Container Orchestration (with Kubernetes) ~~Marketing~~

Peter Chen

About Me

- 2014-2016: grad student at UBC (Ivan was my supervisor)
- 2016-2019: Arista Networks
- 2019-2021: Google Cloud (Knative)
- 2021-Now: Google Research (NLP and Speech)

Container Orchestration

- What are containers?

- What is container orchestration? What problem does it solve?

- How it relates to concepts you've learned in distributed systems?

Container Orchestration - Why we care?

- ~2.9K companies use Kubernetes, a container orchestration system we will talk about, including (Google, Facebook, Shopify, …) to run their internal systems and to power their Cloud offerings
  - https://stackshare.io/kubernetes

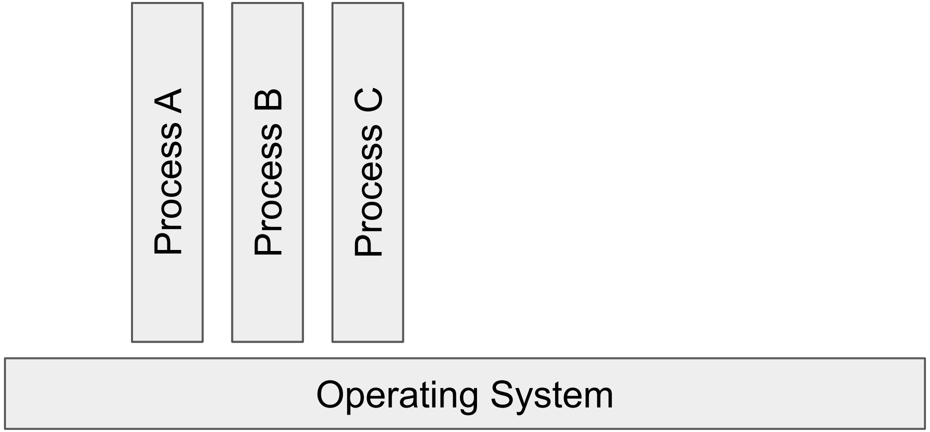
- Large open source community, as well as backed by big companies such as Docker, Microsoft, Google

- Gartner report adoption of containers grew 40% in 2020, by 2023, 70% of **all** organizations will be running containers in some form (in 2019 this was less than 20%)
  - Become the de-facto way to deploy, run and build services

Reminder: Processes

Operating System

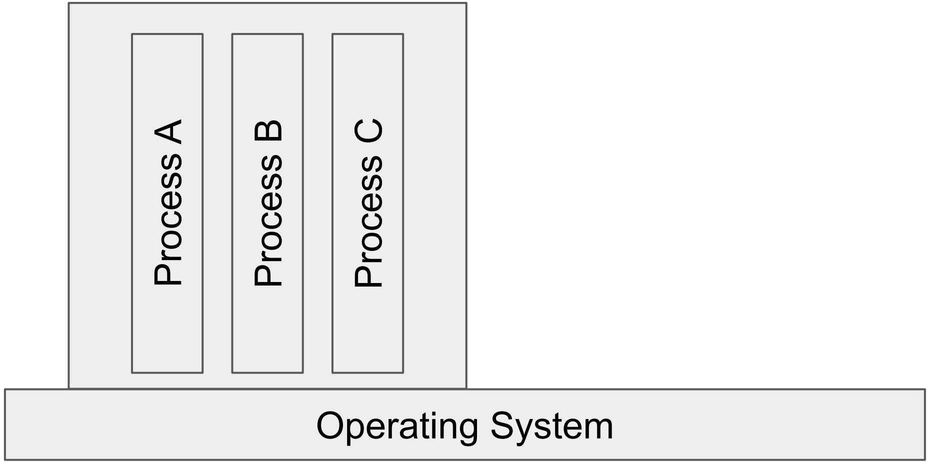
Reminder: Processes



Applications run as the **process** abstraction

Each process has its own memory space and therefore its own execution context

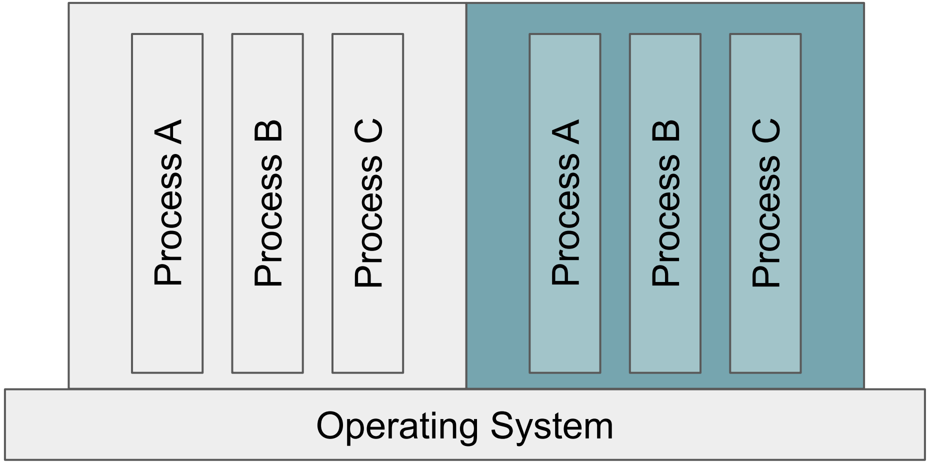
More Info: Processes



But there are other things these process share in the operating system:

- PID (process ids)
- MNT (file system)
- IPC (sockets)
- UTS (time?)
- NET (network e.g., IP tables)
- etc,...

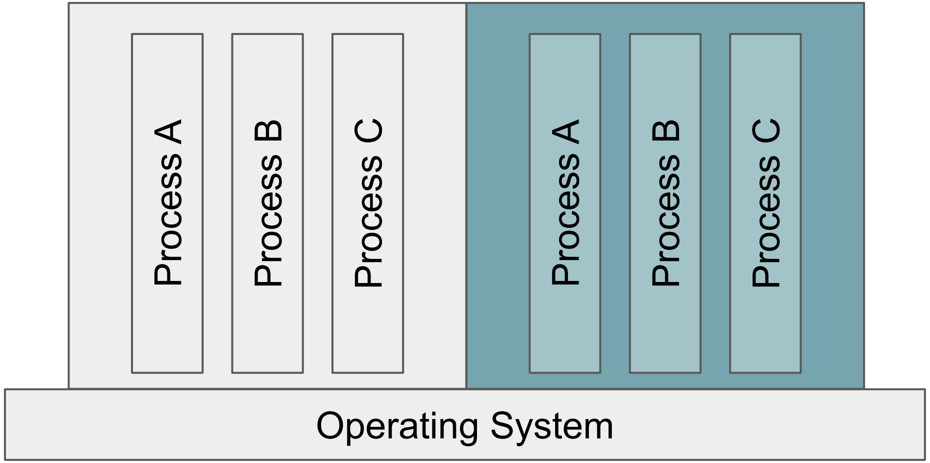
Containers



Nice things about containers, they are:

- **Lightweight**: fast, very little overhead
- **Isolation:** executable package of software with its own code, runtime, tools, libraries and settings
- **Portable:** compiled into an “image” which can be deployed on other machines as a “container” instance

Containers



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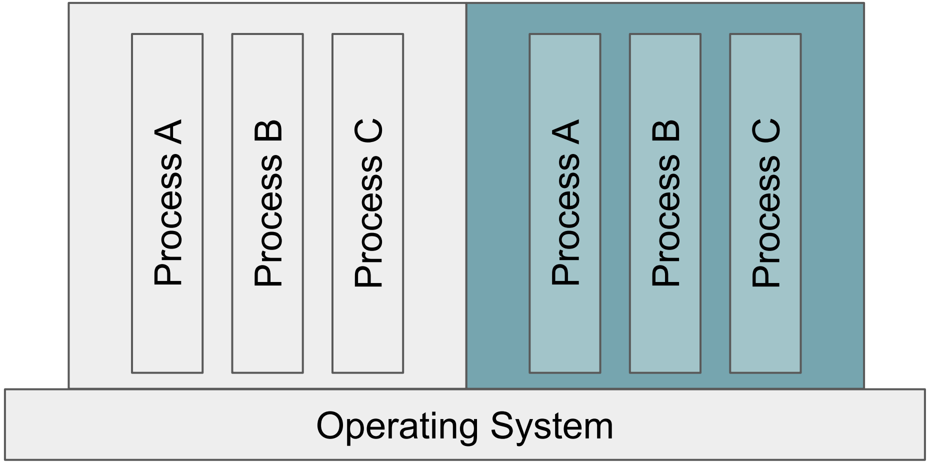
This is a bit different to what you are use to in VMs where the objective is virtualization of hardware resources instead of just isolation of all the aspects of execution.

Containers



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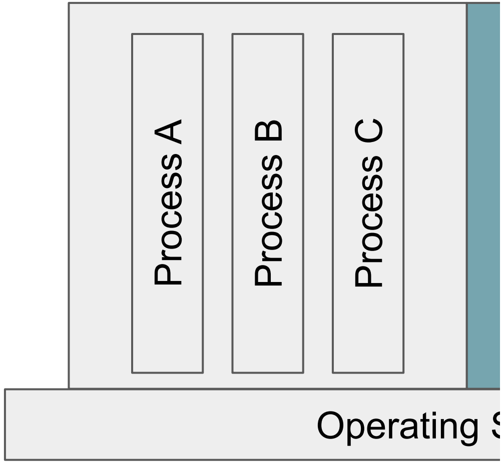
Cost of containers: 5 MB for smallest image, arbitrary amount of CPU
Cost of VMs: (~2GB) for smallest OS, compute cost in increments of 1 CPU

Containers



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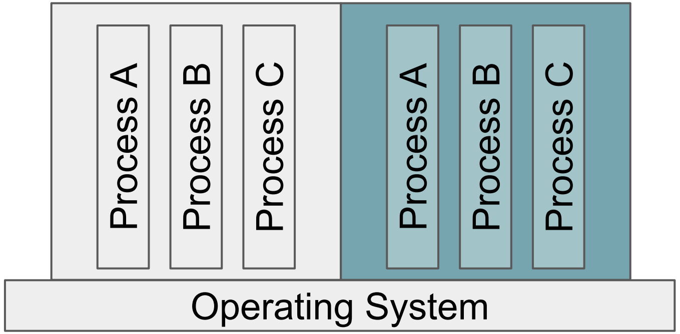
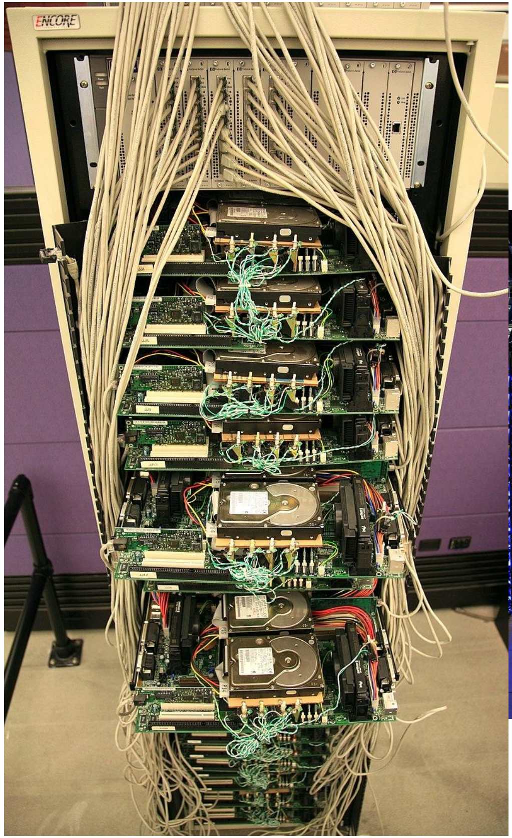
Container Orchestration

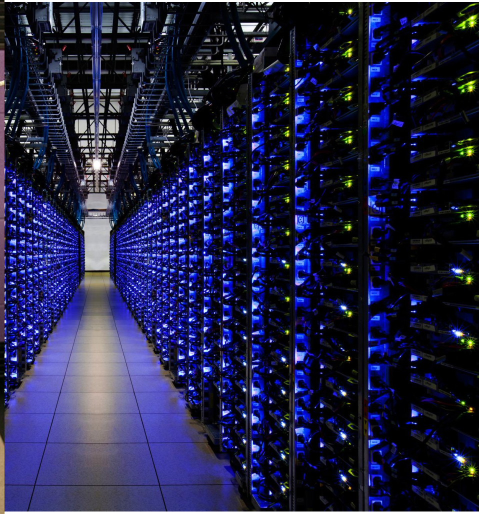
Recap:

- What is the relationship between an “image” and a “container”?
- What does running in a container isolate vs. say a VM?
- What are some of the benefits?

Container Orchestration

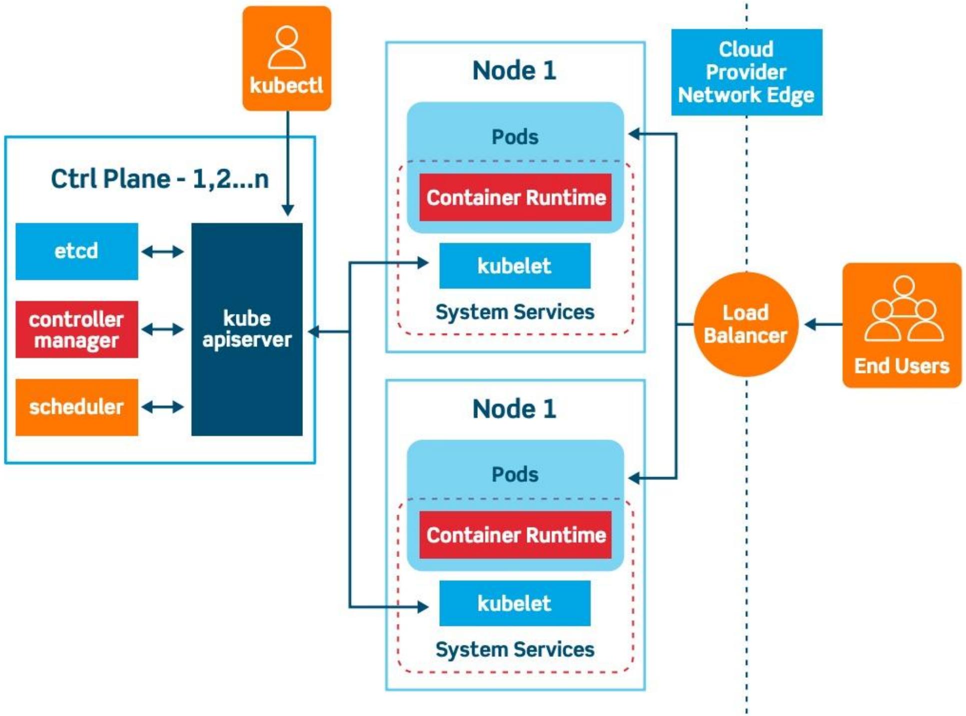






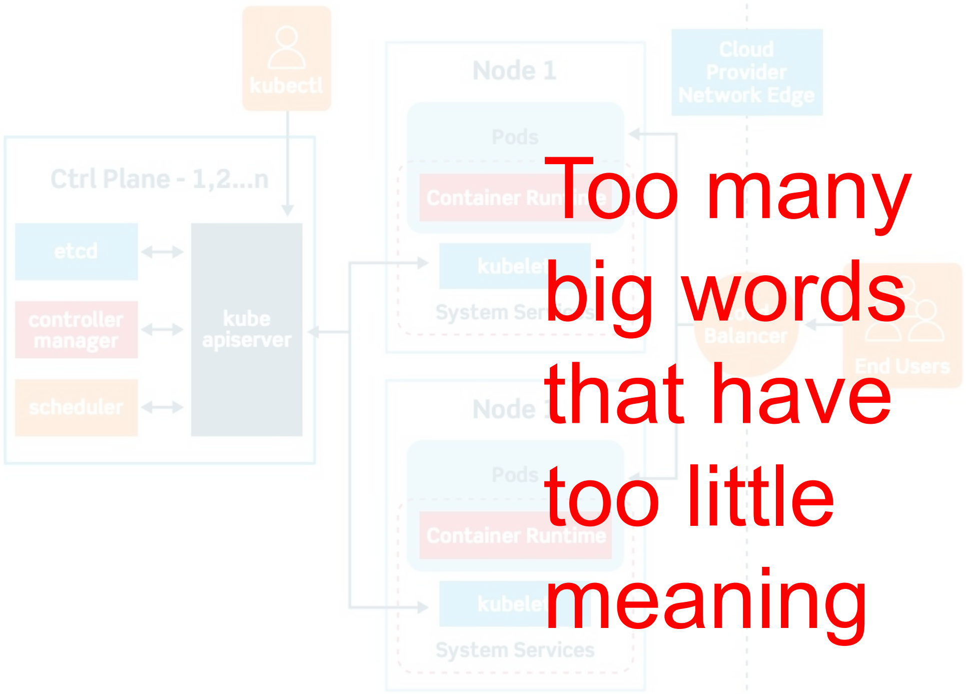
Kubernetes

Kubernetes - Architecture



- Abstractions: Pods, Services, Ingress, Deployments, Volumes…
- Add-ons: Istio, Knative...
- Network: Weave, Flannel…
- Control Plane: scheduler, api-server, controller-manager, etcd...

Kubernetes - Architecture



Too many big words that have too little meaning

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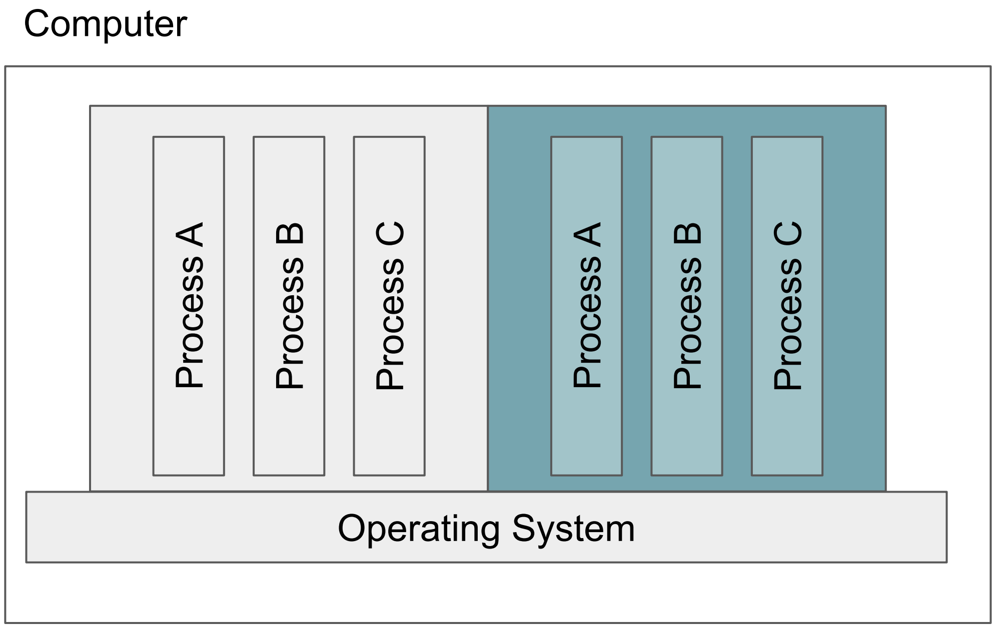
Kubernetes - Execution



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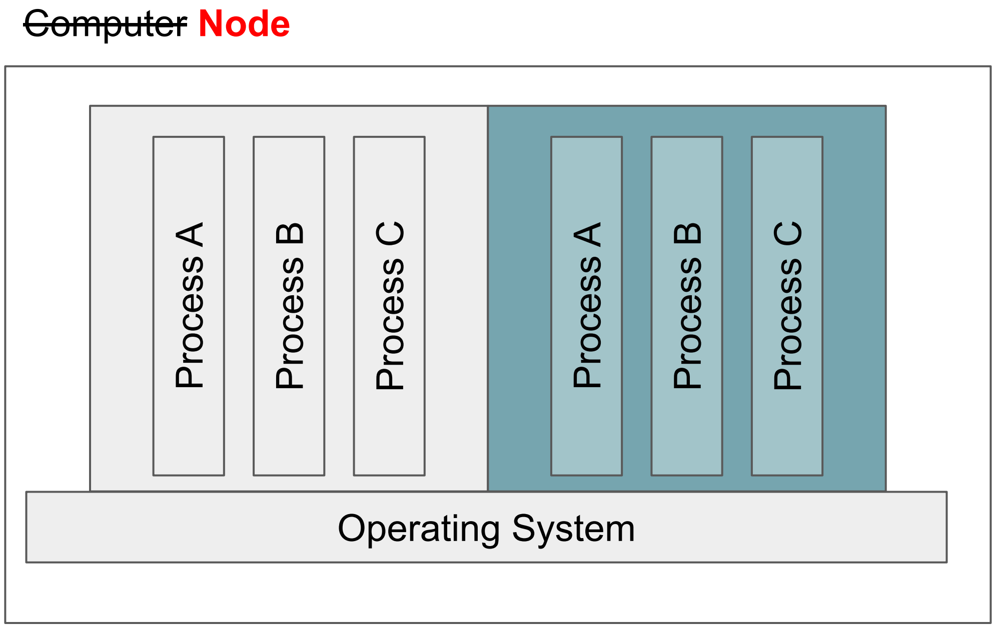

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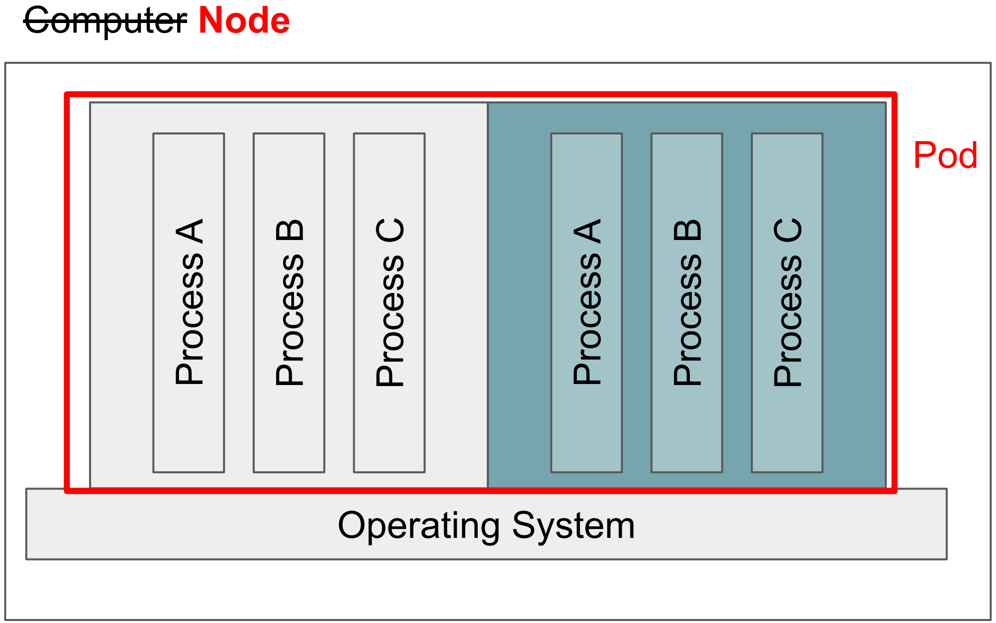

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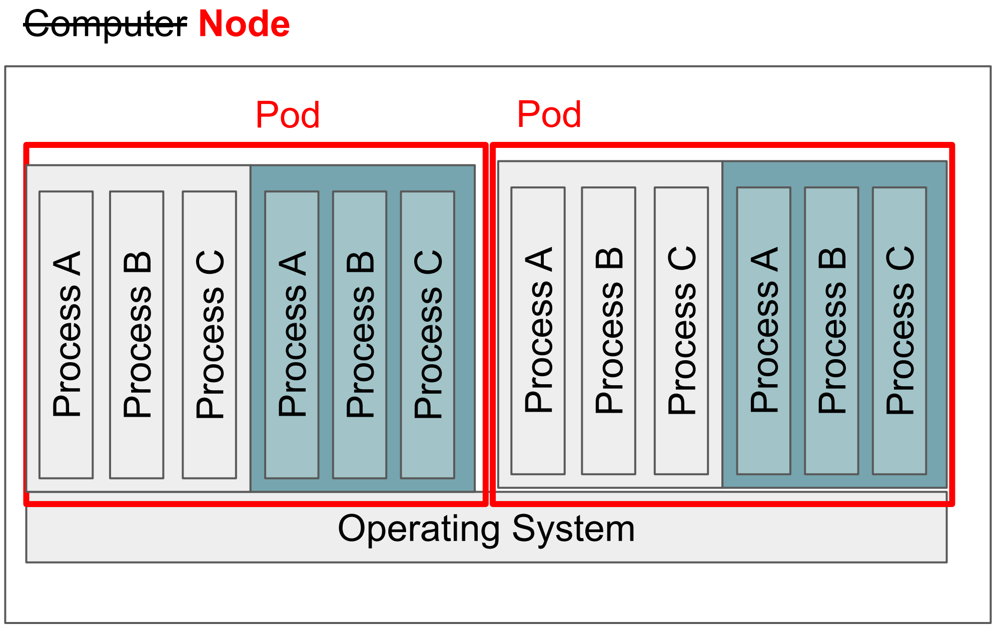

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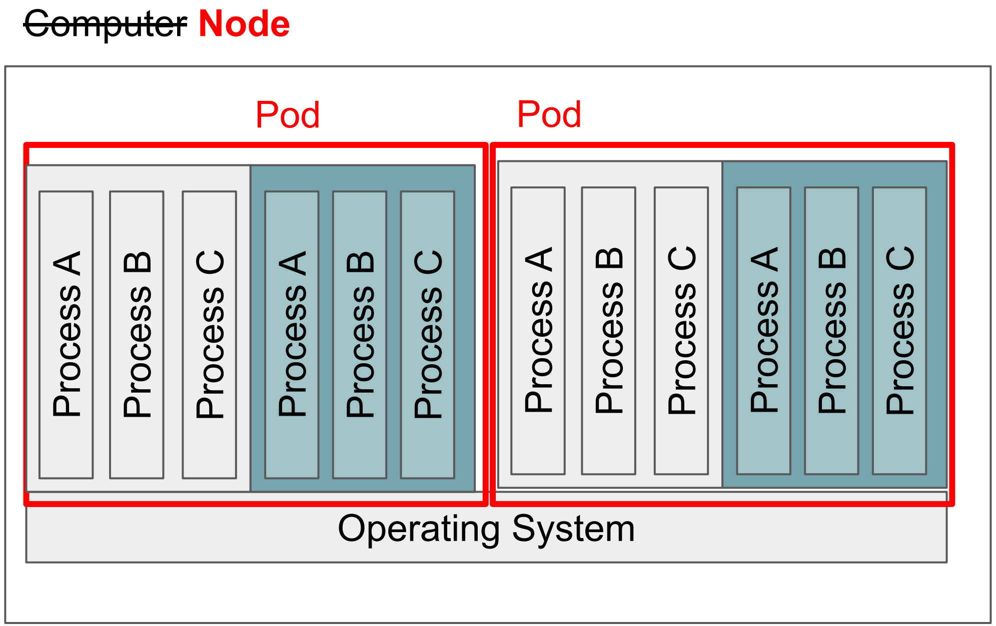

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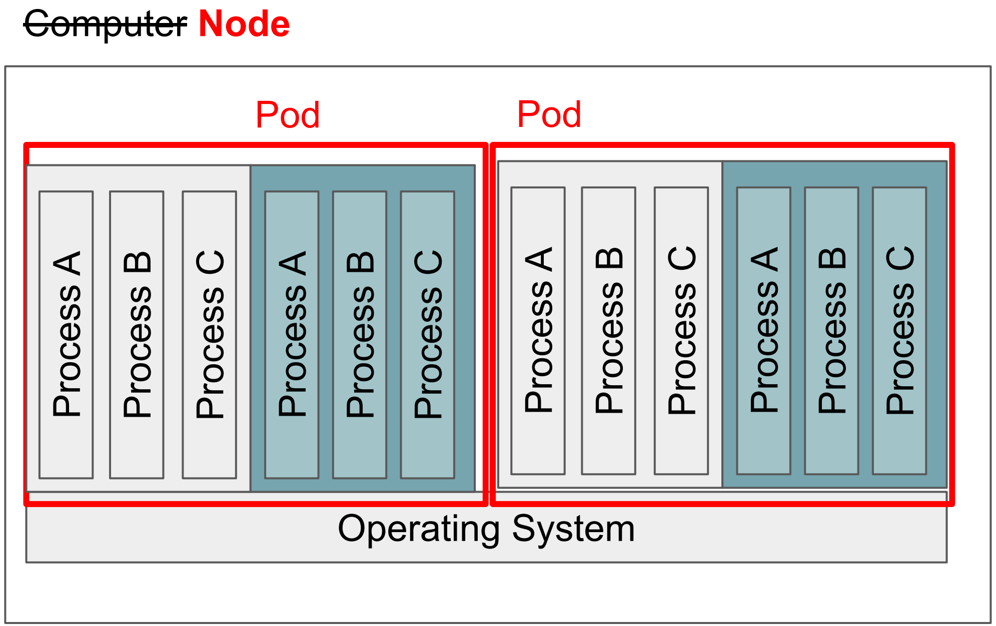

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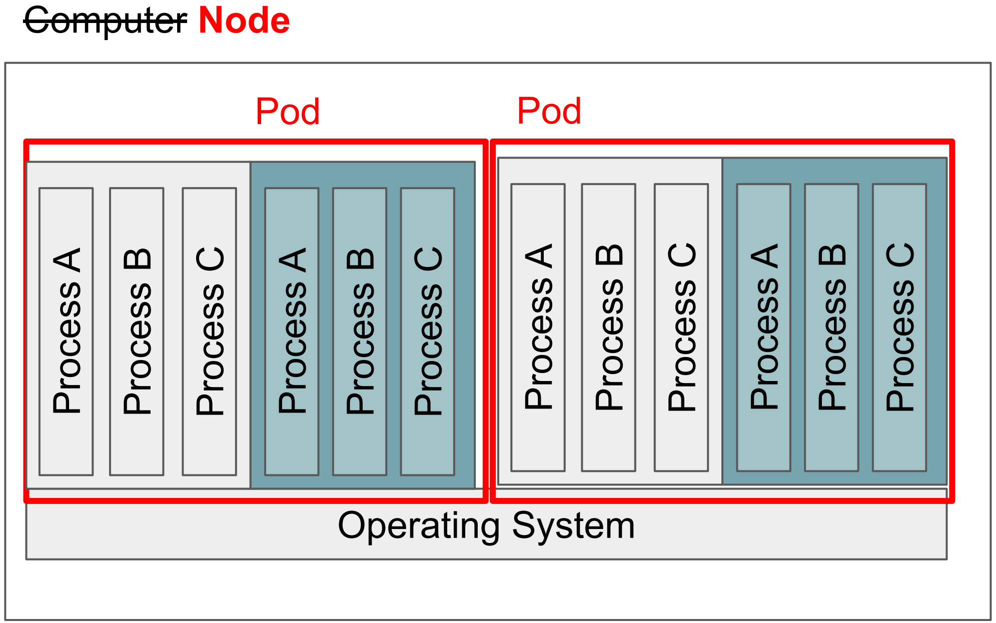
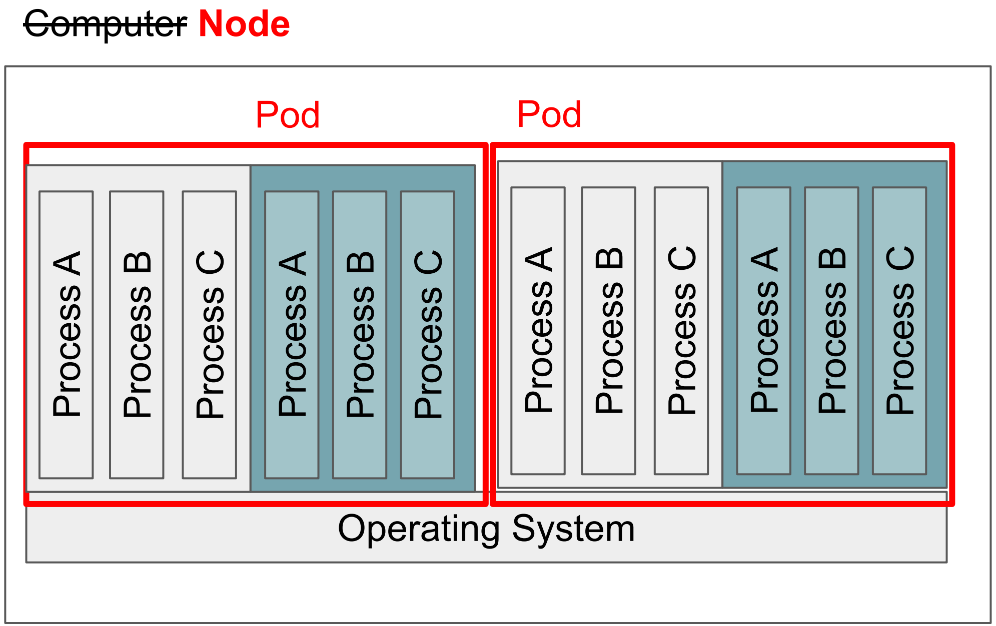


- **Fate sharing:** e.g., processes in a **pod** live/die together (a webserver and its local SQL instance
- **Fault tolerance and scalability:** multiple **pods** can become ***replicas*** and execute on different **nodes** dynamically
- **Multi-tenancy:** multiple **pods** can run on a single **node**, provide scalability and efficient use of cluster-wide resources

Kubernetes - Execution

Do you manually create/delete pods? That would be a huge hassle.



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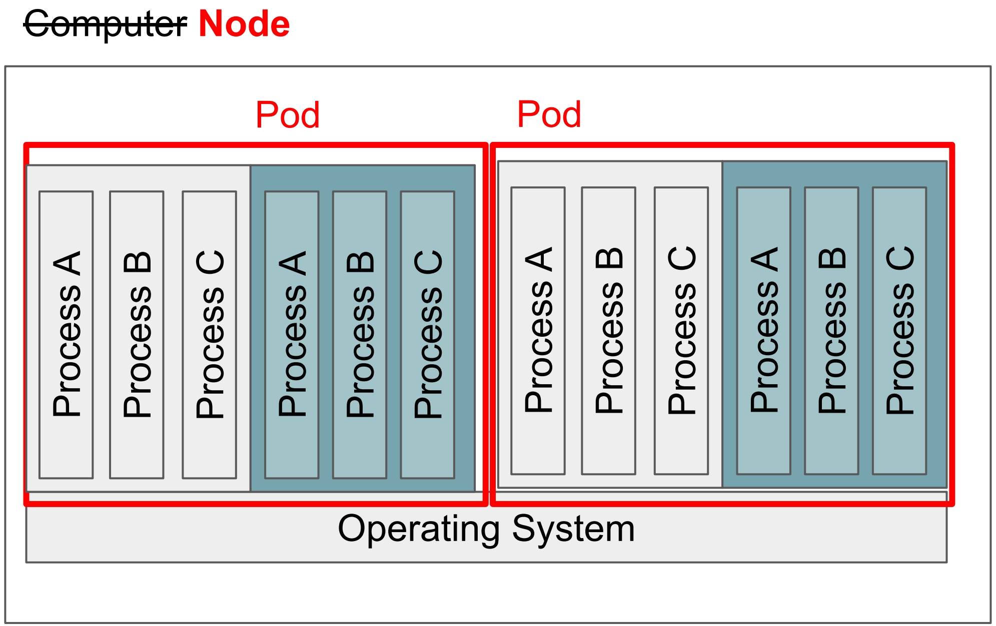


Pods are controlled usually via higher level abstractions (e.g., **Deployment, Jobs**)

Deployment

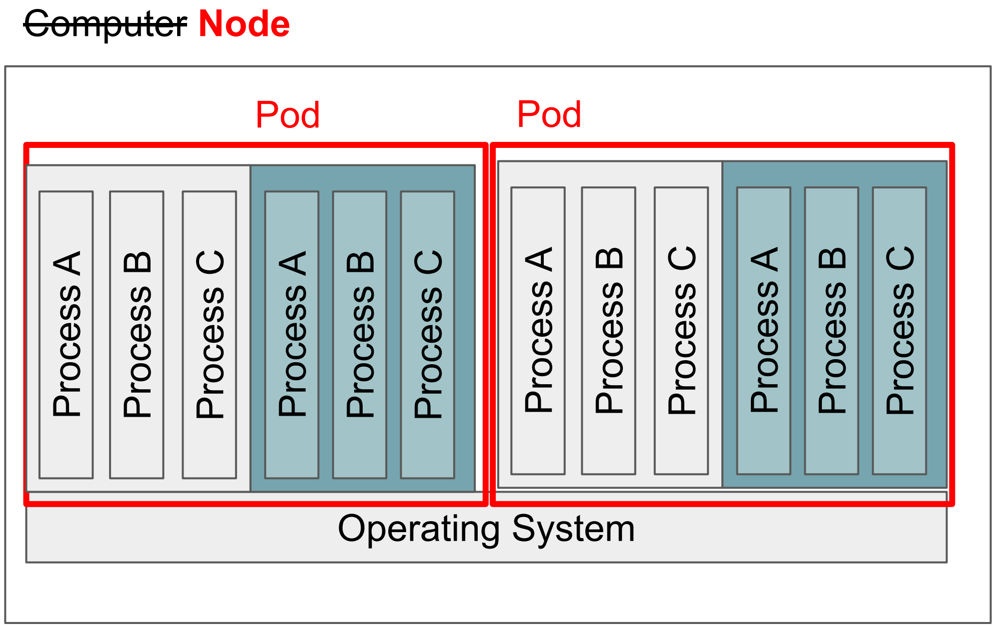
- declares the number of **pods** and what to execute in them
- Maintains that number of pods forever
- To scale up, create another deployment with new number of pods, similarly to scale down

Jobs

- Pod that runs a single time until end of execution and then is deleted
- Timeout

Kubernetes - Execution

What if I don't want to even do manual scaling?

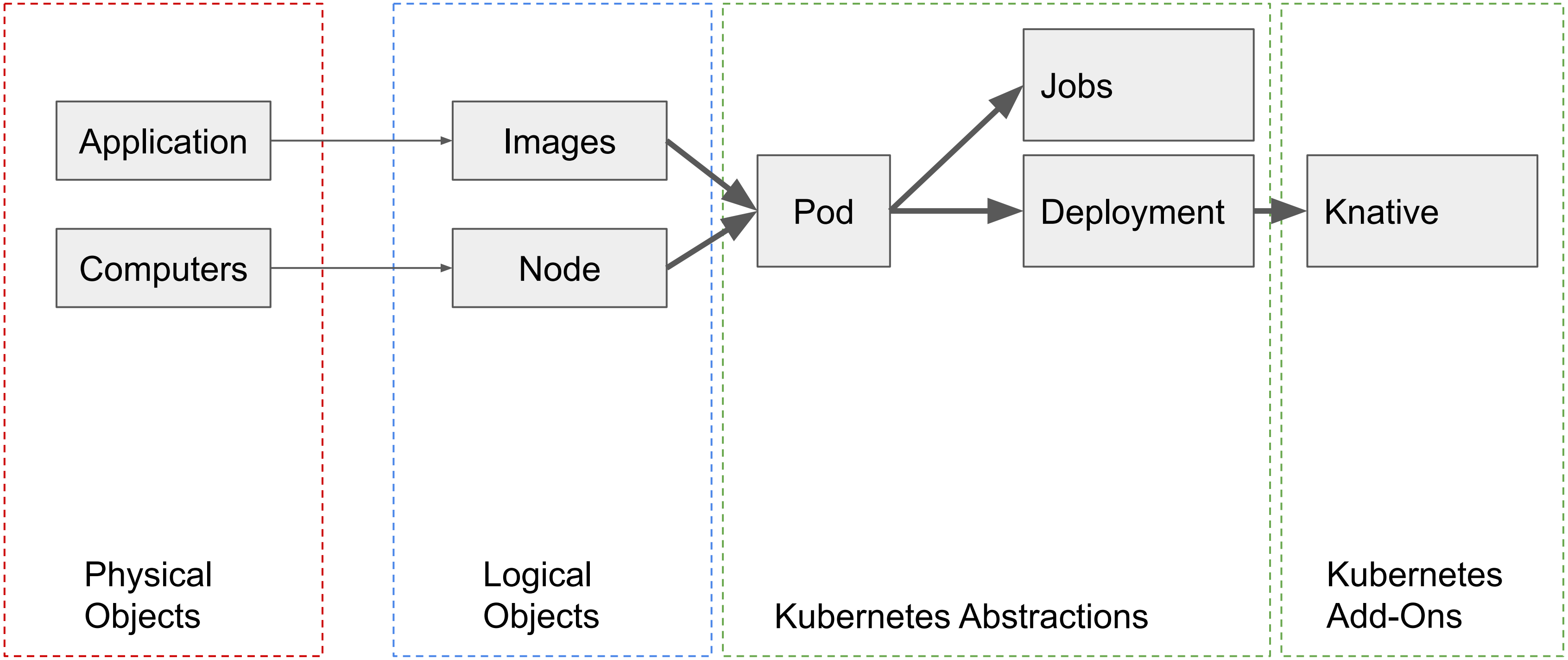


Answer: another layer of abstractions!
Knative!

Knative is a Kubernetes **Add-On**

- Add-on is a fancy word for a bunch of kubernetes abstractions packaged together
- Auto-scales the number of pods according to traffic/demand

Kubernetes - Execution



Kubernetes - Execution Recap

Recap:

- What is a pod?

- How many processes can run in a container?

- If you wanted multiple replicas of the same application, what would you do?

- If you had a web server and a database, how do you run them so that if a node fails, both the web server and database fail together? How would you run them if you wanted them to fail separately?

- What is the difference between a Kubernetes Add-On and Kubernetes abstraction (they are actually called resources, but let’s call them abstractions for generality)?

Kubernetes - Execution Recap

Recap:

- Who are the users of Kubernetes?
- What do developers of Kubernetes develop?

Kubernetes - Networking Model

But **nodes** are physical servers, they don’t have to be in the same network address space in the data center.

Kubernetes - Networking Model

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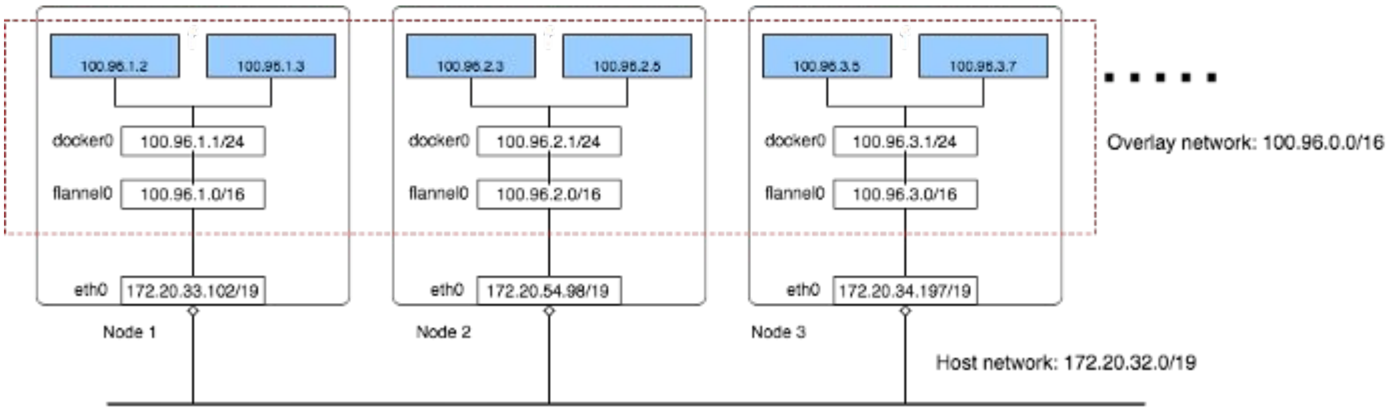
- All containers in a pod are in the same network (as if local)
- All pods are in a flat address space (same subdomain)



Kubernetes - Networking Model

But **nodes** are physical servers, they don't have to be in the same network address space in the data center.

Solution: overlay a logical network onto the physical network (e.g., Flannel, Weave, GCP, AWS, Azure, ….)

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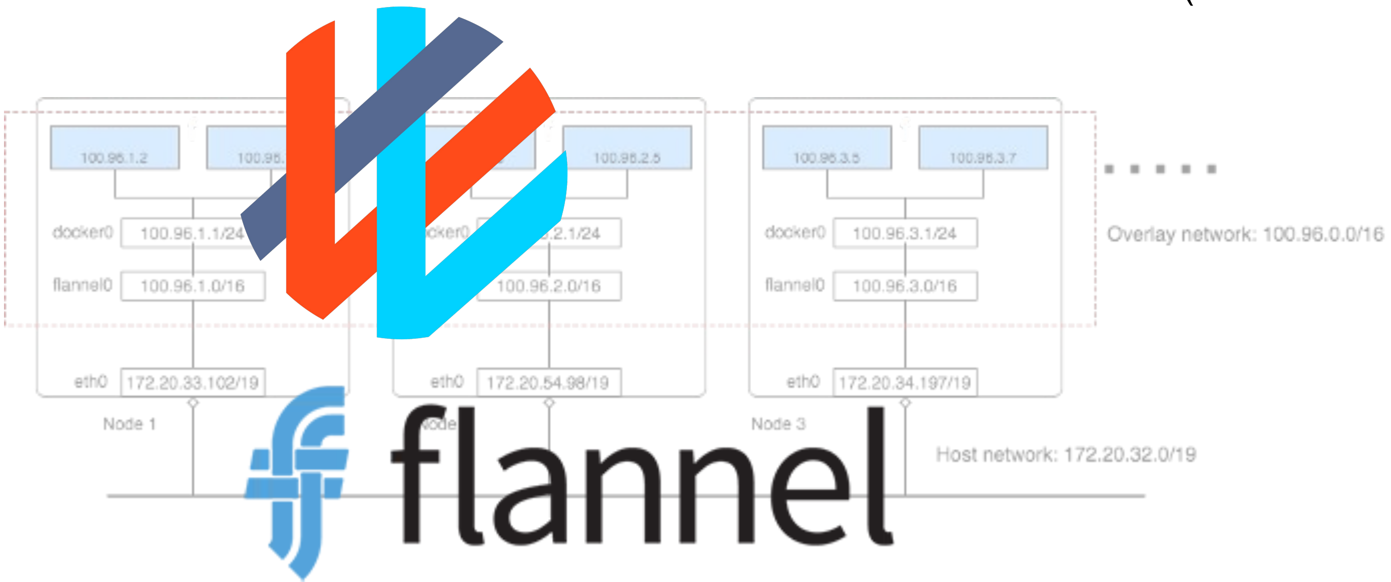
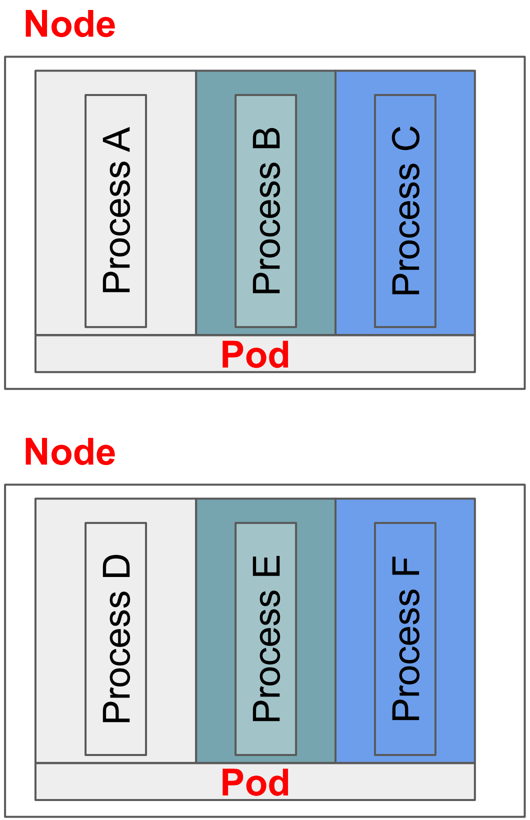


Kubernetes - Discovery



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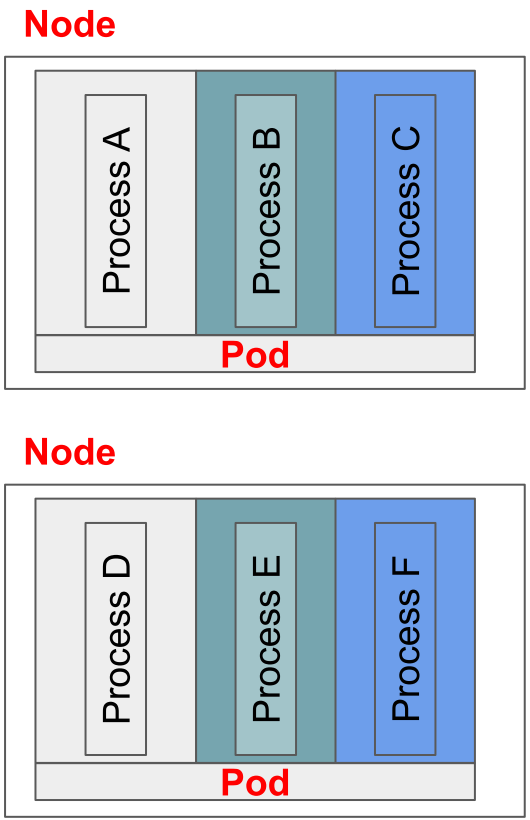

How do pods find each other inside of the flat address space we just created?

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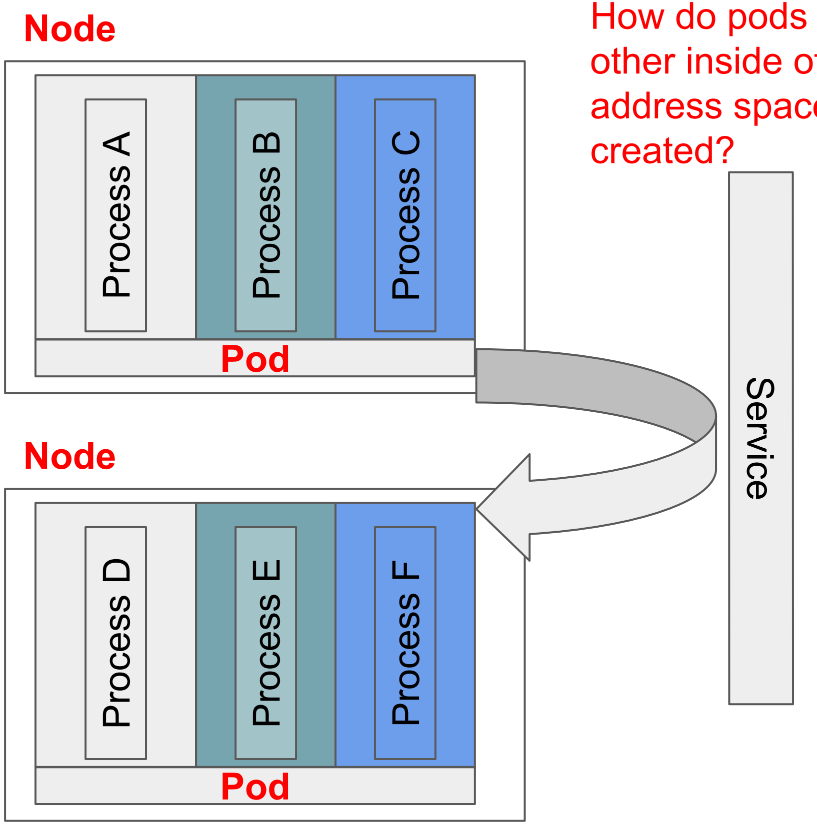
Kubernetes - Service



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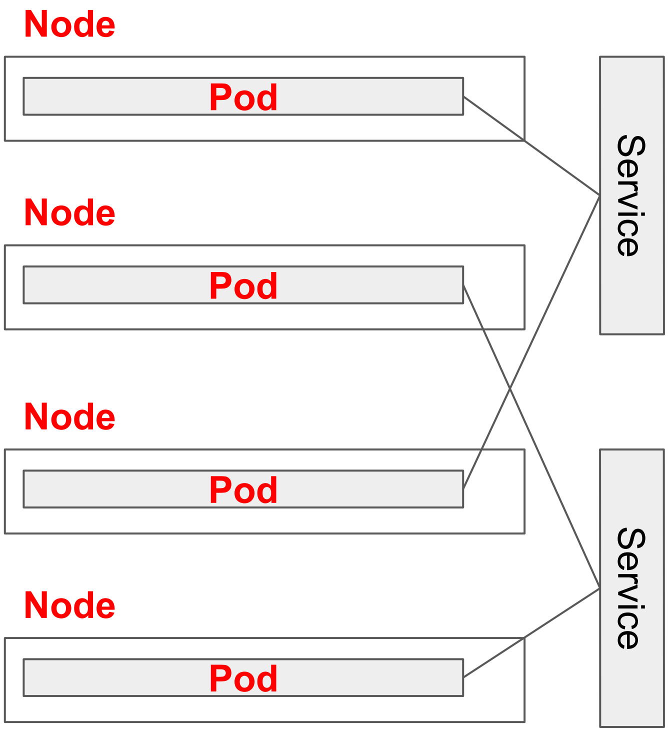
- **Service**: discovery (e.g., DNS), also inter-pod load-balancing

Kubernetes - Service Mesh

Microservices have a lot of services...how do I manage them?



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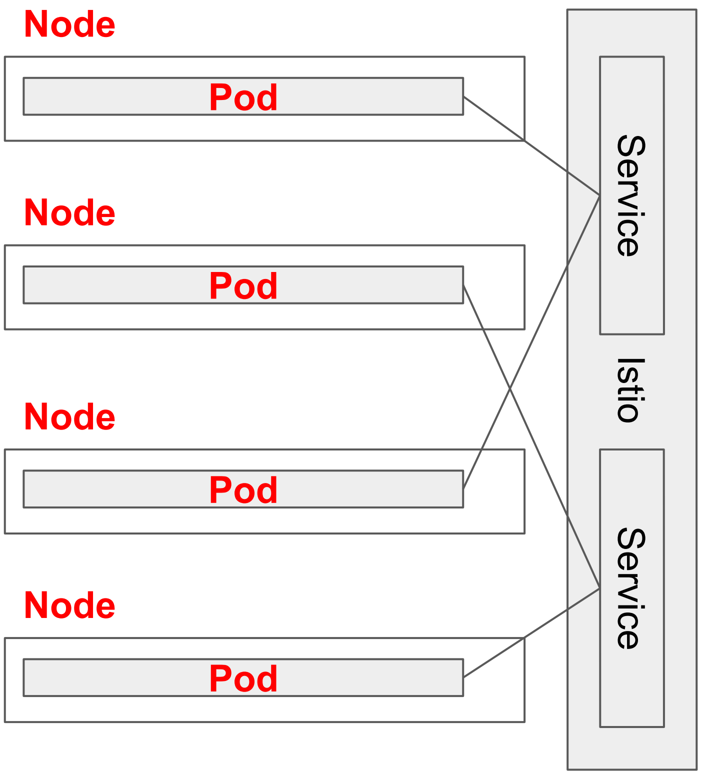
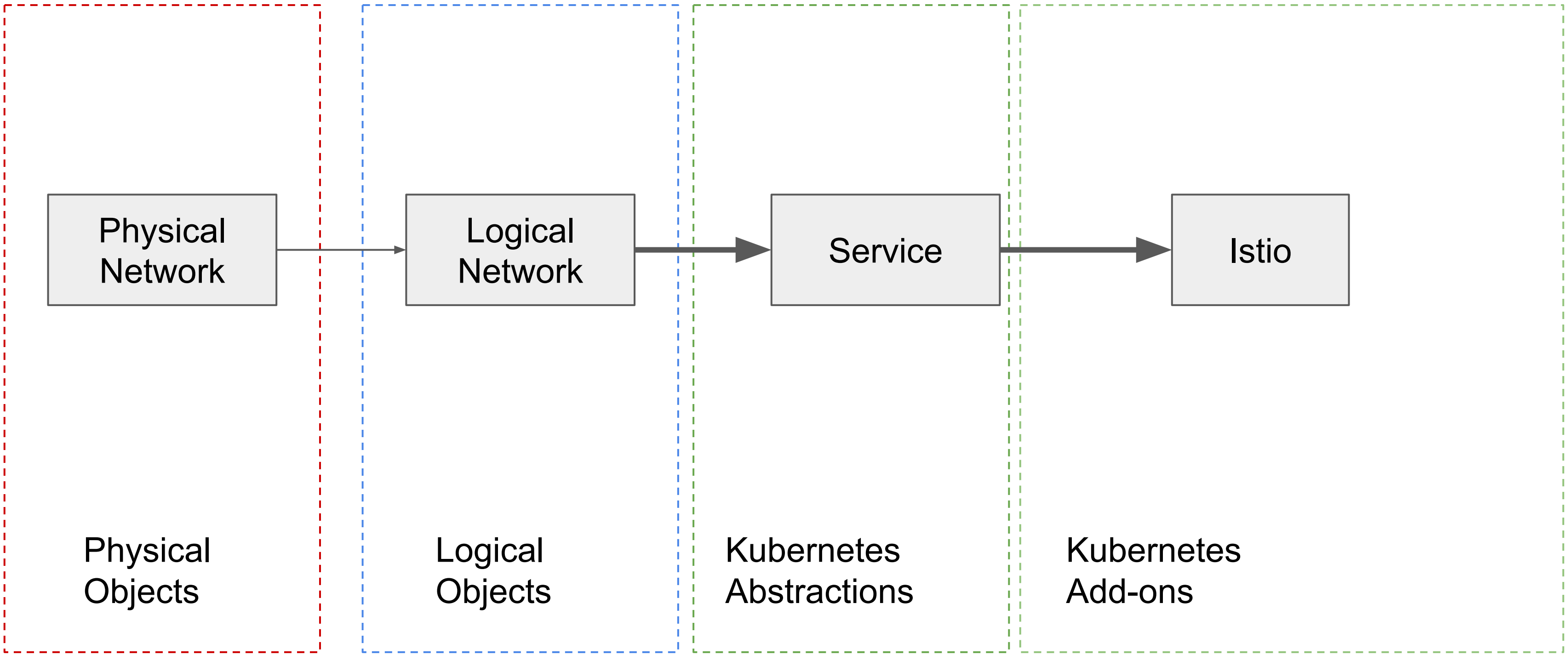


Answer: another layer of abstraction! Another add-on!

Istio: a service mesh manager

- **Control:** traffic splits (e.g., A/B testing)
- **Policies:** rate limiting between services
- **AAA**: authentication, authorization, etc.,
- **Observability**: tracing, metrics, logs

Kubernetes - Network Abstractions



Kubernetes - Network Abstractions Recap

Recap:

- What is needed to get physical servers on different racks to look like they are in the same subdomain? Note: each rack is a different subdomain

- Why would you not just deploy a cluster on a single server rack?

- How do your pods find each other?

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- How do your pods find each other?

- What is the difference between Istio and a Service?

Kubernetes - Persistence

- pods are ephemeral but some states need to persist

Ok but how do I store data persistently for the code I am running in a container in a pod? (e.g., pod get moved to another node, how do I keep the data I wrote to files on the previous node?

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- **volumes**: mount points of **pod** during runtime
  - ephemeral (e.g., use file system on the **node**)
    - Each pod has its own isolated disk space
  - Persistent Disks (e.g., GCP Persistent Disk, AWS Elastic Block Store, Azure Disk, etc,...)
    - Mountable by a single pod at a time
  - Many more
- API calls to your favourite distributed data store (e.g., Spanner, S3, etc,...)

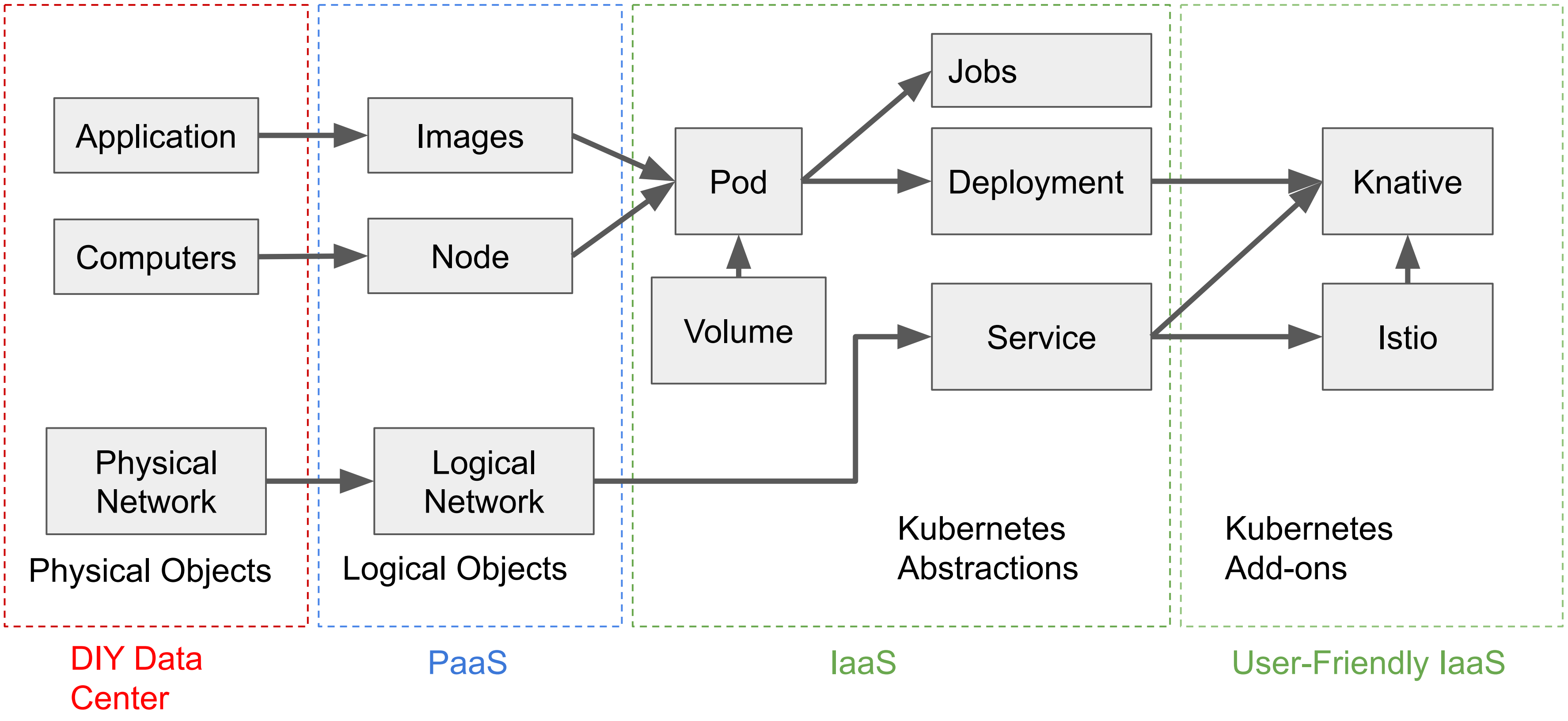
Kubernetes - Persistence Recap

Recap:

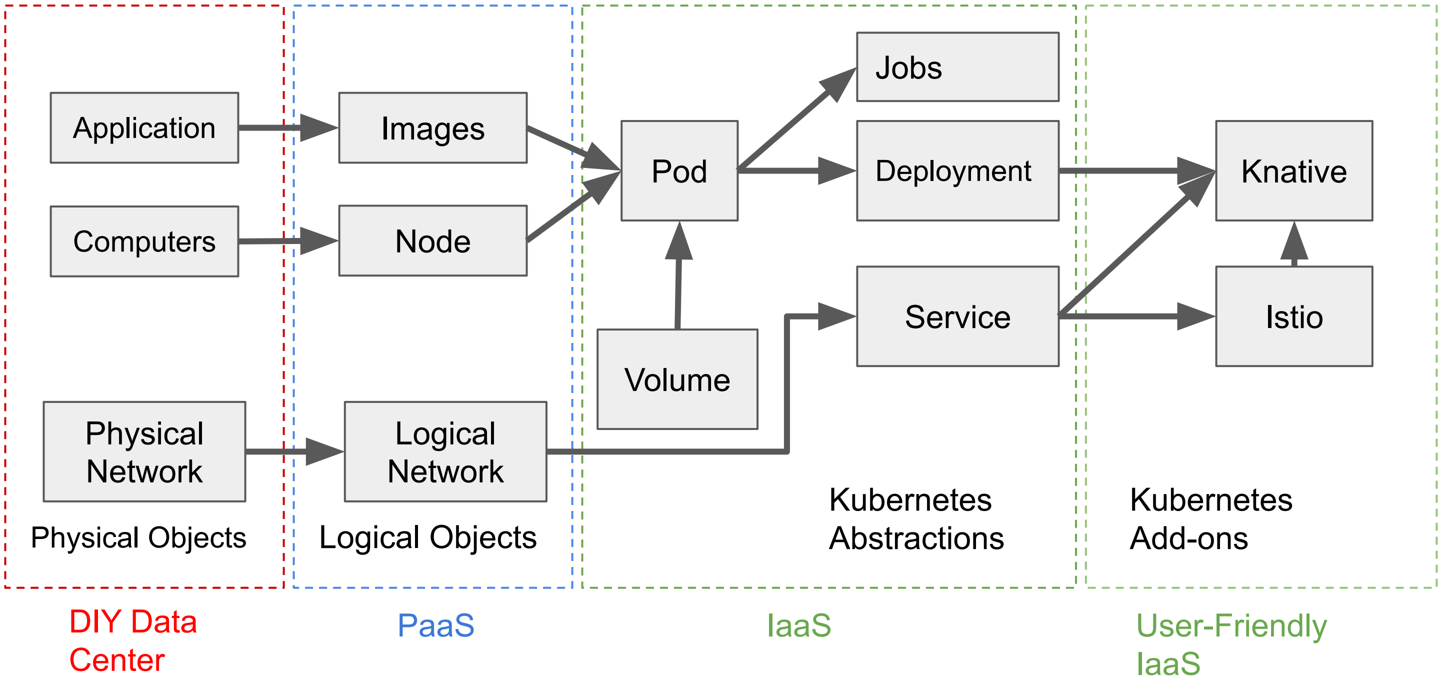
- I have an app that runs in a Kubernetes pod, and I want to store some user data. What are my options?

- What are the benefits of keeping “management” of persistent state out of Kubernetes execution?

Kubernetes - Execution + Network Abstractions = Dataplane



Kubernetes - Execution + Network Abstractions = Dataplane



Extensibility: build your own infrastructure (e.g., cluster-level abstractions)

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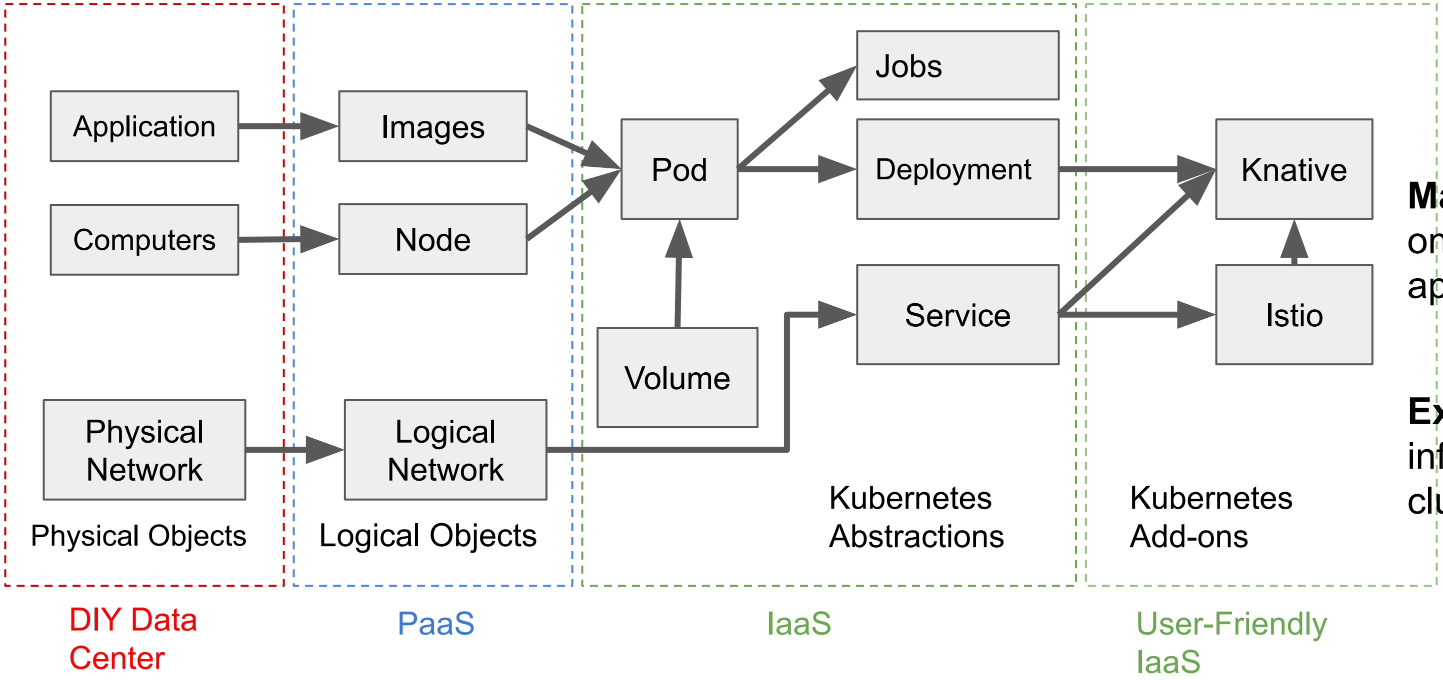

Managed Services: users only need to care about applications

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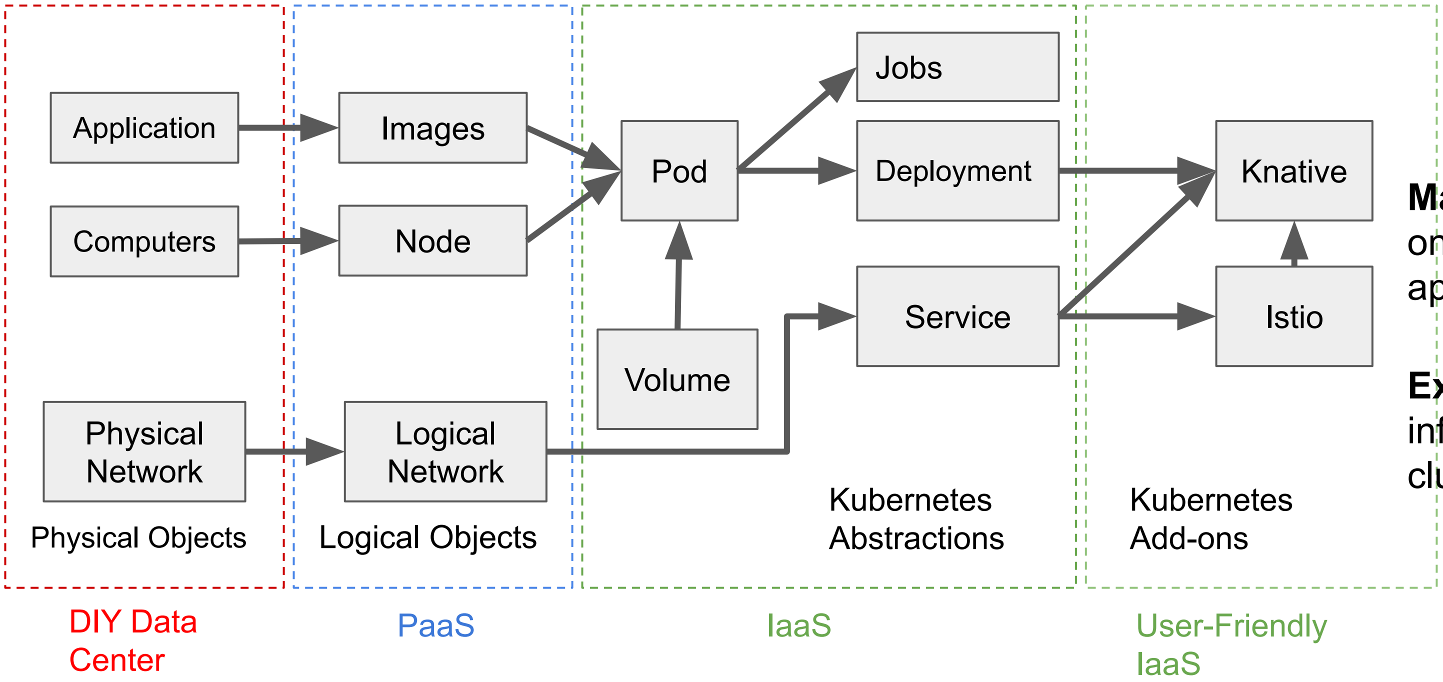


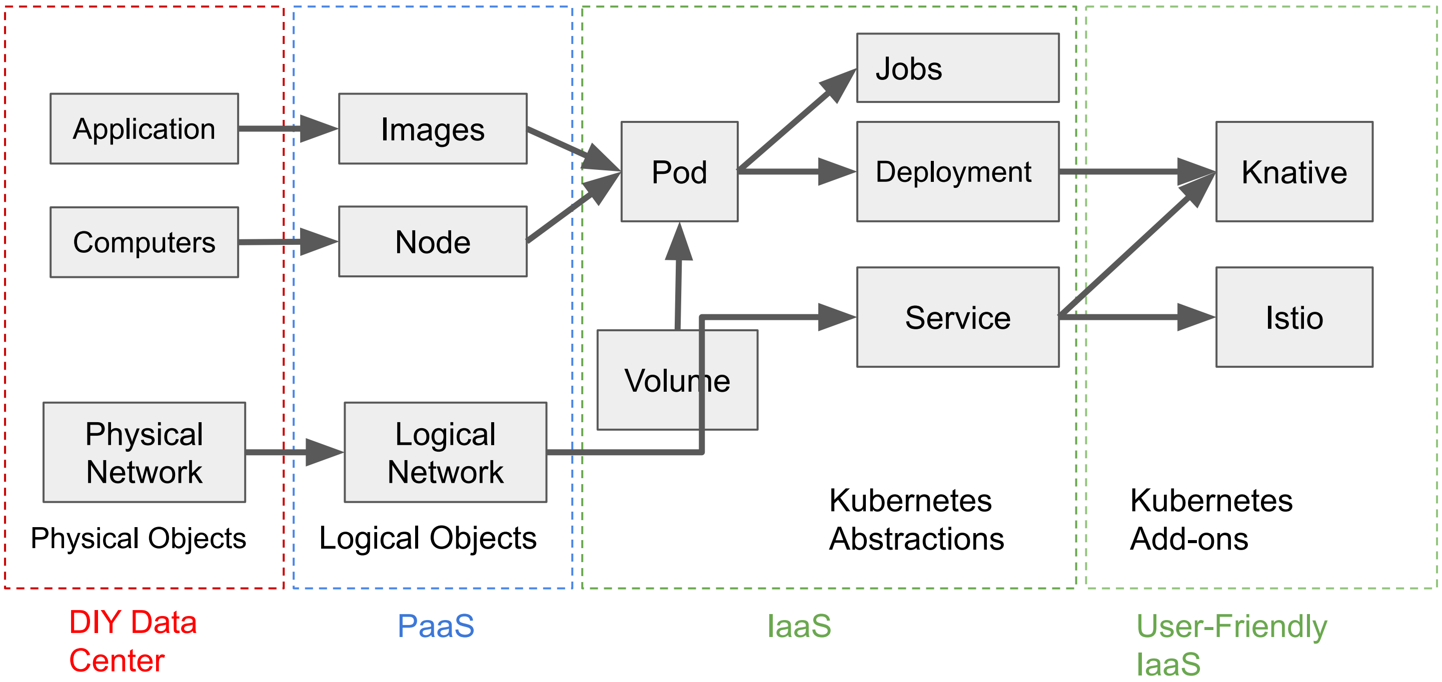
Managed Services: users only need to care about applications

Extensibility: build your own infrastructure (e.g., cluster-level abstractions)

Question: If you where an engineer developing a service, why would you use containers and Kubernetes to deploy your service, what value is it providing you and your organization?

Kubernetes - Management

How is all this controlled and managed?



Kubernetes - Control Plane

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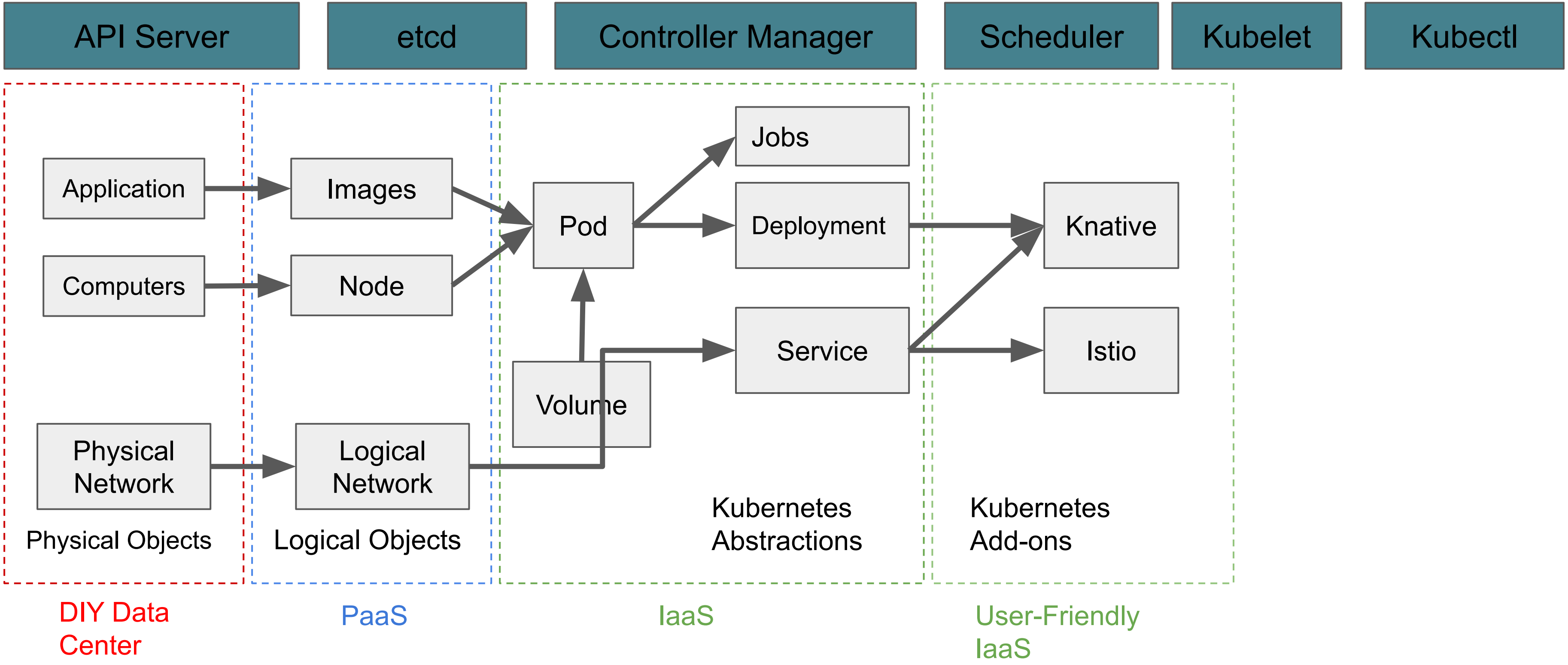


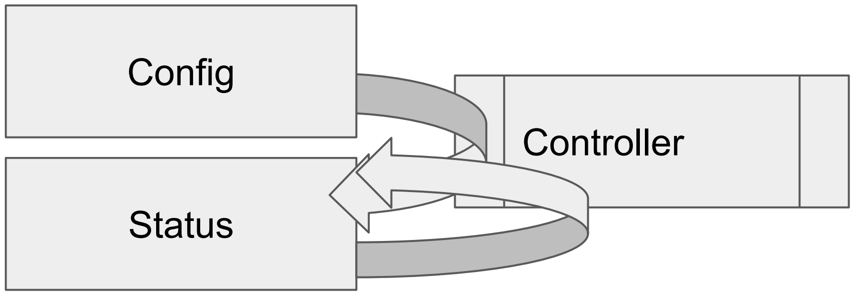
Kubernetes - Control Plane Controller Manager

API Server	etcd	Controller Manager	Scheduler	Kubelet	Kubectl

Where does the logic for the Kubernetes abstractions and add-ons all live?

Kubernetes - Control Plane Controller Manager

API Server | etcd | **Controller Manager** | Scheduler | Kubelet | Kubectl



Where does the logic for the Kubernetes abstractions and add-ons all live?

A controller is:

- A non-terminating code loop that anneals state from desired to current
  - Eventually consistent
- Steps:
  - Look at config
  - Make changes to the cluster (e.g., create/delete pods based on the number configured in **Deployment**)
  - Write result to status

Kubernetes - Control Plane Controller Manager

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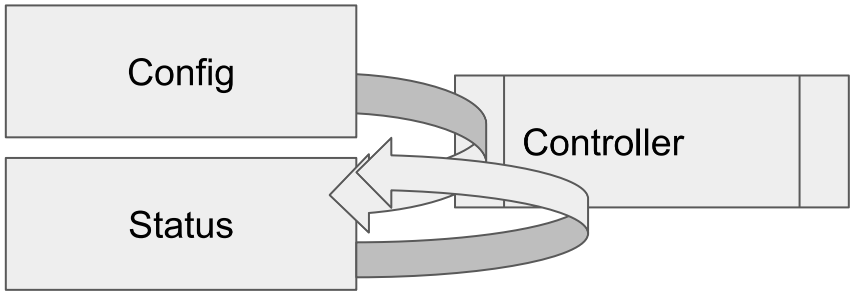

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Option 1: deployed as part of Kubernetes control plane

- Compiled together to create **controller manager**
- Naturally fault-tolerant with the control plane with leader and standby controller managers

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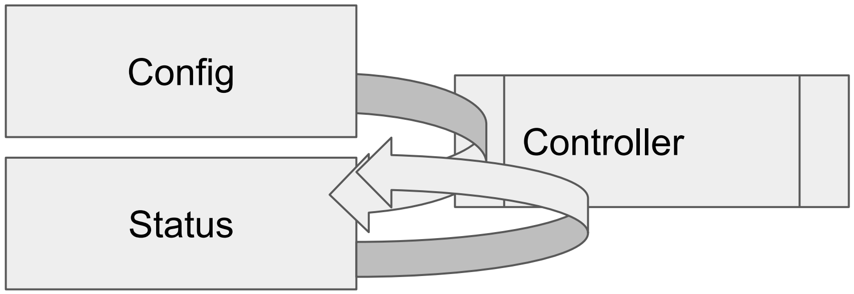

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Option 1: deployed as part of Kubernetes control plane

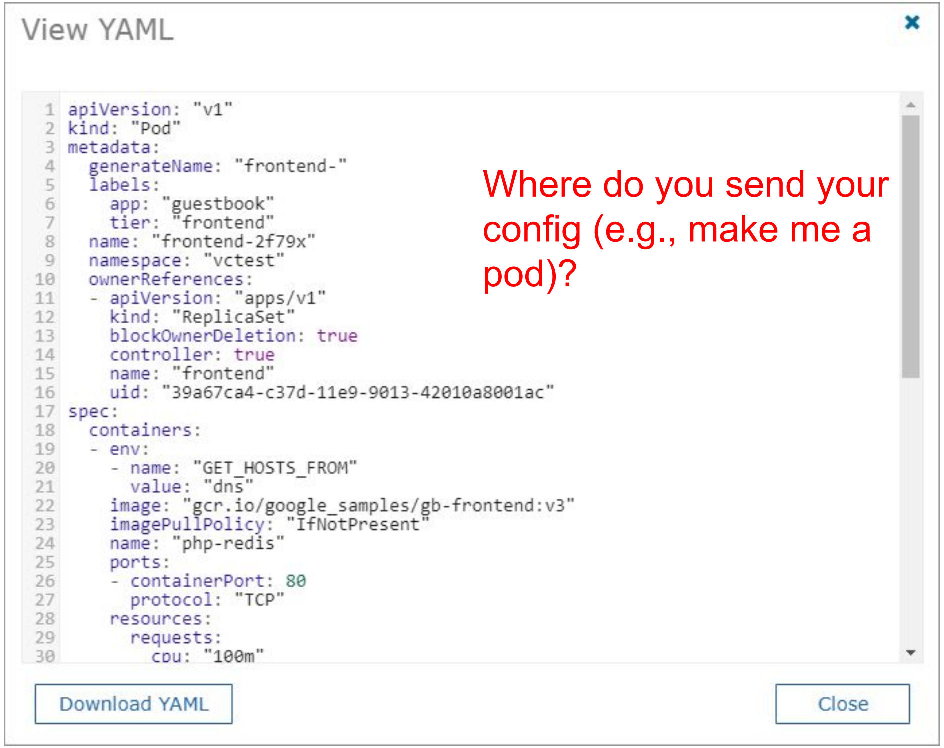
- Compiled together to create **controller manager**
- Naturally fault-tolerant with the control plane with leader and standby controller managers

Option 2: deployed as a pod (extensible)

- Developers self-manage leader election
- Keep only one replica that is managed by native Kubernetes applications (e.g., **Deployment**)

Kubernetes - Control Plane API Server

API Server | etcd | Controller Manager | Scheduler | Kubelet | Kubectl



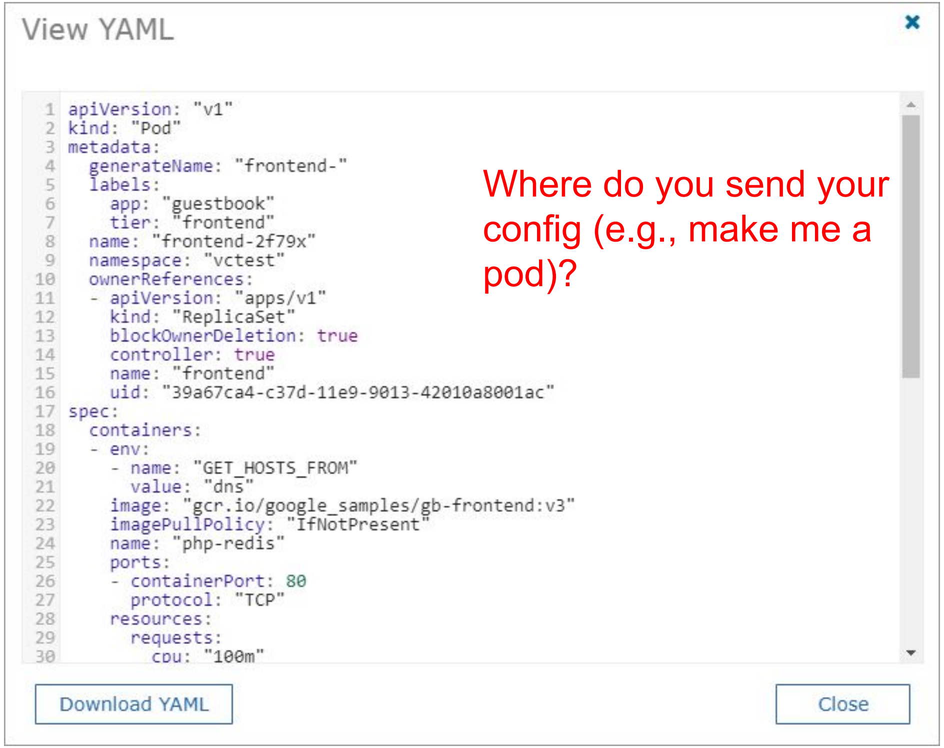
Where do you send your config (e.g., make me a pod)?

Kubernetes - Control Plane API Server

API Server | etcd | Controller Manager | Scheduler | Kubelet | Kubectl

Declarative API

- **Resources**: Kubernetes abstractions such as **pod, service**, etc.,
- HTTP endpoints (e.g. apiextensions.k8s.io/v1)
- YAML



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Kubernetes - Control Plane API Server

API Server | etcd | Controller Manager | Scheduler | Kubelet | Kubectl

Pass information through state
- eventually consistent
- Config (YAML) declares intent to **Controller**
- **Controller** polls intent, takes action and query result of its actions from cluster
- **Controller** writes the result of its actions to status
- Intent and result are made fault-tolerant via state, exist past the lifetime of controllers (e.g., not message passing)

View YAML


```yaml
apiVersion: "v1"
kind: "Pod"
metadata:
  generateName: "frontend-"
  labels:
    app: "guestbook"
    tier: "frontend"
  name: "frontend-2f79x"
  namespace: "vctest"
  ownerReferences:
  - apiVersion: "apps/v1"
    kind: "ReplicaSet"
    blockOwnerDeletion: true
    controller: true
    name: "frontend"
    uid: "39a67ca4-c37d-11e9-9013-42010a8001ac"
spec:
  containers:
  - env:
    - name: "GET_HOSTS_FROM"
      value: "dns"
    image: "gcr.io/google_samples/gb-frontend:v3"
    imagePullPolicy: "IfNotPresent"
    name: "php-redis"
    ports:
    - containerPort: 80
      protocol: "TCP"
    resources:
      requests:
        cpu: "100m"
```


Download YAML | Close

Where do you send your config (e.g., make me a pod)?

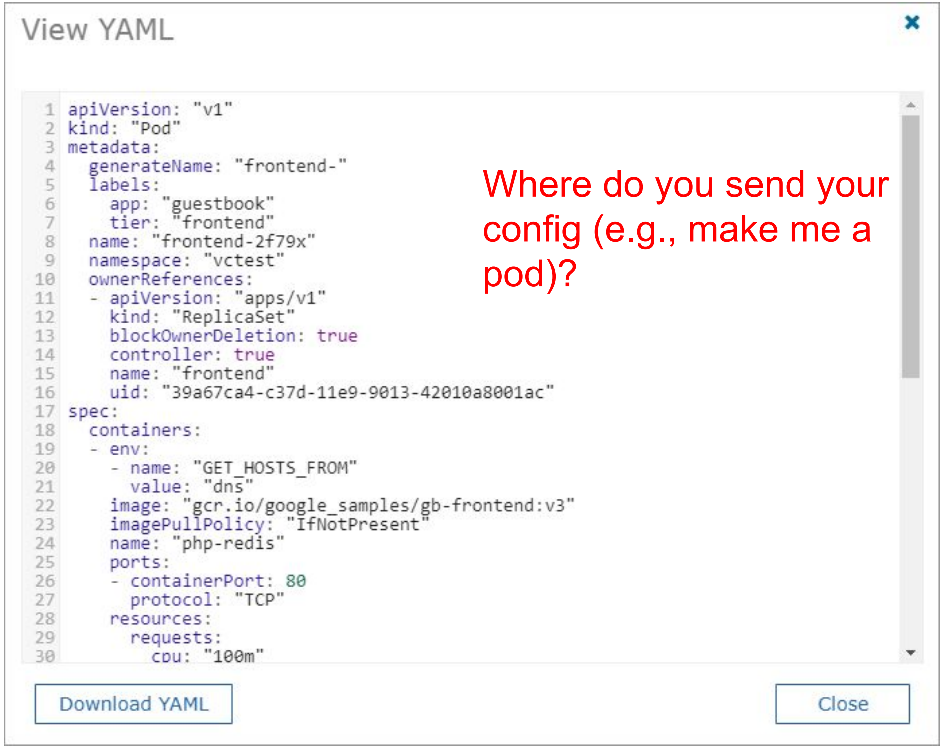
Kubernetes - Control Plane API Server

API Server | etcd | Controller Manager | Scheduler | Kubelet | Kubectl

Pass information through state

- eventually consistent
- Config (YAML) declares intent to **Controller**
- **Controller** react to intent, takes action and query result of its actions from cluster
- **Controller** writes the result of its actions to status
- Intent and result are made fault-tolerant via state, exist past the lifetime of controllers (e.g., not message passing)

Question: why does controller query the state of cluster, instead of just update the status based on the actions it took?



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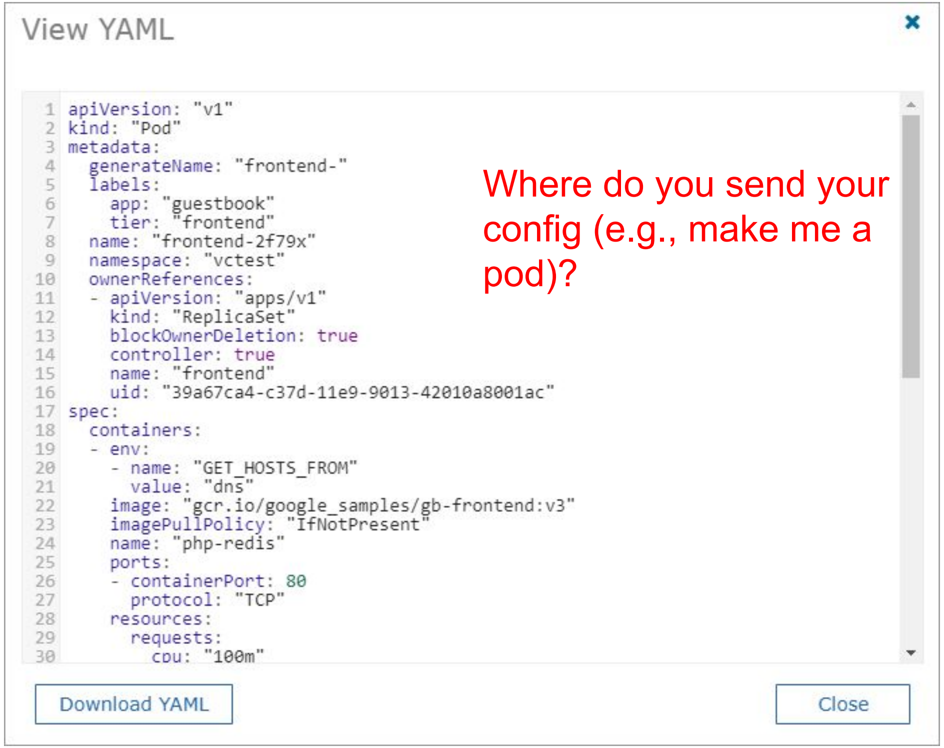
Question: what are the down-side of message passing? (e.g., send config to controller directly and getting status back)

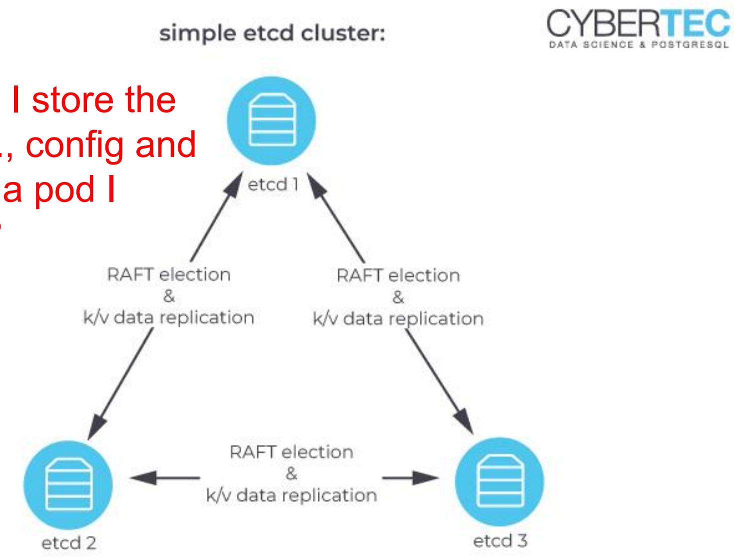


Where do you send your config (e.g., make me a pod)?

Kubernetes - Control Plane State

API Server	etcd	Controller Manager	Scheduler	Kubelet	Kubectl

Where do I store the state (e.g., config and status) of a pod I declared?



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CYBERTEC DATA SCIENCE & POSTGRESQL

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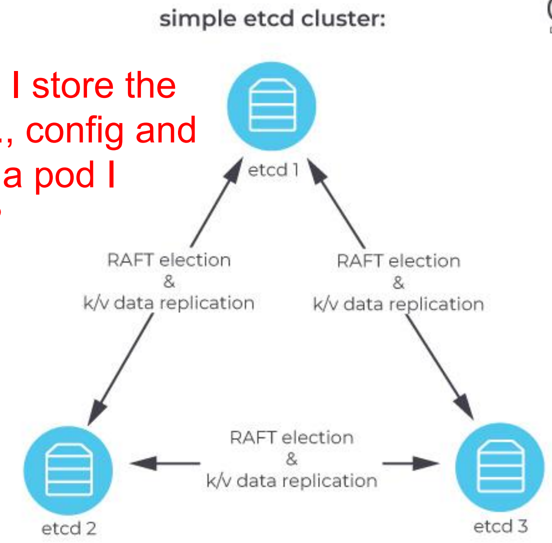

Etcd is a distributed key-value store for cluster states (e.g., API configs, metadata)

Kubernetes - Control Plane State

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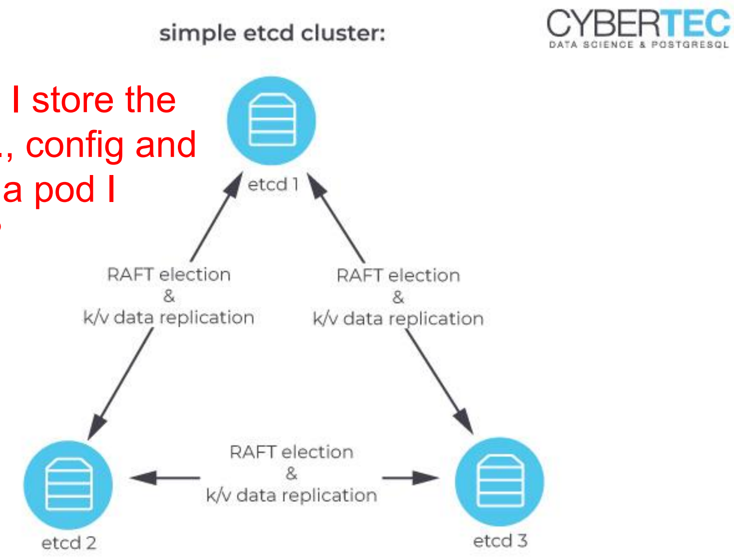

It does:

- state replication
  - leader writes to logs which are replicated to non-leader nodes

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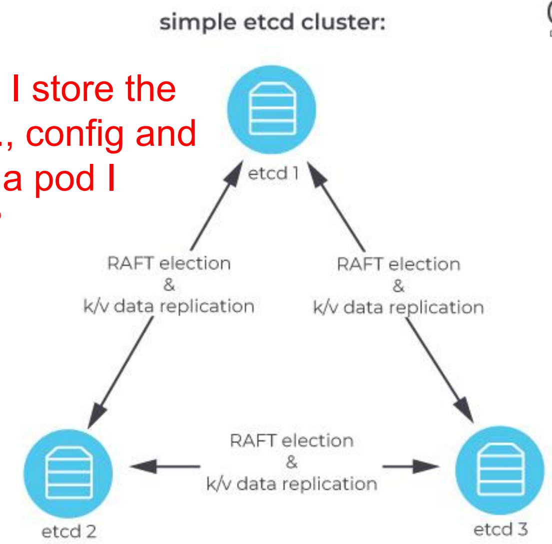

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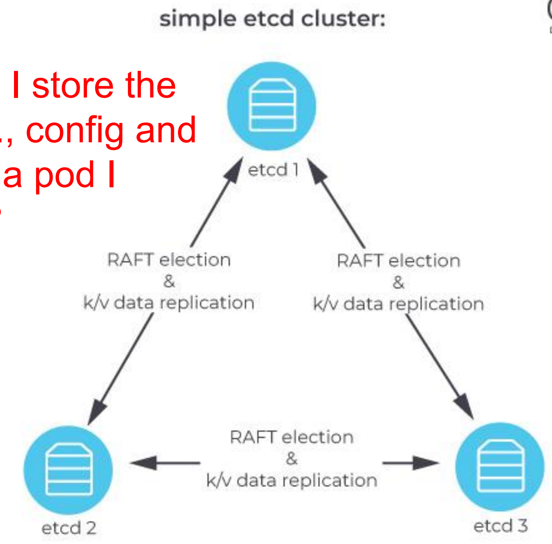

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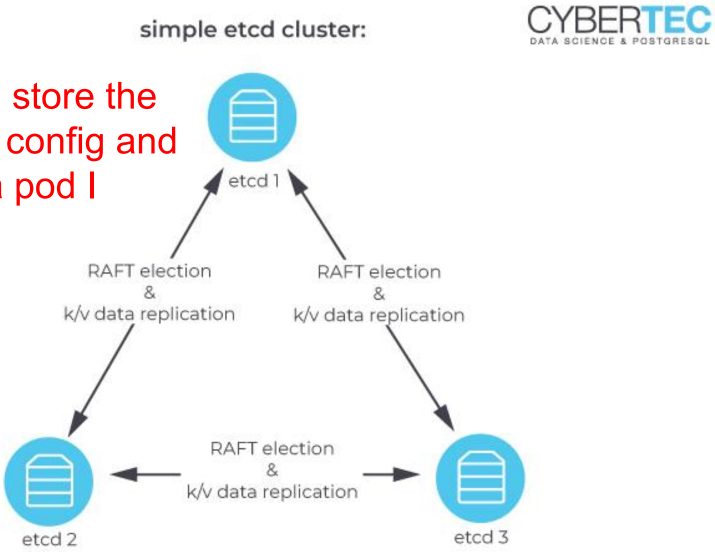

It does:

- state replication
  - leader writes to logs which are replicated to non-leader nodes
- leader election
  - based on Raft (a version of Paxos where there is a trusted leader)
- distributed Locks
  - leader handles lease expiration
- consistency
  - no transactions (not ACID), but have a “transaction abstraction” for compare-and-swap
  - linearizable read
  - Versioned writes with compaction

Kubernetes - Control Plane State

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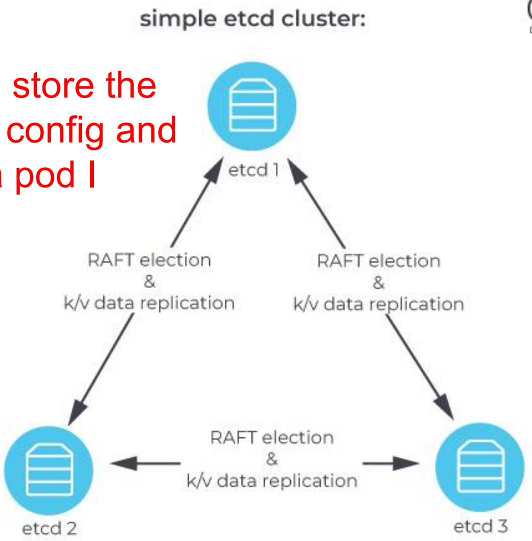


Where do I store the state (e.g., config and status) of a pod I declared?

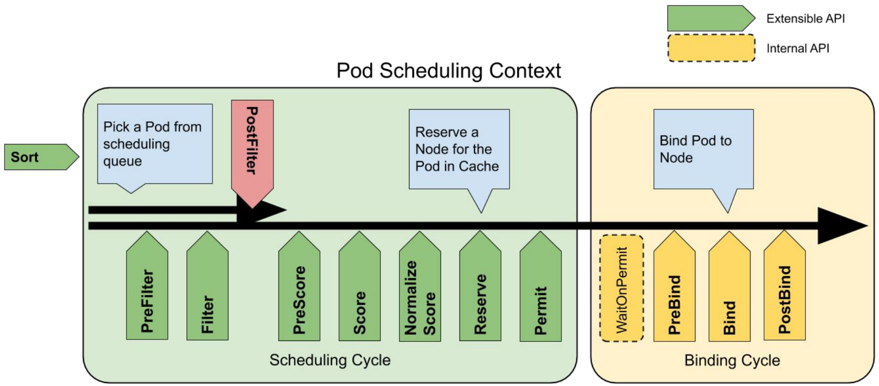
Time to tie everything together.

Questions/Recap

- Why is etcd needed at all? (e.g., how does etcd, controllers and API server all fit together)

Kubernetes - Control Plane Scheduler

API Server	etcd	Controller Manager	Scheduler	Kubelet	Kubectl



How do I do resource control (e.g., map pods to nodes)?

Kubernetes - Control Plane Scheduler

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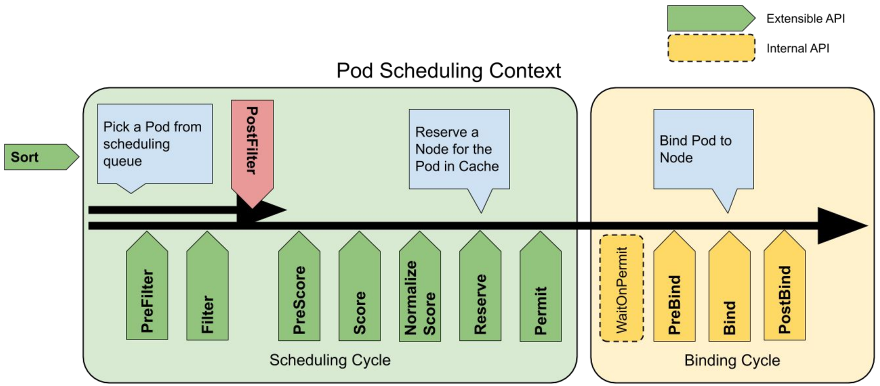

Scheduler calculates a score for which node to run a pod on based on the pod config which contains:

- affinity, anti-affinity
- resource requirements and availability
- soft tolerations and hard constraints (e.g., run only on nodes with label GPU)
- evictability

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Kubernetes - Control Plane Scheduler

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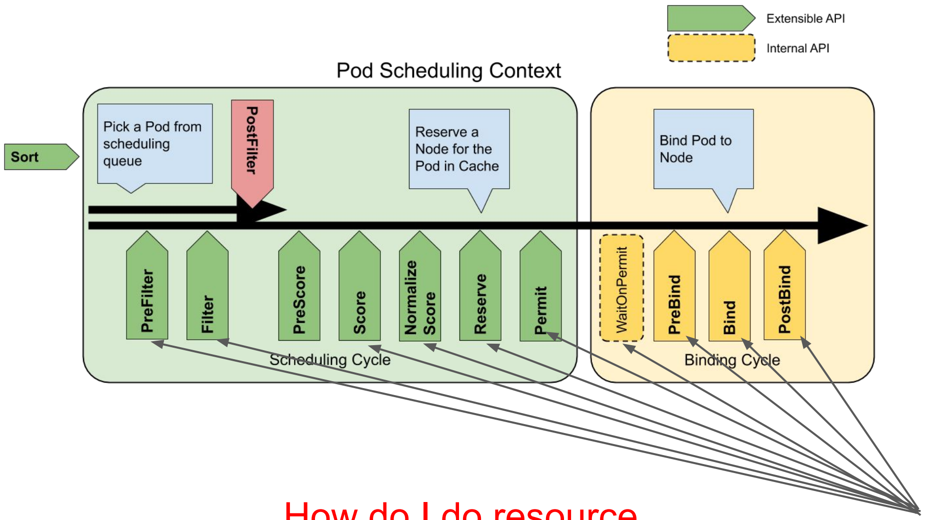

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How do I do resource control (e.g., map pods to nodes)?

Extremely extensible, can interpose at any of the points in the scoring system

Kubernetes - Control Plane Kubelet/Kubectl

API Server	etcd	Controller Manager	Scheduler	Kubelet	Kubectl

Kubelet

- Daemon running on the node that executes commands by the Kubernetes control plane (e.g., start/evict a pod on the node)

Kubectl

- Command-line interface for the Kubernetes cluster (talk to API server)
- What you use to interface with your Kubernetes Cluster

Kubernetes - Control Plane Data Model

Multi-Readers to etcd

- Reads can be linearizable (go to leader etcd node) or serializable (go to any of the replica nodes in etcd)

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Multi-Writers to etcd

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  - Coincident writes are merge/add/delete operation based on data type (single values vs. lists/maps) and last write wins
  - Transient inconsistencies are okay (e.g., 3 replicas, but might overshoot or undershoot temporarily)
  - Controllers fact-check with the actual world instead of state in etcd, what-you-see-is-eventually-what-you-get

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  - Controllers fact-check with the actual world instead of state in etcd, what-you-see-is-eventually-what-you-get
- [Option 2] use etcd in the control plane for serialization with distributed locks

Kubernetes - Integration

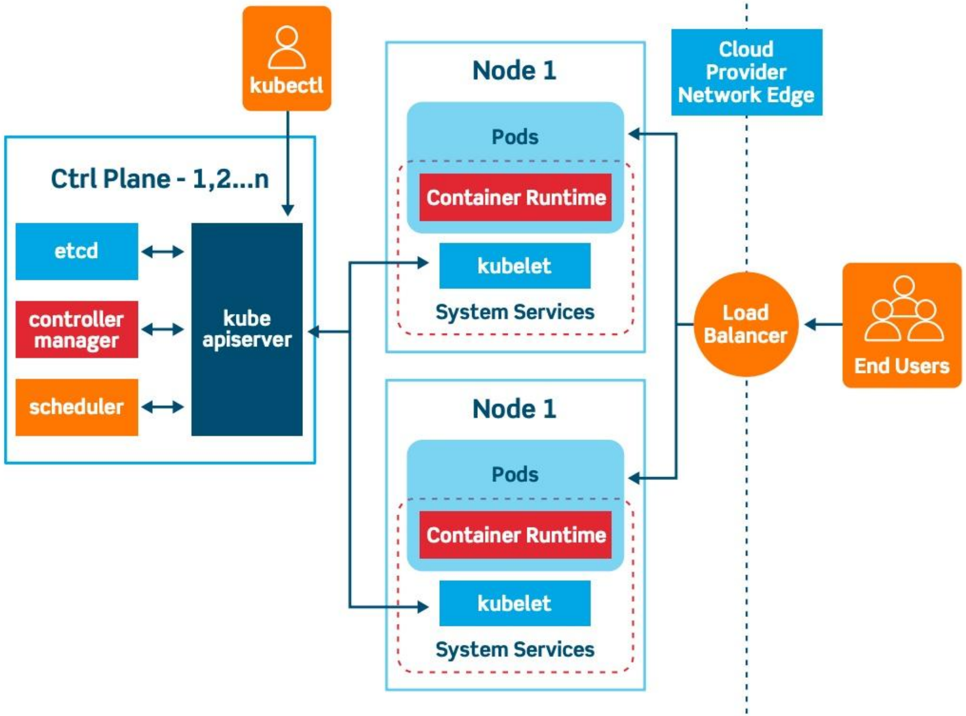
How does what I have in Kubernetes connect with the wider internet/cloud ecosystem?

Load balancer (Internet), Security (IAM), Storage (Google Cloud Storage, Spanner, Google Container Registry), Events (Pub/Sub), Graph (Cloud Build, Google Dataflow), AI (Google Cloud AI)

Kubernetes - Summary

User Apps	Kubernetes API apps (e.g., controllers, sidecars, middleboxes)
Kubernetes APIs (e.g., pods, services, deployments, etc.,...)	Kubernetes Add-ons (Istio, Knative)
Kubernetes Control Plane (scheduler, API server, controller-manager, etcd)	
Logical network (Flannel, Weave, bespoke cloud provider implementation)	
Physical servers and network	

Kubernetes - Architecture



- Abstractions: Pods, Services, Ingress, Deployments, Volumes…
- Add-ons: Istio, Knative...
- Network: Weave, Flannel…
- Control Plane: scheduler, api-server, controller-manager, etcd...

Kubernetes - Interesting Problems

Dependency

- Controllers are all eventually consistent and order agnostic (ideall), but some abstractions have dependencies as outcome of implementation
- Worse, administration of Kubernetes clusters are usually split (between user and cloud provider, neither can be sure what the other has installed)

Configuration

- Thousands of lines of YAML with relationship defined by string **labels**

Debuggability

- Logs are spread out over multiple nodes, something goes wrong, how do you find out what went wrong?
- Distributed system debugging

Efficiency

- Essentially you build applications (containers) that run in cluster wide applications (also defined/built by you) that run on Kubernetes framework (lightweight, but still a cost to it)

Acknowledgement

Thanks to Jon Donovan for helping me edit this