Resource Management - Mesos, YARN, and Borg

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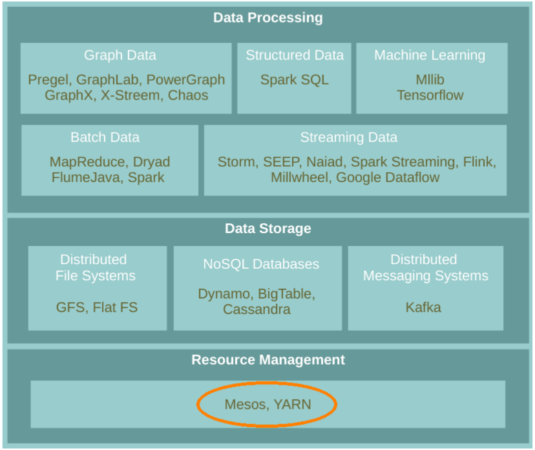
The Course Web Page

https://id2221kth.github.io

https://tinyurl.com/f6x544h

Where Are We?



Data Processing
Graph Data
Pregel, GraphLab, PowerGraph
GraphX, X-Streem, Chaos
Structured Data
Spark SQL
Machine Learning
Mllib
Tensorflow
Batch Data
MapReduce, Dryad
FlumeJava, Spark
Streaming Data
Storm, SEEP, Naiad, Spark Streaming, Flink,
Millwheel, Google Dataflow
Data Storage
Distributed
File Systems
GFS, Flat FS
NoSQL Databases
Dynamo, BigTable,
Cassandra
Distributed
Messaging Systems
Kafka
Resource Management
Mesos, YARN

Motivation

- Rapid innovation in cloud computing.
- No single framework optimal for all applications.
- Running each framework on its dedicated cluster:
  - Expensive
  - Hard to share data

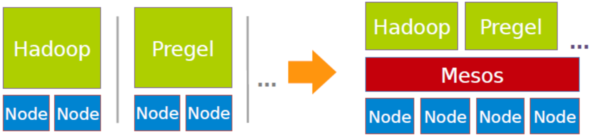
Proposed Solution

- Running multiple frameworks on a single cluster.
- Maximize utilization and share data between frameworks.
- Three resource management systems:
  - Mesos
  - YARN
  - Borg

Mesos

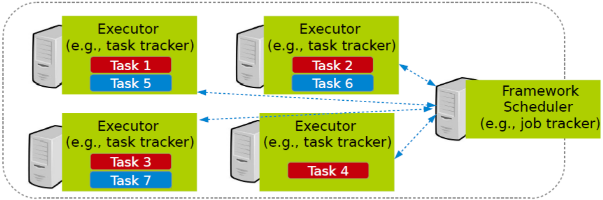
Mesos

- Mesos is a common resource sharing layer, over which diverse frameworks can run.



Computation Model

- A framework (e.g., Hadoop, Spark) manages and runs one or more jobs.
- A job consists of one or more tasks.
- A task (e.g., map, reduce) consists of one or more processes running on same machine.

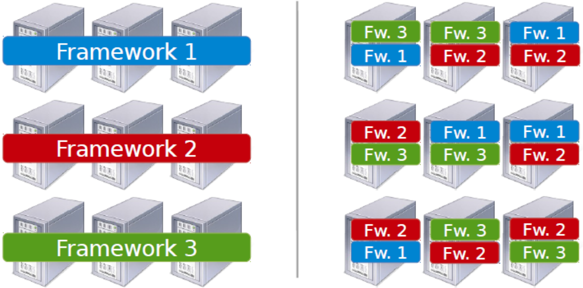


Mesos Design Elements

- Fine-grained sharing
- Resource offers

Fine-Grained Sharing

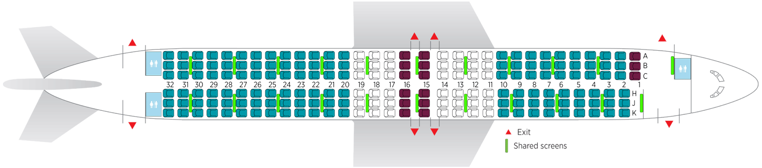
- Allocation at the level of tasks within a job.
- Improves utilization, latency, and data locality.



Coarse-grained sharing   Fine-grained sharing

Resource Offer

- Offer available resources to frameworks, let them pick which resources to use and which tasks to launch.
- Keeps Mesos simple, lets it support future frameworks.



Question?

How to schedule resource offering among frameworks?

Schedule Frameworks

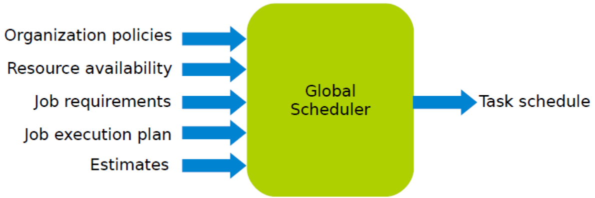
- Global scheduler
- Distributed scheduler

Global Scheduler (1/2)

- Job requirements
  - Response time
  - Throughput
  - Availability

- Job execution plan
  - Task DAG
  - Inputs/outputs

- Estimates
  - Task duration
  - Input sizes
  - Transfer sizes

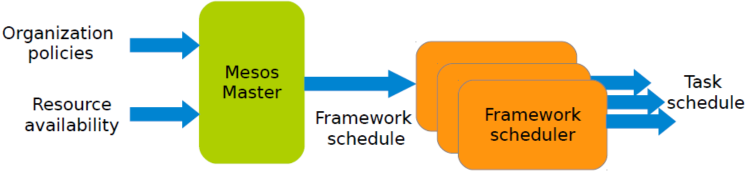


Global Scheduler (2/2)

- Advantages
  - Can achieve optimal schedule.

- Disadvantages
  - Complexity: hard to scale and ensure resilience.
  - Hard to anticipate future frameworks requirements.
  - Need to refactor existing frameworks.

Distributed Scheduler (1/3)



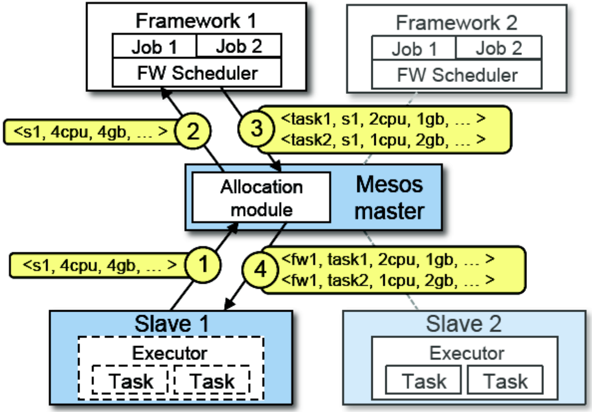
Distributed Scheduler (2/3)

- Master sends resource offers to frameworks.
- Frameworks select which offers to accept and which tasks to run.
- Unit of allocation: resource offer
  - Vector of available resources on a node
  - For example, node1: $\langle 1\mathrm{CPU}, 1\mathrm{GB}\rangle$, node2: $\langle 4\mathrm{CPU}, 16\mathrm{GB}\rangle$

Distributed Scheduler (3/3)

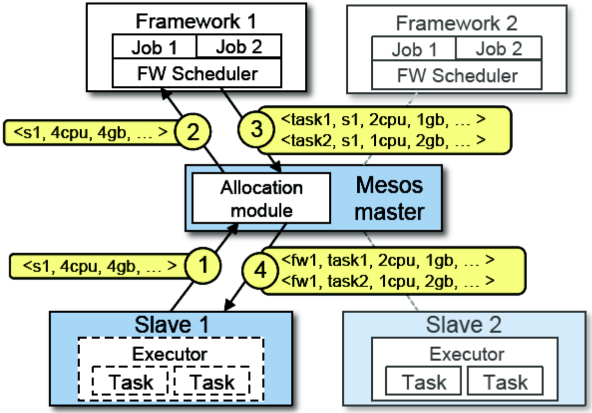
- Advantages
  - Simple: easier to scale and make resilient.
  - Easy to port existing frameworks, support new ones.
- Disadvantages
  - Distributed scheduling decision: not optimal.

Mesos Architecture (1/4)



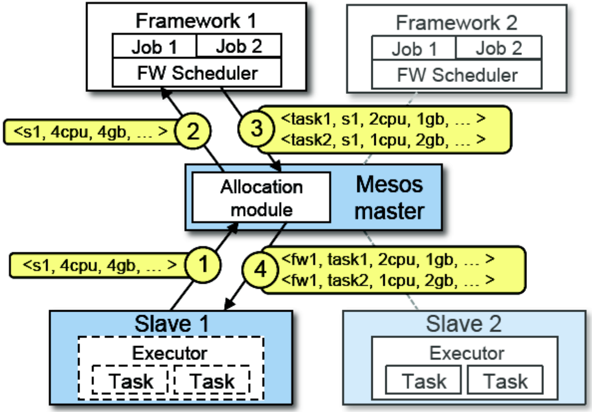
- Slaves continuously send status updates about resources to the Master.

Mesos Architecture (2/4)



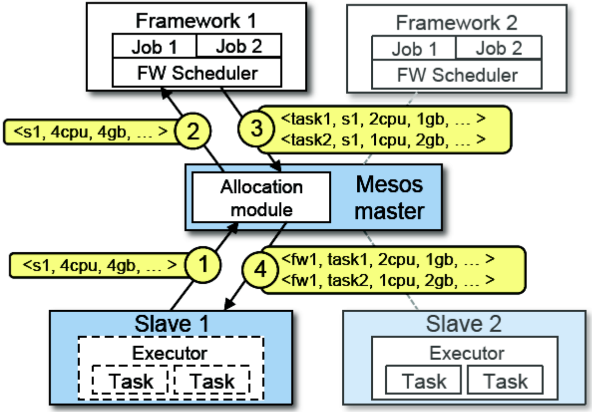
- Pluggable scheduler picks framework to send an offer to.

Mesos Architecture (3/4)



- Framework scheduler selects resources and provides tasks.

Mesos Architecture (4/4)



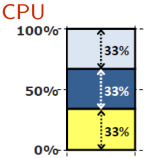
- Framework executors launch tasks.

Question?

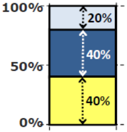
How to allocate resources of different types?

Single Resource: Fair Sharing

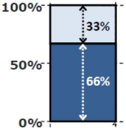
- n users want to share a resource, e.g., CPU.
  - Solution: allocate each $\frac{1}{n}$ of the shared resource.



- Generalized by max-min fairness.
  - Handles if a user wants less than its fair share.
  - E.g., user 1 wants no more than 20%.



- Generalized by weighted max-min fairness.
  - Give weights to users according to importance.
  - E.g., user 1 gets weight 1, user 2 weight 2.



Max-Min Fairness - Example

- 1 resource: CPU
- Total resources: 20 CPU
- User 1 has $\mathtt{x}$ tasks and wants $\langle\mathtt{1CPU}\rangle$ per task
- User 2 has $\mathtt{y}$ tasks and wants $\langle\mathtt{2CPU}\rangle$ per task

$\mathtt{max}(\mathtt{x}, \mathtt{y})$ (maximize allocation)
subject to
$\mathtt{x} + 2\mathtt{y} \leq 20$ (CPU constraint)
$\mathtt{x} = 2\mathtt{y}$
so
$\mathtt{x} = 10$
$\mathtt{y} = 5$

Properties of Max-Min Fairness

- Share guarantee
  - Each user can get at least $\frac{1}{n}$ of the resource.
  - But will get less if her demand is less.
- Strategy proof
  - Users are not better off by asking for more than they need.
  - Users have no reason to lie.
- Max-Min fairness is the only reasonable mechanism with these two properties.
- Widely used: OS, networking, datacenters, ...

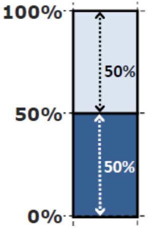
Question?

When is Max-Min Fairness NOT Enough?

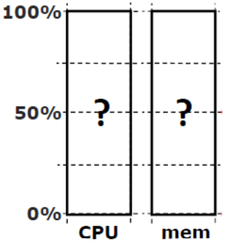
Need to schedule multiple, heterogeneous resources, e.g., CPU, memory, etc.

Problem

- Single resource example
  - 1 resource: CPU
  - User 1 wants $\langle 1\text{CPU} \rangle$ per task
  - User 2 wants $\langle 2\text{CPU} \rangle$ per task



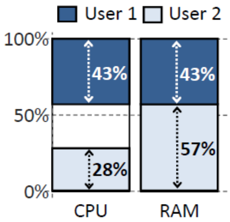
- Multi-resource example
  - 2 resources: CPUs and mem
  - User 1 wants $\langle 1\text{CPU}, 4\text{GB} \rangle$ per task
  - User 2 wants $\langle 2\text{CPU}, 1\text{GB} \rangle$ per task
  - What is a fair allocation?



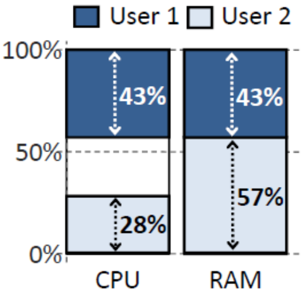
A Natural Policy (1/2)

- Asset fairness: give weights to resources (e.g., 1 CPU = 1 GB) and equalize total value given to each user.
- Total resources: 28 CPU and 56GB RAM (e.g., 1 CPU = 2 GB)
  - User 1 has $\mathtt{x}$ tasks and wants $\langle \mathtt{1CPU}, \mathtt{2GB} \rangle$ per task
  - User 2 has $\mathtt{y}$ tasks and wants $\langle \mathtt{1CPU}, \mathtt{4GB} \rangle$ per task
- Asset fairness yields:

$\mathtt{max(x, y)}$
$\mathtt{x} + \mathtt{y} \leq 28$
$2\mathtt{x} + 4\mathtt{y} \leq 56$
$2\mathtt{x} = 3\mathtt{y}$
User 1: $\mathtt{x} = 12$: $\langle 43\%\mathtt{CPU}, 43\%\mathtt{GB} \rangle$ ($\sum = 86\%$)
User 2: $\mathtt{y} = 8$: $\langle 28\%\mathtt{CPU}, 57\%\mathtt{GB} \rangle$ ($\sum = 86\%$)



A Natural Policy (2/2)



- Problem: violates share grantee.
- User 1 gets less than 50% of both CPU and RAM.
- Better off in a separate cluster with half the resources.

Challenge

- Can we find a fair sharing policy that provides:
  - Share guarantee
  - Strategy-proofness

- Can we generalize max-min fairness to multiple resources?

Proposed Solution

Dominant Resource Fairness (DRF)

Dominant Resource Fairness (DRF) (1/2)

- Dominant resource of a user: the resource that user has the biggest share of.
  - Total resources: $\langle 8\text{CPU}, 5\text{GB} \rangle$
  - User 1 allocation: $\langle 2\text{CPU}, 1\text{GB} \rangle$: $\frac{2}{8} = 25\%$ CPU and $\frac{1}{5} = 20\%$ RAM
  - Dominant resource of User 1 is CPU ($25\% > 20\%$)

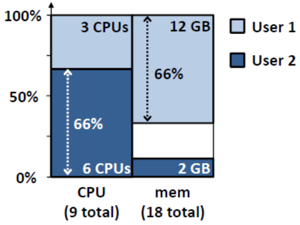
- Dominant share of a user: the fraction of the dominant resource she is allocated.
  - User 1 dominant share is 25%.

Dominant Resource Fairness (DRF) (2/2)

- Apply max-min fairness to dominant shares: give every user an equal share of her dominant resource.

- Equalize the dominant share of the users.
  - Total resources: $\langle 9\text{CPU}, 18\text{GB}\rangle$
  - User 1 wants $\langle 1\text{CPU}, 4\text{GB}\rangle$; Dominant resource: RAM ($\frac{1}{9} < \frac{4}{18}$)
  - User 2 wants $\langle 3\text{CPU}, 1\text{GB}\rangle$; Dominant resource: CPU ($\frac{3}{9} > \frac{1}{18}$)

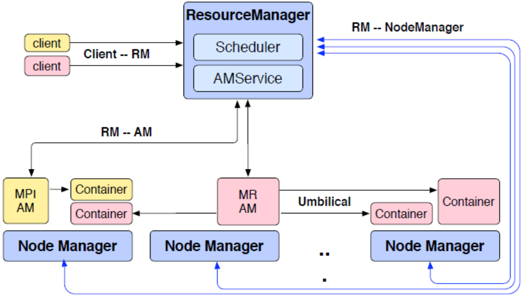
- $\max(x, y)$
  $x + 3y \leq 9$
  $4x + y \leq 18$
  $\frac{4x}{18} = \frac{3y}{9}$
  User 1: $x = 3$: $\langle 33\%\text{CPU}, 66\%\text{GB}\rangle$
  User 2: $y = 2$: $\langle 66\%\text{CPU}, 16\%\text{GB}\rangle$



YARN

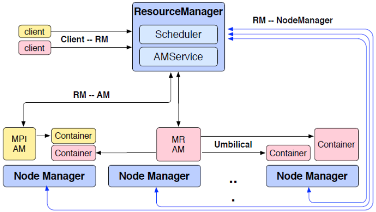
YARN Architecture

- Resource Manager (RM)
- Application Master (AM)
- Node Manager (NM)



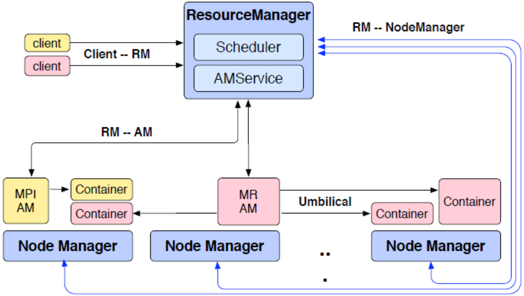
YARN Architecture - Resource Manager (1/2)

- One per cluster
  - Central: global view
- Job requests are submitted to RM.
  - To start a job, RM finds a container to spawn AM.
- Container: logical bundle of resources (CPU/memory)



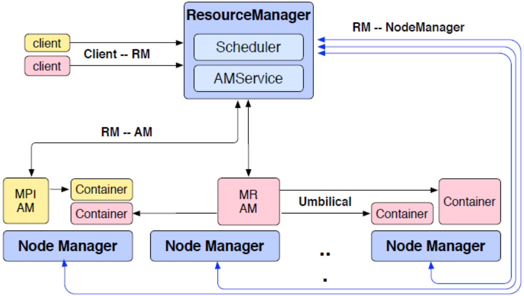
YARN Architecture - Resource Manager (2/2)

- Only handles an overall resource profile for each job.
  - Local optimization is up to the job.
- Preemption
  - Request resources back from an job.
  - Checkpoint jobs



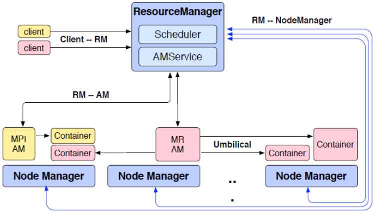
YARN Architecture - Application Manager

- The head of a job.
- Runs as a container.
- Request resources from RM (num. of containers/resource per container/locality ...)



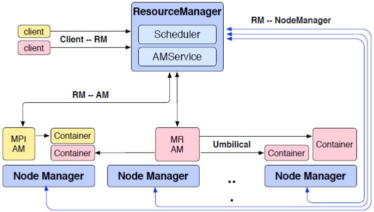
YARN Architecture - Node Manager (1/2)

- The worker daemon.
- Registers with RM.
- One per node.
- Report resources to RM: memory, CPU, ...



YARN Architecture - Node Manager (2/2)

- Configure the environment for task execution.
- Garbage collection.
- Auxiliary services.
  - A process may produce data that persist beyond the life of the container.
  - Output intermediate data between map and reduce tasks.

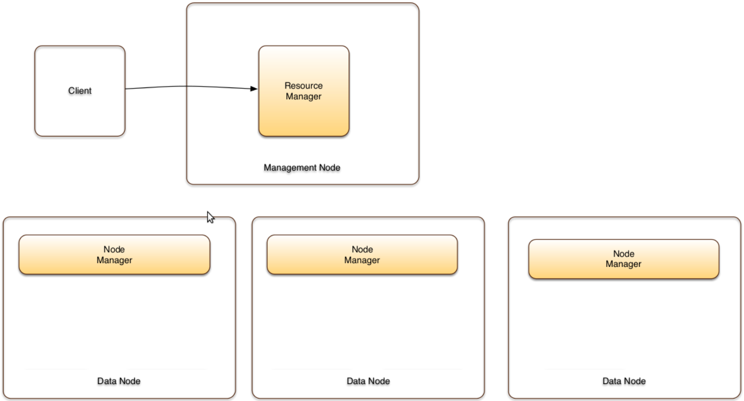


YARN Framework

- Containers are described by a Container Launch Context (CLC).
  - The command necessary to create the process, environment variables, security tokens, etc.
- Submitting the job: passing a CLC for the AM to the RM.
- When RM starts the AM, it should register with the RM.
- Once the RM allocates a container, AM can construct a CLC to launch the container on the corresponding NM.
- Once the AM is done with its work, it should unregister from the RM and exit cleanly.

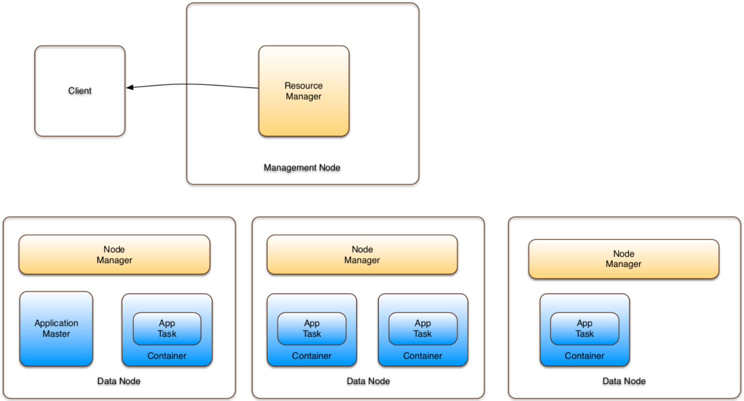
Submitting a Job (1/9)

- A client submits a job.



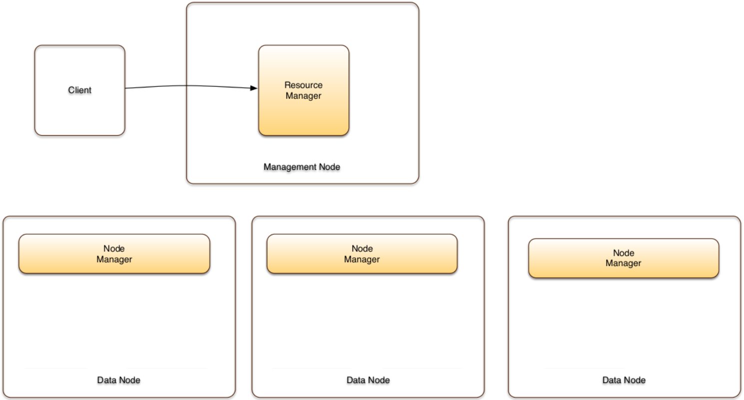
Submitting a Job (2/9)

- The RM provides an Application Id.



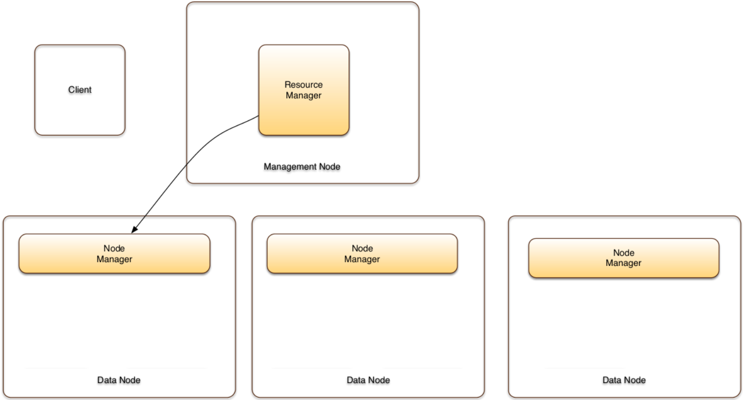
Submitting a Job (3/9)

- The client provides a CLC (queue, resource requirements, files, security token, etc.)



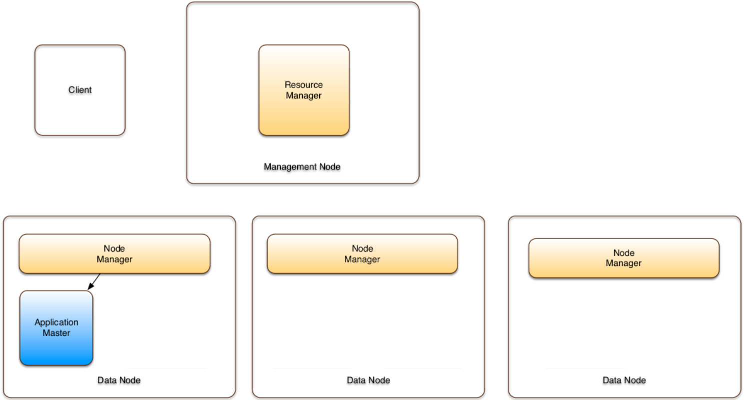
Submitting a Job (4/9)

- The RM asks a NM to launch an AM.



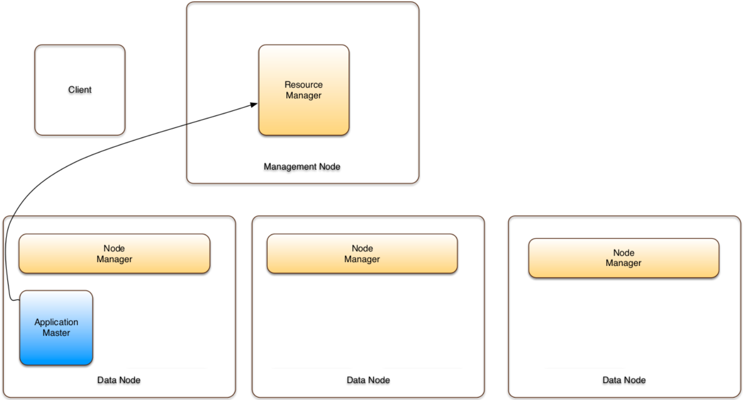
Submitting a Job (5/9)

- The selected NM launches an AM.



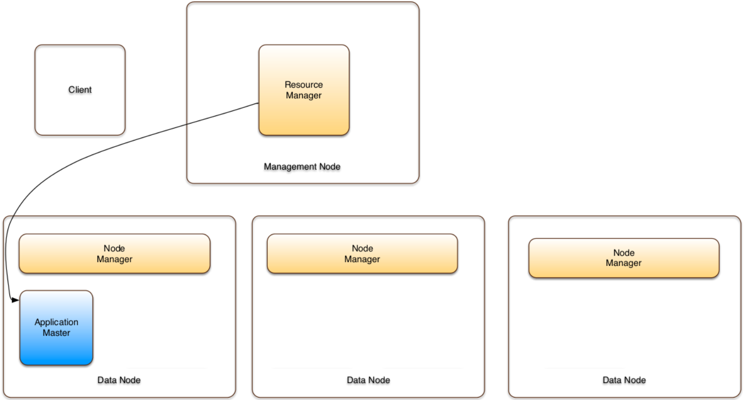
Submitting a Job (6/9)

- The AM registers with the RM.



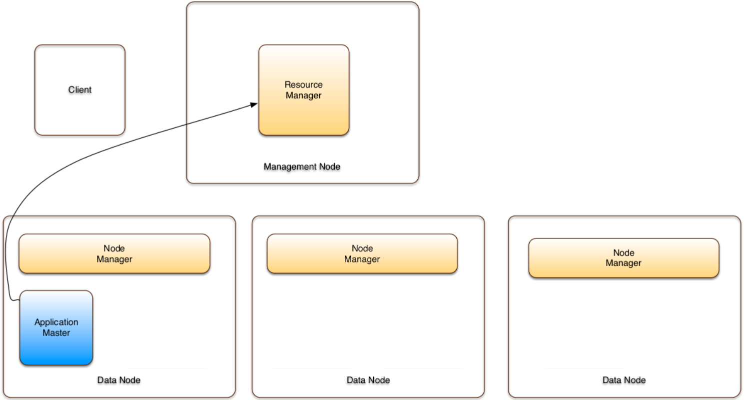
Submitting a Job (7/9)

- The RM shares resource capabilities with the AM.



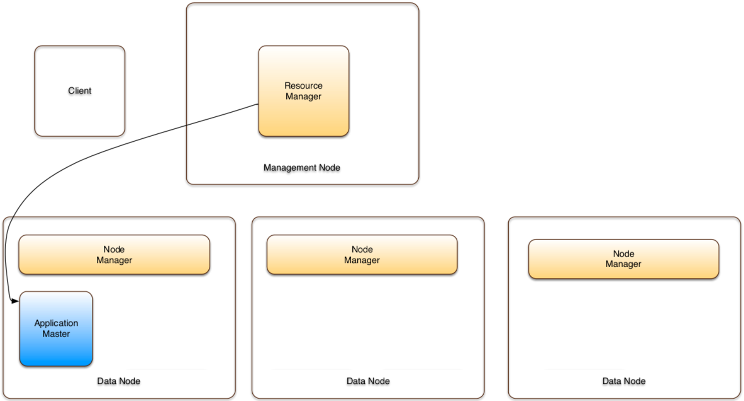
Submitting a Job (8/9)

- The AM requests containers.



Submitting a Job (9/9)

- The RM assigns containers based on policies and available resources.



Borg

Borg

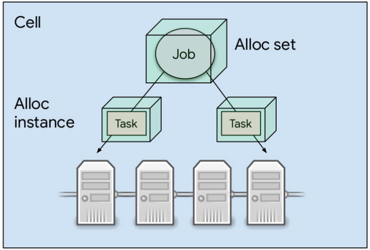
- Cluster management system at Google.

Borg User View

```
job hello_world = {
  runtime = { cell = 'ic' }                  // Cell (cluster) to run in
  binary = '.../hello_world_webserver'       // Program to run
  args = { port = '%port%' }                 // Command line parameters
  requirements = {      // Resource requirements
    ram = 100M
    disk = 100M           (optional)
    cpu = 0.1
  }
  replicas = 10000     // Number of tasks
}
```

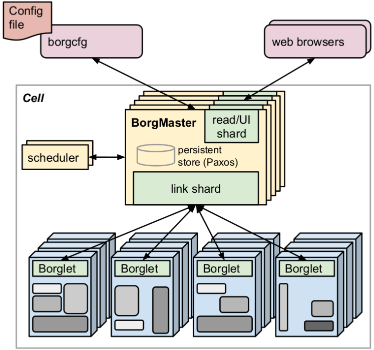
Borg Cell, Job, Task, and Alloc

- Cell: a set of machines managed by Borg as one unit.
- Job: users submit work in the form of jobs.
- Task: each job contains one or more tasks.
- Alloc: reserved set of resources and a job can run in an alloc set.
- Alloc instance: making each of its tasks run in an alloc instance.



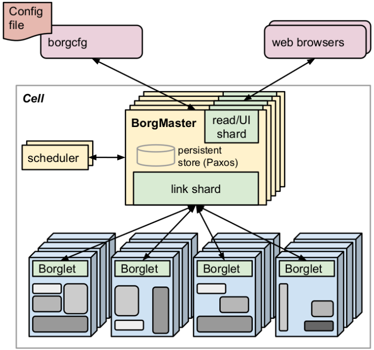
Borg Architecture (1/2)

- BorgMaster
  - The central brain of the system
  - Holds the cluster state
  - Replicated for reliability (using paxos)
  - Scheduling: where to place tasks?
- Borglet
  - Manage and monitor tasks and resource
  - Borgmaster polls Borglet every few seconds



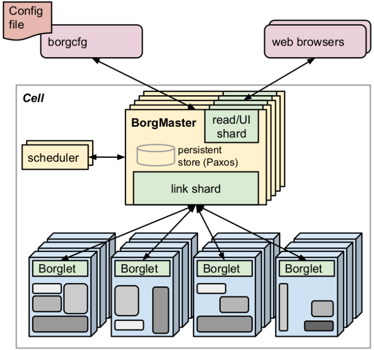
Borg Architecture (2/2)

1. Compile the program and stick it in the cloud
2. Pass configuration to command line (borgcfg)
3. Send an RPC to BorgMaster
4. BorgMaster writes to persistent store and tasks added to pending queue
5. Scheduler asynchronous scan



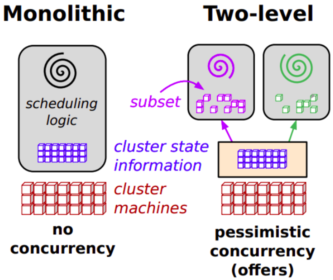
Scheduler

- Feasibility checking: find machines for a given job
- Scoring: pick one machines
- User prefs and built-in criteria
  - Minimize the number and priority of the preempted tasks
  - Picking machines that already have a copy of the task's packages
  - Spreading tasks across power and failure domains
  - Packing by mixing high and low priority tasks



Monolithic vs. Two-Level

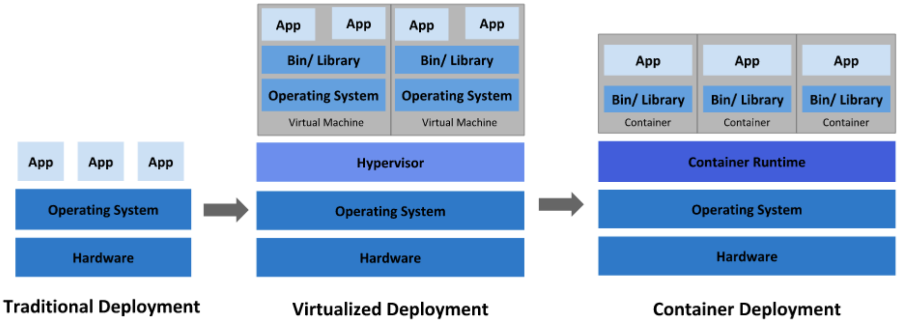
- **Monolithic schedulers**: use a single, centralized scheduling algorithm for all jobs.
  - Borg
- **Two-level schedulers**: separate concerns of resource allocation and task placement.
  - An active resource manager offers compute resources to multiple parallel, independent scheduler frameworks.
  - Mesos and Yarn



[Schwarzkopf et al., Omega: flexible, scalable schedulers for large compute clusters, EuroSys'13.]

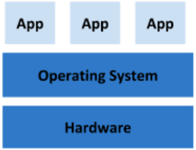
Docker and Kubernetes

Application Deployment



Traditional Deployment Era

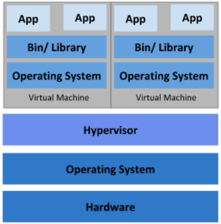
- Running applications on physical servers.
- No resource boundaries for applications in a physical server
- Resource allocation issues, e.g., one application would take up most of the resources, so the other applications would underperform.
- Alternatively runnig each application on a different physical server: not scalable



Traditional Deployment

Virtualized Deployment Era

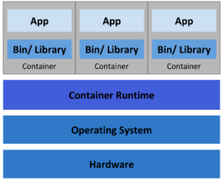
- Virtual Machines (VMs): a full machine running all the components, including its own operating system (OS), on top of the virtualized hardware.
- Virtualization allows to run multiple VMs on a single physical server's CPU.
  - Allows applications to be isolated between VMs.
  - Secure, as the information of one application cannot be freely accessed by another application.
  - Utilizes the resources of a physical server better.
  - Better scalability as applications can be added/updated easily.



Virtualized Deployment

Container Deployment Era

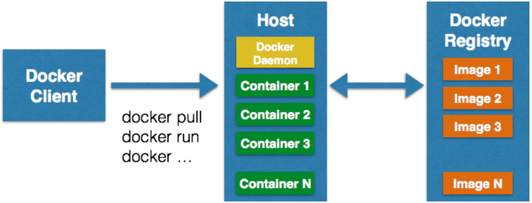
- Containers are similar to VMs, but they have relaxed isolation properties to share the OS among the applications.
- Similar to a VM, a container packages applications as images that contain everything needed to run them: code, runtime environment, libraries, and configuration.
- As they are decoupled from the underlying infrastructure, they are portable across clouds and OS distributions.



Container Deployment

Docker

- Docker is a virtualization software.
- It is a client-server application.
- A docker image is a template, and a container is a copy of that template.



Docker Components

- Docker images: the blueprints of our application that form the basis of containers.
- Docker containers: they are created from images and run the actual application.
  - We can have multiple containers (copies) of the same image.
- Docker daemon: it represents the server.
- Docker client: the command line tool that allows the user to interact with the daemon.
- Docker registries: Docker stores the images in registries (public and private).
  - Docker hub: A public registry of Docker images.

Docker Important Commands (1/2)

```
# get the docker information
docker info
```

```
# download an image
docker pull
```

```
# run an image as a container
docker run -i -t image_name /bin/bash
```

```
# start and stop a container
docker start container_name
docker stop container_name
```

Docker Important Commands (2/2)

```
# list all running containers
docker ps
```

```
# get the container information
docker stats
```

```
# list the downloaded images
docker images
```

Container Challenges

- Container scalability is an operational challenge.
- If we have 10 containers and four applications, it is not difficult to manage the deployment and maintenance of the containers.
- But, what if we have 1000 containers and 400 services?
- Container orchestration can help to manage the lifecycles of containers, especially in large and dynamic environments.

Container Orchestration Tasks (1/2)

- Provisioning and deployment of containers.
- Redundancy and availability of containers.
- Scaling up or removing containers to spread application load evenly across host infrastructure
- Movement of containers from one host to another, if there is a shortage of resources in a host, or if a host dies

Container Orchestration Tasks (2/2)

- Allocation of resources between containers.
- Load balancing of service discovery between containers.
- Health monitoring of containers and hosts
- Configuration of an application in relation to the containers running it.

How Does Container Orchestration Work?

- Typically describe the configuration of your application in a YAML or JSON file.
- Using these configurations files you tell the orchestration tool:
  - Where to gather container images (e.g., from Docker Hub).
  - How to establish networking between containers.
  - How to mount storage volumes.
  - Where to store logs for that container.
- Container orchestration tools: Kubernetes (based on Borg), Marathon (runs on Mesos)

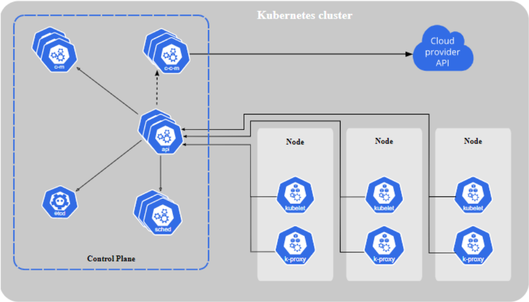
kubernetes

Kubernetes and Borg

- Kubernetes is the Google open source project loosely inspired by Borg.
- Directly derived
  - Borglet → Kubelet
  - alloc → pod
  - Borg containers → docker
  - Declarative specifications
- Improved
  - Job → labels
  - Managed ports → IP per pod
  - Monolithic master → micro-services

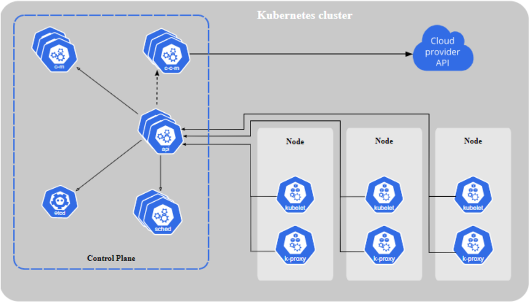
Kubernetes Architecture (1/5)

- Cluster: a set of nodes with at least one master node and several worker nodes (minions).



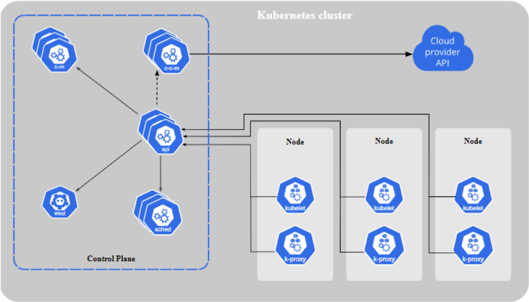
Kubernetes Architecture (2/5)

- Kubernetes master: manages the scheduling and deployment of application instances across nodes.
- The full set of services the master node runs is known as the control plane.



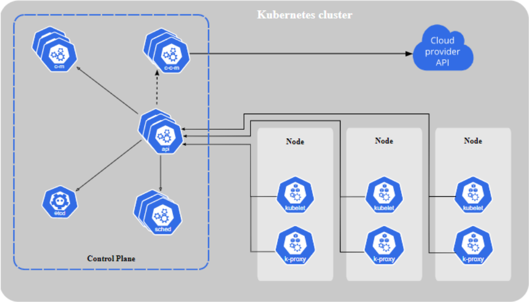
Kubernetes Architecture (3/5)

- Kubelet: an agent process on each Kubernetes node that is responsible for managing the state of the node, e.g., starting, stopping, and maintaining application containers.



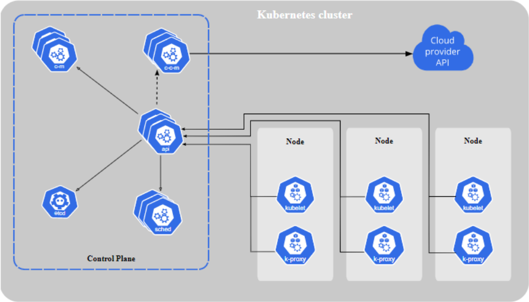
Kubernetes Architecture (4/5)

- Pods: the basic scheduling unit that consists of one or more containers guaranteed to be co-located on the host machine and able to share resources.
- You describe the desired state of the containers in a pod through a YAML or JSON object called a PodSpec.



Kubernetes Architecture (5/5)

- Deployments: a deployment is a YAML object that defines the pods and the number of container instances (replicas) for each pod.
- ReplicaSets: You define the number of replicas you want to have running in the cluster via a ReplicaSet.



Summary

Summary

- Mesos
  - Offered-based
  - Max-Min fairness: DRF
- YARN
  - Request-based
  - RM, AM, NM
- Borg
  - Request-based
  - BorgMaster, Borglet
  - Kubernetes

References

- B. Hindman et al., “Mesos: A Platform for Fine-Grained Resource Sharing in the Data Center”, NSDI 2011
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Questions?

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