Middleware Architectures 1

Lecture 5: Cloud Native and Kubernetes

doc. Ing. Tomáš Vitvar, Ph.D.
tomas@vitvar.com • @TomasVitvar • https://vitvar.com

Czech Technical University in Prague
Faculty of Information Technologies • Software and Web Engineering • https://vitvar.com/lectures

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Overview

- Cloud Native
- Kubernetes

Overview

- The Cloud Native Computing Foundation (CNCF)
  - *Motto: Building sustainable ecosystems for cloud native software*
  - *CNCF is part of the nonprofit Linux Foundation*
- Cloud Native = scalable apps running in modern cloud environments
  - *containers, service mashes, microservices*
  - *Apps must be usually re-built from scratch or refactored*
  - *Benefits:*
    - → *loosely coupled systems that are resilient, manageable, and observable*
    - → *automation allowing for predictable and frequent changes with minimal effort*
  - *Trail Map*
    - → *provides an overview for enterprises starting their cloud native journey*
- Lift and Shift
  - *Cloud transition program in organizations*
  - *Move app from on-premise to the cloud*
  - *Benefits*
    - → *Infrastructure cost cutting (OPEX vs. CAPEX)*
    - → *Improved operations (scaling up/down if possible can be faster)*

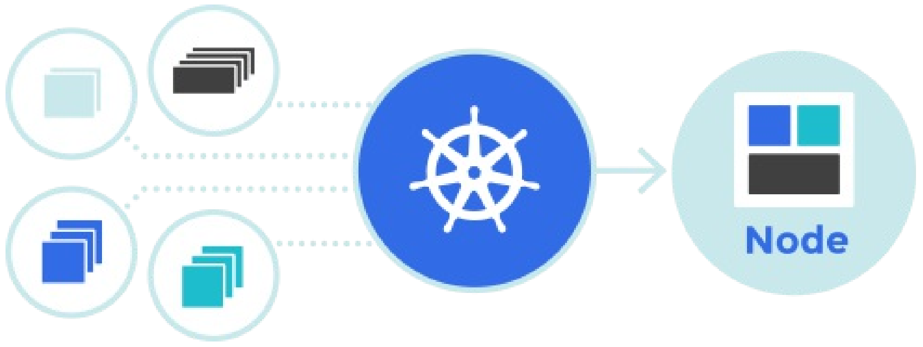
CNCF Trail Map

Overview

- Cloud Native
- Kubernetes
  - *Basic Concepts*
  - *Core Concepts and Architecture*
  - *Workloads*
  - *Services*
  - *Beyond the Basics*

Overview

- In your architecture...
  - *Containers are atomic pieces of application architecture*
  - *Containers can be linked (e.g. web server, DB)*
  - *Containers access shared resources (e.g. disk volumes)*
- Kubernetes
  - *Automation of deployments, scaling, management of containerized applications across number of nodes*
  - *Based on Borg, a parent project from Goolge*

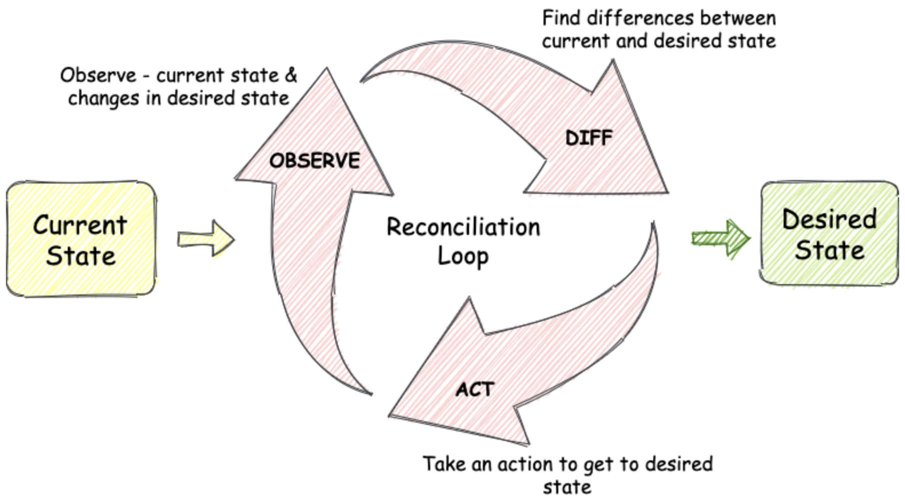


Key Design Principles

- Kubernetes provides abstractions that separate application deployment from the underlying infrastructure details
- Application workloads and infrastructure decoupling
  - ***Compute:*** *Define what to run without specifying where it runs*
  - ***Storage:*** *Applications request storage independent of storage backend*
  - ***Networking:*** *Stable access to applications regardless of IPs or location*
- Benefits
  - *Portability across on-prem and cloud environments*
  - *Scalability and resilience through dynamic scheduling*
  - *Consistency and standardization of deployment model*
  - *Reduced vendor lock-in thanks to open standards*

Desired State and Reconciliation

- Kubernetes operates on a **desired state** model
  - *Users define the state they want through object specifications (YAML)*
  - *Example: "there should be 3 replicas of this application"*
- Actual State vs. Desired State
  - *Kubernetes constantly monitors the cluster*
  - *If the actual state drifts from the desired state, it takes action to fix it*
- Reconciliation Loop
  - *Controllers continuously compare desired vs. actual state*
  - *Automatically performs actions such as restarting, rescheduling, or scaling Pods*


Find differences between current and desired state
Observe - current state & changes in desired state
OBSERVE
DIFF
Current State
Reconciliation Loop
Desired State
ACT
Take an action to get to desired state

Features

- Automatic binpacking
  – *Automatically places containers onto nodes based on their resource requirements and other constraints.*
- Horizontal scaling
  – *Scales your application up and down with a simple command, with a UI, or automatically based on CPU usage.*
- Automated rollouts and rollbacks
  – *Progressive rollout out of changes to application/configuration, monitoring application health and rollback when something goes wrong.*
- Storage orchestration
  – *Automatically mounts the storage system (local or in the cloud)*
- Self-healing
  – *Restarts containers that fail, replaces and reschedules containers when nodes die, kills containers that don't respond to user-defined health checks.*
- Service discovery and load balancing
  – *Gives containers their own IP addresses and a single DNS name for a set of containers, and can load-balance across them.*

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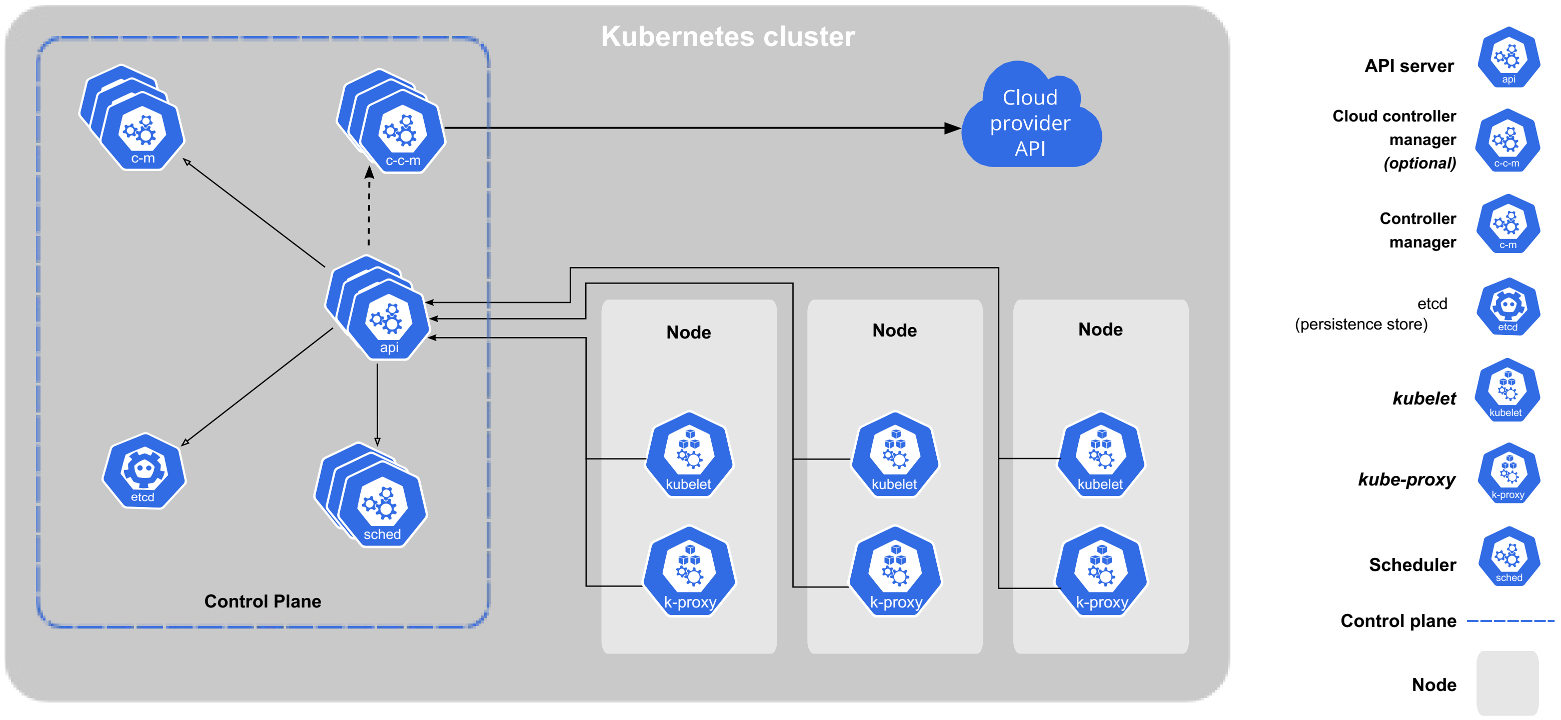
Core Building Blocks

- **Cluster**
  - *A set of worker nodes and a control plane*
  - *Runs and manages containerized applications*
- **Node**
  - *A worker machine in Kubernetes (VM or physical)*
  - *Runs Pods scheduled by the control plane*
- **Control Plane**
  - *Manages the overall state of the cluster*
  - *Schedules workloads and responds to cluster events*
- **Pod**
  - *The smallest deployable unit in Kubernetes*
  - *One or more tightly-coupled containers*
  - *Containers share networking and storage within a Pod*

Architecture



Control Plane Components (Part 1)

- Global decisions about the cluster
  - *Schedulling*
  - *Detecting and responding to cluster events, starting up new pods*
- kube-apiserver
  - *exposes the Kubernetes API*
  - *The API server is the front end for the Kubernetes control plane.*
- etcd
  - *highly-available key value store used to store all cluster data*
- kube-scheduler
  - *watches for newly created Pods with no assigned node*
  - *selects a node for Pods to run on.*
  - *Decision factors: resource requirements, hardware/software/policy constraints, affinity and anti-affinity specifications*

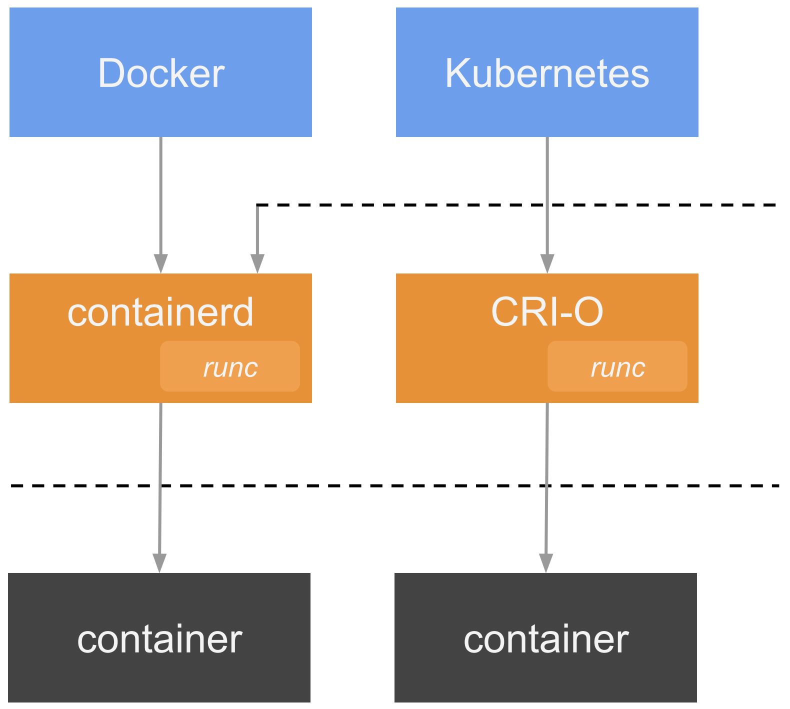
Control Plane Components (Part 2)

- kube-controller-manager
  - *runs controller to ensure the desired state of cluster objects*
  - ***Node controller***
    → *noticing and responding when nodes go down*
  - ***Job controller***
    → *creates Pods to run one-off tasks to completion.*
  - ***Endpoints controller***
    → *Populates the Endpoints object (that is, joins Services, Pods).*
- cloud-controller-manager
  - *Integration with cloud services (when the cluster is running in a cloud)*
  - ***Node controller***
    → *checks if a node has been deleted in the cloud after it stops responding*
  - ***Route controller***
    → *For setting up routes in the underlying cloud infrastructure*
  - ***Service controller***

Node

- Kubernetes runtime environment
  - *Run on every node*
  - *Maintaining running pods*
- kubelet
  - *An agent that runs on each node in the cluster*
  - *It makes sure that containers are running in a Pod.*
- kube-proxy
  - *maintains network rules on nodes*
  - *network rules allow network communication to Pods from inside or outside of the cluster*
  - *uses the operating system packet filtering layer or forwards the traffic itself.*
- Container runtime
  - *Responsible for running containers*
  - *Kubernetes supports several container runtimes (containerd, CRI-O)*
  - *Any implementation of the Kubernetes CRI (Container Runtime*

Container Stack



Tools to manager containers in both dev and prod environments.

Container Runtime Interface (CRI)
Kubernetes API defines how Kubernetes interact with container runtime.

Container runtimes that implement CRI spec. The containerd is a Docker component, it's CRI-compliant via *cri* plugin. CRI-O is a CRI implementation developed by RedHat/IBM.

Open Container Initiative (OCI)
A specification for container images and running containers.

Running containerized processes.

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Namespaces

- Logical grouping of cluster resources
  - *Allow you to organize and separate objects within a Kubernetes cluster*
  - *Useful when multiple teams, environments, or projects share the same cluster*
- Rationale
  - *Provide isolation and boundaries between workloads*
  - *Prevent name collisions*

    $\rightarrow$ *Objects can have the same name if in different namespaces*
  - *Enable resource limits and access control per namespace*
- Usage
  - *Common namespaces:* `default`, `kube-system`, `kube-public`, `kube-node-lease`
  - *Create separate namespaces for e.g. dev, test, prod*
  - *Commands run in a namespace unless another is specified*

Pod

- Pod
  - *A group of one or more tightly-coupled containers.*
  - *Containers share storage and network resources.*
  - *A Pod runs a single instance of a given application*
  - *Pod's containers are always co-located and co-scheduled*
  - *Pod's containers run in a shared context, i.e. in a set of Linux namespaces*
- Pods are created using workload resources
  - *You do not create them directly*
- Pods in a Kubernetes cluster are used in two main ways
  - *Run a single container, the most common Kubernetes use case*
  - *Run multiple containers that need to work together*

Workloads

- An application running on Kubernetes
- Workloads run in a set of Pods
- Pre-defined workload resources to manage lifecylce of Pods
  - ***Deployment*** *and ReplicaSet*
    - → *managing a stateless application workload*
    - → *any Pod in the Deployment is interchangeable and can be replaced if needed*
  - ***StatefulSet***
    - → *one or more related Pods that track state*
    - → *For example, if a workload records data persistently, run a StatefulSet that matches each Pod with a persistent volume.*
  - *DaemonSet*
    - → *Ensures that all (or some) Nodes run a copy of a Pod*
    - → *Such as a cluster storage daemon, logs collection, node monitoring running on every node*
  - *Job and CronJob*
    - → *Define tasks that run to completion and then stop.*
    - → *Jobs represent one-off tasks, whereas CronJobs recur according to a schedule.*

Deployment Spec Example

- Deployment spec

```yaml
apiVersion: apps/v1
kind: Deployment
metadata:
  name: nginx-deployment
spec:
  selector:
    matchLabels:
      app: nginx
  replicas: 3 # tells deployment to run 3 pods matching the template
  template:
    metadata:
      labels:
        app: nginx
    spec:
      containers:
      - name: nginx
        image: nginx:1.14.2
        ports:
        - containerPort: 80
```

  – *A desired state of an application running in the cluster*
  – *Kubernetes reads the Deployment spec and starts three app instances*
  – *If an instance fails, Kubernetes starts a replacement app instance*

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What is a Service?

- A Kubernetes **Service** is an abstraction that defines
  – *A logical set of Pods*
  – *A policy to access them.*
- Pods are ephemeral – their IPs change when recreated
- A Service provides a stable virtual endpoint for a set of Pods
- Services enable reliable communication between components:
  – *Internal pods communication*
  – *External access to cluster workloads*
- Each Service gets
  – *A DNS name and*
  – *virtual IP (ClusterIP) inside the cluster.*
- Kubernetes component `kube-proxy` manage routing to backend Pods.

Service Types

- **ClusterIP**
  - *Exposes the Service on an internal IP in the cluster only.*
  - *Used for internal communication between Pods.*
- **NodePort**
  - *Exposes the Service on each Node's IP at a static port (e.g. 30080).*
  - *Accessible externally via* `NodeIP:NodePort`.
- **LoadBalancer**
  - *Provisions an external load balancer (e.g. in cloud environments).*
  - *Routes external traffic to the Service.*
- **ExternalName**
  - *Maps the Service to an external DNS name.*
  - *No proxying — pure DNS CNAME redirection.*

How Services Work

- **Selector**
  - *A Service usually defines a* `selector` *— a label query used to find matching Pods.*
  - *Example:* `selector: app=nginx` *matches all Pods with label* `app=nginx`*.*
  - *Kubernetes monitors Pods that match this selector and updates Service backends*
- **Endpoints / EndpointSlice**
  - *For every Service with a selector, Kubernetes creates an* `Endpoints` *(or* `EndpointSlice`*) object listing all healthy Pod IPs and ports.*
  - *This list changes dynamically as Pods are added, removed, or become unhealthy.*
- **kube-proxy**
  - *Runs on every Node and watches Service and Endpoint objects.*
  - *Programs* `iptables` *or* `IPVS` *rules to forward traffic from the Service's virtual IP (*`ClusterIP`*) to one of the backend Pod IPs.*
  - *Load balancing is done using round-robin or IPVS algorithms.*
- **DNS Integration**
  - `CoreDNS` *automatically creates a DNS record for each Service:*

    $\longrightarrow$ `<service>.<namespace>.svc.cluster.local`
  - *Pods can reach the Service via DNS without knowing Pod IPs*

    $\longrightarrow$ `curl http://my-service.default.svc.cluster.local`

ClusterIP Service Example

- Example configuration exposing an NGINX Deployment internally:

```yaml
apiVersion: v1
kind: Service
metadata:
  name: nginx-svc
spec:
  selector:
    app: nginx
  ports:
  - protocol: TCP
    port: 80
    targetPort: 8080
  type: ClusterIP
```

- Pods with `app=nginx` receive traffic through `ClusterIP`.
- DNS name: `nginx-svc.default.svc.cluster.local`
- Used by other Pods to connect via `http://nginx-svc:80`.

Packet Forwarding and Load Balancing

- **iptables mode**
  - `kube-proxy` *creates NAT rules in the* `nat` *table to redirect Service traffic.*
  - *Example traffic comming to* `NodeIP:NodePort` *(e.g.* `192.168.1.11:30080`*)*

```
# 1. Match NodePort traffic coming from outside
-A KUBE-NODEPORTS -p tcp --dport 30080 -m addrtype ! --src-type LOCAL \
  -j KUBE-MARK-MASQ
    # Mark all external traffic for SNAT (so replies go back via this node)

# 2. NodePort forwards traffic to the Service chain
-A KUBE-NODEPORTS -p tcp --dport 30080 \
  -m comment --comment "default/my-service: NodePort" \
  -j KUBE-SVC-XYZ123

# 3. Service chain chooses one backend Pod
-A KUBE-SVC-XYZ123 -m statistic --mode random --probability 0.5 \
  -j KUBE-SEP-A1B2C3
-A KUBE-SVC-XYZ123 -j KUBE-SEP-D4E5F6

# 4. Pod DNAT rule to redirect to Pod IP:port
-A KUBE-SEP-A1B2C3 -p tcp -m tcp -j DNAT --to-destination 10.42.0.12:8080
-A KUBE-SEP-D4E5F6 -p tcp -m tcp -j DNAT --to-destination 10.42.1.7:8080
```

  - *The node's routing table determines how to reach the Pod's IP:*
    $\longrightarrow$ `10.42.0.0/24 via 192.168.1.12 dev flannel.1`
    $\longrightarrow$ *packets to Pods in* `10.42.0.0/24` *(running on Node 2) are sent through the VXLAN interface* `flannel.1` *to Node 2's IP* `192.168.1.12`

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Advanced Topics

- Custom APIs and Controllers
  - *CRDs, Operators, reconciliation loops*
  - *Admission webhooks (mutating/validating)*
- Security
  - *RBAC, Namespaces, Pod Security (seccomp, capabilities, rootless)*
  - *Image signing and supply chain (SBOM, cosign), Secret management (Vault/CSI)*
  - *Policy engines: OPA Gatekeeper, Kyverno*
- Networking
  - *CNI, eBPF (Cilium), NetworkPolicies, Ingress*
  - *Gateway API, Service Mesh (mTLS, traffic shaping)*
- Storage
  - *CSI drivers, snapshots, expansion, topology-aware PVs*
  - *Backup/DR (e.g., Velero), StatefulSet patterns*
- Scaling and Scheduling
  - *HPA/VPA/KEDA (event-driven), Cluster Autoscaler*
  - *Affinity/anti-affinity, taints/tolerations, topology spread*
- Ops and Delivery
  - *GitOps (Argo CD/Flux), progressive delivery (canary, blue/green)*