Lightweight Virtualization

Lecture 11

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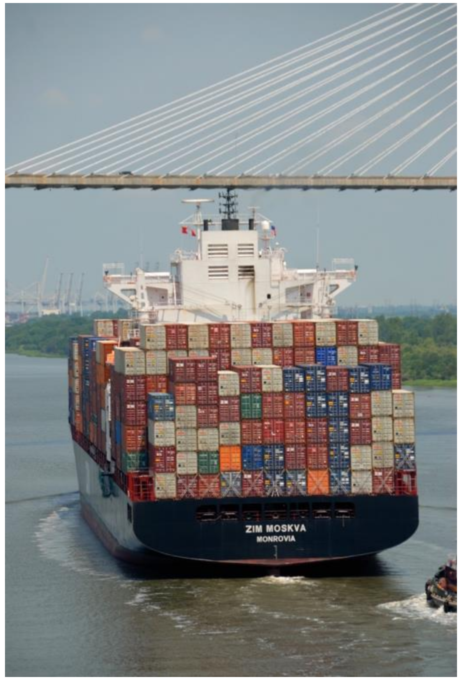
Hardware for System Virtualization

- Last lecture: system virtualization “without” hardware support
  - e.g., x86-32: Use techniques such as DBT and paravirtualization
- CPU and memory hardware support much improved since the 00s!
  - Instruction set and architectural extensions: Intel VT-x, AMD-v
  - Extended page tables: Hardware support for multiple address translations
  - IO support through SR-IOV and IOMMUs
- Paravirtualization is still useful for (further) efficiency but unnecessary for reasonably efficient basic VM functionality
- VMMs built for architectures with native hardware support:
  - KVM/qemu, integrated with Linux
- Xen was the basis of Amazon’s public cloud; KVM since ~2019
  - Do we always need the heavyweight hammer of full virtualization?

Lightweight, OS-level virtualization

- First-party workloads: e.g., within a single company
  - Some degree of implicit trust
  - Consolidation and efficient resource use is more important than full isolation
- Lightweight, operating-system-level virtualization: Containers
- Programs use the system call interface (ideally nothing else)
- No emulation, no need for special hardware support, or OS changes for e.g., paravirtualization
- Containers do need OS changes for finer-grained resource abstraction and control



Benefits of OS-level virtualization

- Application-centric view
- Run any app that is portable with the same system call interface
- No more management of machines & OSes; think of applications
- Decouple the management of OS & hardware from applications
  - Roll out new hardware and OS without worrying about breaking apps
- Match development, testing, and deployment environments
- Convenient access points to communicate with the application
  - E.g., expose health information, communicate resource allocations
- Relate machine telemetry to applications
  - No need to tease out per-app metrics from machine-level metrics
  - “The container is the application.”

Benefits of OS-level virtualization

- Resource sharing across virtualized units (containers)
- Shared OS kernel & utilities limit redundancy & improve consolidation
- Familiar kernel resource abstractions: process scheduling, memory allocation, etc.

- Container refers to two things at once:
    - the run-time abstraction (process, access+resource isolation, FS)
    - the stored software image (all software you need to run)

How are containers built?

What goes into a container?

- More like process virtualization than system virtualization
  - No ISA virtualization; no native hardware support
  - Memory and IO work the same way as processes
- What we call a container is a loose conglomeration of kernel-level mechanisms
- Namespaces: Access isolation for global resources
- Cgroups: Resource/Performance isolation of global resources
- UnionFS: Improving efficiency through shared filesystem data
- Access control mechanisms: capabilities, filtering (eBPF, seccomp, appArmor)

Namespaces

- Access isolation
- Show an instance of a global resource as available to all processes inside a namespace (multiplexing)
- Changes visible to other processes within namespace, but invisible outside the namespace
- Show different “copies” of resources associated with the kind of namespace
  - Network, IPC, mount, PID, …
- Every process starts in init namespace, change with `setns`
- Network: (software/hardware) network device; routing rules; port numbers. `veth` pair connects two network namespaces

Control groups

- Resource/Performance isolation
- Subsystem: a specific kind of resource
  - CPU time, memory, network bandwidth, block device access, priority, CPU and memory (numa) node assignment
  - Many configurable parameters per subsystem
- Control group or cgroup: a set of processes
  - fork()-ed process inherits a bunch of parent attributes including cgroup
- Hierarchy: a tree where each node is a cgroup
  - Many hierarchies can exist, unlike the process hierarchy
- Each subsystem “mounted” onto one hierarchy
  - Possible to use a single hierarchy for multiple subsystems (resources)
- Every process has exactly one reservation per resource

UnionFS: ~~“software images too big”~~

- Context: Data on storage typically “mounted” at some point in the virtual filesystem (/, /home/users/name, etc.)
- Containers want mostly the same files, with a small number of unique modifications per container (e.g., specific library versions)
  - Think: common third-party packages, utilities, shared library images
- Union filesystem: maintain a stack of filesystems at each mount point. Only the highest one is writable; lower layers are read-only
- Inspired by similar use cases in the past: data on a read-only medium that needed a small number of updates before refreshing into a new medium (e.g., working on a CD filesystem in memory)
- Write fresh to the top; copy-on-write; copy up; deletion with “whiteout”. Cache heavily
- Virtual Filesystem (VFS) layer accomplishes this with minimal changes to underlying filesystem

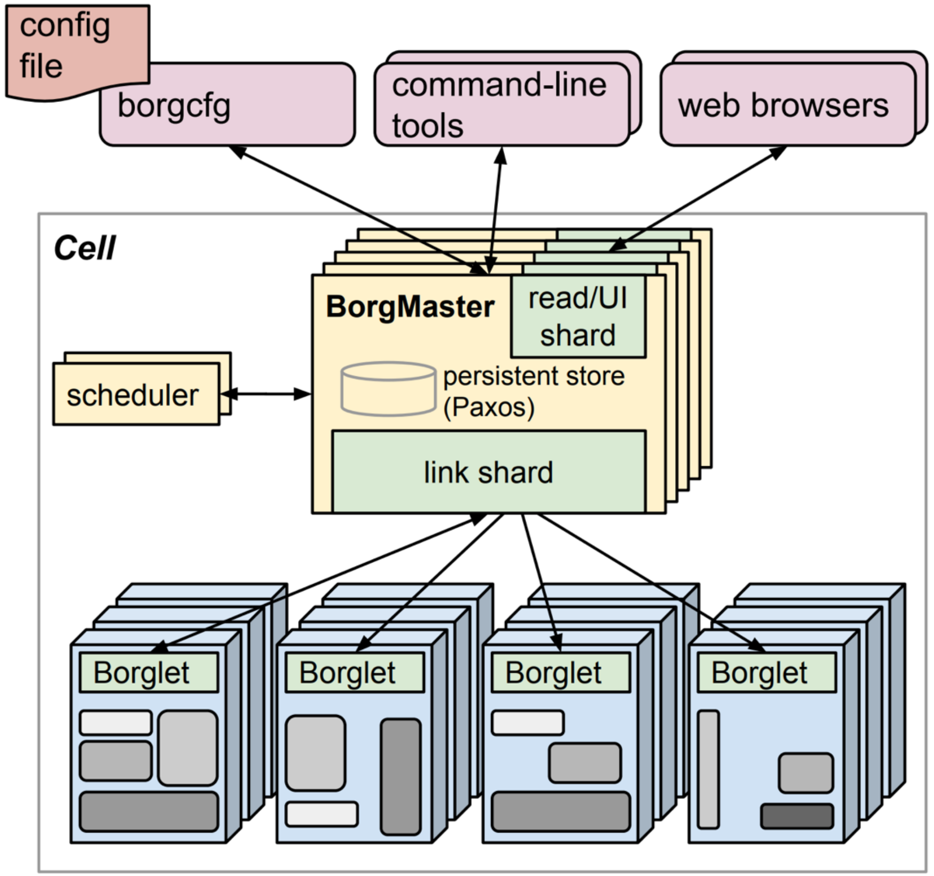
Orchestrating Containers

Why Orchestration?

- When containers are so easy to use, users will create many
- Example: Instances of a microservice
- Example: Co-locating latency-sensitive jobs with batch jobs
- Kubernetes: an orchestrator created and evolved at Google
  - Today, a well-established project with a significant open-source ecosystem
- Pod: a group of related containers (app and allied processes)
  - E.g., web service, along with logging, metrics
- Node: the machine (virtual or physical) on which pod scheduled

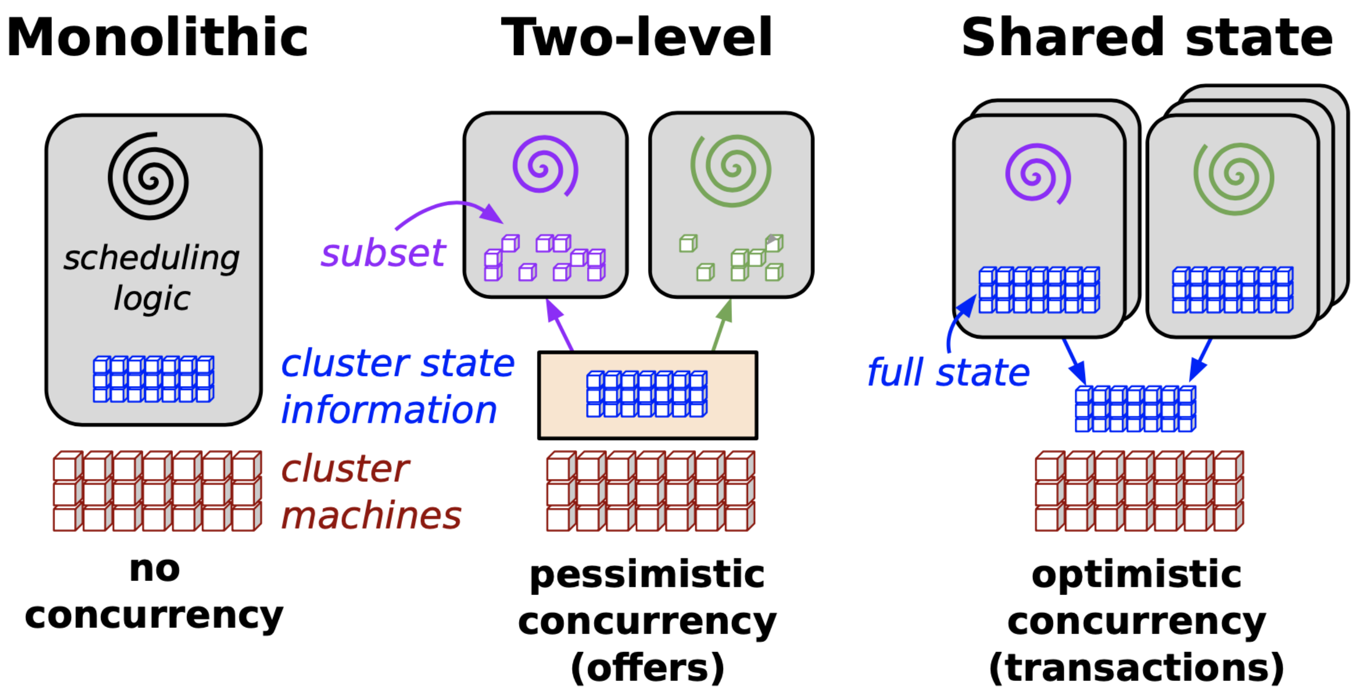
Evolution at Google: Borg

- Borg: a cluster manager
- Cells: units of machines managed by one controller
- Borgmaster: controller
- Borglet: program running locally on each machine to manage its resources
- Cluster state: the controller's view of the mapping from tasks (containers) to nodes, health, resource allocation, etc.
- State is persisted in a highly-available distributed data store (e.g. Paxos)



Evolution at Google: Omega

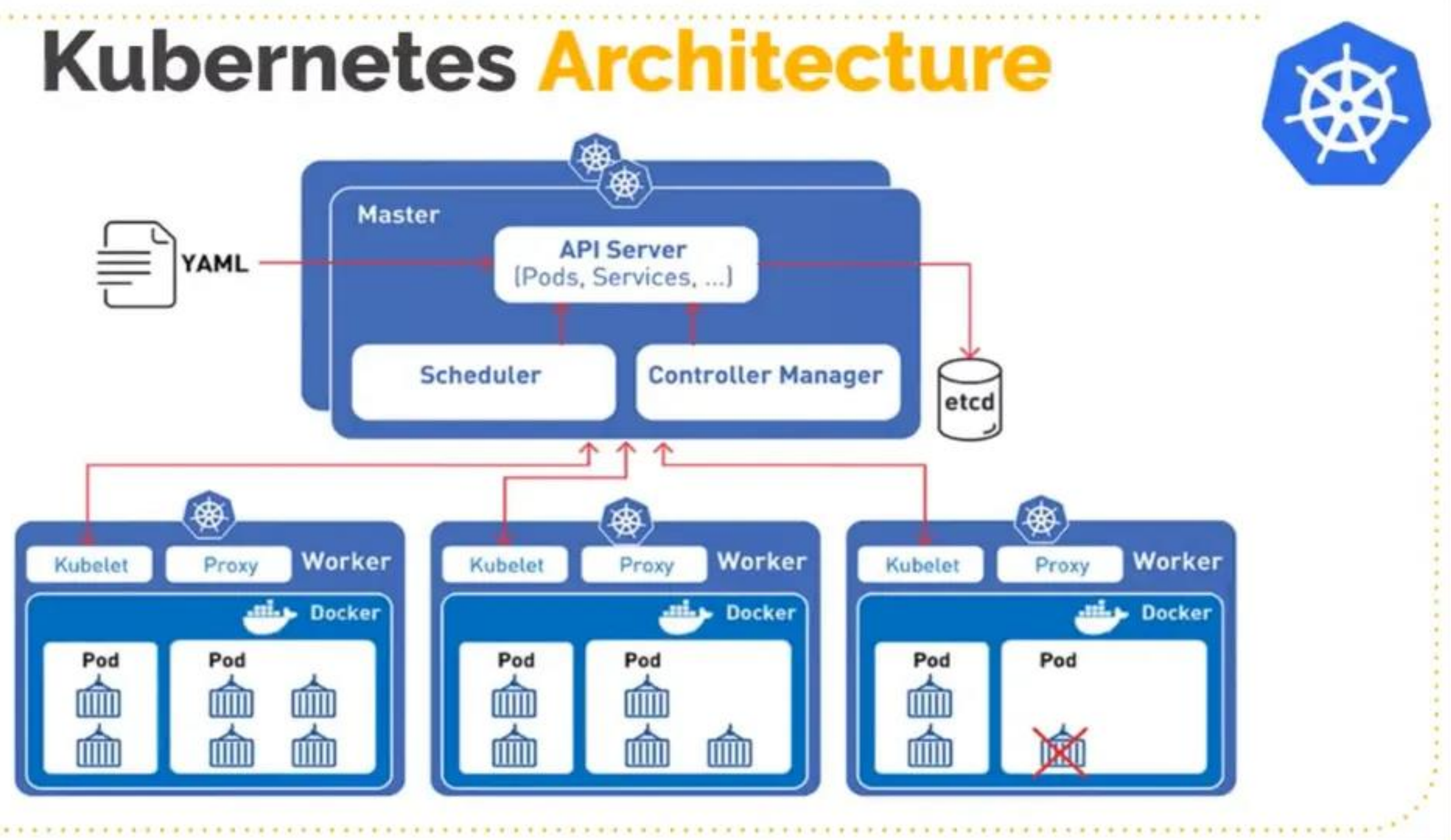
- The controller needs to manage many different aspects of the cluster
  - Mapping from container to node
  - Resource allocation per container
  - Number of instances per container
  - Automatic scaling based or demand and usage
- Decouple cluster state from the (one) controller
- Use many controllers



Clients of the cluster state can read/write the state directly

Evolution at Google: Kubernetes

- Manage access to the cluster state through an API server
- Validation of policies, versioning, default objects, etc.
- Highly-available strongly consistent distributed data store: etcd
- Still use many decoupled controllers
- Kubelet: manage node



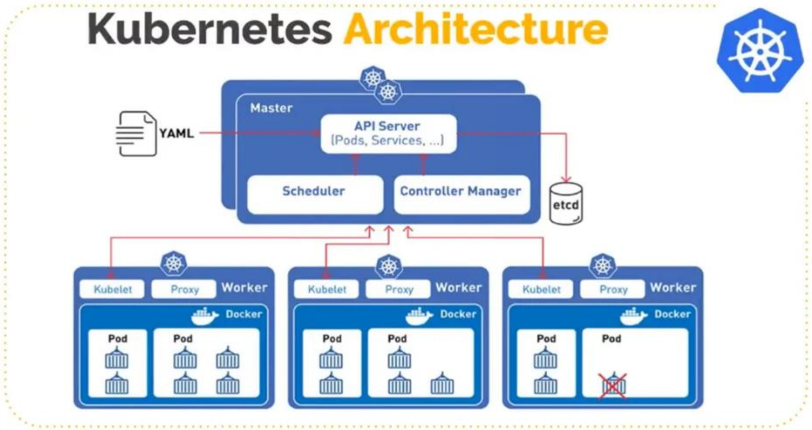
https://blog.devops.dev/the-kubernetes-architecture-e1ee01ccb76d

Kubernetes principles

```yaml
apiversion: extensions/v1beta1
kind: Deployment
metadata:
  name: nginx-deployment
spec:
  revisionHistoryLimit: 5
  minReadySeconds: 10
  selector:
      matchLabels:
        app: nginx
        deployer: distelli
  strategy:
    type: RollingUpdate
    rollingUpdate:
      maxUnavailable: 1
      maxSurge: 1
    replicas: 3
    template:
      metadata:
        labels:
            app: nginx
            deployer: distelli
      spec:
        containers:
          - name: nginx
            image: nginx: 1.7.9
```

- Consistent object representations
  - Metadata (name, ID, version, labels)
  - Specification (desired state)
  - Status (observed state, read-only)
- Reconciliation controller loop: Make the observed state (status) match the desired state (specification)
  - Example: number of replicas of a pod
- Many modular and interacting controllers
  - Example: Auto-scaling and Replica controllers
  - A failed-then-restarted controller has direct access to the observed state; no need to maintain complex internal state machines

More principles



- Each pod gets its own IP address
  - Visible to other pods and apps in the same Kubernetes cluster
  - Full access to all ports
  - This IP address need not agree with physical IP address of the node
  - Container Network Interface (CNI) to manage addressing & routing
- Labels to group containers
  - Don’t just number the containers
  - Key-value pairs that allow operator to define any attribute,
  - e.g., role=frontend
- Label selectors are sufficiently flexible to manage containers at time-varying granularity that is specified at operation time
  - e.g., a controller that only manages role=frontend pods