# Advanced Operating Systems: Three Easy Pieces

## Datacenter OS (DC/OS)

# Outline

- **The Datacenter needs an OS**
  - ❑ Motivation, why, what is needed..
- **What is Apache Mesos**
- **Twitter DC/OS based on Mesos**
  - ❑ Master Node
  - ❑ Agent Node
  - ❑ Frameworks
  - ❑ Others

# The Datacenter needs an OS

# The Datacenter is the new Computer

- **Datacenter is running today's most popular consumer applications:**
  - Facebook, Google, iCloud, etc.

- Needed (Datacenter) for big data in business & Science

- Datacenter is widely accessible through cloud computing/Internet

Claim: **this new "Datacenter / computer" needs an operating system**

# Why Datacenter needs an OS

- **Growing diversity of applications:**
  - ❑ **Computing frameworks:** MapReduce, Dryad[1], Pregel[2], Percolator, Dremel[3]
  - ❑ **Storage systems:** GFS, BigTable, Dynamo, HDFS, etc.

- **Growing diversity of users:**
  - ❑ 200+ Hive users at Facebook

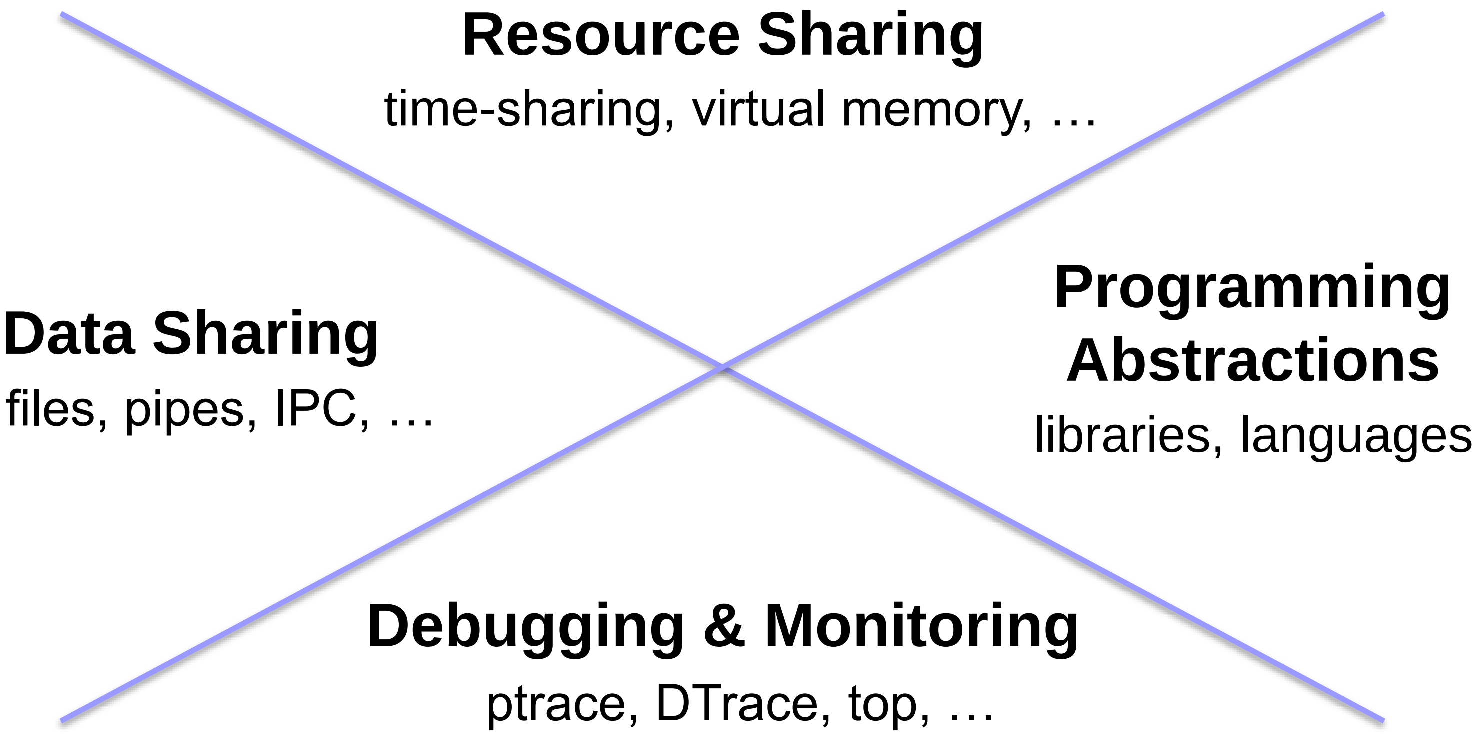
- Same reasons regular computers needed one!

[1] **Dryad**: https://en.wikipedia.org/wiki/Dryad_(programming)
**Microsoft: General purpose data parallel applications**

[2] **Pregel**: https://kowshik.github.io/JPregel/pregel_paper.pdf
**Google: System for large-scale Graph Processing**

**3. DremeL:** https://static.googleusercontent.com/media/research.google.com/en//pubs/archive/36632.pdf
**Google: Interactive Analysis of Web-scale Dataset**

# What Operating System Provide



**Resource Sharing**

time-sharing, virtual memory, …

**Data Sharing**

files, pipes, IPC, …

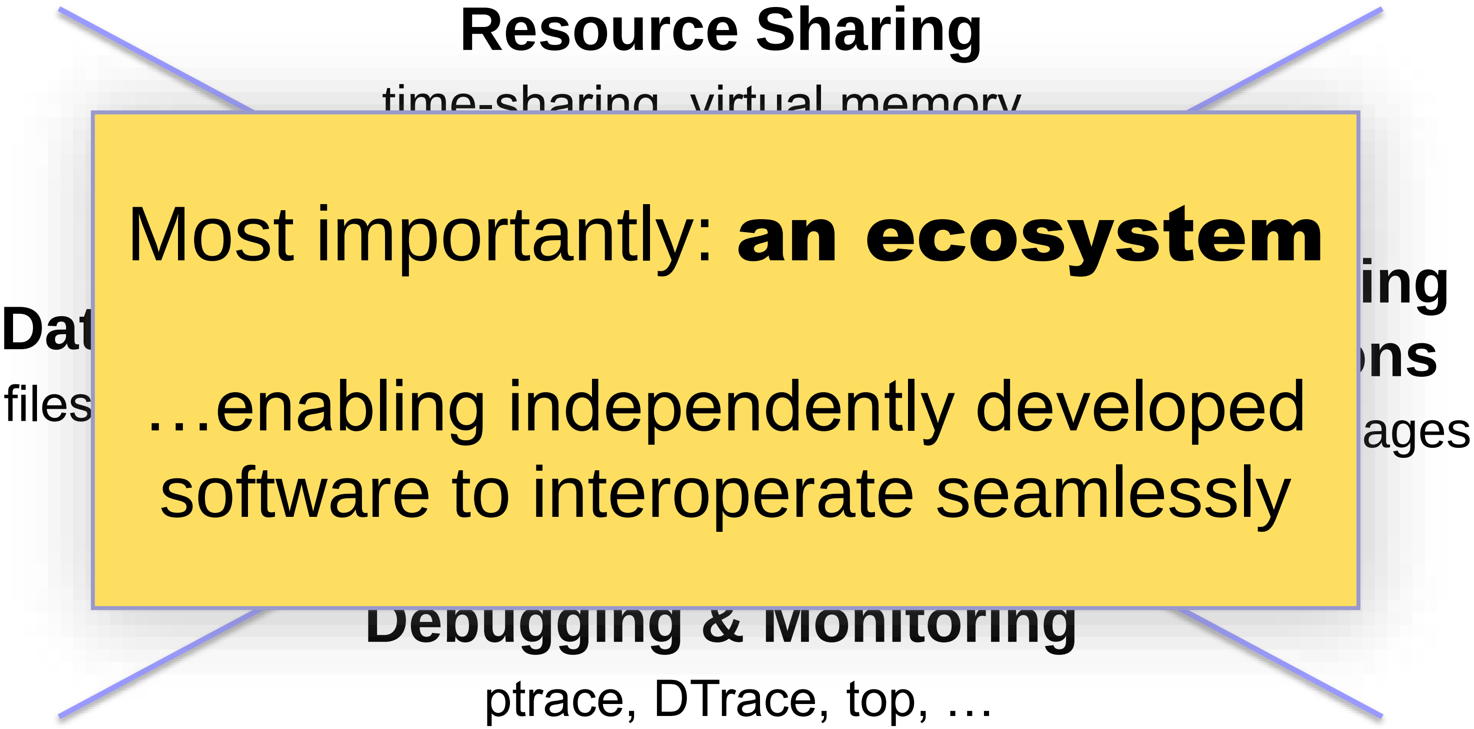
**Programming Abstractions**

libraries, languages

**Debugging & Monitoring**

ptrace, DTrace, top, …

# What Operating System Provide



Resource Sharing

time-sharing, virtual memory

Dat

files

ing

ns

ages

Most importantly: **an ecosystem**

…enabling independently developed software to interoperate seamlessly

Debugging & Monitoring

ptrace, DTrace, top, …

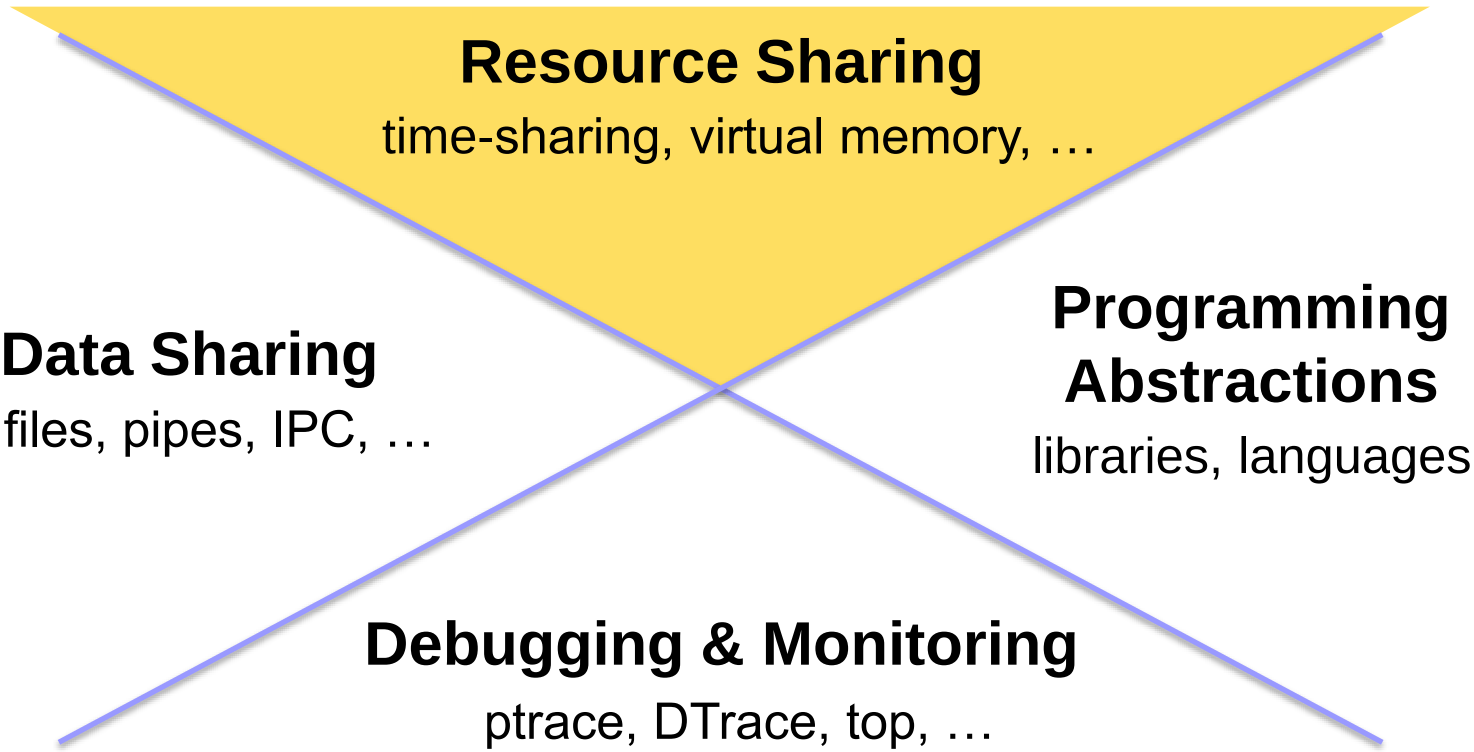
# Today’s Datacenter Operating System

- Platforms like Hadoop are well-aware of these issues:
  - Inter-user resource sharing, but at the level of MapReduce jobs (though this is changing - YARN)
  - InputFormat API for storage systems (but what happens with the next hot platform after Hadoop?)
- Other examples: Amazon services, Google stack

The **problems** motivating a datacenter OS are well recognized, but solutions are **narrowly targeted**

Can researchers take a longer-term view?

# Tomorrow's Datacenter OS



**Resource Sharing**

time-sharing, virtual memory, …

**Data Sharing**

files, pipes, IPC, …

**Programming Abstractions**

libraries, languages

**Debugging & Monitoring**

ptrace, DTrace, top, …

# Resource Sharing

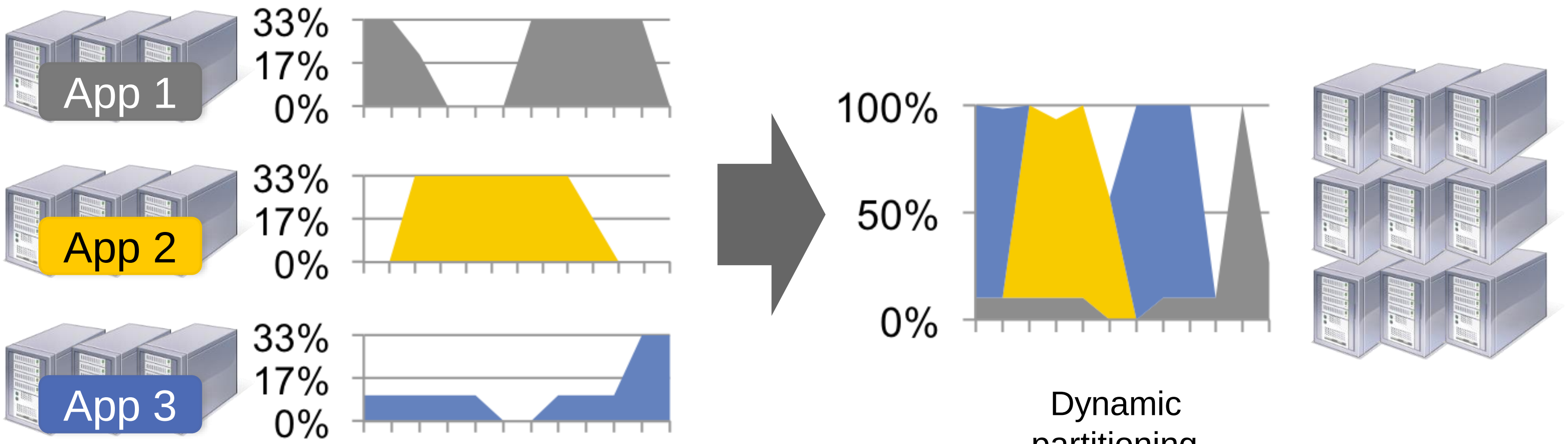
> “To solve these interaction-problems we would like to have a computer made simultaneously available to many users in a manner somewhat like a telephone exchange. Each user would be able to use a console at his own pace and without concern for the activity of others using the system.”

– Fernando J. Corbató, 1962

# Resource Sharing

- **Today**, cluster apps are built to run independently and assume they own a fixed set of nodes
- **Result:** inefficient static partitioning

- **What's the right interface for dynamic sharing?**



Static partitioning

Dynamic partitioning

# Memory Management

- **Memory is an increasingly important resource:**
  - In-memory iterative processing (AllegroGraph "Graph DB based on W3C RDF (Resource Description Framework)", Pregel, Spark, etc.)
  - HDFS cache for MapReduce cluster could serve 90% of jobs at Facebook (HotOS '11)

- **What are the right memory management algorithms for a parallel analytics cluster?**

# Programming and Debugging

- Although there are new programming models for applications, **system programming remains hard**:
  - Can we identify useful common abstractions? (Chubby[1] “lock service for distributed system / Big Table”, Sinfonia[2], Mesos are some examples)
  - How much can languages (e.g., Go, Erlang) help?
- **Debugging is *very* hard:**
  - Magpie[3], X-Trace, Dapper[4] are some steps here
- Can a clean-slate design of the stack help?

[1] **Chubby**: https://static.googleusercontent.com/media/research.google.com/en//archive/chubby-osdi06.pdf

[2] **Sinfonia**: new paradigm to building scalable distributed systems: http://www.sosp2007.org/papers/sosp064-aguilera.pdf

[3] **Magpie**: online modelling & performance-aware systems: https://www.usenix.org/legacy/publications/library/proceedings/hotos03/tech/full_papers/barham/barham_html/paper.html

[4] **Dapper** is a large scale Distributed Systems tracing infrastructure: https://research.google.com/pubs/pub36356.html

# What is Needed

- **Focus on paradigms, not only on performance:**
  - Industry is spending a lot of time on performance
- **Explore clean-slate* approaches:**
  - Much datacenter software is written from scratch
  - People using Erlang, Scala, functional models (MR)
- **Bring cluster computing to non-experts:**
  - Most impactful (**datacenter as the new workstation**)
  - Hard to make a Google-scale stack usable without a Google-scale ops team

* Absence of existing constraints.

# What is Apache Mesos

# 1. Mesos Overview

# 1. Overview

- **Mesos**[1] is a platform for Fine-Grained resource sharing in the data center – **Cluster Manager**.

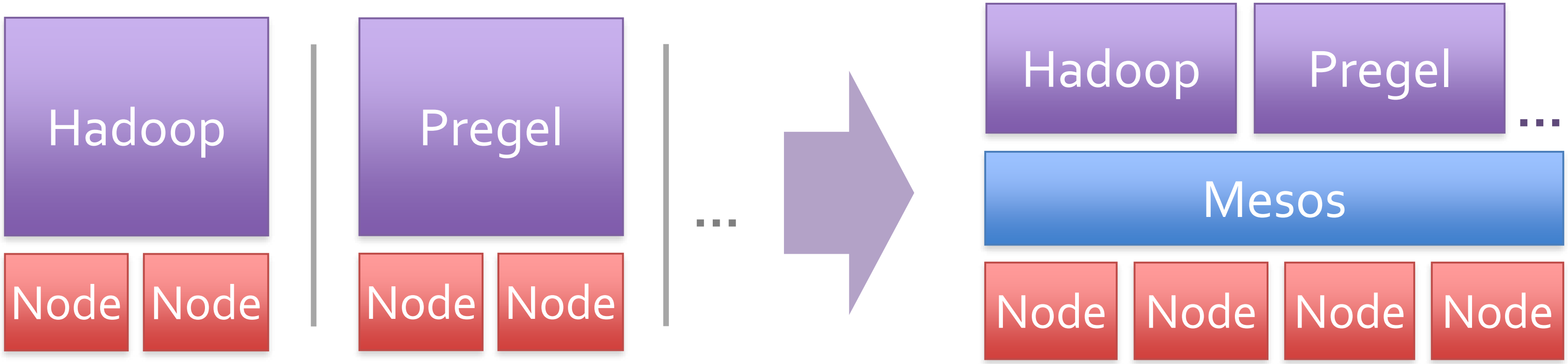
- While there is rapid innovation in cluster computing frameworks, there is no single framework that is optimal for all applications.

- **An Alternative** is to run multiple frameworks in a single cluster, **without static partitioning**, to maximize utilization and to share data between frameworks while providing isolation between the different frameworks ← **Mesos**

1 **Mesos** (Cluster Manager): http://mesos.apache.org/

# 1. Static vs. Dynamic Partitioning

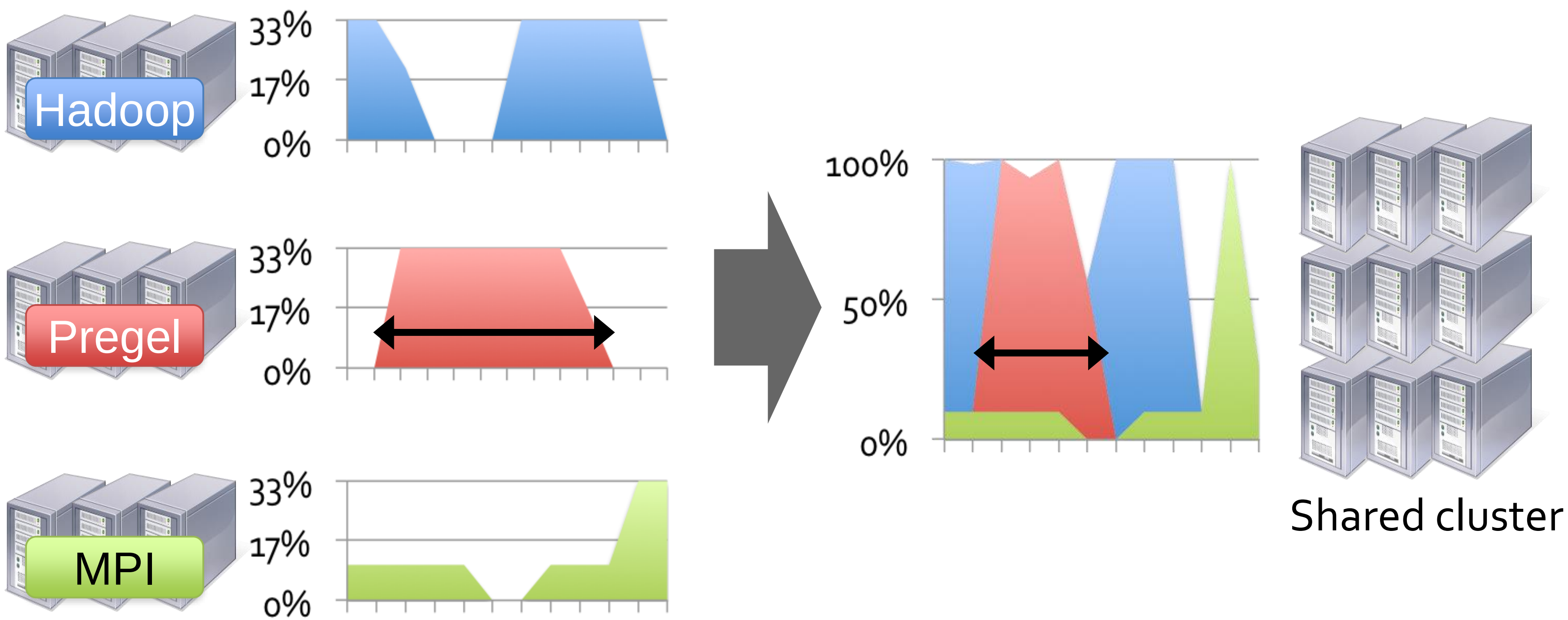
- **Mesos** is a common resource sharing layer over which diverse frameworks can run



# 1. Static vs. Dynamic Partitioning

**Today:** static partitioning

**Mesos:** dynamic sharing



# 1. Other Benefits

- **Run multiple instances of the *same* framework:**
  - Isolate production and experimental (testing) jobs
  - Run multiple versions of the same framework concurrently with complete isolation from each other
- **Build *specialized frameworks* targeting different particular problem domains:**
  - Better performance than general-purpose abstractions + more flexibility

# 2. Mesos Goals

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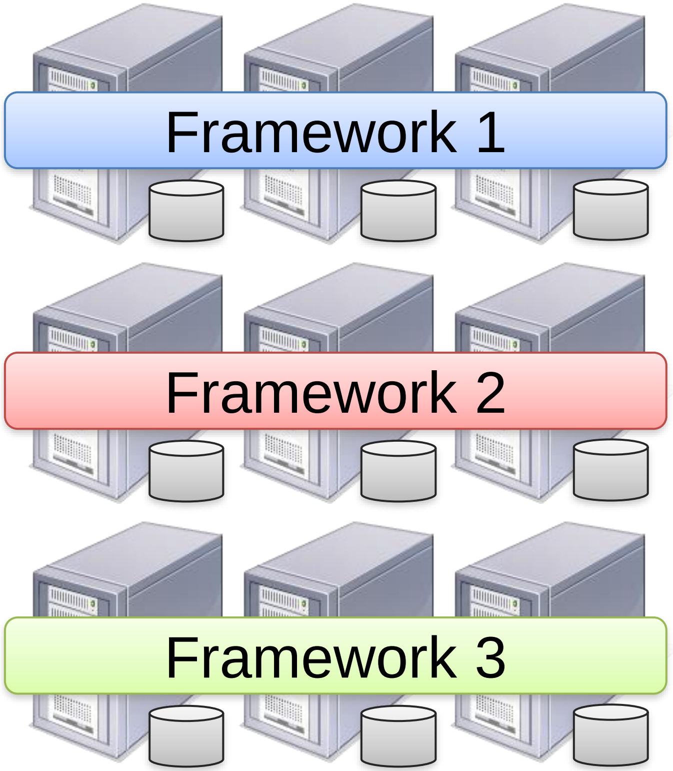
- **High utilization** of resources
- **Support diverse frameworks** (current & future)
- **Scalability** to 10,000's of nodes
- **Reliability** in face of failures
- **Fine-grain sharing,** i.e., one node can run multiple frameworks concurrently
- **Support the "Resource Offers" Model:** simple application-controlled scheduling mechanism

**Resulting design:** Small microkernel-like core that pushes scheduling logic to frameworks

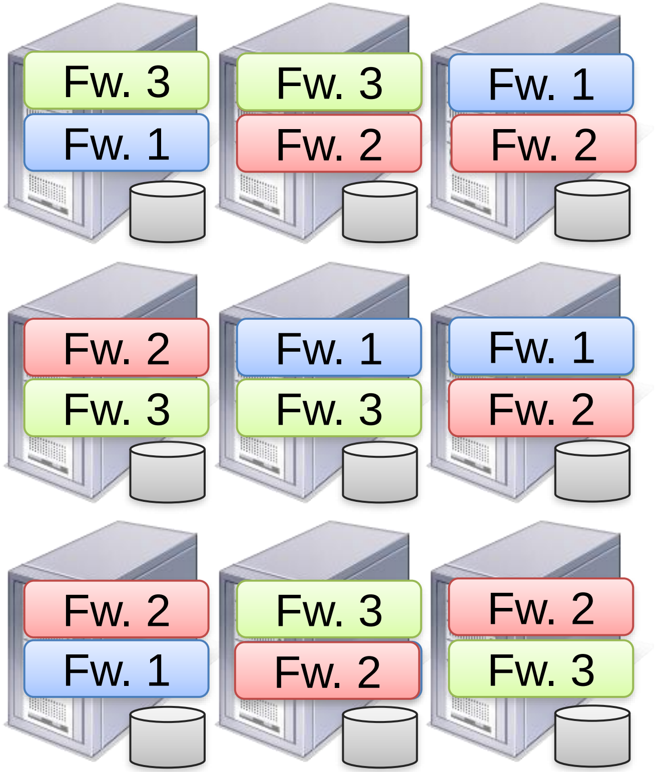
# 2. Fine-Grained Sharing

**Coarse-Grained Sharing (HPC):**



Storage System (e.g., HDFS)

**Fine-Grained Sharing (Mesos):**



Storage System (e.g., HDFS)

+ Improved utilization, responsiveness, data locality

# 2. Resource Offers Model

- **Option:** Global scheduler
  - Frameworks express needs in a specification language, and a global scheduler matches them to available resources in the cluster

  + Can make optimal decisions

- **Complex:** language must support all framework needs:
  - Difficult to scale and be robust
  - Future frameworks may have unanticipated needs

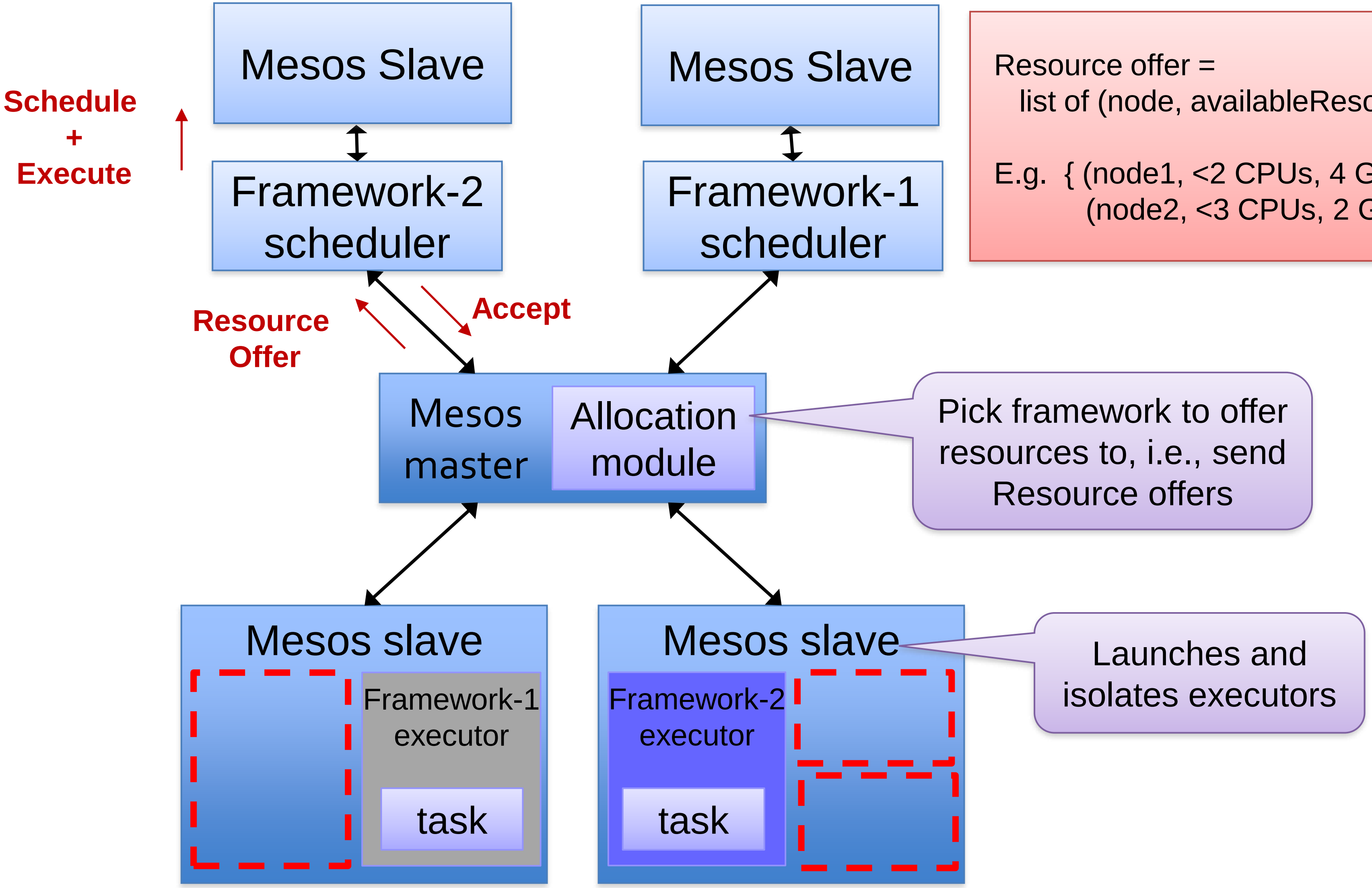
# 2. Mesos Resource Offers

- **Mesos:** Resource offers
  - ❑ Offer available resources to frameworks, let them pick which resources (up to what is being offered) to use and which tasks a framework will launch accordingly

  + Keeps Mesos simple; makes it possible to support future frameworks

  - Decentralized decisions might not be optimal

# 2. Mesos Architecture



Resource offer =
list of (node, availableResources)

E.g. { (node1, <2 CPUs, 4 GB>),
(node2, <3 CPUs, 2 GB>) }

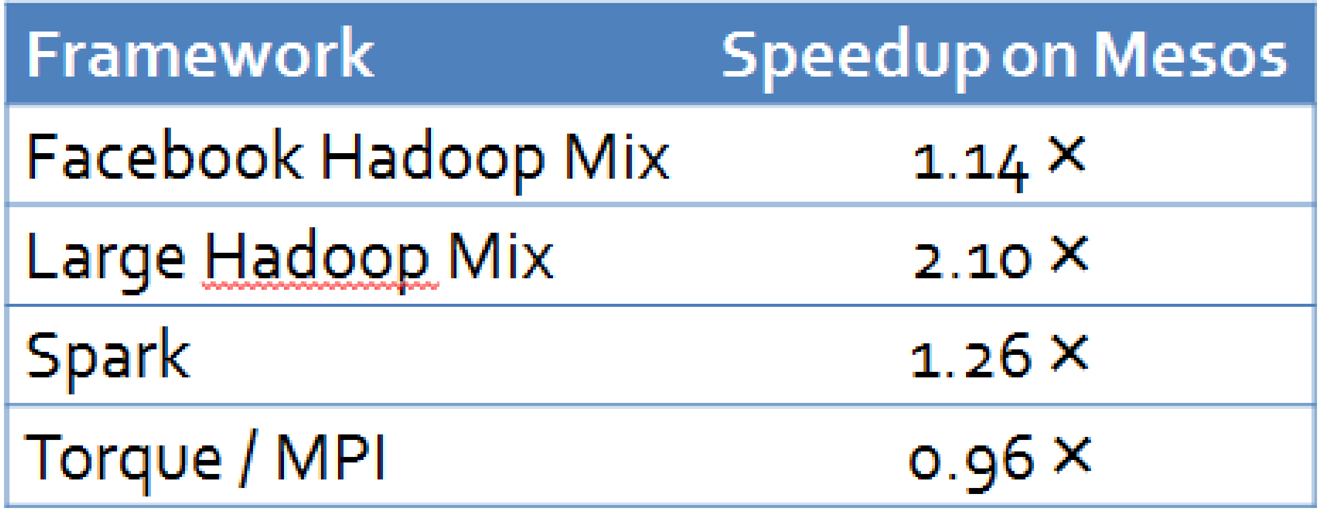
Pick framework to offer resources to, i.e., send Resource offers

Launches and isolates executors

# 3. Results

# 3. Mesos vs. Static Partitioning

- Compared performance with statically partitioned cluster where each framework gets 25% of nodes



| Framework | Speedup on Mesos |
|---|---|
| Facebook Hadoop Mix | 1.14 × |
| Large Hadoop Mix | 2.10 × |
| Spark | 1.26 × |
| Torque / MPI | 0.96 × |

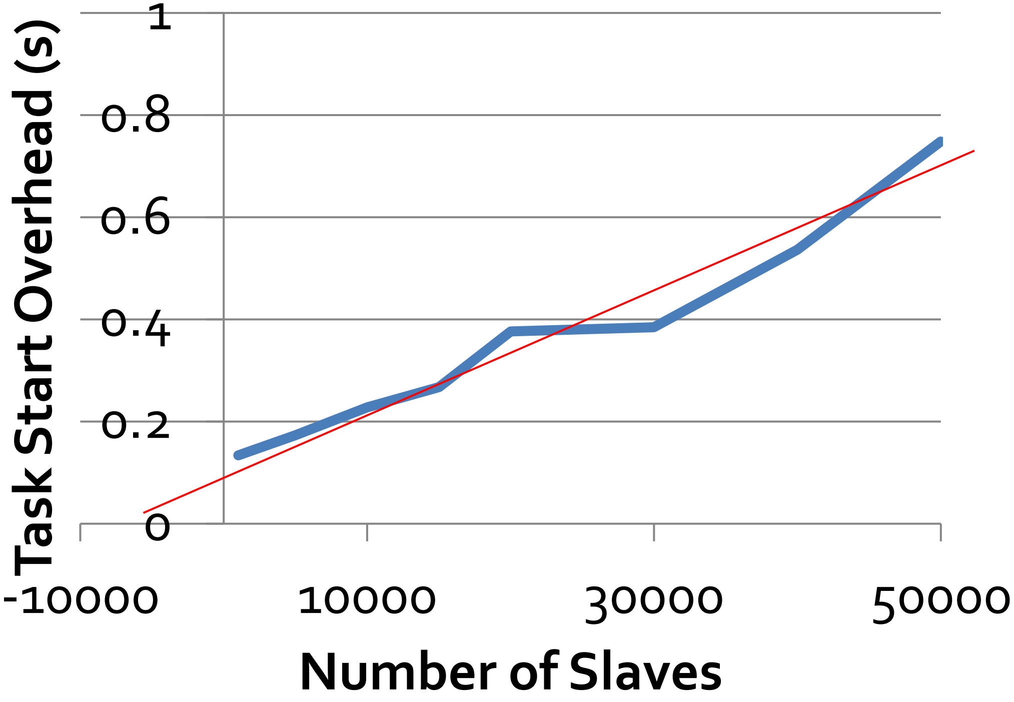
- Overall performance improvement = (1.14 + 2.1 + 1.26 + 0/96)/4 = 1.365 ➔ 36.5% improvement

# 3. Mesos Scalability

- **Mesos only performs** *inter-framework* scheduling (e.g., fair sharing across framework), which is easier than intra-framework (within a framework) scheduling

**Result*:**

Scaled (almost linear) to 50,000 emulated slaves,
200 frameworks,
100K tasks (based on normal distribution with mean = 30 sec len)



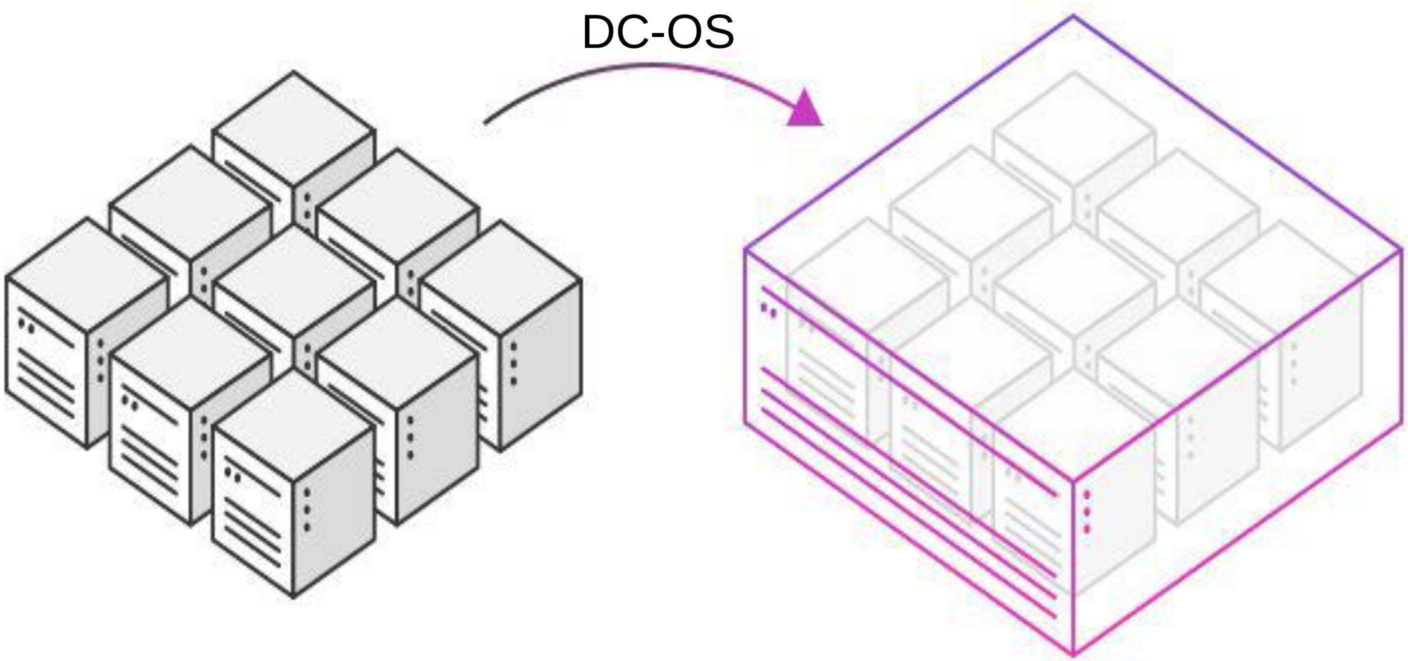
**URL**: https://www.usenix.org/legacy/events/nsdi11/tech/full_papers/Hindman.pdf

# 3. Fault Tolerance

- **Mesos master has only *soft state*:** list of currently running frameworks and tasks
- **Rebuild** a new master: frameworks and slaves re-register with the new master after a failure
- **Result: fault detection and recovery in ~10 sec**

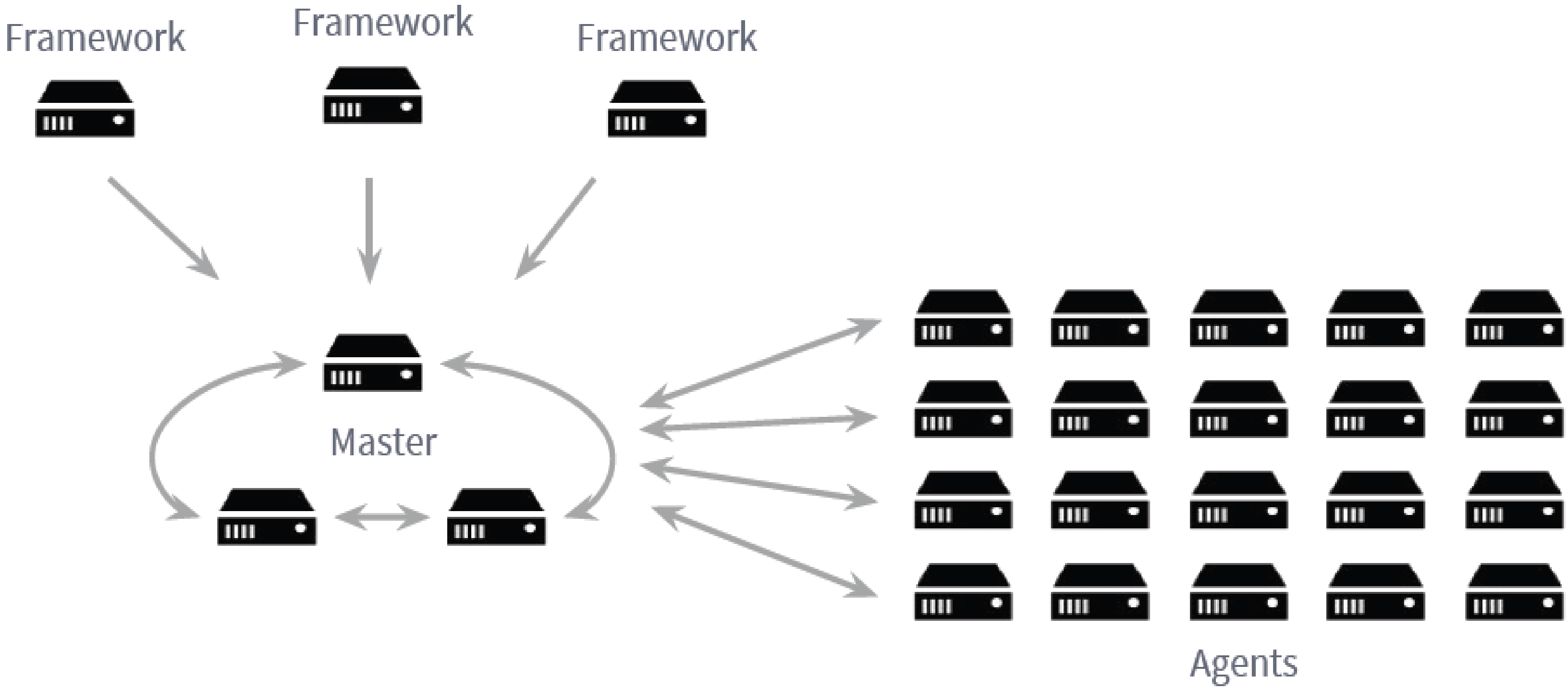
# Twitter DC/OS based on Mesos - Aurora

# The Datacenter Computer

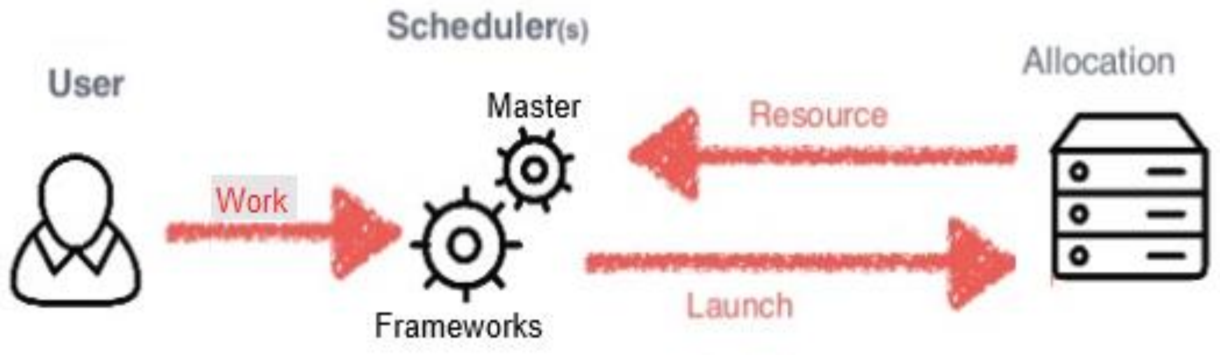


* Do not confuse Twitter’s Aurora with Amazon’s Aurora. Amazon Aurora is an RDBMS that is compatible with MySQL and PostgreSQL and is built for the cloud.

# Two-levels Scheduling

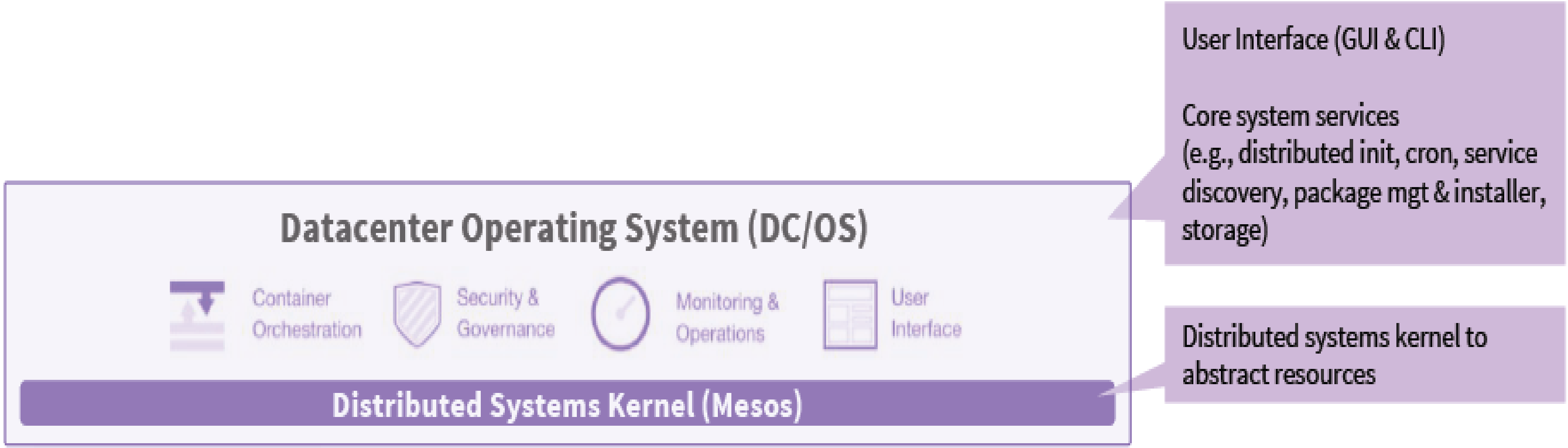


# Two-levels Scheduling



1. Master (Mesos+) schedule global resources to a given framework
2. Framework schedule jobs to agents (Mesos agent+)

# Datacenter Operating System (DC/OS)



Datacenter Operating System (DC/OS)

Container Orchestration

Security & Governance

Monitoring & Operations

User Interface

Distributed Systems Kernel (Mesos)

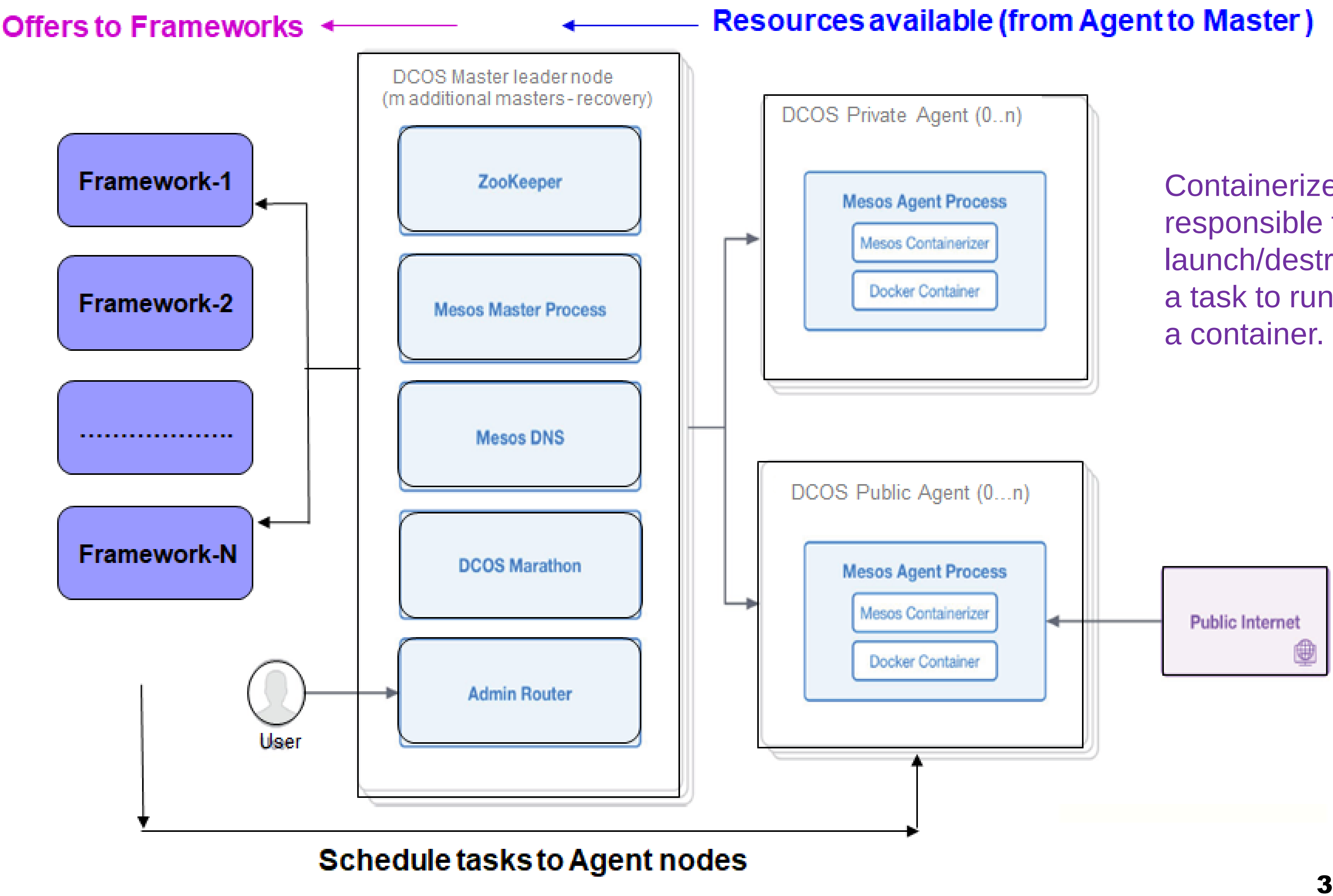
User Interface (GUI & CLI)

Core system services (e.g., distributed init, cron, service discovery, package mgt & installer, storage)

Distributed systems kernel to abstract resources

- **What is included:**
  - **Mesos!**
  - API, CLI and GUI
  - Service discovery & Load balancing
  - Storage Volumes
  - Package Manager
  - Installer on Premise and on Cloud

# Datacenter OS Architecture



Containerizer is responsible to launch/destroy a task to run in a container.

# Datacenter OS Features

- **Kernel == Apache Mesos,** scaling up to 10,000’s nodes
- **Fault tolerance in all components, rolling upgrades throughout**
- **Containers first class citizens** (LXC, Docker)
- **Local OS per node** (container enabled)
- **Scheduling** (long-lived, batch)
- **Service discovery, monitoring, logging, debugging**

# Datacenter Components

1. **Master Node:** one master is assigned as the leader, manage the metadata for the whole system and propagate the metadata to other masters using quorum replication, i.e., not a single point of failure like Hadoop.
2. **Agent Node:** can support multiple tasks executing concurrently belonging to different frameworks with complete isolation, using **cgroups (Linux control groups)**, and managing resources consumption by each task to be limited to what is assigned to that task
3. **Frameworks:** representing different application paradigms, e.g., time sharing, batch, etc. An individual Framework will receive resource offers from the master and schedule tasks to the assigned agent nodes accordingly. **Marathon** is a framework for running long jobs + can be used to launch other frameworks + container orchestration..

# Datacenter Components

1. **Master Node:**
   - ❑ Resource allocation
   - ❑ Resource de-allocation
   - ❑ Resource reservation
   - ❑ Resource isolation
   - ❑ Resource monitoring
   - ❑ Failure detection
   - ❑ Package distribution
   - ❑ Task starting, killing, cleanup
   - ❑ Volume management
   - ❑ ….

2. **Agent Node:**
   - ❑ Notify Master with available/ free resources
   - ❑ Execute tasks assigned to them by different Frameworks
   - ❑ Use **cgroups** to isolate tasks from each other and to ensure that no task consume resources beyond what was assigned to them

3. **Framework:**
   - ❑ Receive resource offers from the master and assign tasks to be executed on the assigned agent nodes
   - ❑ Handle task failure or loss of agent node

# Datacenter Components: Master

- **Master** is the cluster coordinator (cluster configuration Mgr).
- **The cluster will have multiple master nodes** (for fault tolerance). One master functions as the **leader** and propagates the metadata updates to the other masters using quorum replication. If the leader dies, one of the remaining masters is elected as the new leader.
- **The leader monitors** the state of the cluster.
- **Leader receives** resources available from the agent nodes and generates "resource offers" to the available frameworks based on some **policy**; framework scheduler may accept (part or all of the offered resources to use) or reject the offer!
- **The most significant factor** of a leader to manage large cluster is available RAM in the leader node.
- **Twitter** with cluster of **30,000 nodes** they use 5 master nodes.

# Datacenter Components: Agent

- **Agent node** notifies the leader node with available/free resources (CPU, RAM, Storage, Ports)
- **Agent node** execute tasks assigned to them by any of the frameworks supported in the cluster
- **Two tasks belong to different frameworks** are completely isolated from each other as well the agent node guarantee that a task can use only resources assigned to them, i.e., no task can abuse the resources on that node.
- **You can assign resource to a specific role**, i.e., restricting this resource to a specific framework; otherwise, resources can be used by any application.

# Datacenter Components: Framework

- **Tasks** are assigned to **Mesos containerizer** on the agent node by framework. In return, the containerizer will launch/destroy a task to run in a container.
- **Framework** is an application that uses Mesos APIs to receive resource offers from the Master and replies to instruct agent nodes to execute appropriate tasks.
- **Framework** handles task failure or loss of an agent node.

# Datacenter (DC-OS) Components: Others

- **Zookeeper**
- **Admin Router**
- **Metronome (Cron Service for DC/OS)**
- **Mesosphere/Marathon (Container Orchestration / Service scheduler)**
- **Kubernetes (orchestration s/w to deploy/manage containers)**
- **Messos-DNS:** Name service discovery
- **Cosmos**: package manager; run on all master nodes. Used to install DC/OS Services

# END