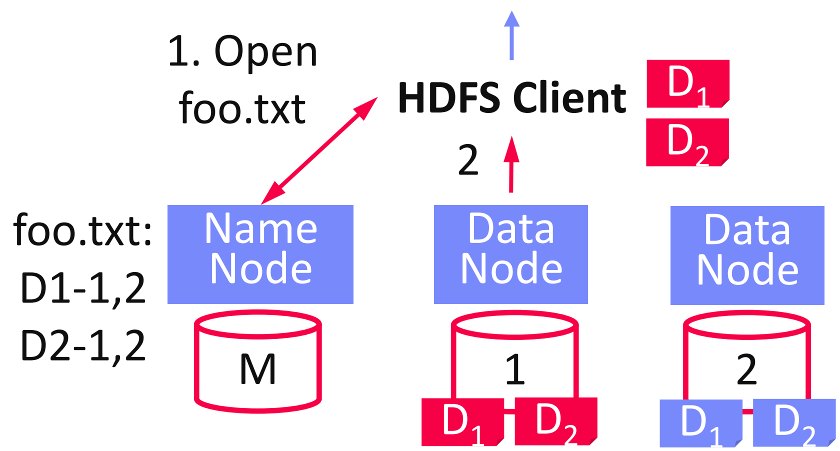
- **HDFS DataNode**
  - Worker daemon per cluster node that manages block storage (list of disks)
  - Block creation, deletion, replication as individual files in local FS
  - On startup: scan local blocks and send **block report** to name node
  - Serving block read and write requests
  - Send heartbeats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



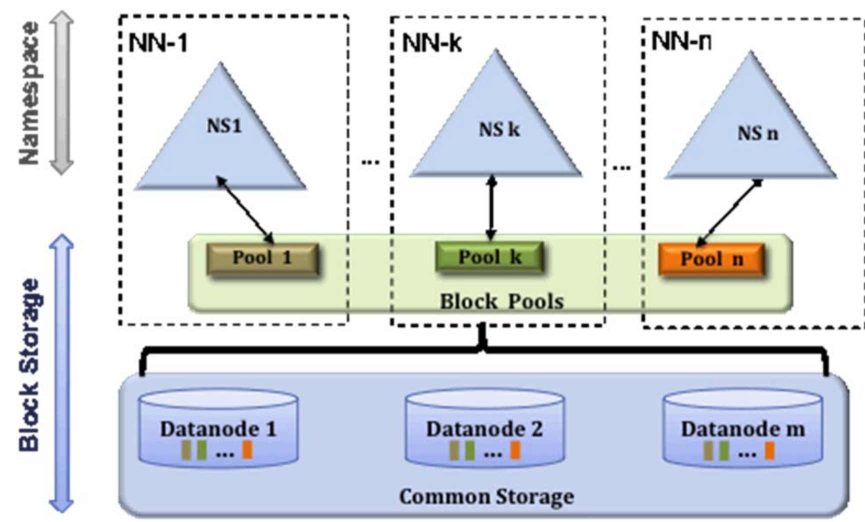
- **HDFS Read**
  - #1 Client RPC to NameNode to open file → DNs for blocks
  - #2 Read blocks sequentially from closest DN w/ block
  - InputFormats and RecordReaders as abstraction for multi-part files (incl. compression/encryption)



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, other-rack DN, same-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]

Excursus: Amazon Redshift

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

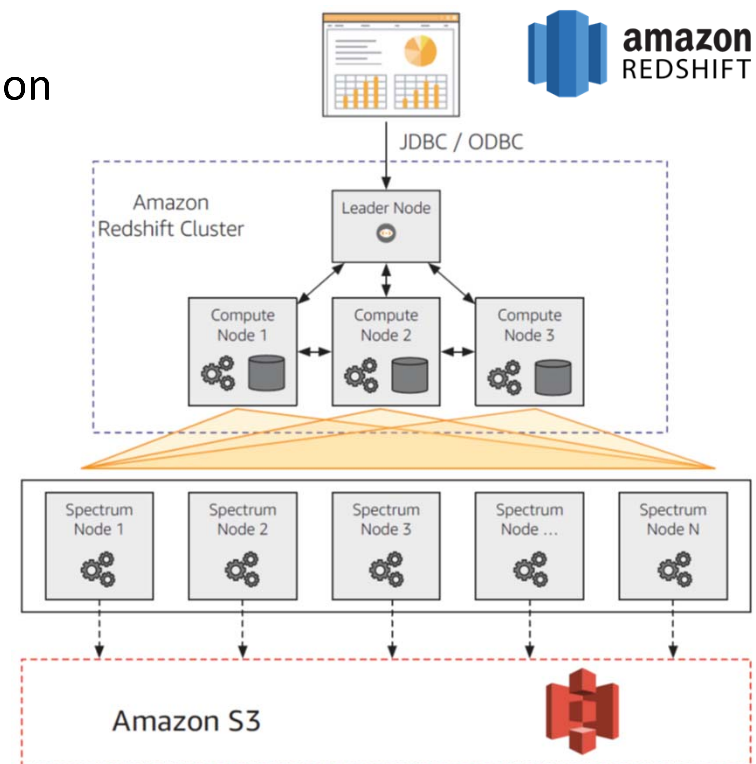
[Mengchu Cai et al.: Integrated Querying of SQL database data and S3 data in Amazon Redshift. **IEEE Data Eng. Bull. 41(2) 2018**]

- **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**
  - 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**
- **Similar Systems**

Google BigQuery

snowflake

Microsoft



Distributed Data Analysis

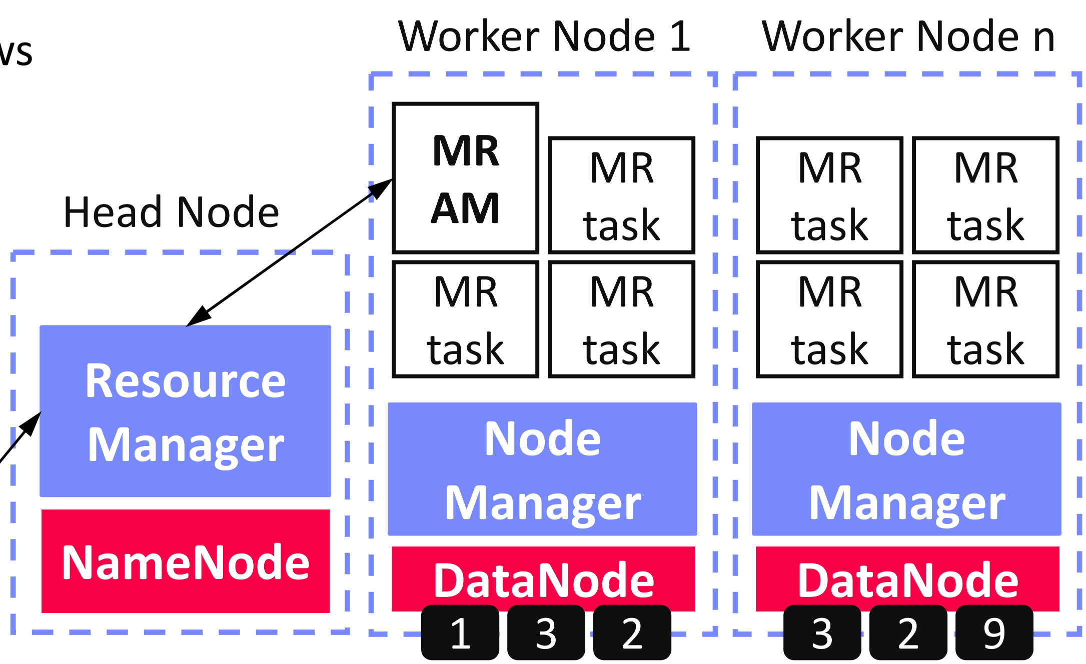
Data-Parallel Computation (MapReduce, Spark)

Hadoop History and Architecture

[Jeffrey Dean, Sanjay Ghemawat: MapReduce: Simplified Data Processing on Large Clusters. **OSDI 2004**]

- **Recap: Brief History**
  - Google's GFS [SOSP'03] + MapReduce
    → Apache Hadoop (2006)
  - Apache Hive (SQL), Pig (ETL), Mahout (ML), Giraph (Graph)
- **Hadoop Architecture / Eco System**
  - Management (Ambari)
  - Coordination / workflows (Zookeeper, Oozie)
  - Storage (**HDFS**)
  - Resources (**YARN**) [SoCC'13]
  - Processing (**MapReduce**)

MR Client



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	Alpha
3	Charlie
5	Echo
6	Foxtrott
7	Golf

MapReduce – Programming Model

- **Overview Programming Model**
  - Inspired by functional programming languages
  - **Implicit parallelism** (abstracts distributed storage and processing)
  - Map function: key/value pair → set of intermediate key/value pairs
  - Reduce function: merge all intermediate values by key

- **Example** `SELECT Dep, count(*) FROM csv_files GROUP BY Dep`

Name	Dep
X	CS
Y	CS
A	EE
Z	CS

Collection of key/value pairs

```
map(Long pos, String line) {
  parts ← line.split(“,”)
  emit(parts[1], 1)
}
```

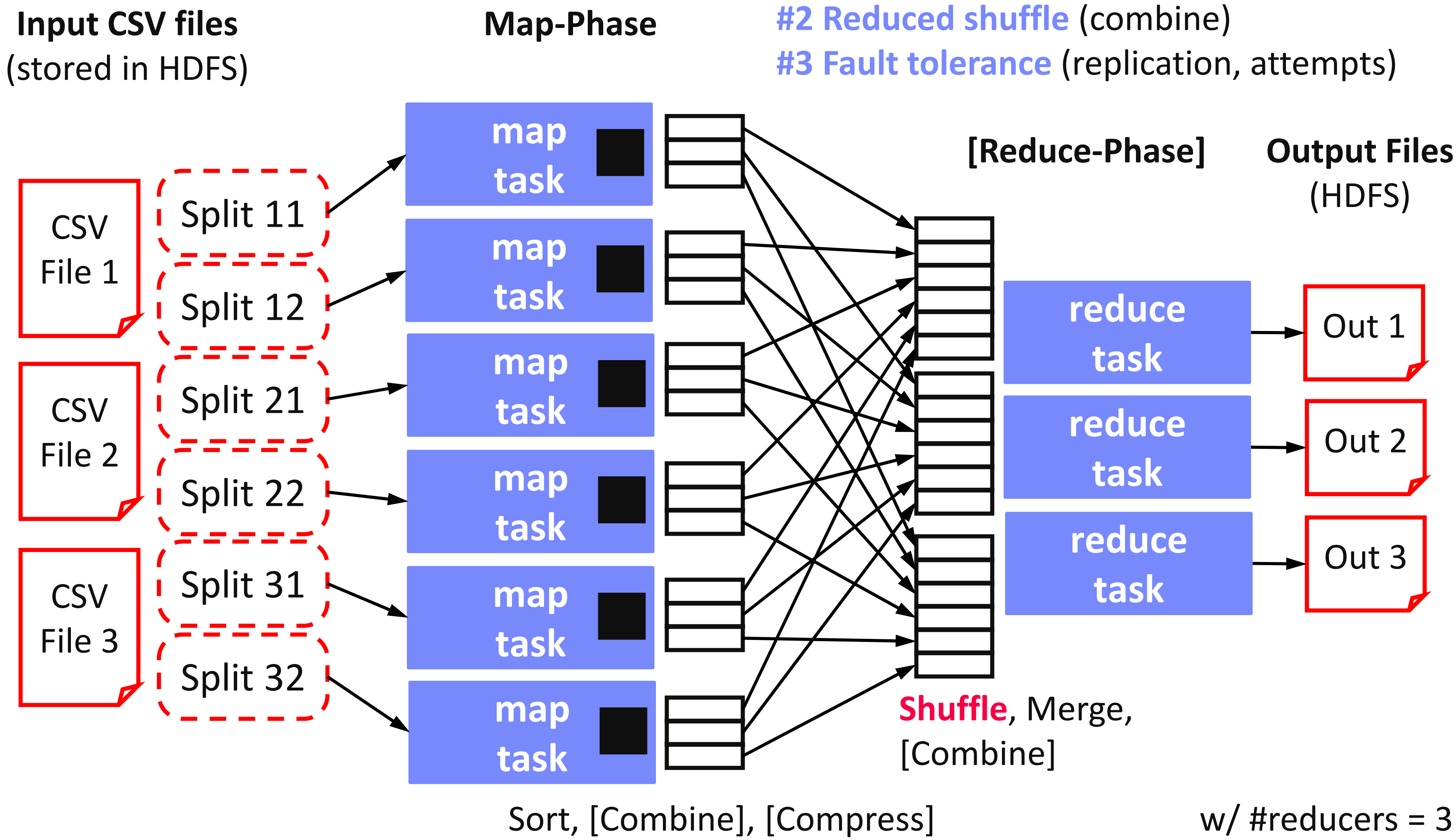
CS	1
CS	1
EE	1
CS	1

```
reduce(String dep,
       Iterator<Long> iter) {
  total ← iter.sum();
  emit(dep, total)
}
```

CS	3
EE	1

MapReduce – Execution Model

#1 Data Locality (delay sched., write affinity)
#2 Reduced shuffle (combine)
#3 Fault tolerance (replication, attempts)



Spark History and Architecture

- **Summary MapReduce**
  - Large-scale & fault-tolerant processing w/ UDFs and files → **Flexibility**
  - Restricted functional APIs → **Implicit parallelism and fault tolerance**
  - **Criticism**: #1 **Performance**, #2 **Low-level APIs**, #3 **Many different systems**
- **Evolution to Spark** (and Flink)
  - Spark [HotCloud'10] + RDDs [NSDI'12] → **Apache Spark** (2014)
  - **Design: standing executors with in-memory storage**, lazy evaluation, and fault-tolerance via RDD lineage
  - **Performance:** In-memory storage and fast job scheduling (100ms vs 10s)
  - **APIs:** Richer functional APIs and general computation DAGs, high-level APIs (e.g., DataFrame/Dataset), unified platform

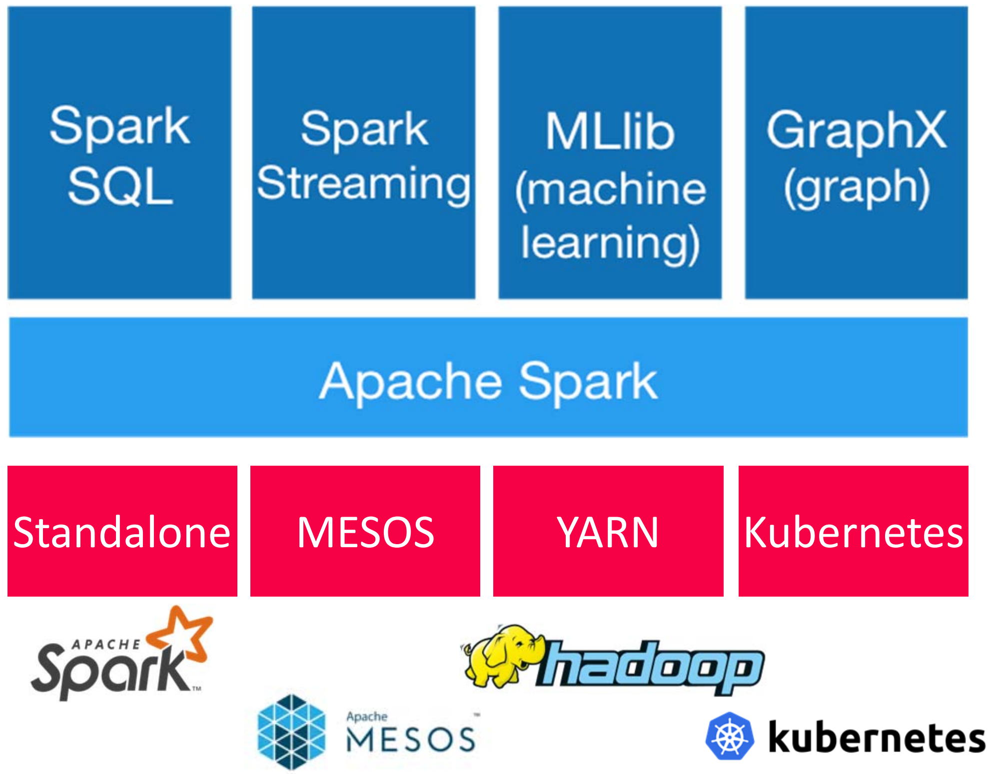
→ **But many shared concepts/infrastructure**

  - **Implicit parallelism through dist. collections** (data access, fault tolerance)
  - Resource negotiators (YARN, Mesos, Kubernetes)
  - HDFS and object store connectors (e.g., Swift, S3)

Spark History and Architecture, cont.

- **High-Level Architecture**
  - **Different language bindings**: Scala, Java, Python, R
  - **Different libraries**: SQL, ML, Stream, Graph
  - Spark core (incl RDDs)
  - **Different cluster managers**: Standalone, Mesos, **Yarn**, **Kubernetes**
  - Different file systems/ formats, and data sources: **HDFS**, **S3**, SWIFT, **DBs**, **NoSQL**

[https://spark.apache.org/]



- **Focus on a unified platform for data-parallel computation**

Resilient Distributed Datasets (RDDs)

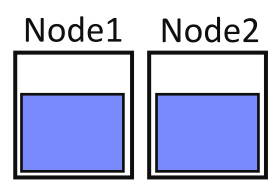
- **RDD Abstraction**
  - **Immutable**, partitioned **collections of key-value pairs**
  - **Coarse-grained** deterministic operations (transformations/actions)
  - Fault tolerance via lineage-based re-computation

```
JavaPairRDD
  <MatrixIndexes,MatrixBlock>
```

- **Operations**
  - Transformations: define new RDDs
  - Actions: return result to driver

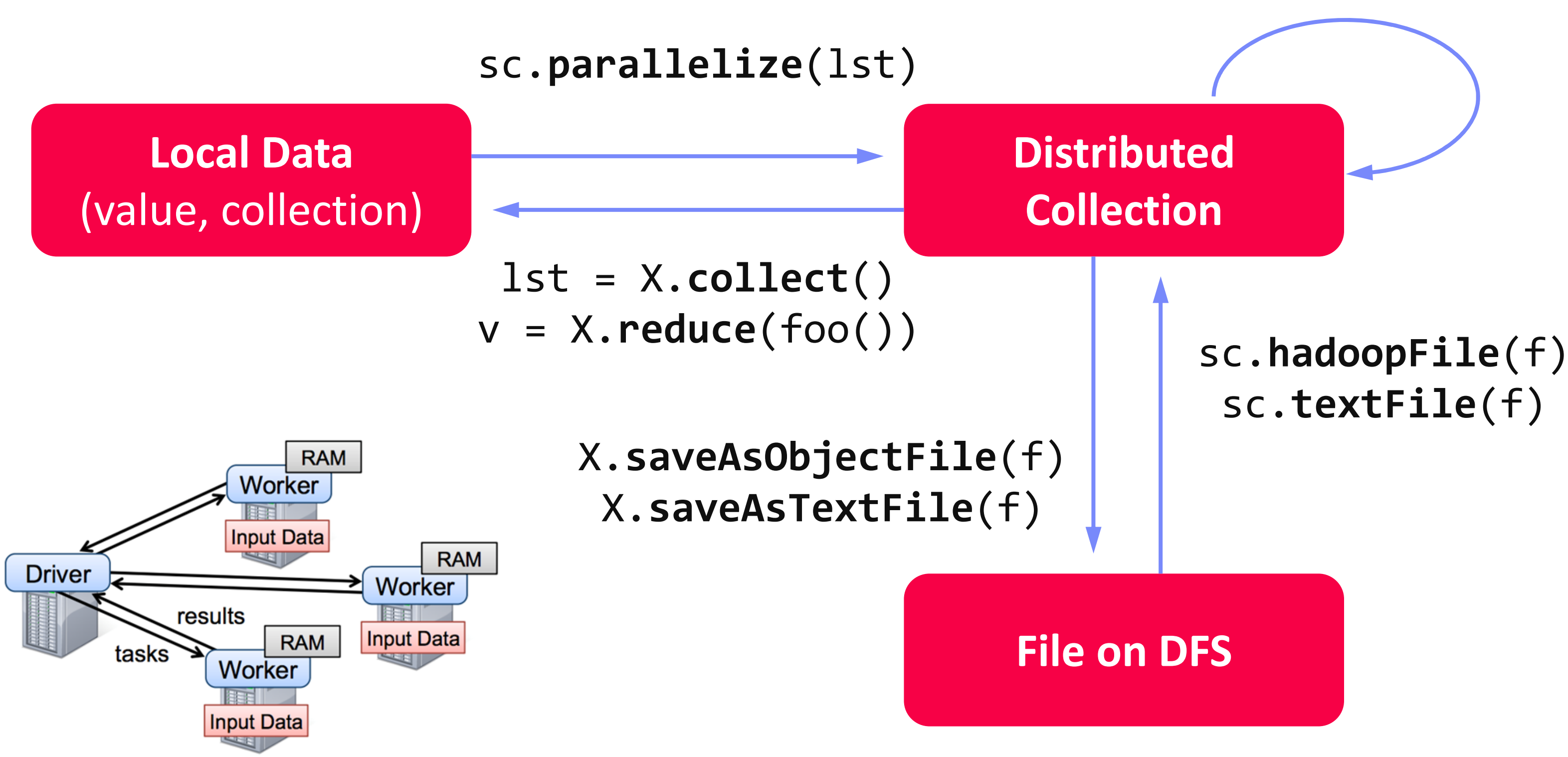
Type	Examples
Transformation (**lazy**)	`map`, `hadoopFile`, `textFile`, `flatMap`, `filter`, `sample`, `join`, `groupByKey`, `cogroup`, `reduceByKey`, `cross`, `sortByKey`, `mapValues`
Action	`reduce`, `save`, `collect`, `count`, `lookupKey`

- **Distributed Caching**
  - Use fraction of worker **memory for caching**
  - Eviction at granularity of individual partitions
  - **Different storage levels** (e.g., mem/disk x serialization x compression)



Spark Resilient Distributed Datasets (RDDs), cont.

- **Lifecycle of an RDD**
  - Note: can't broadcast an RDD directly



Partitions and Implicit/Explicit Partitioning

- **Spark Partitions**
  - Logical key-value collections are split into **physical partitions**
  - Partitions are granularity of **tasks, I/O, shuffling, evictions**

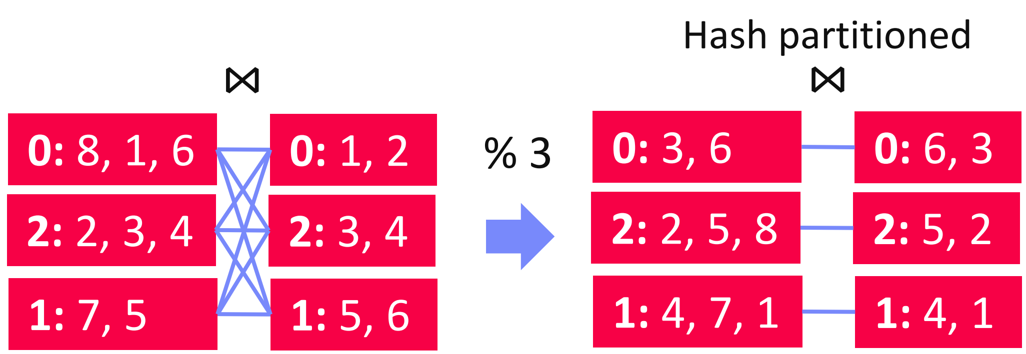
~128MB

- **Partitioning via Partitioners**
  - Implicitly on every data shuffling
  - Explicitly via `R.repartition(n)`

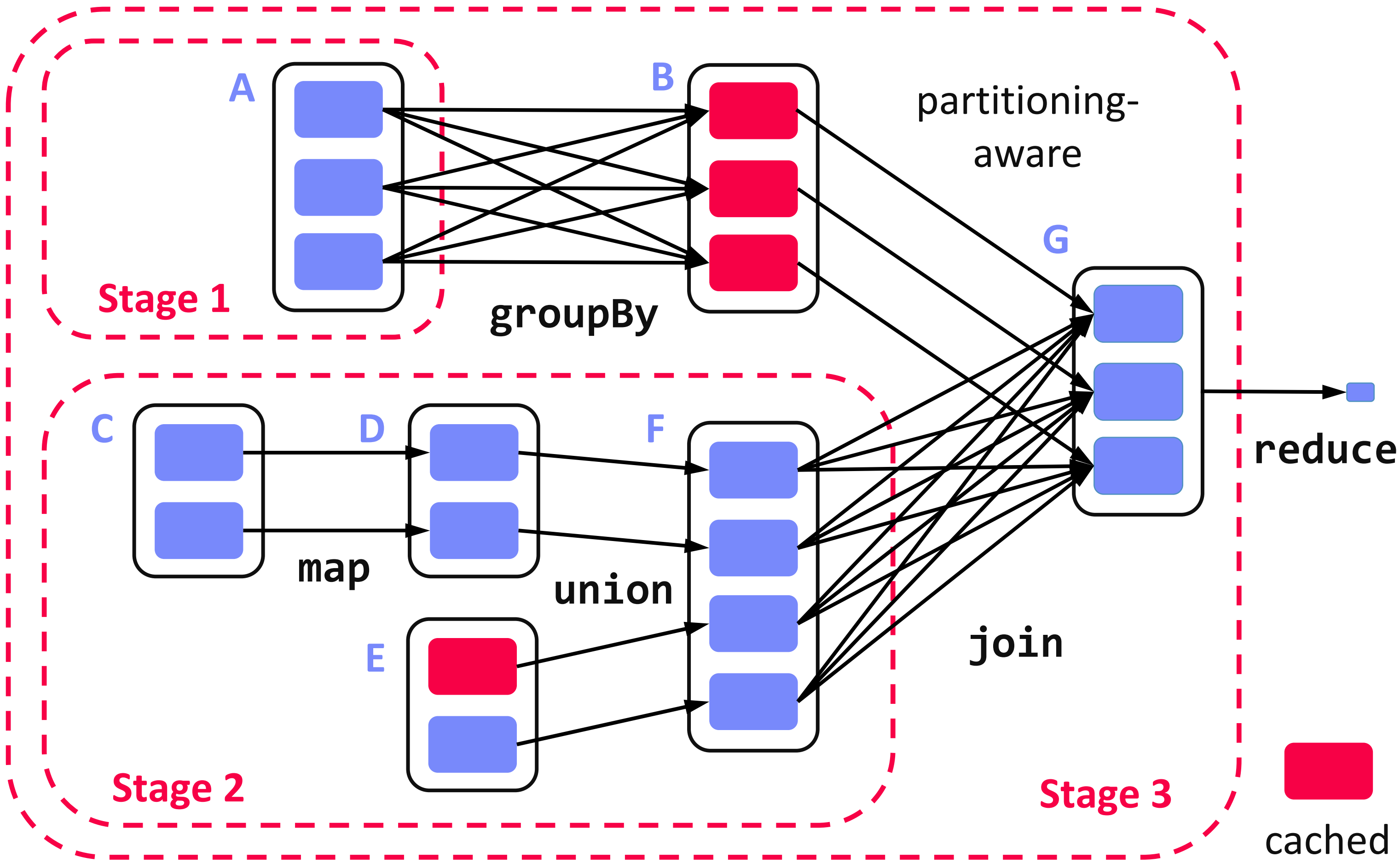
Example Hash Partitioning:
For all (k,v) of R:
pid = hash(k) % n

- **Partitioning-Preserving**
  - All operations that are guaranteed to keep keys unchanged (e.g. `mapValues()`, `mapPartitions()` w/ preservesPart flag)

- **Partitioning-Exploiting**
  - Join: R3 = R1.join(R2)
  - Lookups: `v = C.lookup(k)`



Spark Lazy Evaluation, Caching, and Lineage



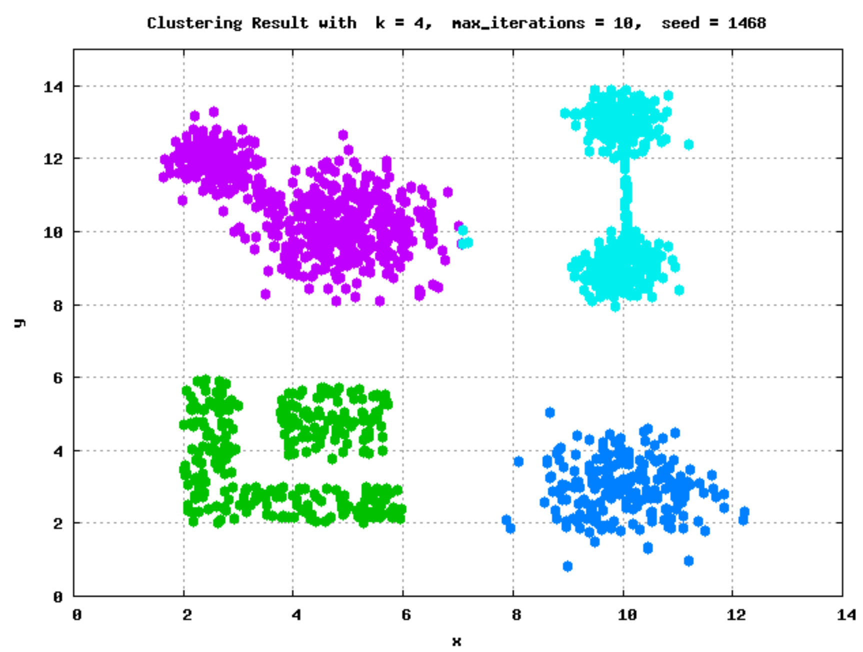
[Matei Zaharia, Mosharaf Chowdhury, Tathagata Das, Ankur Dave, Justin Ma, Murphy McCauly, Michael J. Franklin, Scott Shenker, Ion Stoica: Resilient Distributed Datasets: A Fault-Tolerant Abstraction for In-Memory Cluster Computing. **NSDI 2012**]

Example: k-Means Clustering

- **k-Means Algorithm**
  - Given dataset D and number of clusters k, find cluster centroids (“mean” of assigned points) that minimize within-cluster variance
  - Euclidean distance: **sqrt**(**sum**((**a**-**b**)^2))

- **Pseudo Code**

```
function Kmeans(D, k, maxiter) {
  C‘ = randCentroids(D, k);
  C = {};
  i = 0; //until convergence
  while( C‘ != C & i<=maxiter ) {
    C = C‘;
    i = i + 1;
    A = getAssignments(D, C);
    C‘ = getCentroids(D, A, k);
  }
  return C‘
}
```



Example: K-Means Clustering in Spark

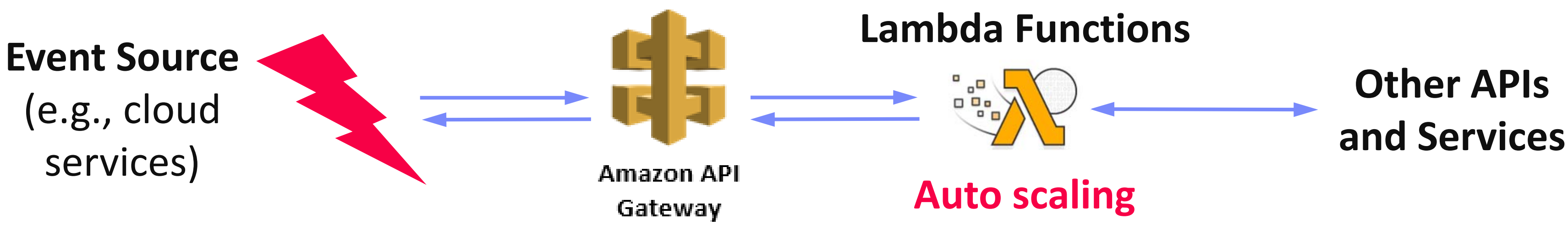
```
// create spark context (allocate configured executors)
JavaSparkContext sc = new JavaSparkContext();

// read and cache data, initialize centroids
JavaRDD<Row> D = sc.textFile("hdfs:/user/mboehm/data/D.csv")
  .map(new ParseRow()).cache(); // cache data in spark executors
Map<Integer,Mean> C = asCentroidMap(D.takeSample(false, k));

// until convergence
while( !equals(C, C2) & i<=maxiter ) {
  C2 = C; i++;
  // assign points to closest centroid, recompute centroid
  Broadcast<Map<Integer,Row>> bC = sc.broadcast(C)
  C = D.mapToPair(new NearestAssignment(bC))
       .foldByKey(new Mean(0), new IncComputeCentroids())
       .collectAsMap();
}

return C;
```

Note: Existing library algorithm
[https://github.com/apache/spark/blob/master/mllib/src/main/scala/org/apache/spark/mllib/clustering/KMeans.scala]

Serverless Computing

[Joseph M. Hellerstein et al: Serverless Computing: One Step Forward, Two Steps Back. **CIDR 2019**]

- **Definition Serverless**
  - **FaaS:** functions-as-a-service (event-driven, stateless input-output mapping)
  - Infrastructure for deployment and auto-scaling of APIs/functions
  - Examples: **Amazon Lambda**, **Microsoft Azure Functions**, etc



Auto scaling
Pay-per-request
(1M x 100ms = 0.2$)

- **Example**

```
import com.amazonaws.services.lambda.runtime.Context;
import com.amazonaws.services.lambda.runtime.RequestHandler;

public class MyHandler implements RequestHandler<Tuple, MyResponse> {
    @Override
    public MyResponse handleRequest(Tuple input, Context context) {
       return expensiveStatelessComputation(input);
    }
}
```

Conclusions and Q&A

- **Cloud Computing Overview**
- **Distributed Data Storage**
- **Distributed Data Analysis**

- **Next Lectures** (Part B: Modern Data Management)
  - **12 Data Stream Processing Systems** [Jan 25]
  - **Written Exam** [Feb 12] 12.30-2.30pm, 3.30-5.30pm, 6.30-8.30pm