# Resource Management - Mesos, YARN, and Borg

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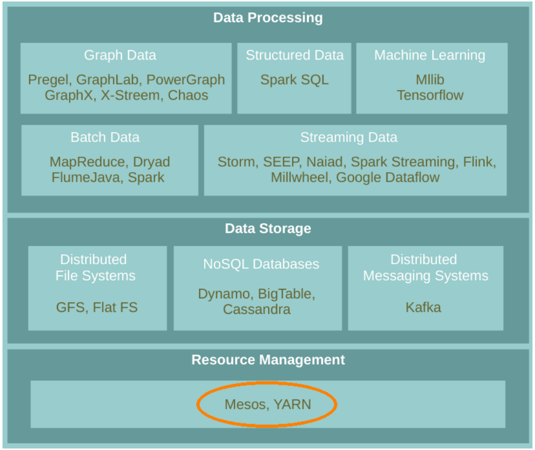
# The Course Web Page

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.

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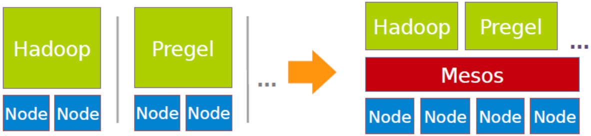
- Running multiple frameworks on a single cluster.
- Maximize utilization and share data between frameworks.
- Three resource management systems:
  - Mesos
  - YARN
  - Borg

# Mesos

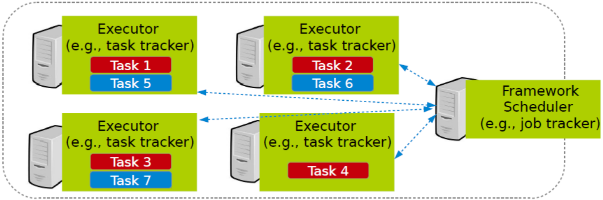
# Mesos

- 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.



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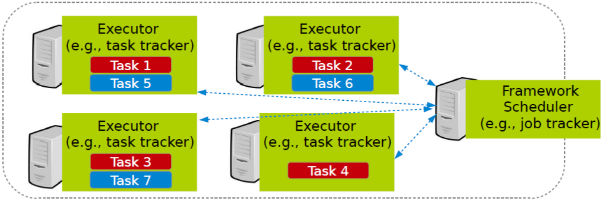
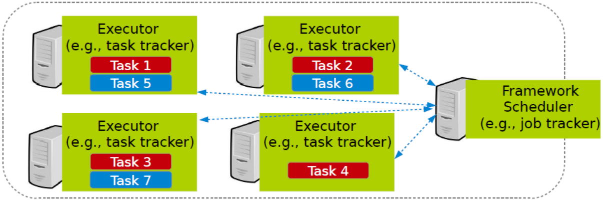


# Computation Model

- 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.

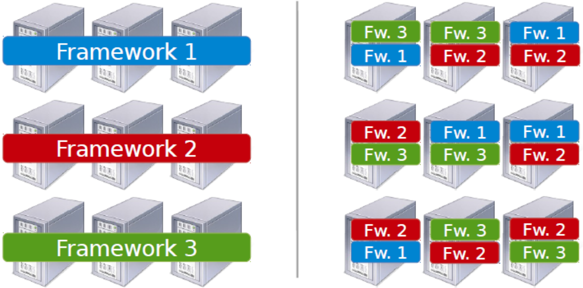


# Mesos Design Elements

- Fine-grained sharing
- Resource offers

# Fine-Grained Sharing

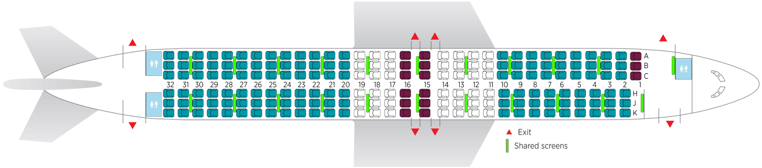
- Allocation at the level of tasks within a job.
- Improves utilization, latency, and data locality.




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?

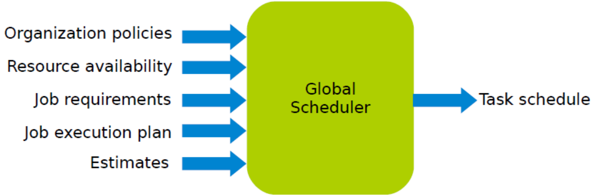
How to schedule resource offering among frameworks?

# Schedule Frameworks

- Global scheduler
- Distributed scheduler

# Global Scheduler (1/2)

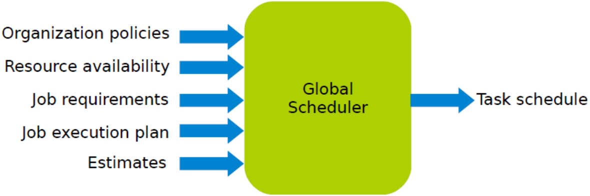
- Job requirements
  - Response time
  - Throughput
  - Availability



# Global Scheduler (1/2)

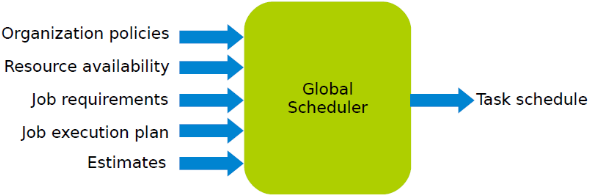
- Job requirements
  - Response time
  - Throughput
  - Availability

- Job execution plan
  - Task DAG
  - Inputs/outputs



# 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.

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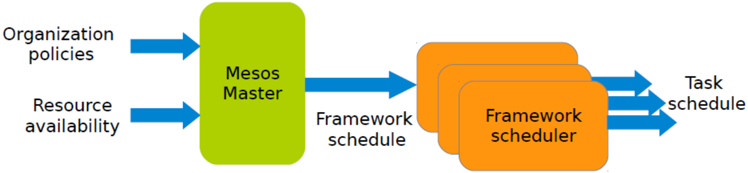
- Advantages
  - Can achieve optimal schedule.

- 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.
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- Unit of allocation: resource offer
  - Vector of available resources on a node
  - For example, node1: $\langle 1\text{CPU}, 1\text{GB}\rangle$, node2: $\langle 4\text{CPU}, 16\text{GB}\rangle$

# Distributed Scheduler (3/3)

- Advantages
  - Simple: easier to scale and make resilient.
  - Easy to port existing frameworks, support new ones.

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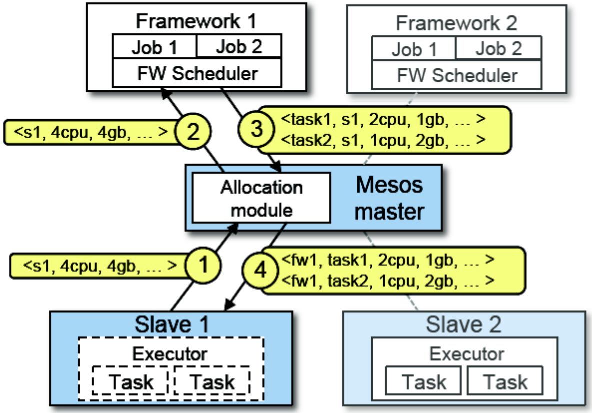
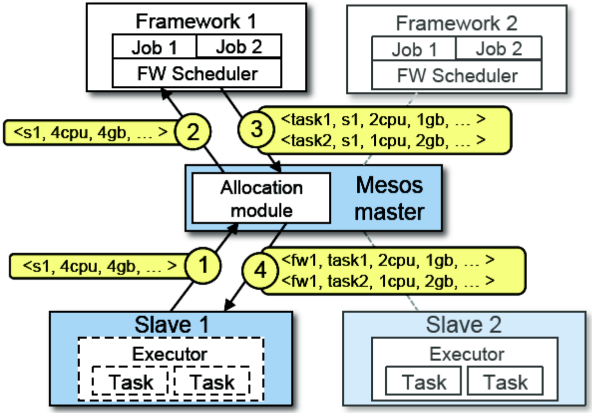
- Disadvantages
  - Distributed scheduling decision: not optimal.

# Mesos Architecture (1/4)



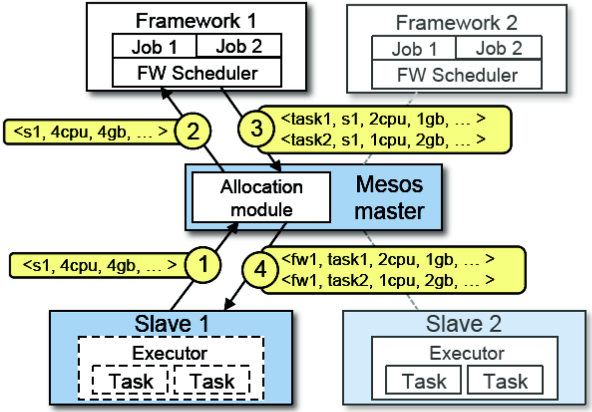

- Slaves continuously send status updates about resources to the Master.

# Mesos Architecture (2/4)



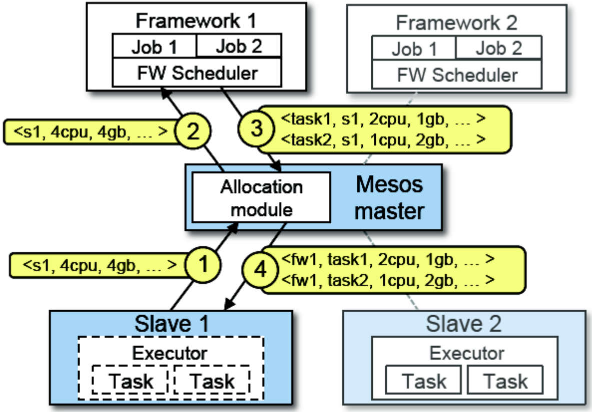

- Pluggable scheduler picks framework to send an offer to.

# Mesos Architecture (3/4)




- Framework scheduler selects resources and provides tasks.

# Mesos Architecture (4/4)



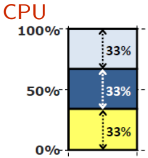

- Framework executors launch tasks.

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.



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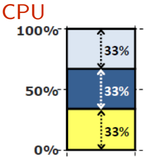
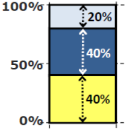



- Generalized by max-min fairness.
  - Handles if a user wants less than its fair share.
  - E.g., user 1 wants no more than 20%.



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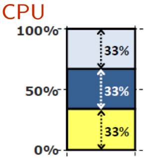


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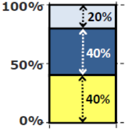
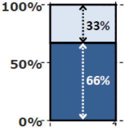



- Generalized by weighted max-min fairness.
  - Give weights to users according to importance.
  - E.g., user 1 gets weight 1, user 2 weight 2.



# Max-Min Fairness - Example

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

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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.

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- 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?

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When is Max-Min Fairness NOT Enough?

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

# Problem

- Single resource example
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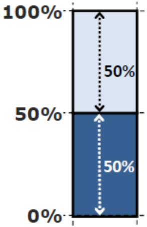

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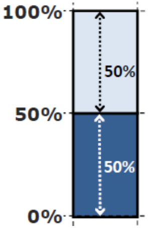
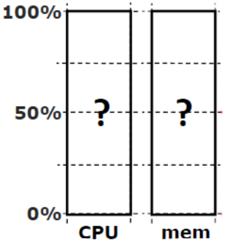



- Multi-resource example
  - 2 resources: CPUs and mem
  - User 1 wants $\langle 1\text{CPU}, 4\text{GB} \rangle$ per task
  - User 2 wants $\langle 2\text{CPU}, 1\text{GB} \rangle$ per task



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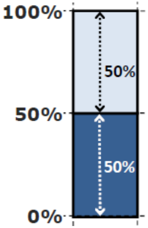
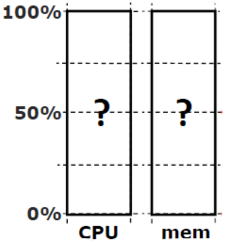



- **Multi-resource example**
  - 2 resources: CPUs and mem
  - User 1 wants $\langle 1CPU, 4GB \rangle$ per task
  - User 2 wants $\langle 2CPU, 1GB \rangle$ per task
  - What is a fair allocation?



# A Natural Policy (1/2)

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- 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

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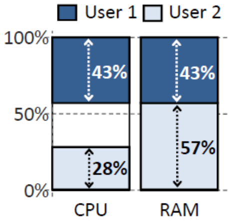



- Asset fairness yields:

$\mathtt{max}(\mathtt{x}, \mathtt{y})$

$\mathtt{x} + \mathtt{y} \leq 28$

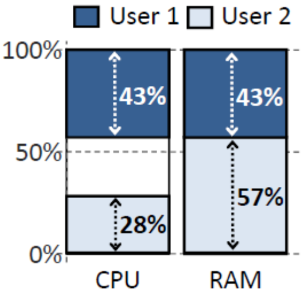
$2\mathtt{x} + 4\mathtt{y} \leq 56$

$2\mathtt{x} = 3\mathtt{y}$

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: $\langle 2\text{CPU}, 1\text{GB} \rangle$: $\frac{2}{8} = 25\%\ \text{CPU}$ and $\frac{1}{5} = 20\%\ \text{RAM}$
  - Dominant resource of User 1 is CPU ($25\% > 20\%$)

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

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- 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 ($\frac{1}{9} < \frac{4}{18}$)
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- $\max(x, y)$

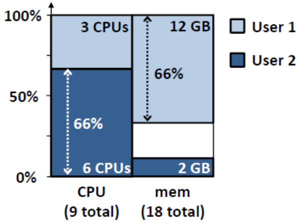
  $x + 3y \leq 9$

  $4x + y \leq 18$

  $\frac{4x}{18} = \frac{3y}{9}$

  User 1: $x = 3$: $\langle 33\%\text{CPU}, 66\%\text{GB} \rangle$

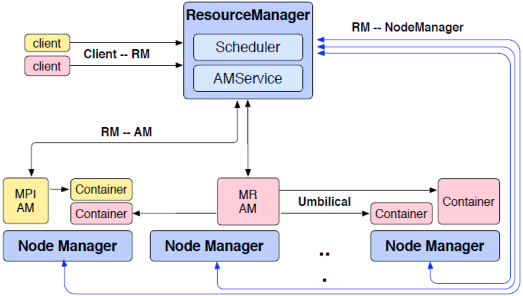
  User 2: $y = 2$: $\langle 66\%\text{CPU}, 16\%\text{GB} \rangle$



# YARN

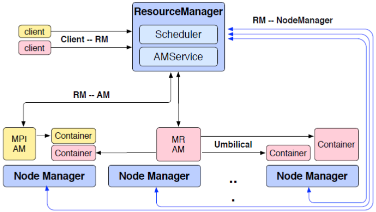
# YARN Architecture

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



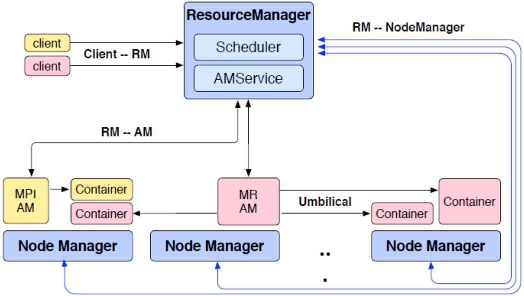
# YARN Architecture - Resource Manager (1/2)

- 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)



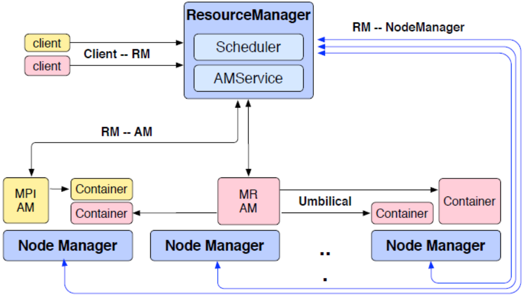
# YARN Architecture - Resource Manager (2/2)

- 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



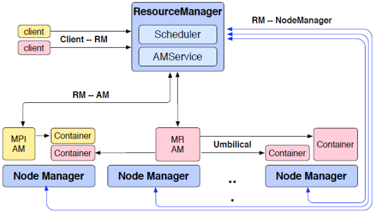
# YARN Architecture - Application Manager

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



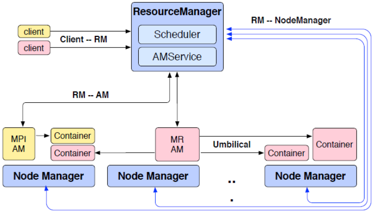
# YARN Architecture - Node Manager (1/2)

- 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.



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- Submitting the job: passing a CLC for the AM to the RM.
- When RM starts the AM, it should register with the RM.

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- 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.

# YARN Framework

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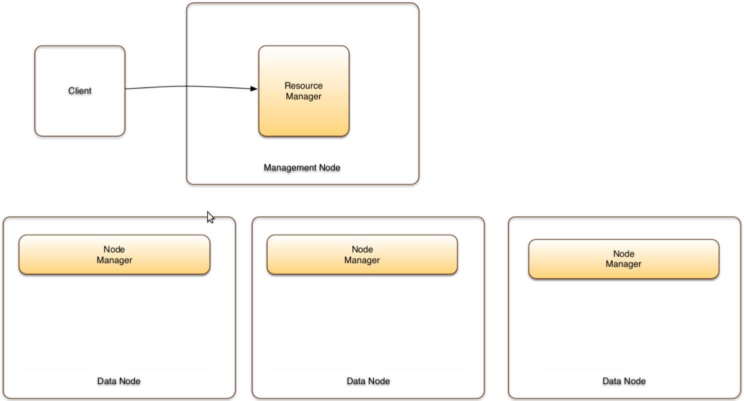
- Once the AM is done with its work, it should unregister from the RM and exit cleanly.

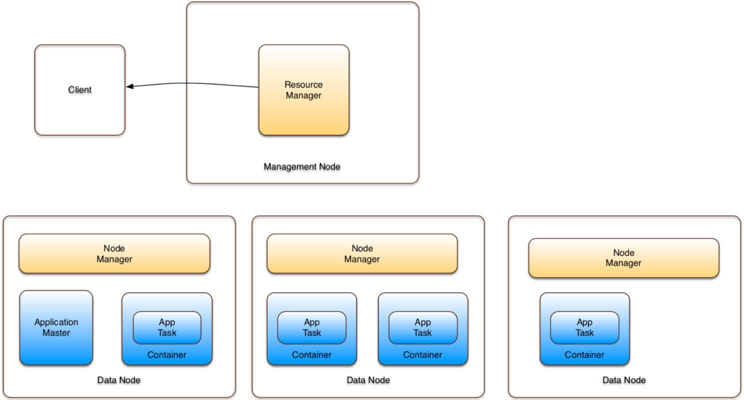
# Submitting a Job (1/9)

- A client submits a job.



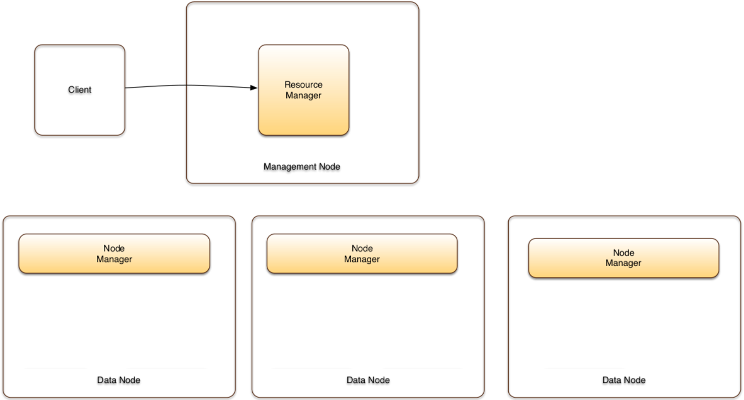
# Submitting a Job (2/9)

- The RM provides an Application Id.



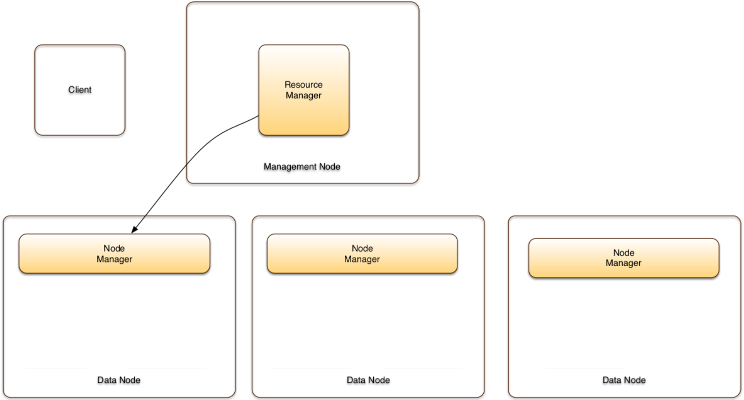
# Submitting a Job (3/9)

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



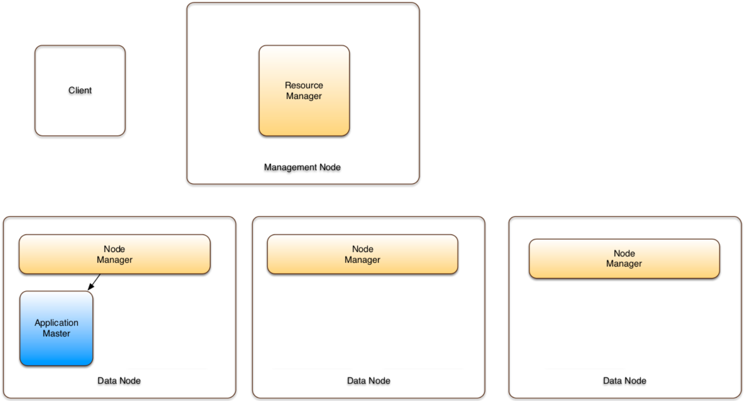
# Submitting a Job (4/9)

- The RM asks a NM to launch an AM.



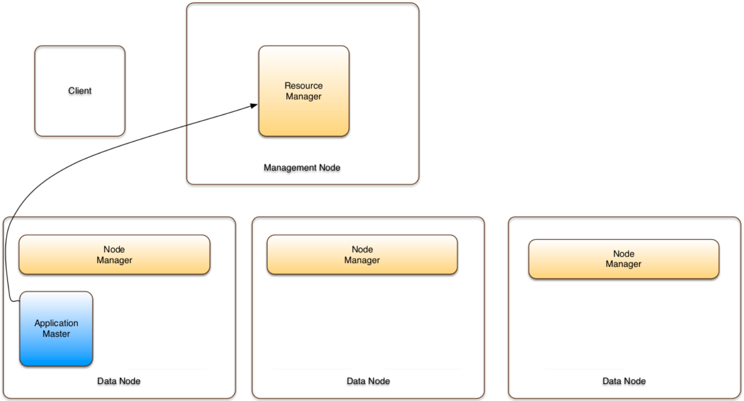
# Submitting a Job (5/9)

- The selected NM launches an AM.



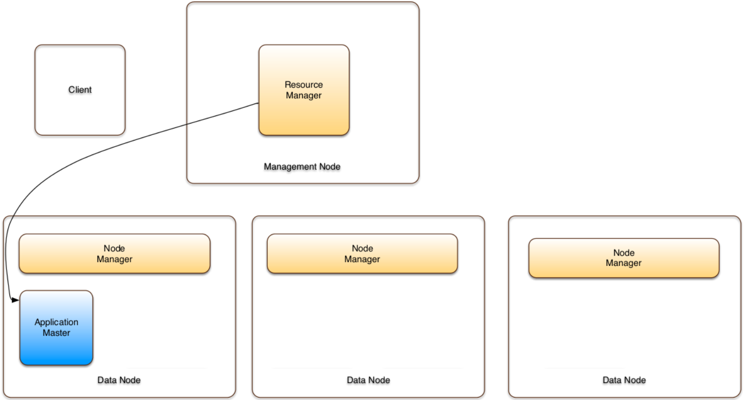
# Submitting a Job (6/9)

- The AM registers with the RM.



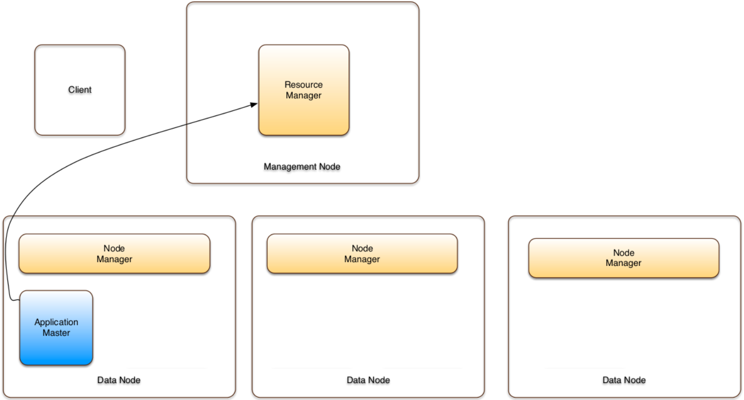
# Submitting a Job (7/9)

- The RM shares resource capabilities with the AM.



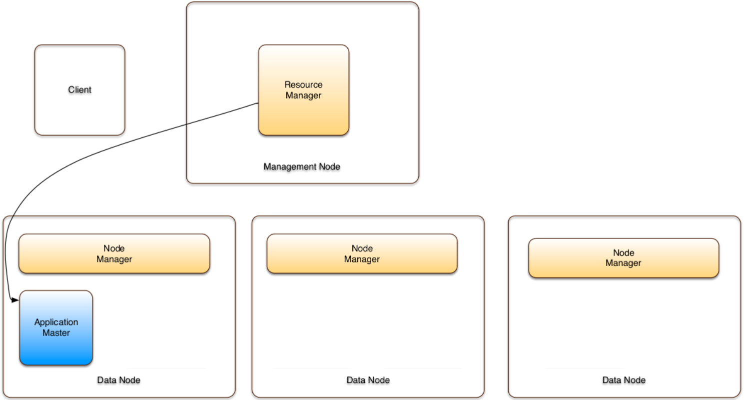
# Submitting a Job (8/9)

- The AM requests containers.



# Submitting a Job (9/9)

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



# Borg

# Borg

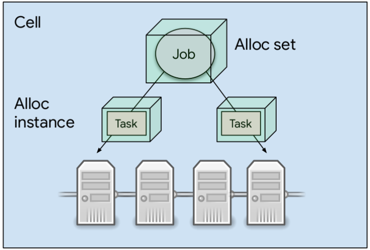
- Cluster management system at Google.

# 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.



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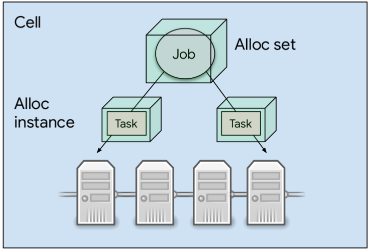

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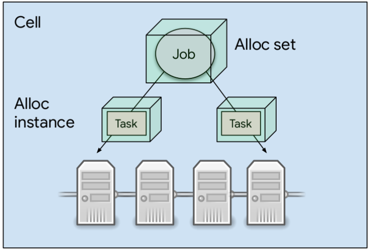

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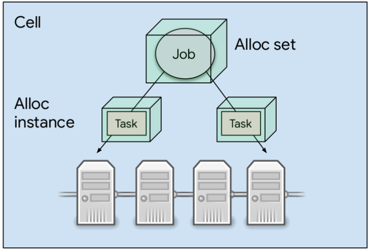

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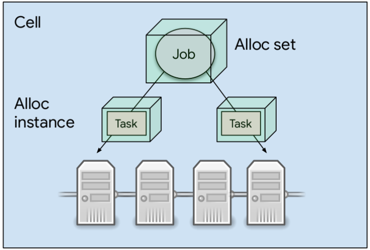
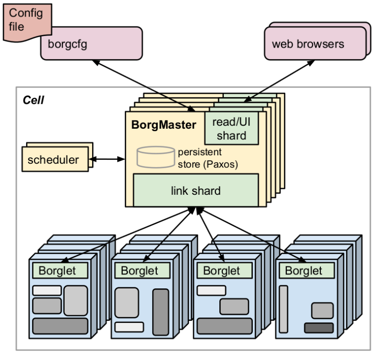
- Alloc instance: making each of its tasks run in an alloc instance.



# 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?



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- BorgMaster
  - The central brain of the system
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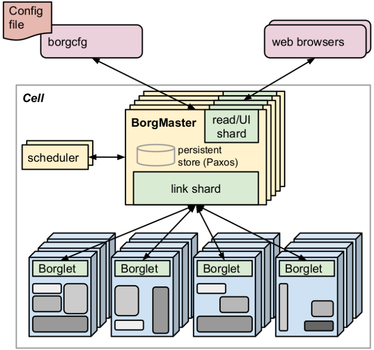
- Borglet
  - Manage and monitor tasks and resource
  - Borgmaster polls Borglet every few seconds



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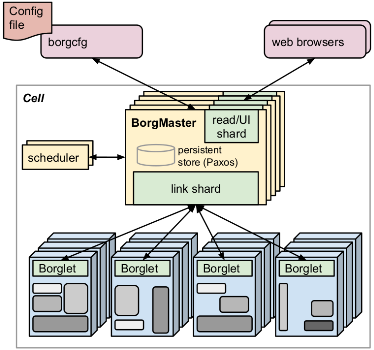

# Borg Architecture (2/2)

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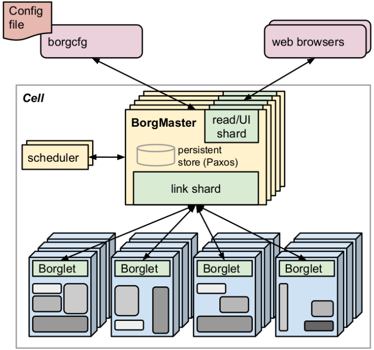

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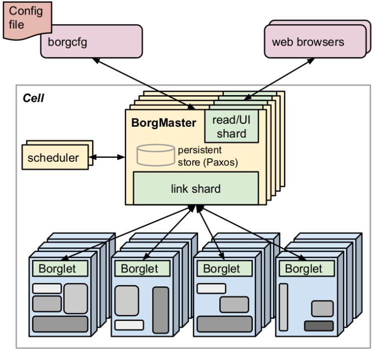

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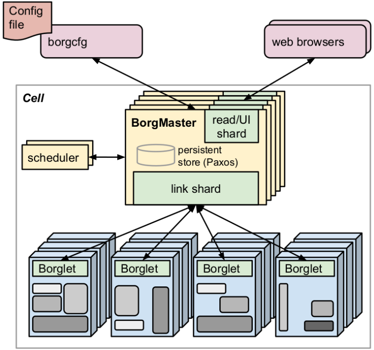

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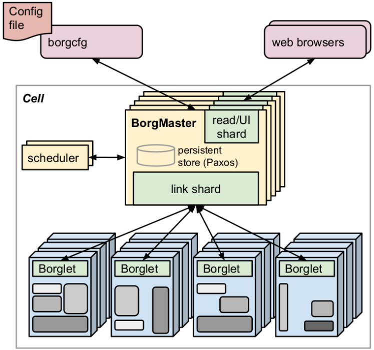
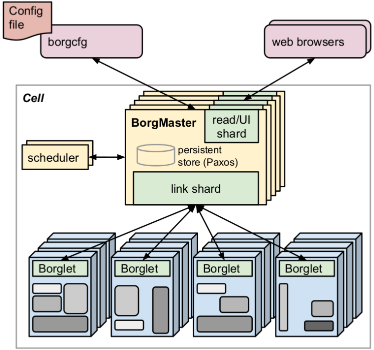


# Scheduler

- Feasibility checking: find machines for a given job



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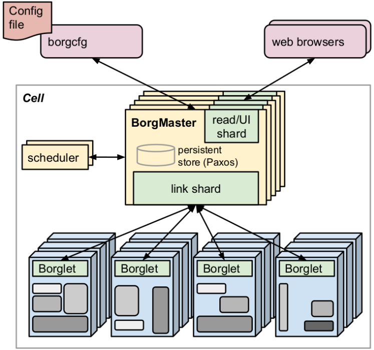

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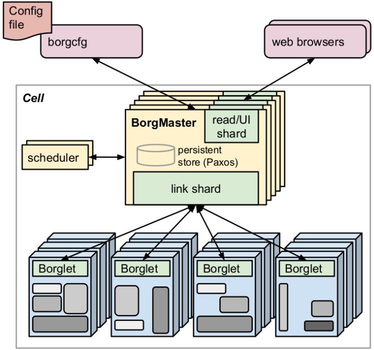

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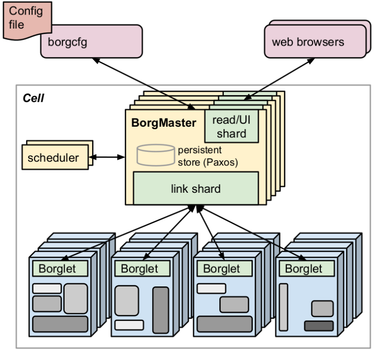

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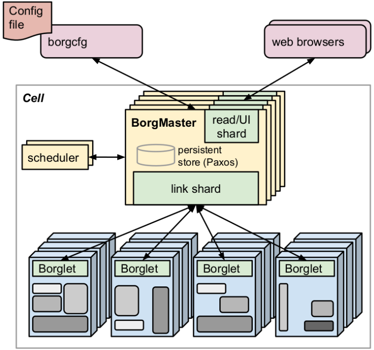

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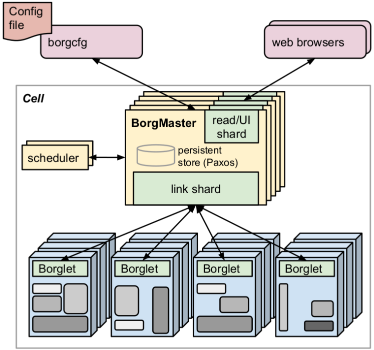

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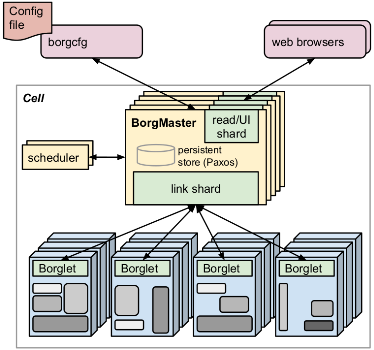
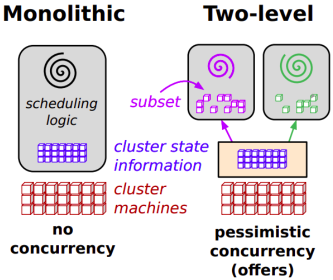


# Monolithic vs. Two-Level

- Monolithic schedulers: use a single, centralized scheduling algorithm for all jobs.




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

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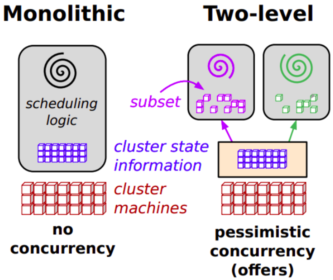


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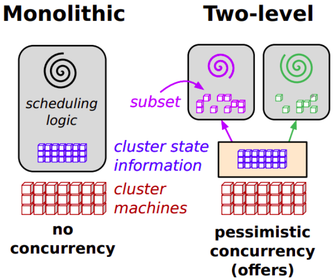


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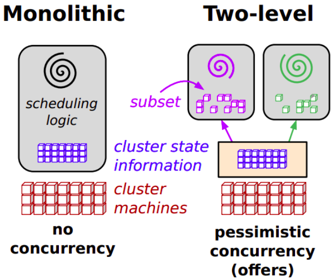


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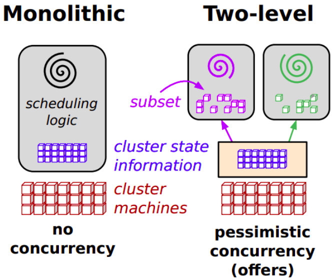


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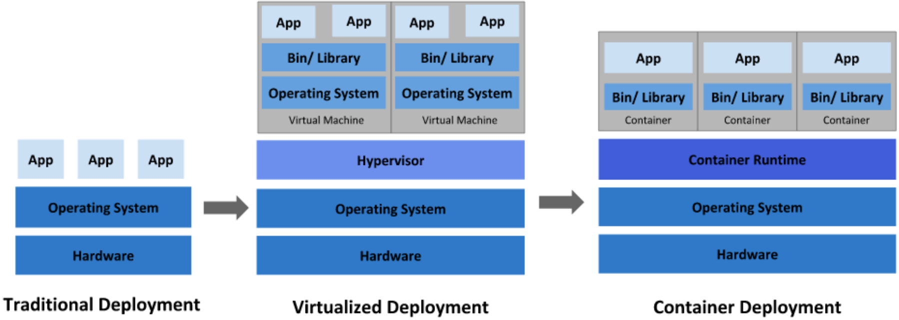
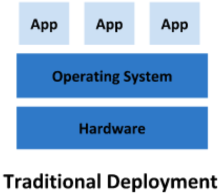
# Docker and Kubernetes

# Application Deployment



# Traditional Deployment Era

- Running applications on physical servers.



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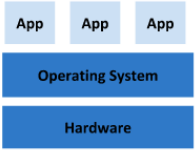


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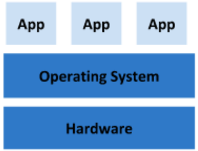


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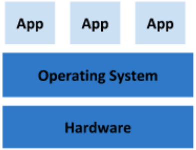
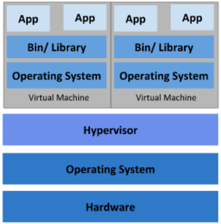
- Alternatively runnig each application on a different physical server: not scalable




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.

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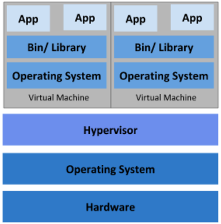


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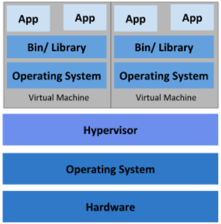


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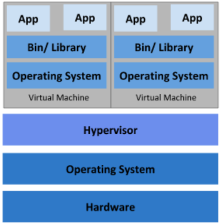


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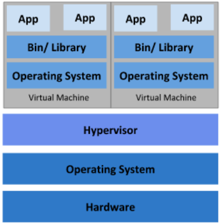


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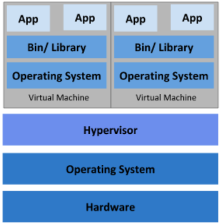
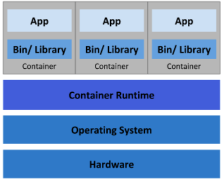
  - Utilizes the resources of a physical server better.
  - Better scalability as applications can be added/updated easily.




Virtualized Deployment

# Container Deployment Era

- Containers are similar to VMs, but they have relaxed isolation properties to share the OS among the applications.




Container Deployment

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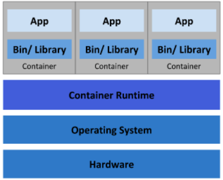

Container Deployment

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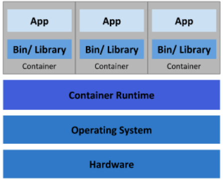
- Similar to a VM, a container packages applications as images that contain everything needed to run them: code, runtime environment, libraries, and configuration.
- As they are decoupled from the underlying infrastructure, they are portable across clouds and OS distributions.




Container Deployment

# Docker

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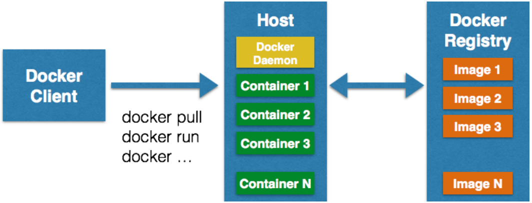

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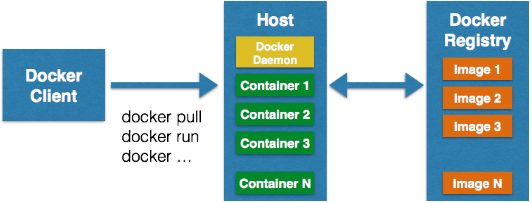

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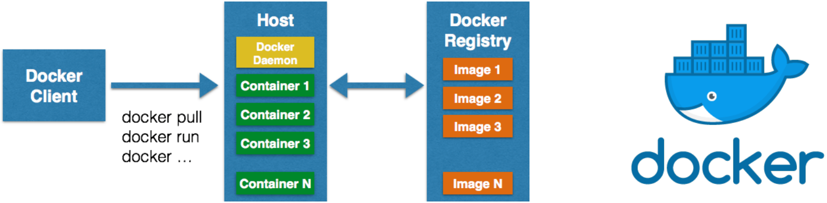
- Docker is a virtualization software.
- It is a client-server application.
- A docker image is a template, and a container is a copy of that template.



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  - 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)

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docker stop container_name
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- 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)

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- 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)

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- Health monitoring of containers and hosts
- Configuration of an application in relation to the containers running it.

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- Container orchestration tools: Kubernetes (based on Borg), Marathon (runs on Mesos)

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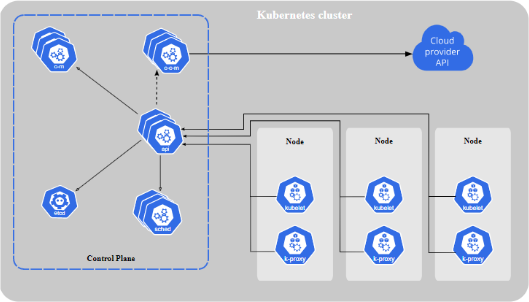
  - Borglet $\rightarrow$ Kubelet
  - alloc $\rightarrow$ pod
  - Borg containers $\rightarrow$ docker
  - Declarative specifications
- Improved
  - Job $\rightarrow$ labels
  - Managed ports $\rightarrow$ IP per pod
  - Monolithic master $\rightarrow$ micro-services

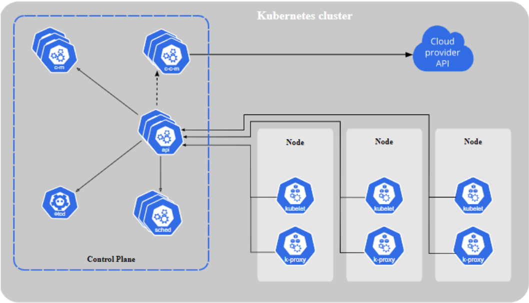
# Kubernetes Architecture (1/5)

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



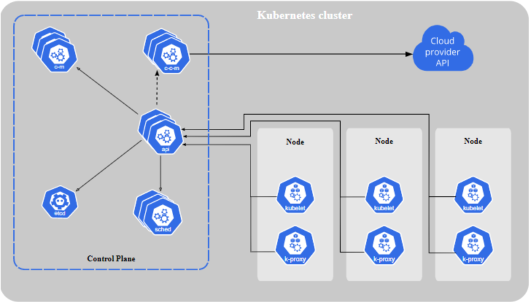
# Kubernetes Architecture (2/5)

- 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.



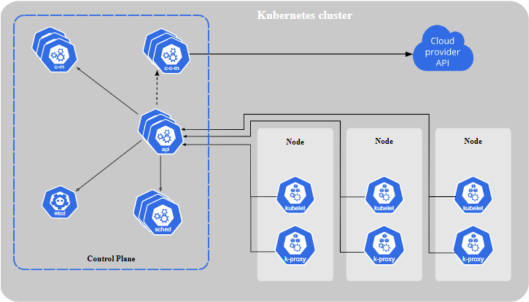
# Kubernetes Architecture (3/5)

- **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.



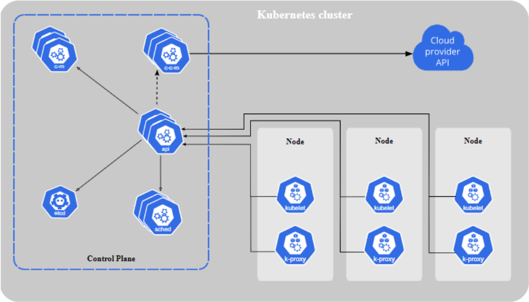
# Kubernetes Architecture (4/5)

- 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
- V. Vavilapalli et al., "Apache hadoop yarn: Yet another resource negotiator", ACM Cloud Computing 2013
- A. Verma et al., "Large-scale cluster management at Google with Borg", EuroSys 2015

# Questions?

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