SCIENCE
PASSION
TECHNOLOGY

# Data Integration and Analysis
# 09 Cloud Resource Management

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Last update: Dec 04, 2019

# Announcements/Org

- **#1 Video Recording**
  - Link in TeachCenter & TUbe (lectures will be public)
  - Optional attendance (independent of COVID)
- **#2 COVID-19 Restrictions** (HS i5)
  - Corona Traffic Light: **RED → ORANGE** (Dec 07)
  - Temporarily webex lectures and recording
- **Projects and Exercises**
  - **34x** SystemDS projects
  - **11x** exercise projects
  - **Today 5.30pm** leftover discussion

**If there are problems, reach out**
(preferred via WIP PR, or email)

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

**12 Distributed Stream Processing** [Jan 24]

**13 Distributed Machine Learning Systems** [Jan 31]

Compute/ Storage

**11 Distributed Data-Parallel Computation** [Jan 17]

**10 Distributed Data Storage** [Jan 10]

Infra

**09 Cloud Resource Management and Scheduling** [Dec 13]

**08 Cloud Computing Fundamentals** [Dec 06]

# Agenda

- **Motivation, Terminology, and Fundamentals**
- **Resource Allocation, Isolation, and Monitoring**
- **Task Scheduling and Elasticity**

# Motivation, Terminology, and Fundamentals

# Recap: Motivation Cloud Computing

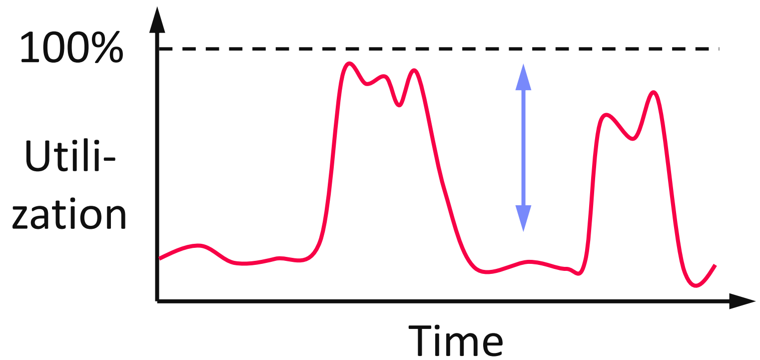
- **Definition Cloud Computing**
  - **On-demand, remote storage and compute resources, or services**
  - **User:** computing as a utility (similar to energy, water, internet services)
  - **Cloud provider:** computation in data centers / multi-tenancy
- **Service Models**
  - **IaaS: Infrastructure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

# Recap: 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**

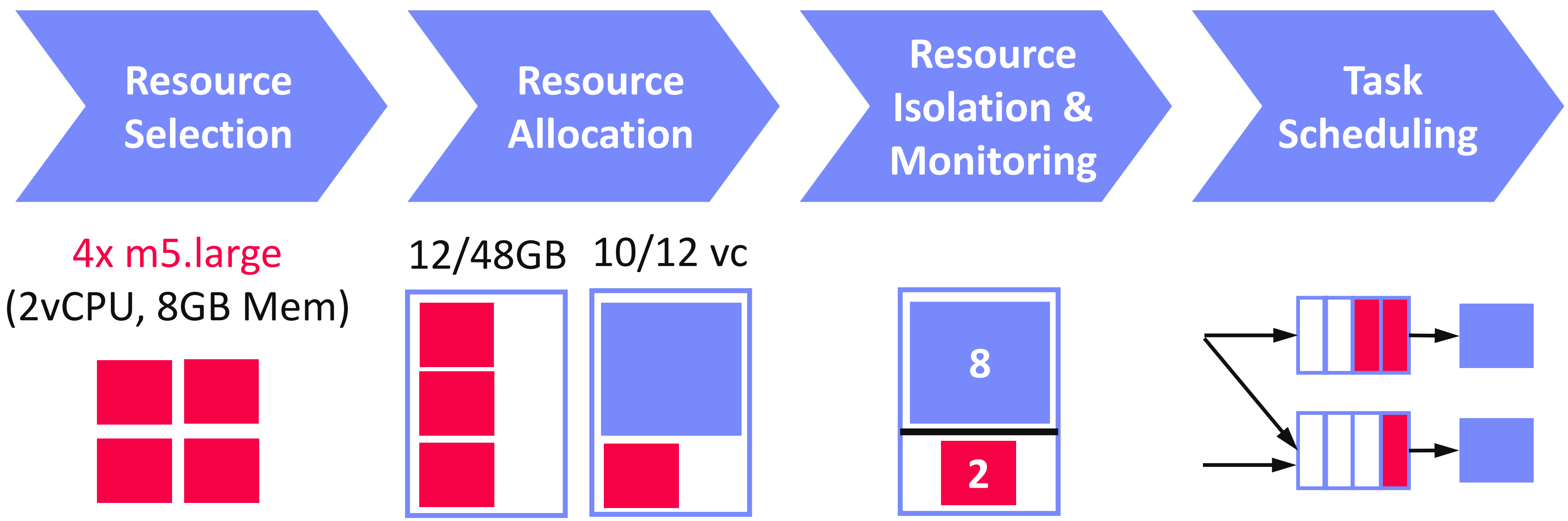
(but beware Amdahl's law: max speedup **sp = 1/s**)

# Overview Resource Management & Scheduling

- **Resource Bundles**
  - Logical containers (aka nodes/instances) of different resources (**vcores**, **mem**)
  - Disk capacity, **disk** and **network** bandwidth
  - Accelerator devices (**GPUs**, FPGAs), etc

Scheduling is a fundamental computer science technique (at many different levels)

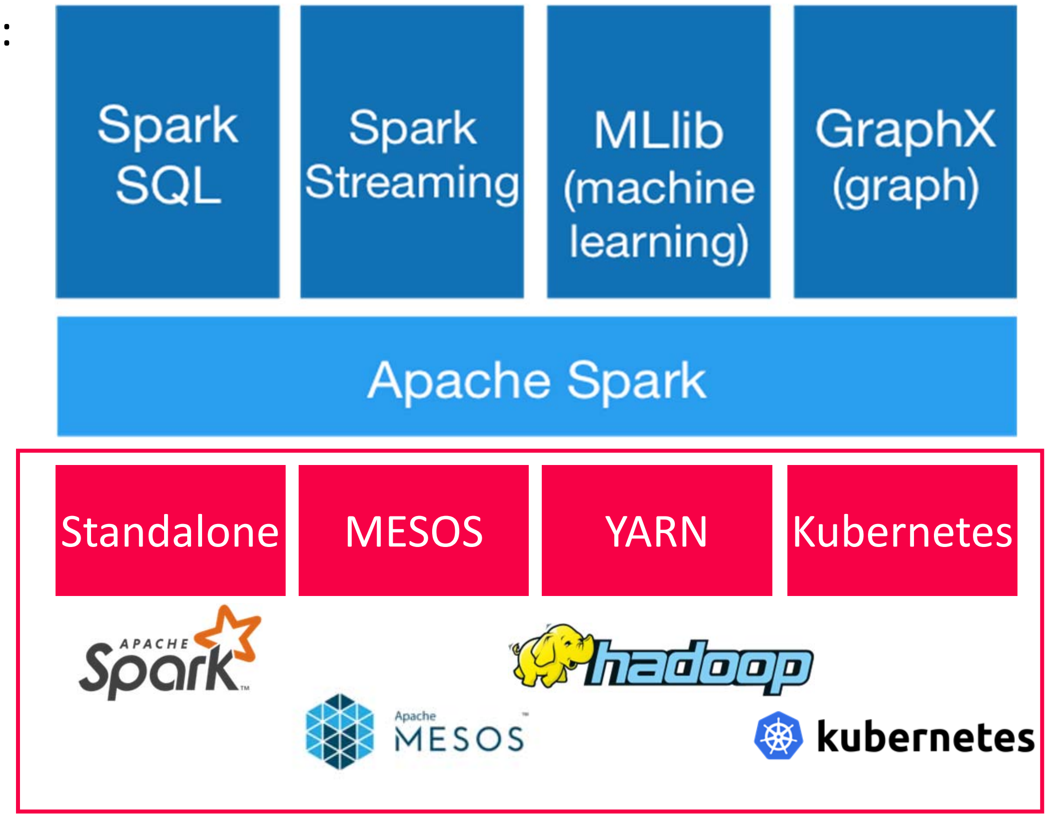
- **Resource Management**



# Recap: Apache Spark History and Architecture

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

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



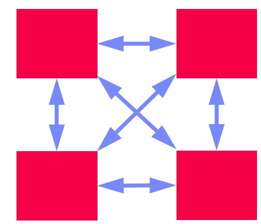

➔ **Separation of concerns: resource allocation vs task scheduling**

# Scheduling Problems

[Eleni D. Karatza: Cloud Performance Resource Allocation and Scheduling Issue, **Aristotle University of Thessaloniki 2018**]

- **Bag-of-Tasks Scheduling**
  - Job of independent (embarrassingly parallel) tasks
  - **Examples:** EC2 instances, map tasks

- **Gang Scheduling**
  - Job of frequently communicating parallel tasks
  - **Examples:** MPI programs, parameter servers

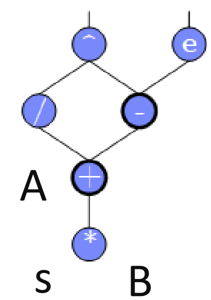


- **DAG Scheduling**
  - Job of tasks with precedence constraints (e.g., data dependencies)
  - **Examples:** Op scheduling Spark, TensorFlow, SystemDS

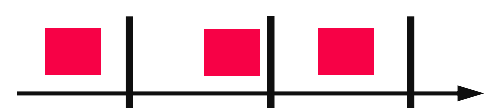
$\mathbf{C} = \mathbf{A} + s * \mathbf{B}$

$\mathbf{D} = (\mathbf{C}/2)\hat{}(\mathbf{C}\text{-}1)$

$\mathbf{E} = \exp(\mathbf{C}\text{-}1)$




- **Real-Time Scheduling**
  - Job or task with associated deadline (soft/hard)
  - **Examples:** rendering, car control



# Basic Scheduling Metrics and Algorithms

- **Common Metrics**
  - Mean time to completion (total runtime for job), and max-stretch (completion/work – relative slowdown)
  - Mean response time (job waiting time for resources)
  - Throughput (jobs per time unit)
- **#1 FIFO (first-in, first-out)**
  - Simple queueing and processing in order
  - **Problem:** Single long-running job can stall many short jobs
- **#2 SJF (shortest job first)**
  - Sort jobs by expected runtime and execute in order ascending
  - **Problem:** Starvation of long-running jobs
- **#3 Round-Robin (FAIR)**
  - Allocate similar time (tasks, time slices) to all jobs

# Resource Allocation, Isolation, and Monitoring

# Resource Selection

- **#1 Manual Selection**
  - Rule of thumb (I/O, mem, CPU characteristics of app)
  - Data characteristics, and framework configurations, experience

- **Example Spark Submit**

```
export HADOOP_CONF_DIR=/etc/hadoop/conf
SPARK_HOME=../spark-2.4.0-bin-hadoop2.7

$SPARK_HOME/bin/spark-submit \
  --master yarn --deploy-mode client \
  --driver-java-options "-server -Xms40g -Xmn4g" \
  --driver-memory 40g \
  --num-executors 32 \
  --executor-memory 80g \
  --executor-cores 24 \
  SystemDS.jar -f test.dml -stats -explain -args …
```

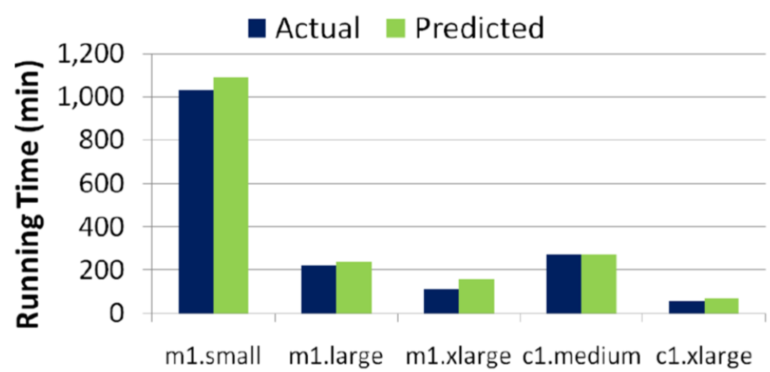
# Resource Selection, cont.

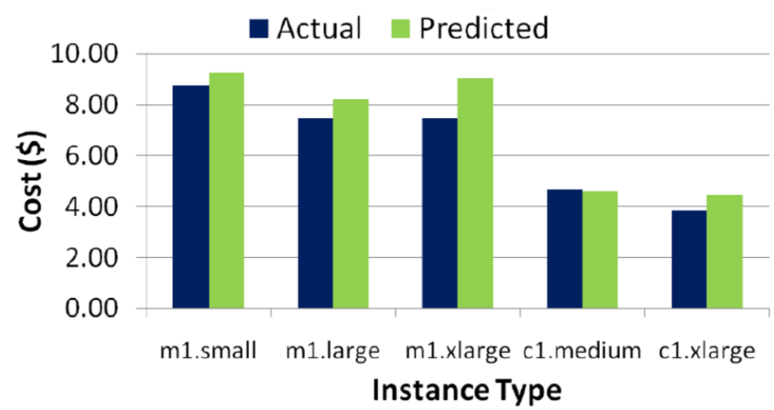
- **#2 Application-Agnostic, Reactive**
  - Dynamic allocation based on workload characteristics
  - **Examples:** Spark dynamic allocation, Databricks AutoScaling

- **#3 Application-Aware, Proactive**
  - Estimate time/costs of job under different configurations (what-if)
  - Min $costs under time constraint
  - Min runtime under $cost constraint

[Herodotos Herodotou, Fei Dong, Shivnath Babu: No one (cluster) size fits all: automatic cluster sizing for data-intensive analytics. **SoCC 2011**]

(fixed MR job w/ 6 nodes)

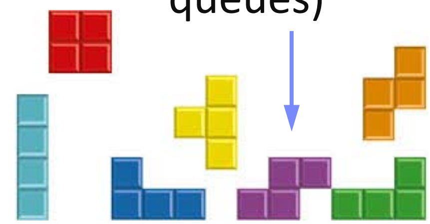


# Resource Negotiation and Allocation

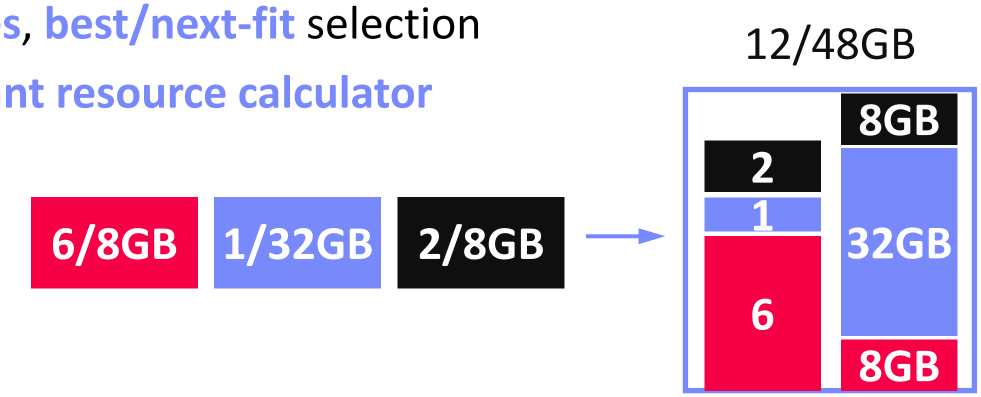
- **Problem Formulation**
  - N nodes with memory and CPU constraints
  - Stream of jobs with memory and CPU requirements
  - Assign jobs to nodes (or to minimal number of nodes)
  - ➔ **Knapsack problem** (**bin packing problem**)

"Tetris Analogy" (w/ expiration and queues)



- **In Practice: Heuristics**
  - Major concern: **scheduling efficiency** (online, cluster bottleneck)
  - Approach: **Sample queues**, **best/next-fit** selection
  - Multiple metrics: **dominant resource calculator**

[https://blog.cloudera.com/managing-cpu-resources-in-your-hadoop-yarn-clusters/]



# Slurm Workload Manager

- **Slurm Overview**
  - Simple Linux Utility for Resource Management (SLURM)
  - Heavily used in **HPC clusters** (e.g., MPI gang scheduling)

- **Scheduler Design**
  - Allocation/placement of requested resources
  - Considers nodes, sockets, cores, HW threads, memory, GPUs, file systems, SW licenses
  - Job submit options: **`sbatch`** (async job script), **`salloc`** (interactive), **`srun`** (sync job submission and scheduling)
  - **Configuration:** cluster, node count (ranges), task count, mem, etc
  - **Constraints via filters:** sockets-per-node, cores-per-socket, threads-per-core mem, mem-per-cpu, mincpus, tmp min-disk-space
  - Elasticity via re-queueing

[Don Lipari: The SLURM Scheduler Design, User Group Meeting, **2012**]

# Background: Hadoop JobTracker (anno 2012)

- **Overview**
  - Hadoop cluster w/ fixed configuration of **n map** slots, **m reduce slots** (fixed number and fixed memory config map/reduce tasks)
  - JobTracker schedules map and reduce tasks to slots
  - FIFO and FAIR schedulers, account for data locality

- **Data Locality**
  - Levels: **data local**, **rack local**, **different rack**
  - **Delay scheduling** (with FAIR scheduler) wait 1-3s for data local slot

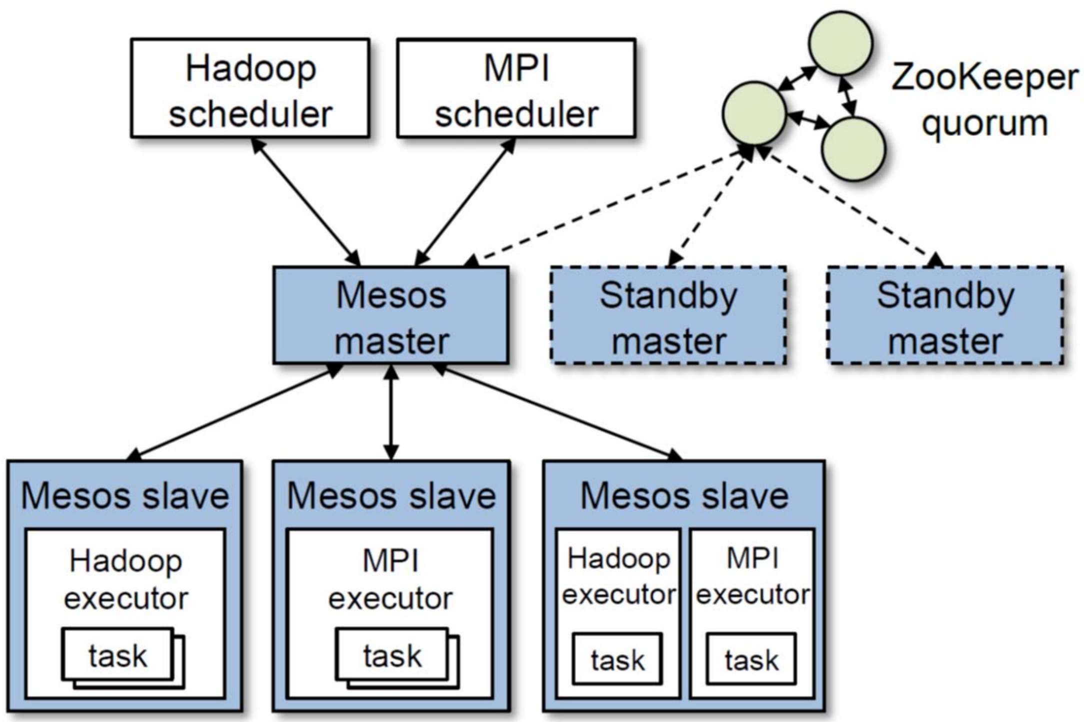
[Matei Zaharia et al: Delay scheduling: a simple technique for achieving locality and fairness in cluster scheduling. **EuroSys 2010**]

- **Problem**
  - Intermixes resource allocation and task scheduling
    → **Scalability problems in large clusters**
  - Forces every application into MapReduce programming model

# Mesos Resource Management

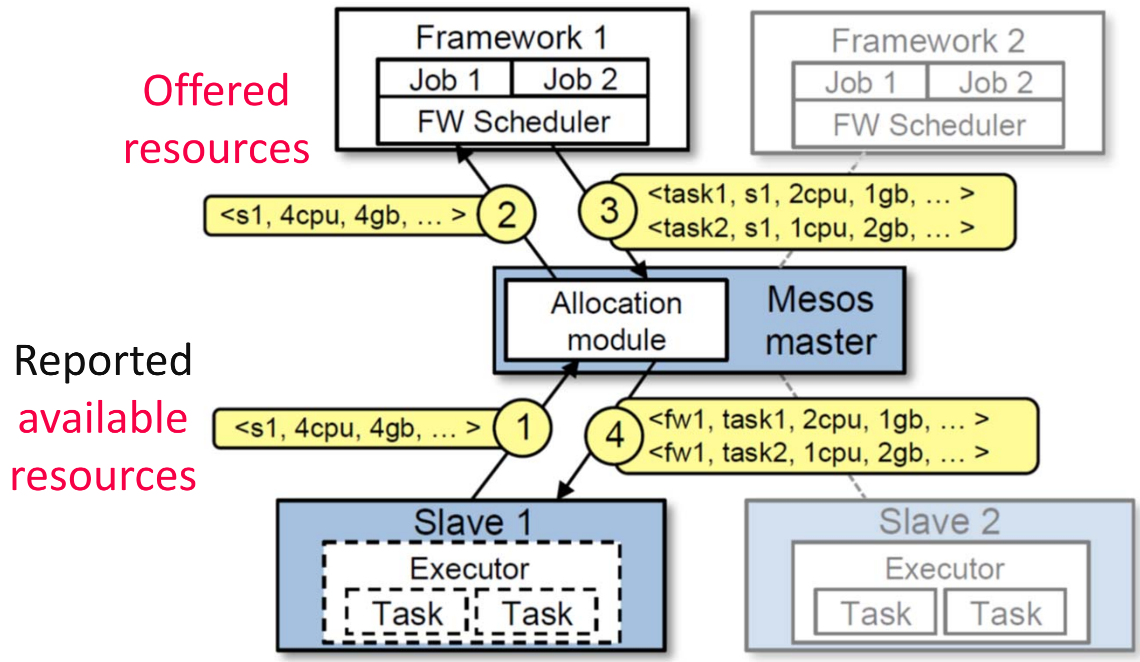
[Benjamin Hindman et al: Mesos: A Platform for Fine-Grained Resource Sharing in the Data Center. **NSDI 2011**]

- **Overview Mesos**
  - Fine-grained, **multi-framework cluster sharing**
  - Scalable and efficient scheduling → **delegated to frameworks**
  - **Resource offers**



# Mesos Resource Management, cont.

- **Resource Offers**
  - Mesos master decides how many resources to offer
  - Framework scheduler decides which offered resources to accept/reject
  - **Challenge:** long waiting times, lots of offers → **filter specification**




**Mesosphere Marathon:** container orchestration (e.g., Docker)

# YARN Resource Management

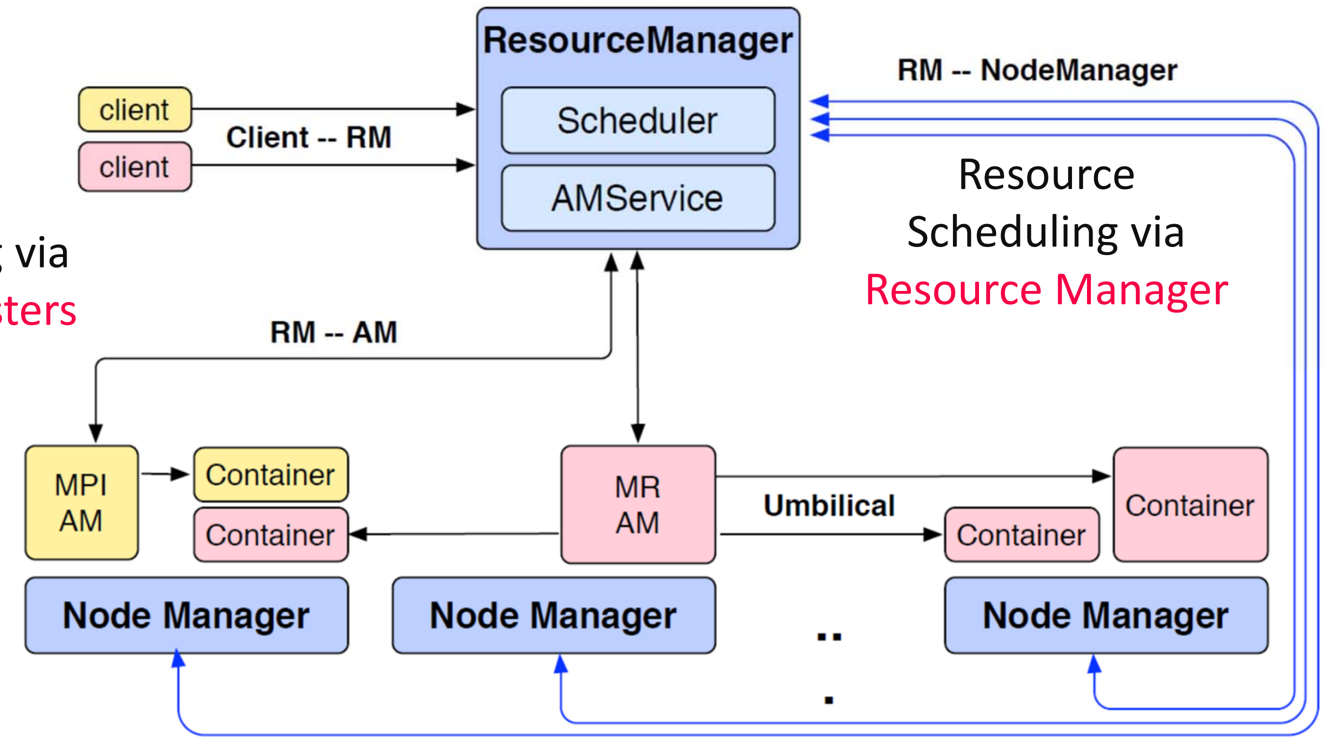
[Vinod Kumar Vavilapalli et al: Apache Hadoop YARN: yet another resource negotiator. **SoCC 2013**]

- **Overview YARN**
  - Hadoop 2 decoupled resource scheduler (negotiator)
  - Independent of programming model, **multi-framework cluster sharing**
  - **Resource Requests**

Task Scheduling via Application Masters (AMs)

Resource Scheduling via Resource Manager

Resource Isolation via Node Managers



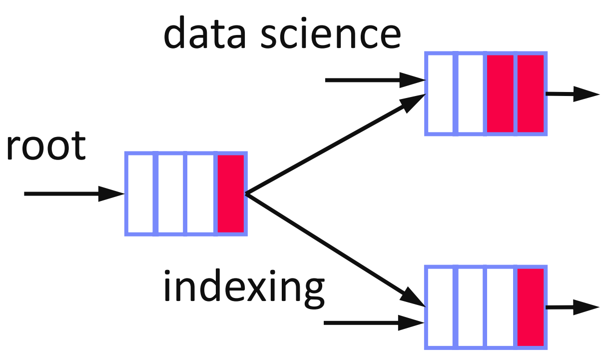
# YARN Resource Management, cont.

- **Example Apache SystemML AM Submission (anno 2014)**

```
// Set up the container launch context for the application master
ContainerLaunchContext amContainer =
    Records.newRecord(ContainerLaunchContext.class);
amContainer.setCommands(Collections.singletonList(command));
amContainer.setLocalResources(constructLocalResourceMap(yconf));
amContainer.setEnvironment(constructEnvionmentMap(yconf));

// Set up resource type requirements for ApplicationMaster
Resource capability = Records.newRecord(Resource.class);
capability.setMemory((int)computeMemoryAllocation(memHeap));
capability.setVirtualCores(numCores);

// Finally, set-up ApplicationSubmissionContext for the application
String qname = _dmlConfig.getTextValue(DMLConfig.YARN_APPQUEUE);
appContext.setApplicationName(APPMASTER_NAME); // application name
appContext.setAMContainerSpec(amContainer);
appContext.setResource(capability);
appContext.setQueue(qname); // queue (w/ min/max capacity constraints)

// Submit application (non-blocking)
yarnClient.submitApplication(appContext);
```

# YARN Resource Management, cont.

- **Capacity Scheduler**
  - Hierarchy of queues w/ shared resource among sub queues
  - Soft (and optional hard) [min, max] constraints of max resources
  - Default queue-user mapping
  - No preemption during runtime (only redistribution over queues)




- **Fair Scheduler**
  - All applications get same resources over time
  - Fairness decisions on memory requirements, but dominant resource fairness possible too

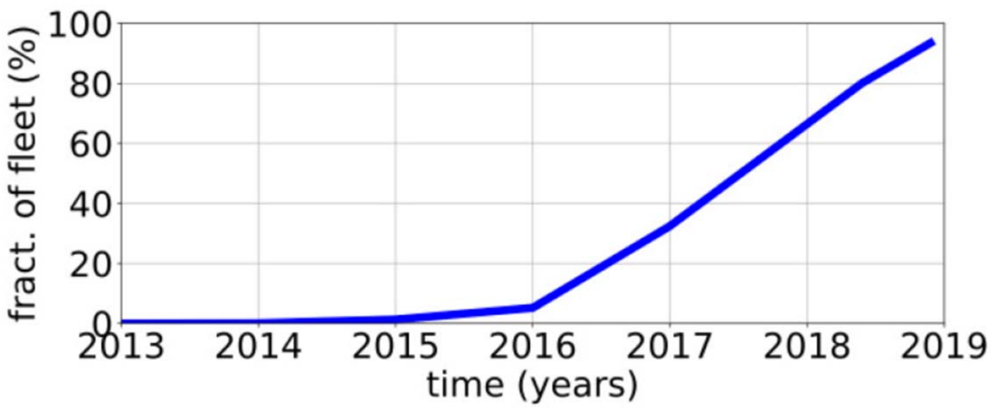
# Hydra: Federated RM @ Microsoft

[Carlo Curino et al.: Hydra: a federated resource manager for data-center scale analytics. **NSDI 2019**]

[https://www.youtube.com/watch?v=k_X13YamZXY&feature=emb_logo]

- **Overview Hydra**
  - Federated RM for internal MS big-data cluster
  - Leverage **sub-clusters w/ YARN RM + router**
  - AM-RM proxy (comm. across sub clusters)
  - Global policy generator + state store for runtime adaptation

- **Deployment Statistics**




**>250K** servers
**>500K** daily jobs
**>1 ZB** data processed
**>1T** tasks scheduled
(~2G tasks daily)
**>70K** QPS (scheduling)
**~60%** avg CPU util

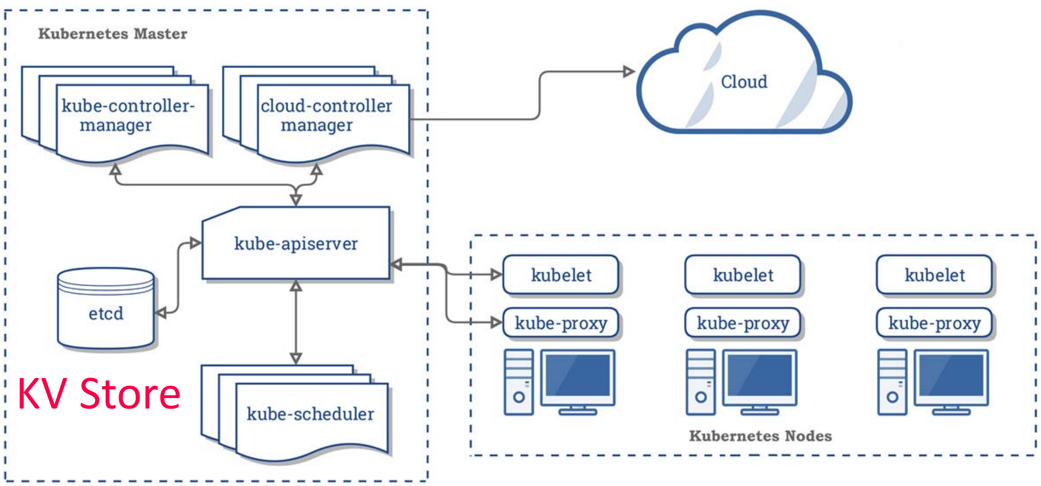
# Kubernetes Container Orchestration

- **Overview Kubernetes**
  - Open-source system for automating, deployment, and management of containerized applications
  - Container: resource isolation and application image

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

- **System Architecture**
  - **Pod:** 1 or more containers w/ individual IP
  - **Kubelet:** node manager
  - **Controller:** app master
  - **API Server** + **Scheduler**
  - Namespaces, quotas, access control, auth., logging & monitoring
  - Wide variety of applications

KV Store




[https://kubernetes.io/docs/concepts/overview/components/]

# Kubernetes Container Orchestration, cont.

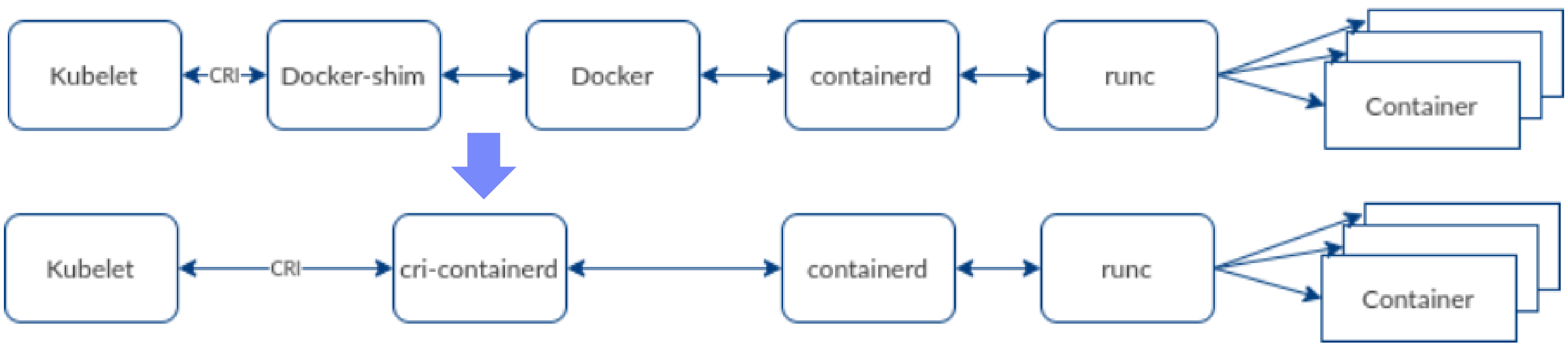
- **Pod Scheduling (Placement)**
  - Default scheduler: `kube-scheduler`, custom schedulers possible
  - **#1 Filtering:** finding feasible nodes for pod
    (resources, free ports, node selector, requested volumes, mem/disk pressure)
  - **#2 Scoring:** score feasible nodes → select highest score
    (spread priority, inter-pod affinity, requested priority, image locality)
  - Tuning: # scored nodes: `max(50, percentageOfNodesToScore [1,100])`
    (sample taken round robin across zones)

  → **Binding:** scheduler notifies API server

# Container Runtime

- **Container Stack**
  [https://www.inovex.de/blog/containers-docker-containerd-nabla-kata-firecracker/]
  - Docker as stack of development and runtime services
  - `containerd`: high-level daemon for image management
  - `runc`: low-level container runtime

[**Credit:** www.inovex.de]




- **Kubernetes deprecated Docker** (as of 12/2020)
  [https://kubernetes.io/blog/2016/12/container-runtime-interface-cri-in-kubernetes/]
  - Container Runtime Interface (CRI)
  - Integrate other runtimes: cri-containerd, cri-o (Open Container Initiative)

# Resource Isolation

- **Overview Key Primitives**
  - Platform-dependent resource isolation primitives → container runtime
  - **Linux namespaces:** restricting visibility
  - **Linux cgroups:** restricting usage

**Linux Containers**
(e.g., basis of Docker)

- **Cgroups (Control Groups)**
  - Developed by Google engineers → Kernel 2.6.24 (2008)
  - **Resource metering and limiting** (memory, CPU, block I/O, network)
  - Each subsystem has a hierarchy (tree) with each node = group of processes
  - Soft and hard limits on groups
  - **Mem** hard limit → triggers OOM killer (physical, kernel, total)
  - **CPU** → set weights (time slices)/no limits, cpuset to pin groups to CPUs

[Jérôme Petazzoni: Cgroups, name-spaces and beyond: What are containers made from? DockerConEU 2015.]

[https://www.youtube.com/watch?v=sK5i-N34im8&feature=youtu.be]

# Resource Isolation, cont.

[https://developer.ibm.com/hadoop/2017/06/30/deep-dive-yarn-cgroups/]

- **Example YARN**
  - Set max CPU time per node manager
  - Container weights: cores/total cores
  - OOM killer if mem w/ overhead exceeded

```
<property>
  <name>yarn.nodemanager.resource.
   percentage-physical-cpu-limit<name>
  <value>60</value>
</property>
```

(hard → strict/soft)

- **Lesson Learned**
  - “The resource isolation provided by containers has enabled Google to drive utilization significantly higher than industry norms. [..] Borg uses containers to co-locate batch jobs with latency-sensitive, user-facing jobs on the same physical machines. ”
  - “The isolation is not perfect, though: containers cannot prevent interference in resources that the operating-system kernel doesn’t manage, such as level 3 processor caches and memory bandwidth […]”

[Abhishek Verma et al. Large-scale cluster management at Google with Borg. **EuroSys 2015**]

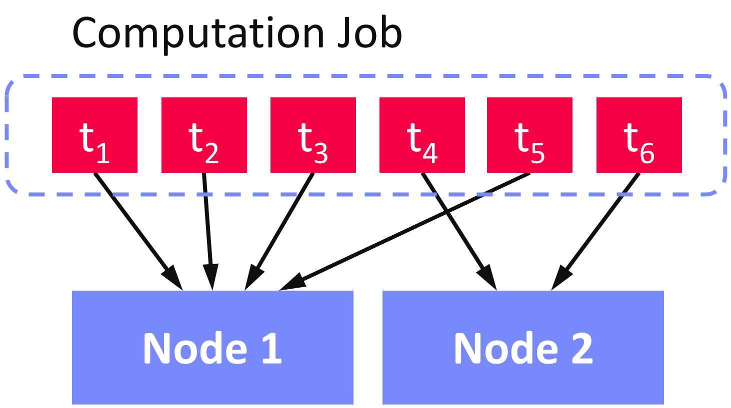
[Malte Schwarzkopf et al.: Omega: flexible, scalable schedulers for large compute clusters. **EuroSys 2013**]

[Brendan Burns et al.: Borg, Omega, and Kubernetes. **ACM Queue 14(1): 10 (2016)**]

# Task Scheduling and Elasticity

# Task Scheduling Overview

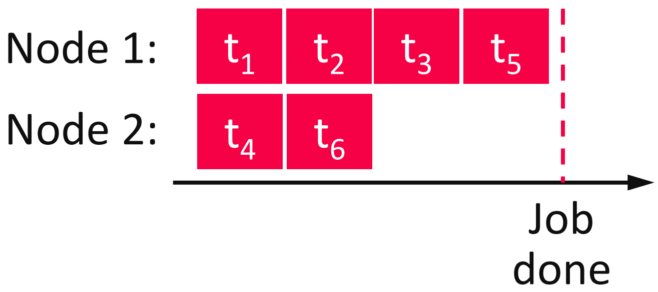
- **Problem Formulation**
  - Given computation job and set of resources (servers, threads)
  - Distribute job in pieces across resources




- **#1 Job-Task Partitioning**
  - Split job into sequence of N tasks

- **#2 Task Placement / Execution**
  - Assign tasks to K resources for execution

- **Goal: Min Job Completion Time**
  - **Beware:** Max runtime per resource determines job completion time

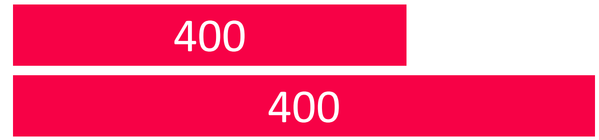


# Task Scheduling – Partitioning

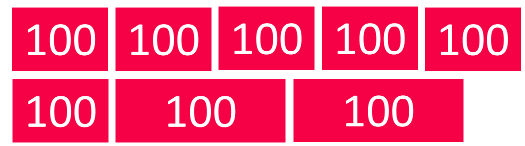
**Example Hyper-param Tuning**

```
parfor(i in 1:800)
  R[i,] = lm(X,y,reg[i])
```

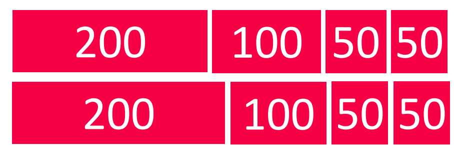
- **Static Partitioning**
  - M = K tasks, task size ceil(N/K)
  - Low overhead, poor load balance




- **Fixed Partitioning**
  - M = N/d tasks, task size d
  - E.g., # iterations, # tuples to process



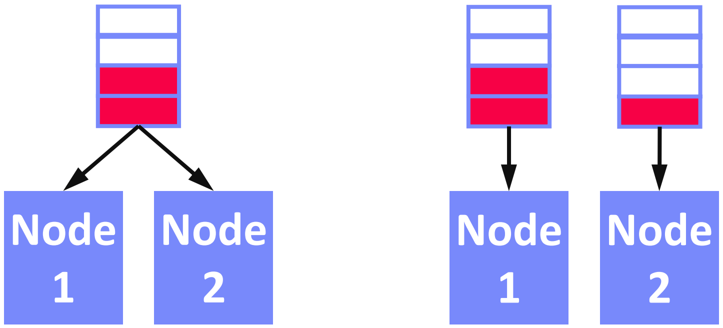

- **Self-Scheduling**
  - Exponentially decreasing task sizes d<br>→ M = log N tasks (w/ min task size)
  - Low overhead and good load balance at end
  - **Guided self scheduling**
  - **Factoring:** waves of task w/ equal size




[Susan Flynn Hummel, Edith Schonberg, Lawrence E. Flynn: Factoring: a practical and robust method for scheduling parallel loops. **SC 1991**]

# Task Scheduling – Placement

- **Task Queues**
  - Sequence of tasks in FIFO queue
  - **#1 Single Task Queue** (self-balancing, but contention)
  - **#2 Per-Worker Task Queue** (work separation, and preparation)




"Airport" "Super Market"

- **Work Stealing**
  - On **empty worker queue**, probe other queues and **"steal"** tasks
  - More common in multi-threading, difficult in distributed systems

- **Excursus: Power of 2 Choices**
  - Choose d bins at random, task in least full bin
  - Reduce max load from $\frac{\log M}{\log \log M}$ to $\frac{\log \log M}{\log M}$

[Michael D. Mitzenmacher: The Power of Two Choices in Randomized Load Balancing, **PhD Thesis UC Berkeley 1996**]

# Spark Task Scheduling

- **Overview**
  - Schedule job DAGs in stages (shuffle barriers)
  - Default task scheduler: **FIFO**; alternative: **FAIR**

**SystemDS Example (80GB):**

```
X = rand(rows=1e7,cols=1e3)
parfor(i in 1:4)
  for(j in 1:10000)
    print(sum(X)) #spark job
```

**FIFO**

| Stage Id ▾ | Description | | | Submitted | Duration | Tasks: Succeeded/Total | Input | Output | Shuffle Rea |
|---|---|---|---|---|---|---|---|---|---|
| 37 | fold at RDDAggregateUtils.java:150 | +details | (kill) | 2019/12/12 23:48:07 | Unknown | 0/596 | | | |
| 36 | fold at RDDAggregateUtils.java:150 | +details | (kill) | 2019/12/12 23:48:06 | 0.7 s | 391/596 (23 running) | 48.9 GB | | |
| 35 | fold at RDDAggregateUtils.java:150 | +details | (kill) | 2019/12/12 23:48:05 | 1 s | 424/596 (20 running) | 53.0 GB | | |
| 34 | fold at RDDAggregateUtils.java:150 | +details | (kill) | 2019/12/12 23:48:05 | 2 s | 504/596 (20 running) | 63.0 GB | | |

**FAIR**

Fair Scheduler Pools (5)

| Pool Name | Minimum Share | Pool Weight | Active Stages | Running Tasks | SchedulingMode |
|---|---|---|---|---|---|
| default | 0 | 1 | 0 | 0 | FIFO |
| parforPool2 | 0 | 1 | 1 | 38 | FIFO |
| parforPool1 | 0 | 1 | 1 | 16 | FIFO |
| parforPool3 | 0 | 1 | 1 | 3 | FIFO |
| parforPool0 | 0 | 1 | 1 | 43 | FIFO |

Active Stages (4)

| Stage Id ▾ | Pool Name | Description | | | Submitted | Duration | Tasks: Succeeded/Total | Input | Output | Shuffle Rea |
|---|---|---|---|---|---|---|---|---|---|---|
| 206 | parforPool0 | fold at RDDAggregateUtils.java:150 | +details | (kill) | 2019/12/12 23:14:20 | 1.0 s | 368/596 (67 running) | 46.0 GB | | |
| 205 | parforPool2 | fold at RDDAggregateUtils.java:150 | +details | (kill) | 2019/12/12 23:14:20 | 1 s | 432/596 (43 running) | 54.0 GB | | |
| 204 | parforPool1 | fold at RDDAggregateUtils.java:150 | +details | (kill) | 2019/12/12 23:14:19 | 2 s | 561/596 (11 running) | 70.1 GB | | |
| 203 | parforPool3 | fold at RDDAggregateUtils.java:150 | +details | (kill) | 2019/12/12 23:14:19 | 2 s | 590/596 (6 running) | 73.7 GB | | |

# Spark Task Scheduling, cont.

- **Fair Scheduler Configuration**
  - Pools with shares of cluster
  - Scheduling modes: FAIR, FIFO
  - **weight:** relative to equal share
  - **minShare:** min numCores

```
<allocations>
  <pool name="data_science">
    <schedulingMode>FAIR</schedulingMode>
    <weight>1</weight>
    <minShare>6</minShare>
  </pool>
  <pool name="indexing">
    <schedulingMode>FIFO</schedulingMode>
    <weight>2</weight>
    <minShare>8</minShare>
  </pool>
</allocations>
```

- **Spark on Kubernetes**
  - Run Spark in shared cluster with Docker container apps, Distributed TensorFlow, etc
  - Custom controller, and shuffle service (dynAlloc)

```
$SPARK_HOME/bin/spark-submit \
  --master k8s://https://<k8s-api>:<k8s-api-port> \
  --deploy-mode cluster
  --driver-java-options "-server -Xms40g -Xmn4g" \
  --driver-memory 40g \
  --num-executors 32 \
  --executor-memory 80g \
  --executor-cores 24 \
  --conf spark.kubernetes.container.image=<sparkimg> \
  SystemDS.jar -f test.dml -stats -explain -args …
```

# Spark Dynamic Allocation

[https://spark.apache.org/docs/latest/job-scheduling.html]

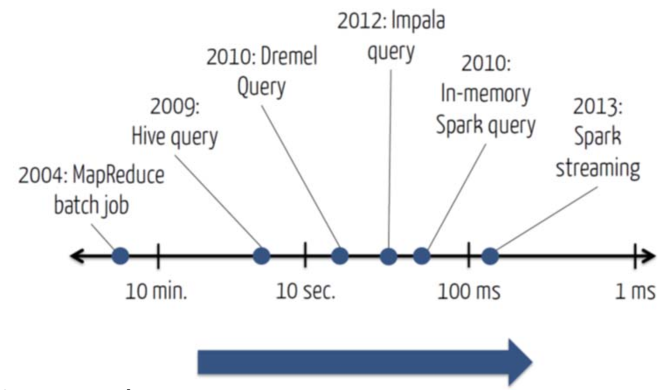
- **Configuration for YARN/Mesos**
  - Set `spark.dynamicAllocation.enabled = true`
  - Set `spark.shuffle.service.enabled = true` (robustness w/ stragglers)

- **Executor Addition/Removal**
  - **Approach:** look at task pressure (pending tasks / idle executors)
  - Increase exponentially (add **1**, **2**, **4**, **8**) if pending tasks for `spark.dynamicAllocation.schedulerBacklogTimeout`
  - Decrease executors they are idle for `spark.dynamicAllocation.executorIdleTimeout`

# Sparrow Task Scheduling

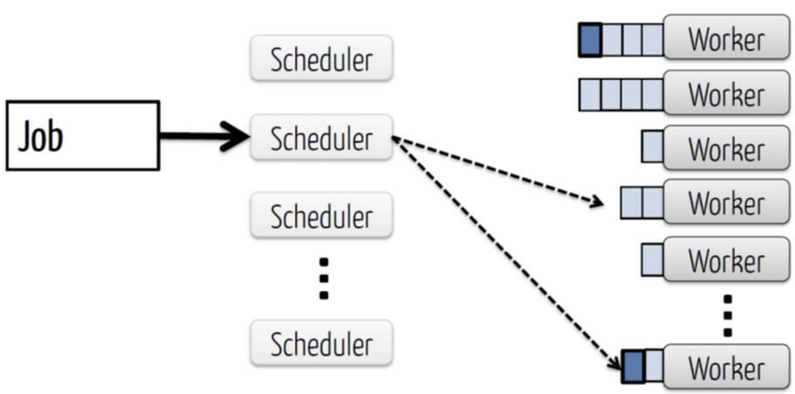
[Kay Ousterhout, Patrick Wendell, Matei Zaharia, Ion Stoica: Sparrow: distributed, low latency scheduling. **SOSP 2013**]

- **Sparrow Overview**
  - Decentralized, randomized task scheduling with constraints, fair sharing
  - **Problems: Low latency**, quality placement, fault tolerance, high throughput

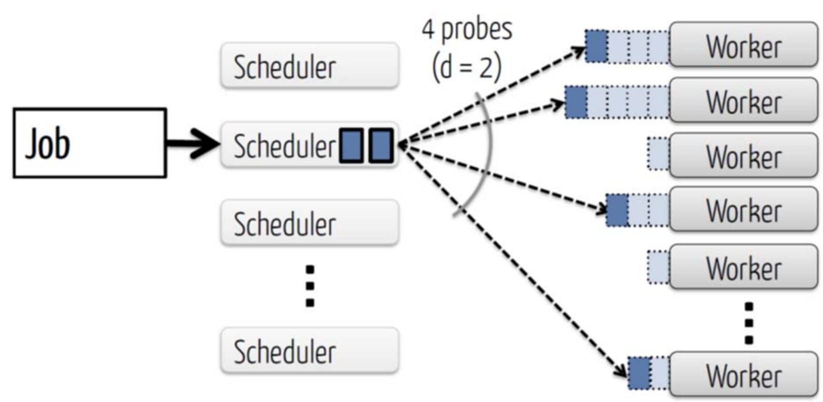



- **Approach**
  - **Baselines:** Random, Per-task (power of two choices)
  - New Techniques: **Batch Scheduling**, **Late Binding**

**Baseline: Per-task sampling**




**Batch sampling w/ late binding**

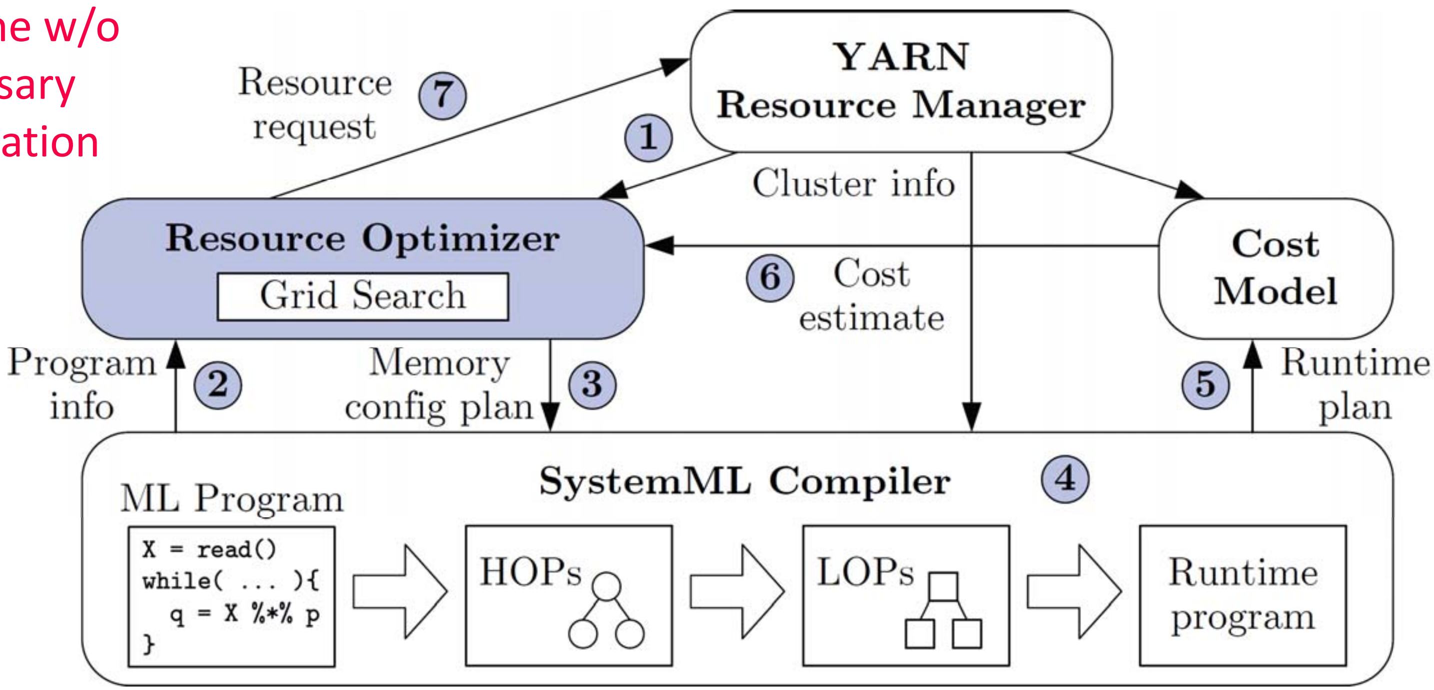


# Resource Elasticity in SystemML

[Botong Huang et al.: Resource Elasticity for Large-Scale Machine Learning. **SIGMOD 2015**]

- **Basic Ideas**
  - Optimize ML program resource configurations via **online what-if analysis**
  - Generating and **costing runtime plans** for local/MR
  - **Program-aware** grid enumeration, pruning, and re-optimization techniques

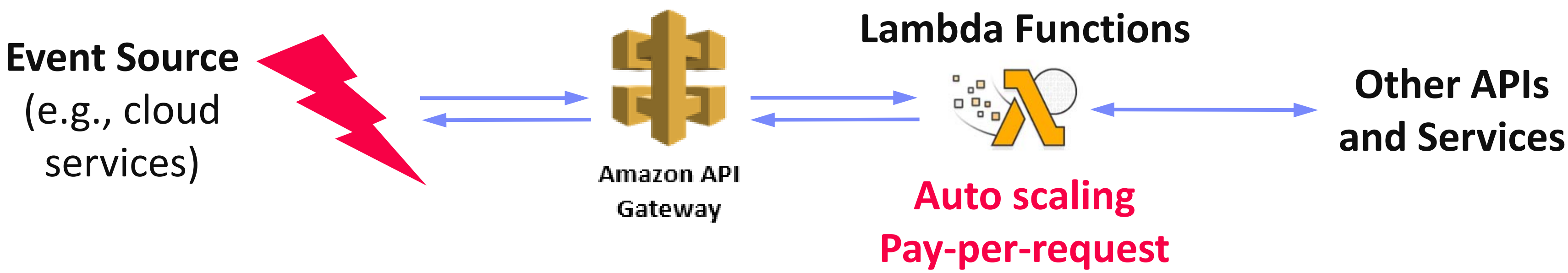
Min runtime w/o unnecessary over-allocation



# Serverless Computing (FaaS)

[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




- **Example**

```java
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);
    }
}
```

# Summary and Q&A

- **Motivation, Terminology, and Fundamentals**
- **Resource Allocation, Isolation, and Monitoring**
- **Task Scheduling and Elasticity**

- **Next Lectures**
  - **10 Distributed Data Storage** [Dec 11]
  - **11 Distributed, Data-Parallel Computation** [Jan 08]
  - **12 Distributed Stream Processing** [Jan 15]
  - **13 Distributed Machine Learning Systems** [Jan 22]