Cluster Schedulers

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Introduction and Preliminaries

Overview of the Lecture

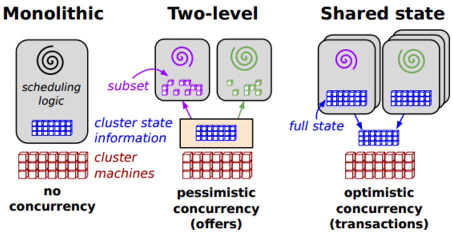
- **General overview of cluster scheduling principles**
  - General objectives
  - A taxonomy
  - Current architectures
- **In depth presentation of three representative examples**
  - Yarn
  - Mesos
  - Borg (Kubernetes)

Cluster Scheduling Principles

Objectives

- **Large-scale clusters are expensive, so it is important to use them well**
  - Cluster utilization and efficiency are key indicators for good resource management and scheduling decisions
  - Translates directly to cost arguments: better scheduling $\rightarrow$ smaller clusters
- **Multiplexing to the rescue**
  - Multiple, heterogeneous mixes of application run concurrently
  - $\rightarrow$ The scheduling problem is a challenge
- **Scalability bottlenecks**
  - Cluster and workload sizes keep growing
  - Scheduling complexity roughly proportional to cluster size
  - $\rightarrow$ Schedulers must be scalable

Current Scheduler Architectures

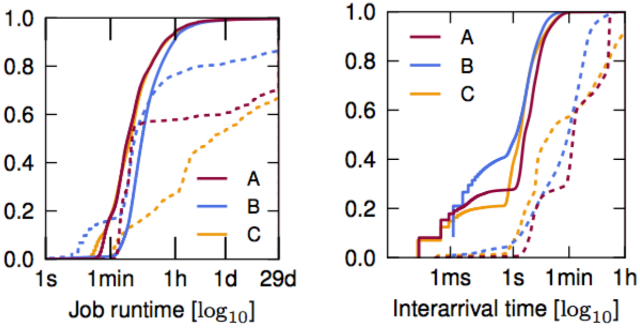


- **Monolitic:** use a centralized scheduling and resource management algorithm for all jobs
  - Difficult to add new scheduling policies
  - Do not scale well to large cluster sizes
- **Two-level:** single resource manager that grants resources to independent "framework schedulers"
  - Flexibility in accommodating multiple application frameworks
  - Resource management and locking are conservative, which can hurt cluster utilization and performance

Typical workloads to support

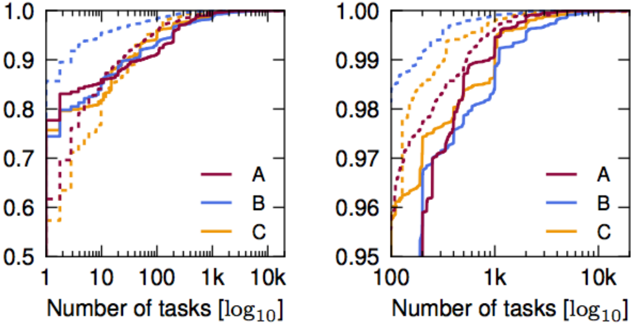
- **Cluster scheduler must support heterogeneous workloads and clusters**
  - Clusters are made of several generations of machines
  - Workloads evolve in time, and can be made of a variety of applications
- **Rough categorization of job types**
  - Batch jobs: e.g., MapReduce computations
  - Service jobs: e.g., end-user facing web service
- **Knowing your workload is fundamental!**
  - Next, some examples from real cluster traces
  - The rationale: measurements can inform scheduling design

Real cluster trace: workload characteristics



- Solid lines: batch jobs, dashed lines: service jobs

Real cluster trace: workload characteristics



- Solid lines: batch jobs, dashed lines: service jobs

Short Taxonomy of Scheduling Design Issues

- **Scheduling Work Partitioning:** how to distribute work across frameworks
  - Workload-oblivious load-balancing
  - Workload partitioning and specialized schedulers
  - Hybrid
- **Resource choice:** which cluster resources are available to concurrent frameworks
  - All resources available
  - A subset of cluster resources is granted (or offered)
  - NOTE: preemption primitives help scheduling flexibility at the cost of potentially wasting work

Short Taxonomy of Scheduling Design Issues

- **Interference:** what to do when multiple frameworks attempt at using the same resources
  - Pessimistic concurrency control: make sure to avoid conflicts, by partitioning resources across frameworks
  - Optimistic concurrency control: hope for the best, otherwise detect and undo conflicting claims

- **Allocation Granularity:** task “scheduling” policies
  - Atomic, all-or-nothing gang scheduling: e.g. MPI
  - Incremental placement, hoarding: e.g. MapReduce

- **Cluster-wide behavior:** some requirements need global view
  - Fairness across frameworks
  - Global notion of priority

Summary of design knobs

Approach	*Resource choice*	*Interference*	*Alloc. granularity*	*Cluster-wide policies*
Monolithic	all available	none (serialized)	global policy	strict priority (preemption)
Statically partitioned	fixed subset	none (partitioned)	per-partition policy	scheduler-dependent
Two-level (Mesos)	dynamic subset	pessimistic	hoarding	strict fairness

- **Comparison of cluster scheduling approaches**

Architecture Details

- **High-level summary of scheduling objectives**
  - Minimize the job queueing time, or more generally, the system response time (queueing + service times)
  - Subject to
    - Priorities among jobs
    - Per-job constraints
    - Failure tolerance
    - Scalability

- **Scheduling architectures**
  - Monolithic schedulers
  - Statically partitioned schedulers
  - Two-level schedulers
  - Shared-state schedulers (cf. Omega paper)

Monolithic Schedulers

- **Single centralized instance**
  - Typical of HPC setting
  - Implements all policies in a single code base
  - Applies the same scheduling algorithm to all incoming jobs
- **Alternative designs**
  - Support multiple code paths for different jobs
  - Each path implements a different scheduling logic
  - $\rightarrow$ Difficult to implement and maintain

Statically Partitioned Schedulers

- **Standard "Cloud-computing" approach**
  - Underlying assumption: each framework has complete control over a set of resources
  - Depend on statically partitioned, dedicated resources
  - Examples: Hadoop 1.0, Quincy scheduler
- **Problems with static partitioning**
  - Fragmentation of resources
  - Sub-optimal cluster utilization

Two-level Schedulers

- **Obviates the problems of static partitioning**
  - Dynamic allocation of resources to concurrent frameworks
  - Use a “logically centralized” coordinator to decide how many resources to grant
- **A first example: Mesos**
  - Centralized resource allocator, with dynamic cluster partitioning
  - **Available** resources are *offered* to competing frameworks
  - Avoids interference by exclusive offers
  - Frameworks lock resources by accepting offers → **pessimistic concurrency control**
  - No global cluster state available to frameworks
- **Another tricky example: YARN**
  - Centralized resource allocator (RM), with per-job framework master (AM)
  - AM only provides job management services, not proper scheduling

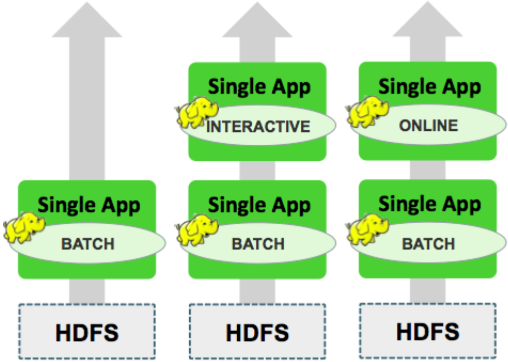
  → YARN is closer to a monolithic architecture

Representative Cluster Schedulers

YARN

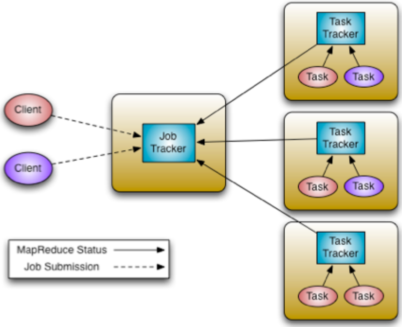
Introduction and Motivations

Hadoop 1.0: Focus on Batch applications



- **Built for batch applications**
  - Supports only MapReduce applications
- **Different silos for each usage pattern**

Hadoop 1.0: Architecture (reloaded)

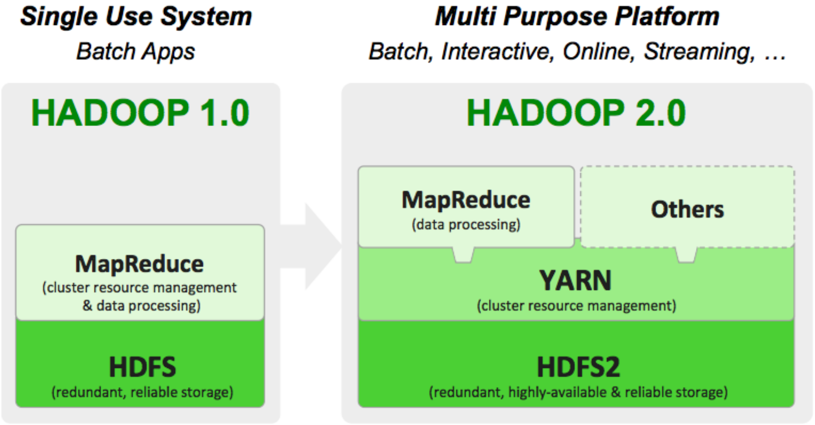


- **JobTracker**
  - Manages cluster resources
  - Performs Job scheduling
  - Performs Task scheduling
- **TaskTracker**
  - Per machine agent
  - Manages Task execution

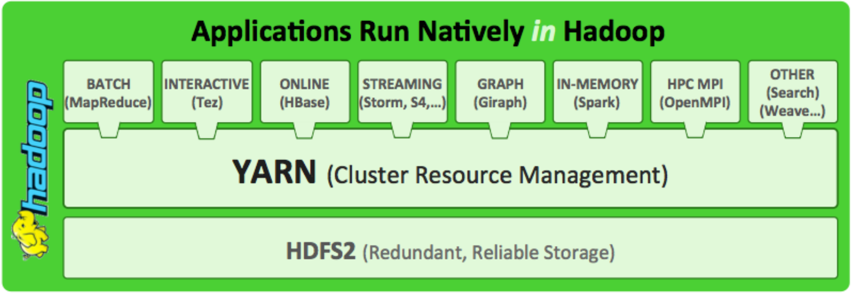
Hadoop 1.0: Limitations

- **Only supports MapReduce, no other paradigms**
  - Everything needs to be cast to MapReduce
  - Iterative applications are slow
- **Scalability issues**
  - Max cluster size roughy 4,000 nodes
  - Max concurrent tasks, roughly 40,000 tasks
- **Availability**
  - System failures destroy running and queued jobs
- **Resource utilization**
  - Hard, static partitioning of resources in Map or Reduce slots
  - Non-optimal resource utilization

Next Generation Hadoop



The YARN ecosystem



- **Store all data in one place**
  - Avoids costly duplication
- **Interact with data in multiple ways**
  - Not only in batch mode, with the rigid MapReduce model
- **More predictable performance**
  - Advanced scheduling mechanisms

Key Improvements in YARN (1)

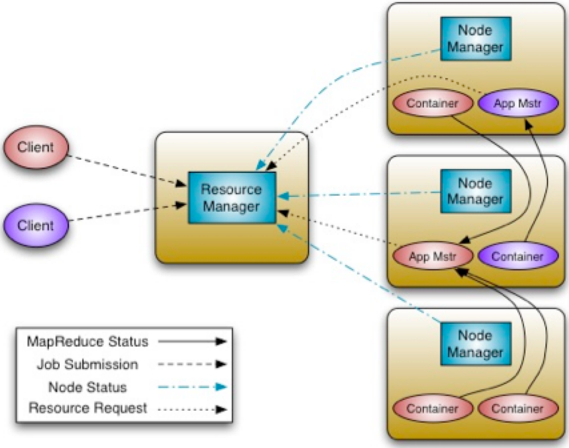
- **Support for multiple applications**
  - Separate generic resource brokering from application logic
  - Define protocols/libraries and provide a framework for custom application development
  - Share same Hadoop Cluster across applications
- **Improved cluster utilization**
  - Generic resource container model replaces fixed Map/Reduce slots
  - Container allocations based on locality and memory
  - Sharing cluster among multiple application
- **Improved scalability**
  - Remove complex app logic from resource management
  - State machine, message passing based loosely coupled design
  - Compact scheduling protocol

Key Improvements in YARN (2)

- **Application Agility**
  - Use Protocol Buffers for RPC gives wire compatibility
  - Map Reduce becomes an application in user space
  - Multiple versions of an app can co-exist leading to experimentation
  - Easier upgrade of framework and applications
- **A data operating system: shared services**
  - Common services included in a pluggable framework
  - Distributed file sharing service
  - Remote data read service
  - Log Aggregation Service

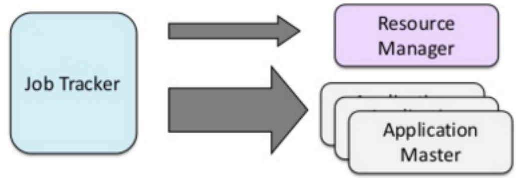
YARN Architecture Overview

YARN: Architecture Overview



YARN: Design Decisions

- **No static resource partitioning**
  - There are no more slots
  - Nodes have resources, which are allocated to applications when requested
- **Separate resource management from application logic**
  - Cluster-wide resource allocation and management
  - Per-application master component
  - Multiple applications $\rightarrow$ multiple masters

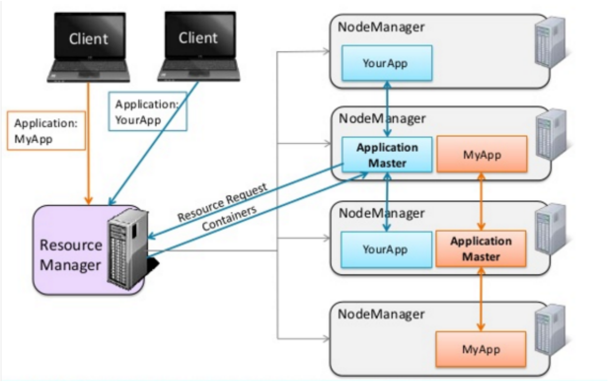


YARN Daemons

- **Resource Manager (RM)**
  - Runs on master node
  - Global resource manager and scheduler
  - Arbitrates system resources between **competing** applications
- **Node Manager (NM)**
  - Run on slave nodes
  - Communicates with RM
  - Reports utilization
- **Resource containers**
  - Created by the RM upon request
  - Allocate a certain amount of resources on slave nodes
  - Applications run in one or more containers
- **Application Master (AM)**
  - One per application, **application specific**[1]
  - Requests more containers to execute application tasks
  - Runs in a container

[1] Every new application requires a new AM to be designed and implemented!

YARN: Example with 2 Applications

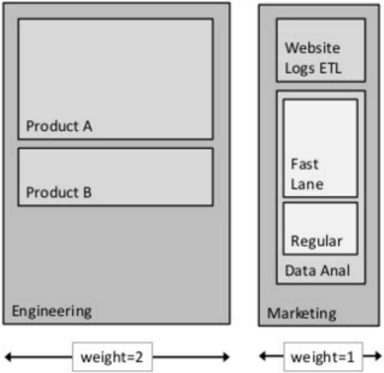


YARN Core Components

YARN Schedulers (1)

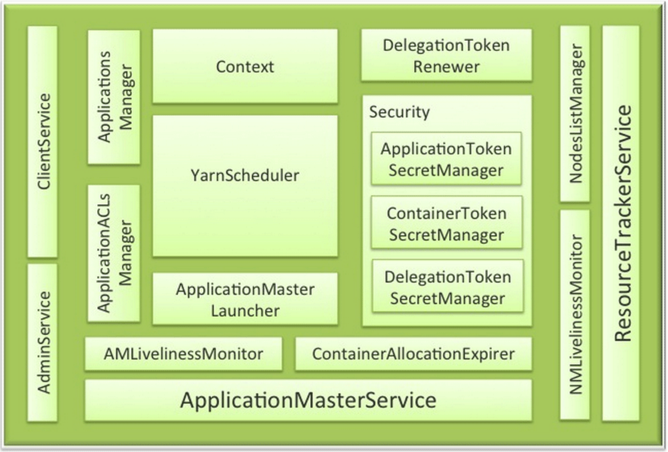
- **Schedulers are a pluggable component of the RM**
  - In addition to existing ones, advanced scheduling is supported
- **Current supported schedulers**
  - The Capacity scheduler
  - The Fair scheduler
  - Dominant Resource Fairness
- **What's different w.r.t. Hadoop 1.0?**
  - Support any YARN application, not just MapReduce
  - No more slots, tasks are scheduled based on resources
  - Some terminology change

YARN Schedulers (2)



- **Hierarchical queues**
  - Queues can contain sub-queues
  - Sub-queues share resources assigned to queues

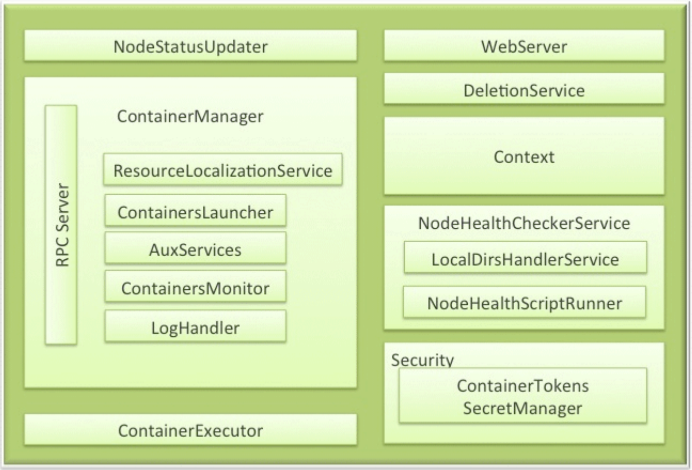
YARN Resource Manager: Overview



YARN Resource Manager: Operations

- **Node Management**
  - Tracks hearbeats from NMs
- **Container Management**
  - Handles AM requests for new containers
  - De-allocates containers when they expire or application finishes
- **AM Management**
  - Creates a container for every new AM, and tracks its health
- **Security Management**
  - Kerberos integration

YARN Node Manager: Overview



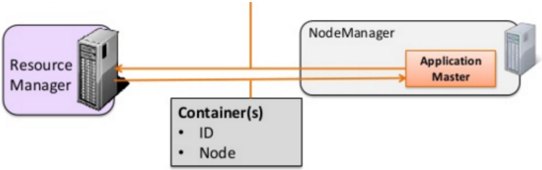
YARN Node Manager: Operations

- **Manages communications with the RM**
  - Registers, monitors and communicates node resources
  - Sends heartbeats and container status
- **Manages processes in containers**
  - Launches AMs on request from the RM
  - Launches application processes on request from the AMs
  - Monitors resource usage
  - Kills processes and containers
- **Provides logging services**
  - Log aggregation and roll over to HDFS

YARN Resource Request

Resource Request

- **Resource name:** hostname, rackname, *
- **Priority:** within the same application, not across apps
- **Resource requirements:** memory, CPU, and more to come...
- **Number of containers**



YARN Containers

Container Launch Context

- **Container ID**
- **Commands to start application task(s)**
- **Environment configuration**
- **Local resources:** application/task binary, HDFS files

YARN Fault Tolerance

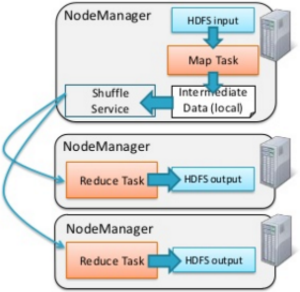
- **Container failure**
  - AM re-attempts containers that complete with exceptions or fail
  - Applications with too many failed containers are considered failed

- **AM failure**
  - If application or AM fail, the RM will re-attempt the whole application
  - Optional strategy: job recovery
    - If false, all containers are re-scheduled
    - If true, uses state to find which containers succeeded and which failed, to re-schedule only failed ones

YARN Fault Tolerance

- **NM failure**
  - If NM stops sending heartbeats, RM removes it from active node list
  - Containers on the failed node are re-scheduled
  - AM on the failed node are re-submitted completely
- **RM failure**
  - No application can be run if RM is down
  - Can work in active-passive mode (just like the NN of HDFS)

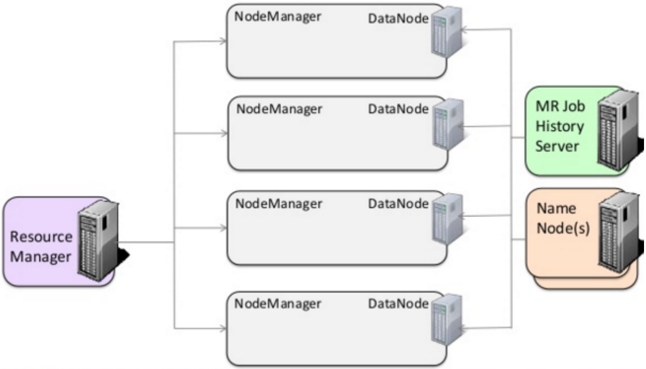
YARN Shuffle Service



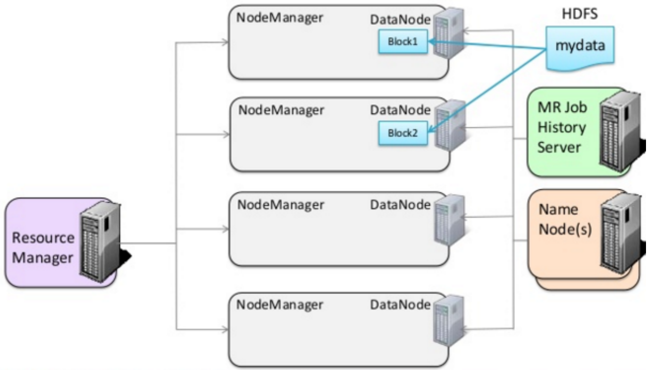
- **The Shuffle mechanism is now an auxiliary service**
  - Runs in the NM JVM as a persistent service

YARN Application Example

YARN WordCount execution



YARN WordCount execution



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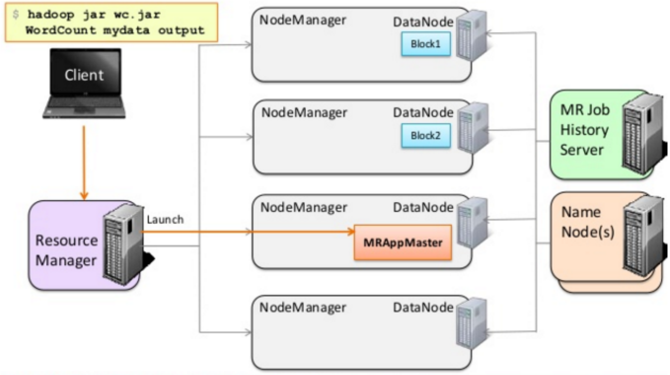

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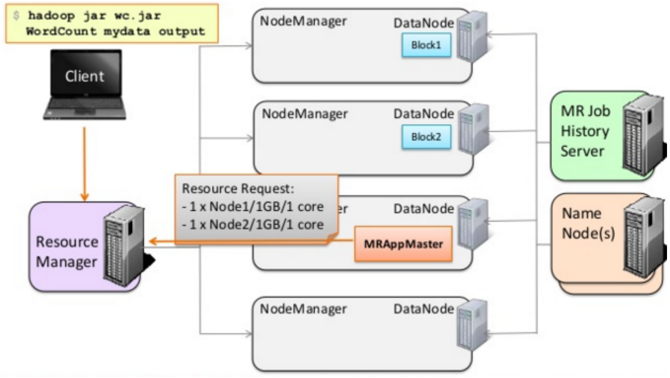

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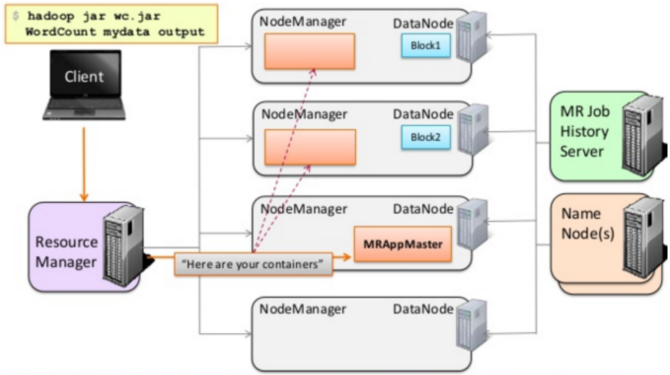

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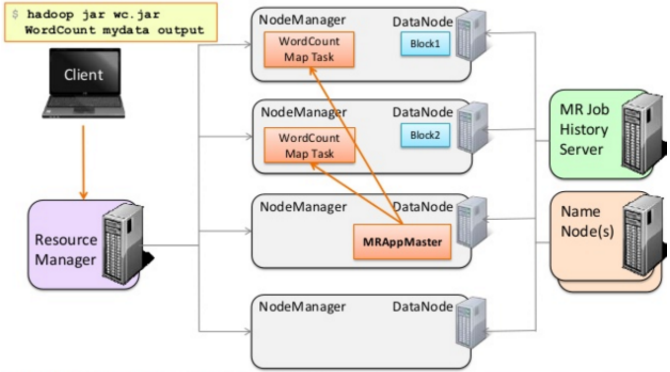

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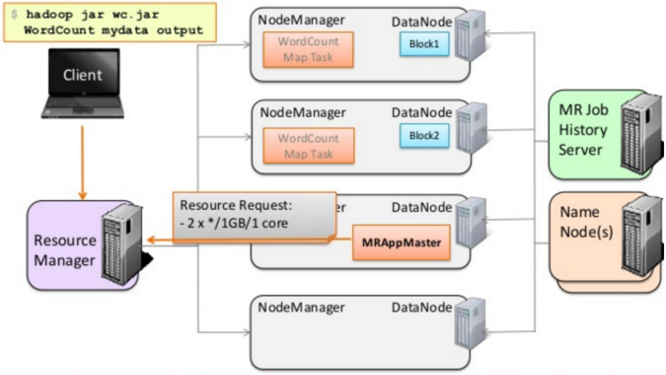

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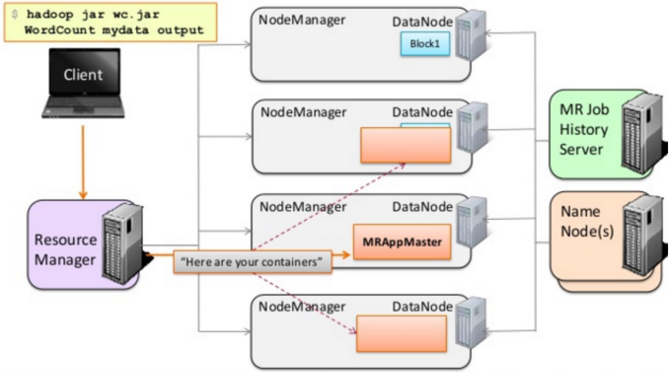

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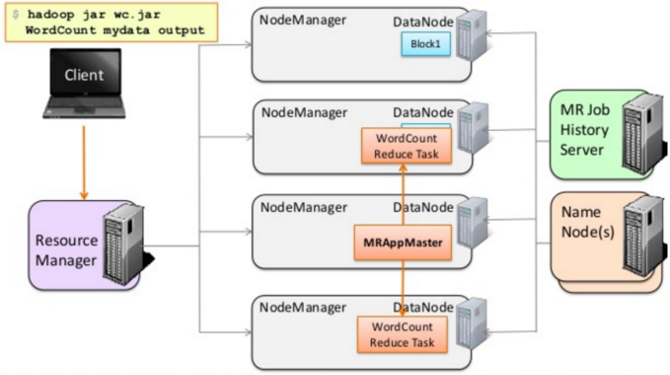

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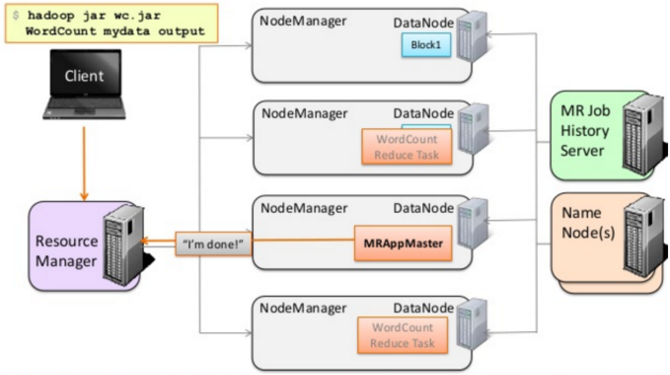


Mesos

Introduction

Introduction and Motivations

- **Clusters of commodity servers major computing platform**
  - Modern Internet Services
  - Data-intensive applications
- **New** *frameworks* **developed to "program the cluster"**
  - Hadoop MapReduce, Apache Spark, Microsoft Dryad
  - Pregel, Storm, ...
  - and many more
- **No** *one-size fit them all*
  - Pick the right frameworks for the application
  - Run multiple frameworks at the same time

→ **Multiplexing cluster resources among frameworks**
  - Improves cluster utilization
  - Allows sharing of data without the need to replicate it

Common Solutions to Share a Cluster

- **Common practice to achieve cluster sharing**
  - *Static* partitioning
  - Traditional virtualization

- **Problems of current approaches**
  - Mismatch between allocation granularities
  - No mechanism to allocate resources to short-lived tasks

$\rightarrow$ **Underlying hypothesis for Mesos**
  - Cluster frameworks operate with short tasks
  - Cluster resources free up quickly
  - This allows to achieve **data locality**

Mesos Design Objectives

Mesos: a thin resource sharing layer enabling fine-grained sharing across diverse frameworks

- **Challenges**
  - Each supported framework has different scheduling needs
  - Scalability is crucial: Mesos must scale to clusters of 10,000+ nodes, running hundreds of jobs with millions of tasks
  - Fault-tolerance and high availability

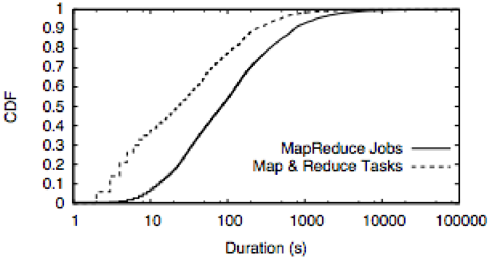
- **Would a centralized approach work?**
  - Input: framework requirements, instantaneous resource availability, organization policies
  - Output: global schedule for all tasks of all jobs of all frameworks

Mesos Key Design Principles

- **Centralized approach does not work**
  - Complexity
  - Scalability and resilience
  - Moving framework-specific scheduling to a centralized scheduler requires expensive refactoring
- **A decentralized approach**
  - Based on the abstraction of a *resource offer*
  - Mesos decides **how many** resources to offer to a framework
  - The framework decides **which** resources to accept and which tasks to run on them

Target Workloads

Target Environment



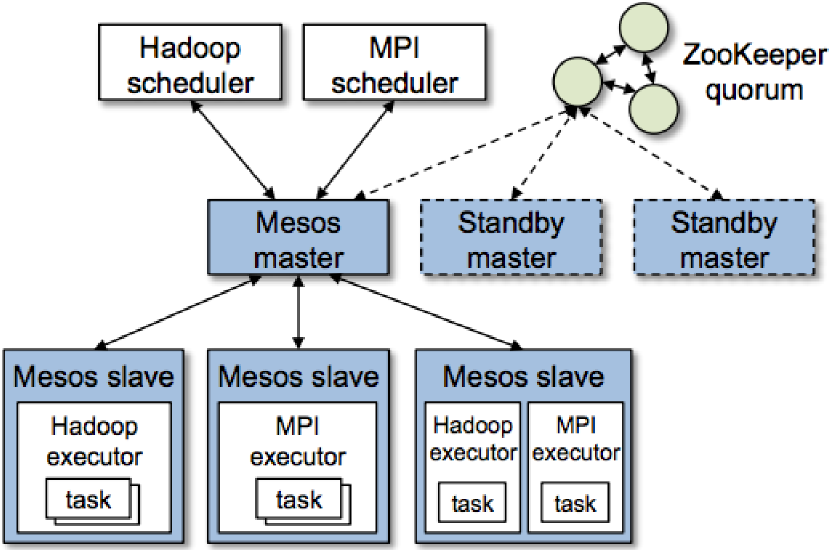
- **Typical workloads in "Data Warehouse" systems**
  - Heterogeneous MapReduce jobs, *production* and *ad-hoc* queries
  - Large scale machine learning
  - SQL-like queries

Architecture

Design Philosophy

- **Data center operating system**
  - Scalable and resilient core exposing low-level interfaces
  - High-level libraries for common functionalities
- **Minimal interface to support resource sharing**
  - Mesos manages cluster resources
  - Frameworks control task scheduling and execution
- **Benefits of two-level approach**
  - Frameworks are independent and can support diverse scheduling requirements
  - Mesos is kept simple, minimizing the rate of change to the system

Architecture Overview



Architecture Overview

The Mesos Master

- Uses **Resource Offers** to implement fine-grained sharing
- Collects resource utilization from slaves
- Resource offer: list of free resources on multiple slaves

First-level Scheduling

- Master decides how many resources to offer a framework
- Implements a cluster-wide allocation policy:
  - Fair Sharing
  - Priority based

Architecture Overview

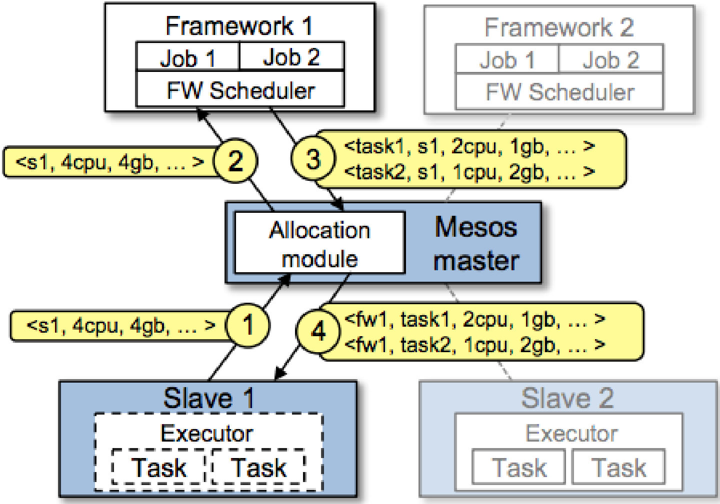
Mesos Frameworks

- Framework **scheduler**
  - Registers to the master
  - Selects **which offer to accept**
  - Prepares a description of the tasks to launch on accepted resources
- Framework **executor**
  - Launched on Mesos slaves executing on accepted resources
  - Takes care of running the framework's tasks

Second-level Scheduling

- One framework scheduler per application
- Framework decides how to execute a job and its tasks
- **NOTE:** The actual task execution is requested by the master

Resource Offer Example



Consequences of the Mesos Architecture

- **Mesos makes no assumptions on Framework requirements**
  - This is unlike other approaches, which requires the cluster scheduler to understand application constraints
  - This does not mean that users are not required to express their applications' constraints
- **Rejecting offers**
  - It is the framework that decides to reject a resource offer that does not satisfy application constraints
  - Frameworks can **wait** for offers to satisfy constraints

Arbitrary and complex resource constraints

- Delegate logic and control to individual frameworks
- Mesos also implements **filters** to optimize the resource offer mechanism

Resource Allocation

- **Pluggable allocation module**
  - Max-min Fairness
  - Strict priority
- **Fundamental assumption**
  - Tasks are short
  - $\rightarrow$ Mesos only reallocates resources when tasks finish
- **Example**
  - Assume a Framework's share is 10% of the cluster
  - It needs to wait 10% of the mean task length to receive its share

Resource Revocation

- **Short vs. long lived tasks**
  - Some jobs (e.g. streaming) may have long tasks
  - In this case, Mesos can **Kill** running tasks
- **Preemption primitives**
  - Require knowledge about potential resource usage by frameworks
  - Killing might be wasteful, although not critical (e.g. MapReduce)
  - Some applications (e.g. MPI) might be harmed
- **Guaranteed allocation**
  - Minimum set of resources granted to a framework
  - If below guaranteed allocation $\rightarrow$ never kill tasks
  - If above guaranteed allocation $\rightarrow$ kill any tasks

Performance Isolation

- **Isolation between executors on the same slave**
  - Achieved through low-level OS primitives
  - Pluggable isolation modules to support a variety of OS
- **Currently supported mechanisms**
  - Limit CPU, memory, network and I/O bandwidth of a process tree
  - Linux Containers and Solaris Cages
- **Advantages and limitations**
  - Better isolation than current approach, process-based
  - Fine grained isolation is not yet fully functional

Mesos Scalability

- **Filter mechanism**
  - Short-circuit the rejection process, avoids unnecessary communication
  - Filter type 1: restrict which slave machines to use
  - Filter type 2: check resource availability on slaves
- **Incentives to speed-up the resource offer mechanism**
  - Mesos counts offers to a framework toward its allocation
  - Frameworks have to answer and/or filter as quickly as possible
- **Rescinding offers**
  - Mesos can decide to invalidate an offer to a framework
  - This avoids blocking and misbehavior

Mesos Fault Tolerance

- **Master designed with *Soft State***
  - List of active slaves
  - List of registered frameworks
  - List of running tasks
- **Multiple masters in a hot-standby mode**
  - Leader election through Zookeeper
  - Upon failure detection new master is elected
  - Slaves and executors help populating the new master's state
- **Helping frameworks to tolerate failure**
  - Master sends "health reports" to framework schedulers
  - Master allows multiple schedulers for a single framework

System behavior: a very rough Mesos "model"

Overview: Mesos in a nutshell

- **Ideal workloads for Mesos**
  - Elastic frameworks, supporting scaling up and down seamlessly
  - Task durations are homogeneous (and short)
  - No strict preference over cluster nodes
- **Frameworks with cluster node preferences**
  - Assume frameworks prefer different (and possibly disjoint) nodes
  - Mesos can emulate a centralized scheduler
  - Cluster and Framework wide fair resource sharing
- **Heterogeneous task durations**
  - Mesos can handle coexisting short and long lived tasks
  - Performance degradation is acceptable

Definitions

- **Workload characterization**
  - *Elasticity:* elastic workloads can use resources as soon as they are acquired, and releases them as soon as tasks finish; in contrast, rigid frameworks (e.g. MPI) can only start a job when **all** resources have been acquired, and do not work well with scaling
  - *Task runtime distribution:* both homogeneous and not

- **Resource characterization**
  - *Mandatory:* resource that a framework **must** acquire to work. Assumption: mandatory resources $<$ guaranteed share
  - *Preferred:* resources that a framework **should** acquire to achieve better performance, but are not necessary for the job to work

Performance Metrics

- **Performance metrics**
  - *Framework ramp-up time:* time it takes a new framework to achieve its fair share
  - *Job completion time:* time it takes a job to complete. Assume one job per framework
  - *System utilization:* total cluster resource utilization, with focus on CPU and memory

Homogeneous Tasks

- Cluster with *n* slots and a framework *f* entitled with *k* slots
- Task runtime distribution: uniform and exponential
- Mean task duration T
- Job duration: $\beta k T$

$\rightarrow$ If *f* has *k* slots, then job duration is βT

	Elastic Framework		Rigid Framework	
	Constant dist.	Exponential dist.	Constant dist.	Exponential dist.
Ramp-up time	T	$T \ln k$	T	$T \ln k$
Completion time	$(1/2 + \beta)T$	$(1 + \beta)T$	$(1 + \beta)T$	$(\ln k + \beta)T$
Utilization	1	1	$\beta/(1/2 + \beta)$	$\beta/(\ln k - 1 + \beta)$

Placement preferences

Consider two cases:

- **There exist a configuration satisfying all frameworks constraints**
  - The system will eventually converge to the state in which the optimal allocation is achieved, and this in at most one T interval
- **No such allocation exists, e.g. demand is larger than supply**
  - **Lottery Scheduling** to achieve a **weighted fair allocation**
  - Mesos offers a slot to framework i with probability

$$\frac{s_i}{\sum_{i=1}^{m} s_i}$$

  - where s_i is framework's i **intended** allocation, and m is the total number of frameworks registered to Mesos

Heterogeneous Tasks

- **Assumptions**
  - Workloads with tasks that are either long or short
  - Mean duration of long task is longer than short ones
- **Worst case scenario**
  - All nodes required by a “short job” are filled with long tasks, which means it has to wait for a long time
- **How likely is the worst case?**
  - Assume $\phi < 1$, where ϕ fraction of long tasks
  - Assume a cluster with S available slots per node

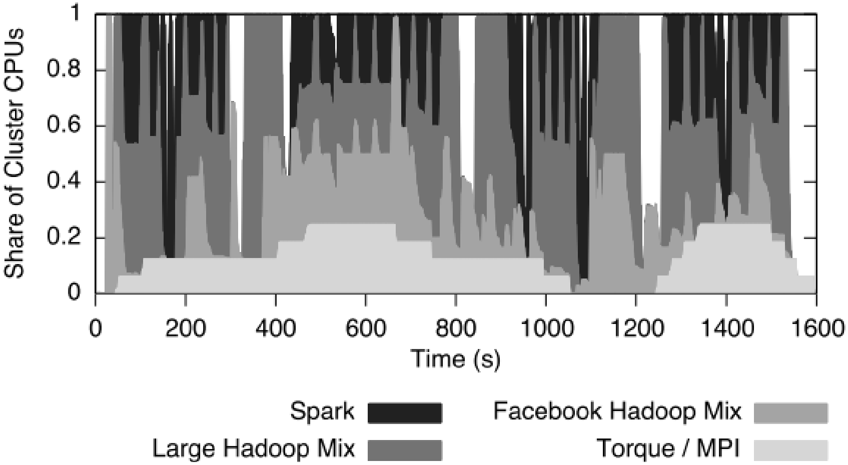
  $\rightarrow$ Probability for a node to be filled with long tasks is ϕ^S
  - $S = 8$ and $\phi = 0.5$ gives a 0.4% chance

Limitations of Distributed Scheduling

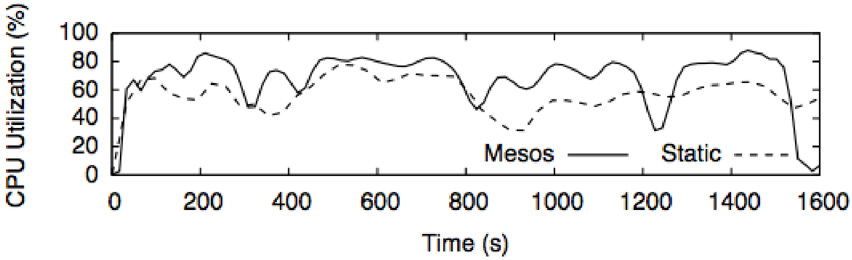
- **Fragmentation**
  - Provokes under utilization of system resources
  - Distributed collection of frameworks might not achieve the same “packing” quality of a centralized scheduler
  - → This is mitigated by having clusters of “big” nodes (many CPUs, many cores) running “small” tasks
- **Starvation**
  - Large jobs may wait indefinitely for slots to become free
  - Small tasks from small jobs might monopolize the cluster
  - → This is mitigated by a *minimum offer size* mechanism

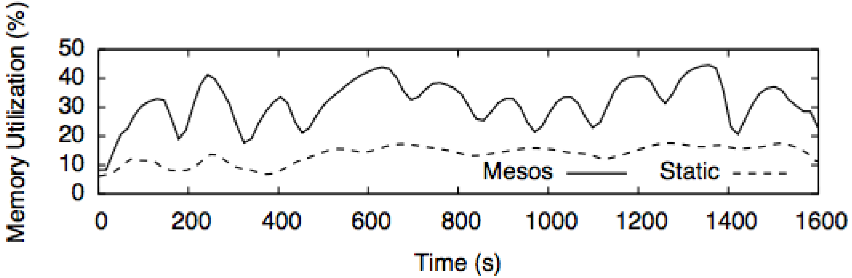
Experimental Mesos Performance Evaluation

Resource Allocation

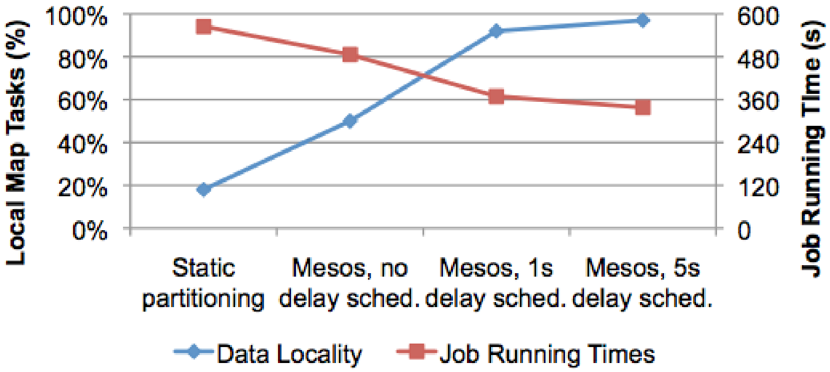


Resource Utilization





Data Locality



Borg

Introduction

Introduction and Objectives

- **Hide the details of resource management**
  - Let users instead focus on application developlemt
- **Operate applications with high reliability and availability**
  - Tolerate failures within a datacenter and across datacenters
- **Run heterogeneous workloads and scale across thousands of machines**

The User Perspective

Terminology

- **Users develop applications called *jobs***
- **Jobs consists in one or more *tasks***
- **All tasks run the same binary**
- **Each job runs in a set of machines managed as a unit, called a *Borg Cell***

Workloads

- **Two main categories supported**
  - Long-running services: jobs that should "never" go down, and handle short-lived, latency-sensitive requests
  - Batch jobs: delay-tolerant jobs that can take from few seconds to few days to complete
  - Storage services: these are long-running services like above, that are used to store data
- **Workload composition in a cell is dynamic**
  - It varies depending on the tenants using the cell
  - It varies with time: diurnal usage pattern for end-user-facing jobs, irregular pattern for batch jobs
- **Examples**
  - High-priority, `production` jobs $\rightarrow$ long-running services
  - Low-priority, `non-production` jobs $\rightarrow$ batch jobs
  - In a typical Borg Cell
    - Prod Jobs: 70% of CPU allocation, representing 60% of CPU usage
    - Non-prod Jobs: 55% of CPU allocation, representing 85% of CPU usage

Clusters and Cells

- **Borg Cluster:** a set of machines connected by a high-performance datacenter-scale network fabric
  - The machines in a Borg Cell all belong to a *single* cluster
  - A cluster lives inside a datacenter building
  - A collection of building makes up a *Site*
- **Borg Machines:** physical servers dedicated to execute Borg applications
  - They are generally highly heterogeneous in terms of resources
  - They may expose a public IP address
  - They may expose advanced features, like SSD or GPGPU
- **Examples**
  - A typical cluster usually hosts one large cell and a few small-scale test cells
  - The *median cell size* is about 10k machines
  - Borg uses those machines to schedule application tasks, install their binaries and dependencies, monitor their health and restarting them if they fail

Jobs and Tasks

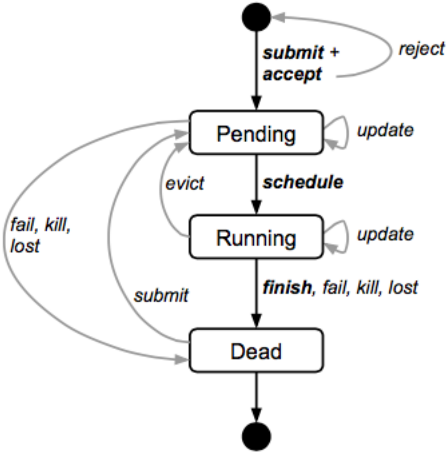
- **Job Definition**
  - Name, owner and number of tasks
  - *Constraints* to force tasks run on machines with particular *attributes*
  - Constraints can be **hard** or **soft** (*i.e.*, preferences)
  - Each task maps to a set of UNIX processes running in a container on a Borg machine in a Borg Cell

- **Task Definition**
  - Task index within their parent job
  - Resource requirements
  - Generally, all tasks have the *same* definition
  - Tasks can run on **any resource dimension**: there are no fixed-size slots or buckets

Jobs and Tasks

- **The Borg Configuration Language**
  - Declarative language to specify jobs and tasks
  - Lambda functions to allow calculations
  - Some application descriptions can be over 1k lines of code
- **User interacting with live jobs**
  - This is achieved mainly using RPC
  - Users can update the specification of tasks, while their parent job is running
  - Updates are non-atomic, executed in a rolling-fashion
- **Task updates "side-effects"**
  - Always require restarts: e.g., pushing a new binary
  - Might require migration: e.g., change in specification
  - Never require restarts nor migrations: e.g., change in priority

Jobs State Diagram



Resource Allocations

- **The Borg “Alloc”**
  - Reserved set of resources on **an individual machine**
  - Can be used to execute one or more tasks, that equally share resources
  - **Resources remain assigned whether or not they are used**

- **Typical use of Borg Allocs**
  - Set resources aside for future tasks
  - Retain resources between stopping and starting tasks
  - Consolidate (gather) tasks from different jobs on the same machine

- **Alloc Sets**
  - Group of allocs on different machines
  - Once an alloc set has been created, one or more jobs can be submitted

Priority, Quota and Admission Control

- **Mechanisms to deal with resource demand and offer**
  - What to do when more work shows up than can be accommodated?
  - Note: this is not *scheduling*, it is more admission control
- **Job priority**
  - Non-overlapping *priority bands* for different uses
  - This essentially means users must "manually" cluster their applications according to such bands
  - → Tasks from high-priority jobs can preempt low-priority tasks
  - Cascade preemption is avoided by disabling it for same-band jobs
- **Job/User quotas**
  - Used to decide which job to admit for scheduling
  - Expressed as a vector of resource quantities
- **Pricing**
  - Underlying mechanism to regulate user behavior
  - Aligns user incentives to better resource utilization
  - Discourages over-buying by over-selling quotas at lower priority

Naming Services

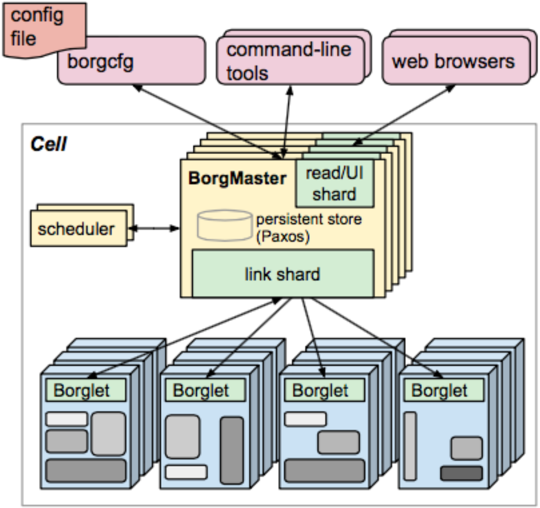
- **Borg Name Service**
  - A mechanism to assign a name to tasks
  - Task name = Cell name, job name and task number
- **Uses the Chubby coordination service**
  - Writes task names into it
  - Writes also health information and status
  - Used by Borg RPC mechanism to establish communication endpoints
- **DNS service inherits from BNS**
  - Example: the 50th task in job "jfoo" owned by user "ubar" in a Borg Cell called "cc"
  - `50.jfoo.ubar.cc.borg.google.com`

Monitoring Services

- **Every task in Borg has a built-in HTTP server**
  - Provides health information
  - Provides performance metrics
- **Borg SIGMA**
  - Monitoring UI Service
  - State of jobs, of cells
  - Drill-down to task level
  - **Why pending?**
    - "Debugging" service
    - Helps users with finding job specifications that can be easily scheduled
- **Billing services**
  - Use monitoring information to compute usage-based charging
  - Help users debug their jobs
  - Used for capacity planning

Borg Architecture

Architecture Overview



Architecture Overview

- **Architecture components**
  - A set of physical machines
  - A *logically centralized* controller, the **Borgmaster**
  - An agent process running on all machines, the **Borglet**

The Borgmaster: Components

- **The Borgmaster**
  - One per Borg Cell
  - Orchestrates cell resources
- **Components**
  - The Borgmaster process
  - The scheduler process
- **The Borgmaster process**
  - Handles client RPCs that either mutate state or lookup for state
  - Manages the state machines for all Borg “objects” (machines, tasks, allocs, etc...)
  - Communicates with all Borglets in the cell
  - Provides a Web-based UI

The Borgmaster: Reliability

- **Borgmaster reliability achieved through replication**
  - Single logical process, replicated 5 times in a cell
  - Single master elected using Paxos when starting a cell, or upon failure of the current master
  - Master serves as Paxos leader and cell state mutator
- **Borgmaster replicas**
  - Maintain an **in-memory** fresh copy of the cell state
  - Persist their state to a distributed Paxos-based store
  - Help building the most up-to-date cell state when a new master is elected

The Borgmaster: State

- **Borgmaster checkpoints its state**
  - Time-based and event-based mechanism
  - State include everything related to a cell
- **Checkpoint utilization**
  - Restore the state to a functional one, e.g. before a failure or a bug
  - Studying a faulty state a fixing it by hand
  - Build a persistent log of events for future queries
  - Use it for offline simulations

The Fauxmaster

- **A high-fidelity simulator**
  - It reads checkpoint files
  - Full-fledged Borgmaster code
  - Stubbed-out interfaces to Borglets
- **Fauxmaster operation**
  - Accepts RPCs to make state machine changes
  - Connects to simulated Borglets that replay real interactions from checkpoint files
- **Fauxmaster benefits**
  - Help users debug their application
  - Capacity planning, e.g. “How many new jobs of this type would fit in the cell?”
  - Perform sanity checks for cell configurations, e.g. “Will this new configuration evict any important jobs?”

Scheduling

- **Queue based mechanism**
  - New submitted jobs (and their tasks) are stored in the Paxos store (for reliability) and put in the *pending queue*
- **The scheduler process**
  - Operates at the task level, not the job level
  - Scans **asynchronously** the pending queue
  - Assigns tasks to machines that satisfy constraints and that have enough resources
- **Pending task selection**
  - Scanning proceeds from high to low priority tasks
  - Within the same priority class, scheduling uses a round-robin mechanism

  → Ensures fairness

  → Avoids head-of-line blocking behind large jobs

Scheduling Algorithm

- **The scheduling algorithm has two main processes**
  - **Feasibility checking**: find a set of machines that
    - ★ Meet tasks' constraints
    - ★ Have enough available resources, including those that are currently assigned to low-priority tasks that can be evicted
  - **Scoring**: among the set returned by the previous process, rank such machines to
    - ★ Minimize the number and priority of preempted tasks
    - ★ Prefer machines with a local copy of tasks binaries and dependencies
    - ★ Spread tasks across failure and power domains
    - ★ Pack and spread tasks, mixing high and low priority ones on the same machine to allow high-priority tasks to eventually expand

More on the scoring mechanism

- **Worst-fit scoring: spreading tasks**
  - Single cost value across heterogeneous resources
  - Minimize the change in cost when placing a new task
  - → Leaves headroom for load spikes
  - → But leads to fragmentation

- **Best-fit scoring: "waterfilling" algorithm**
  - Tries to fill machines as tightly as possible
  - → Leaves empty machines that can be used to place large tasks
  - → But difficult to deal with load spikes as the headroom left in each machine depends highly on load estimation

- **Hybrid**
  - Tries to reduce the amount of stranded resources
  - Performs better than best-fit

Task startup latency

- **Task startup latency is a very important metric to optimize**
  - Time from job submission to a task running
  - Highly variable
  - Median is about 25s

- **Techniques to reduce latency**
  - The main culprit for high latency is binary and package installations
  - Idea: place tasks on machines that already have dependencies installed
  - Packages and binaries distributed using a BitTorrent-like protocol

The Borglet

- **The Borglet**
  - Borg agent present on every machine in a cell
  - Starts and stop tasks
  - Restarts failed tasks
  - Manages machine resources interacting with the OS
  - Maintains and rolls over debug logs
  - Report the state of the machine to the Borgmaster

- **Interaction with the Borgmaster**
  - Pull-based mechanism: heartbeat-like messages every few seconds
  - → Borgmaster perform flow and rate control to avoid message storms
  - Borglet continues operation even if communication to Borgmaster is interrupted
  - A failed Borglet is blacklisted and all tasks are rescheduled

Borglet to Borgmaster communication

- **How to handle control message overhead?**
  - Many Borgmaster replicas receive state updates
  - Many Borglets communicate concurrently

- **The link shard mechanism**
  - Each borgmaster replica communicates with a subset of the cell Borglets
  - Partitioning is computed at each leader election
  - Borglets report full state, but the link shard mechanism aggregate state information

  → Differential state update, to reduce the load at the master

Scalability

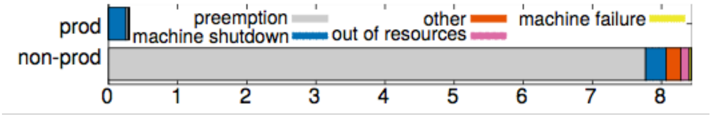
- **A typical Borgmaster resource requirements**
  - Manages 1000s of machines in a cell
  - Arrival rates of 10,000 tasks per minute
  - 10+ cores, 50+ GB of RAM
- **Decentralized design**
  - Scheduler process separate from Borgmaster process
  - One scheduler per Borgmaster replica
  - Scheduling is somehow decentralized
  - State change communicated from replicas to elected Borgmaster, that finalizes the state update
- **Additional techniques to achieve scalability**
  - Score caching
  - Equivalence class
  - Relaxed randomization

Borg Behavior: Experimental Perspective

Also, additional details on how Borg works...

Availability

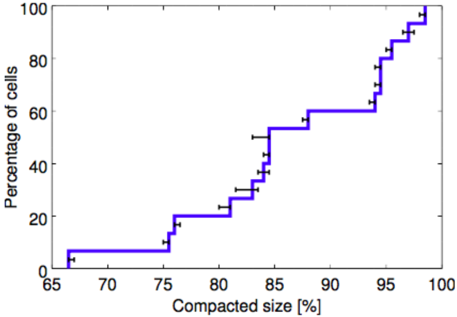
- **In large scale systems, failure are the norm not the exception**
  - Everything can fail, and both Borg and its running applications must deal with this
- **Baseline techniques to achieve high availability**
  - Replication
  - Storing persistent state in a distributed file system
  - Checkpointing
- **Additional techniques**
  - Automatic rescheduling of failed tasks
  - Mitigating correlated failures
  - Rate limitation
  - Avoid duplicate computation
  - Admission control to avoid overload
  - Minimize external dependencies for task binaries



System Utilization

- **The primary goal of a cluster scheduler is to achieve high utilization**
  - Machines, network fabric, power, cooling ... represent a significant financial investment
  - Increasing utilization by a few percent can save millions!
- **A sophisticated metric: Cell Compaction**
  - Replaces the typical "average utilization" metric
  - Provides a fair, consistent way to compare scheduling policies
  - Translates directly into cost/benefit result
  - Computed as follows:
    - Given a workload in a point in time (so this is not trace driven simulation)
    - Enter a loop of workload packing
    - At each iteration, remove physical machines from the cell
    - Exit the loop when the workload can no longer fit the cell size
- **Use the Fauxmaster to produce experimental results**

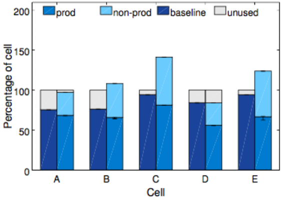
System Utilization: Compaction



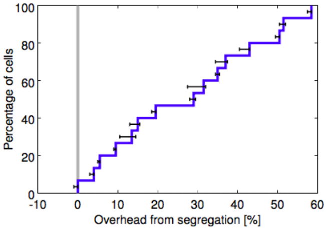
- This graphs shows how much smaller cells would be if we applied compaction to them

System Utilization: Cell Sharing

- **Fundamental question: to share or not to share?**
  - Many current systems apply static partitioning: one cluster **dedicated only** to prod jobs, one cluster for non-prod jobs
- **Benefits from sharing**
  - Borg can reclaim resources reserved by “anxious” prod jobs



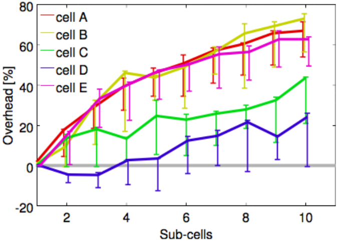
(a) *The left column for each cell shows the original size and the combined workload; the right one shows the segregated case.*



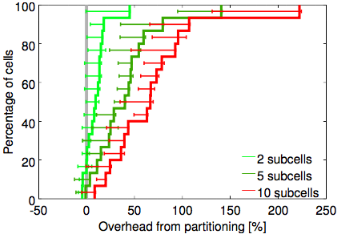
(b) *CDF of additional machines that would be needed if we segregated the workload of 15 representative cells.*

System Utilization: Cell Sizing

- **Fundamental question: large or small cells?**
  - Large cells to accommodate large jobs
  - Large cells also avoid fragmentation



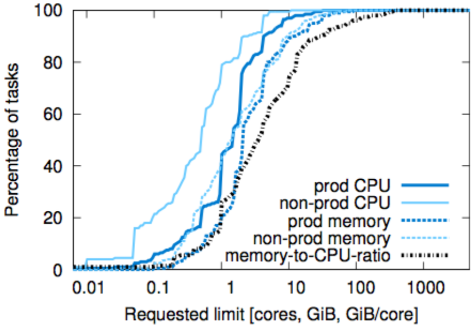
(a) *Additional machines that would be needed as a function of the number of smaller cells for five different original cells.*



(b) *A CDF of additional machines that would be needed to divide each of 15 different cells into 2, 5 or 10 cells.*

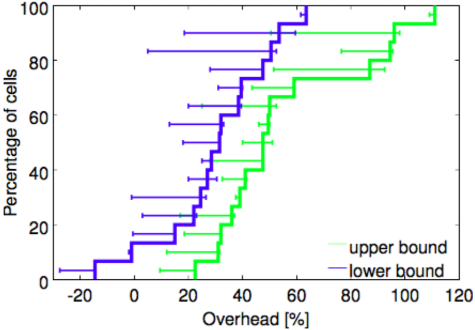
System Utilization: Fine-grained Resource Requests

- **Borg users specify Job requirements in terms of resources**
  - For CPU: this is done in milli-core
  - For RAM and disk: this is done in bytes



System Utilization: Fine-grained Resource Requests

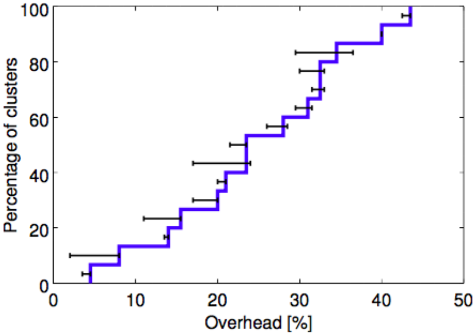
- **Would fixed size containers (or slot) be good?**
  - No! It would require more machines in a cell!



System Utilization: Resource Reclamation

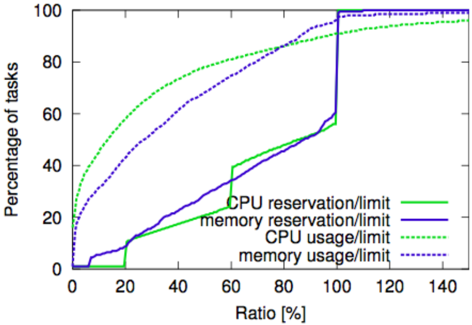
- **Borg users specify resource *limits* for their jobs**
  - Used to perform admission control
  - Used for feasibility checking (*i.e.,* find sets of suitable machines in a cell)
- **Borg users have the tendency to "over provision" for their jobs**
  - Some tasks, occasionally need to use all their resources
  - Most of the tasks never use all resources
- **Resource reclamation**
  - Borg builds estimates of resource usage: these are called **resource reservations**
  - Borgmaster receives usage updates from Borglets
  - Prod jobs are treated differently: they do not rely on reclaimed resources, Borgmaster only uses resource limits

System Utilization: Resource Reclamation



- Resource reclamation is quite effective. A CDF of the additional machines that would be needed if it was disabled.

System Utilization: Resource Reclamation



- Resource estimation is successful at identifying unused resources. Most tasks use much less than their limit, although a few use more CPU than requested.

Isolation

- **Sharing a multi-tenancy are beneficial, but...**
  - Tasks may interfere one with each other
  - Need a good mechanism to prevent interference (both in terms of security and performance)
- **Performance isolation**
  - All tasks run in Linux cgroup-based containers
  - Borglets operate on the OS to control container resources
  - A control-loop assigns resources based on predicted future usage or on memory pressure
- **Additional techniques**
  - Application classes: latency-sensitive, vs. batch
  - Resource classes: compressible and non-compressible
  - Tuning of the underlying OS, especially the OS scheduler

Lessons learned from building and operating Borg

And what has been included in Kubernetes, the open source version of Borg...

Lessons Learned: the Bad

- **The "job" abstraction is too simplistic**
  - Multi-job services cannot be easily managed, nor addressed
  - Kubernetes uses scheduling units called **pods** (*i.e.,* the Borg allocs) and **labels** (key/value pairs describing objects)
- **Addressing services is critical**
  - One IP address implies managing ports as a resource, which complicates tasks
  - Kubernetes uses Linux name-spaces, such that each pod has its own IP address
- **Power or casual users?**
  - Borg is geared toward power users: e.g., BCL has about 230 parameters!
  - Build automation tools, and template settings from historical executions

Lessons Learned: the Good

- **Allocs are useful**
  - Resource envelope for one or more container co-scheduled on the same machine and that can share resources
- **Cluster management is more than task management**
  - Naming and load balancing are first-class citizens
- **Introspection is vital**
  - Clearly true for debugging
  - Key for capacity planning and monitoring
- **The master is the kernel of a distributed system**
  - Monolithic designs are not working well
  - Cooperation of micro-services that use a common low-level API to process requests and manipulate state