Kubernetes Networking

IBM **Developer**

Networking Models

TCP/IP Model (Internet Protocol Suit)

- Link Layer, corresponds to L2 in OSI model.
- Internet Layer (IP), networking interface or internetworking, addressing and routing for TCP/IP
- Transport Layer (UDP/TCP)
- Application Layer (HTTP, FTP, etc) corresponds to L5/L6/L7 in OSI model.

Open Systems Interconnection (OSI) Model

- L1 – Physical
- L2 – Data Link (Ethernet, PPP, VLAN, etc)
- L3 – Network (NAT, IP, IPSEC etc)
- L4 – Protocol Suites (NetBIOS, SCTP, TCP, UDP, etc)
- L5 – Session (RPC, SDP, SMB, SOCKS, etc)
- L6 – Presentation (TLS, SSL, FTP, IMAP, SSH, etc)
- L7 – Application (SOAP, DHCP, DNS, HTTP, HTTPS, NFS, POP3, SMTP, FTP, IRC, SSH, etc)

OSI Model for Kubernetes

L6: Containers (Rocket, Docker, Podman, CRIO, containerd)

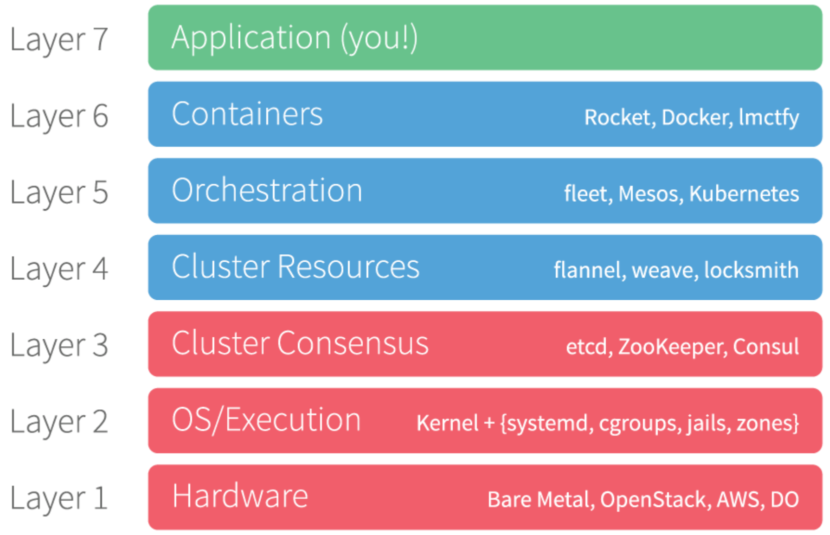
L5: Container Orchestration (CO) (Kubernetes, OpenShift, CloudFoundry)

L4: Cluster Resources (CNI, CSI)

L3Cluster Consensus (etcd (consensus db built with Raft consensus algorithm), Apache ZooKeeper, consul)

L2: OS, Machine Application Binary Interface (ABI) (system calls, device drivers, etc), kernel + [system, cgroups/namespaces, jails, zones) (RHEL, CoreOS)

L1: bare metal, VMs, cloud (CPU, RAM, disk, network)



source: https://coreos.com/blog/cluster-osi-model.html

Etcd: The etcd project's focus is safely storing critical data of a distributed system and it demonstrated its quality early on. etcd was created by the CoreOS team in 2013, inspired by Chubby, a key-value store created for Google's internal cluster infrastructure. Etcd was contributed to the CNCF by Red Hat and CoreOS in December 2018. source: https://coreos.com/blog/history-etcd

Etcd uses Raft, a consensus algorithm for distributing configuration, state and metadata information within a cluster and monitoring for any changes to the data stack

Software Defined Networking (SDN)

Software Defined Networking (SDN) uses software-based controllers or APIs to create and control a virtual network or traditional hardware.

Network virtualization segments different virtual networks within a single physical network or connect devices on different physical networks to create a single virtual network.

SDN is a software defined way to control the traffic or routing of data packets through a server.

- Using an open standard software-based controller, using a single protocol to communicate with different hardware devices.
- Configure network services and allocate virtual resources to change network infrastructure in real time, to optimize data flow.
- Visibility into the entire network and creation of separate zones for devices with different security levels.

Parts of SDN architecture:

- Applications,
- Controllers,
- Networking devices.

Network Functions Virtualization (NFV) abstracts network functions from hardware and supports SDN by providing the infrastructure on which SDN software runs.
Network Service Chaining, also known as **Service Function Chaining (SFC)** uses SDN to create a chain of connected network services, such as L4-7 services like firewalls, network address translation (NAT), and intrusion protection.

Network Functions Virtualization (NFV)

Network Functions Virtualization (NFV) is a way to virtualize network services such as routers, firewalls, and load balancers.

The NFV architecture is proposed by the European Telecommunications Standards Institute (ETSI), NFV consists of

- Virtualized Network Functions (VNF),
- Network Functions Virtualization infrastructure (NFVi), such as Hypervisors, and
- Management, Automation and Network Orchestration (MANO).

Container Networking

Container Networking is based for a large part on Linux networking. Containers use Linux partitioning features as *Cgroups* and *Namespaces* that allow container processes to map to network, storage and other namespaces. Container networking uses network namespaces of the Linux kernel.

Network namespaces:

- A container isolated network uses its own virtual interfaces like routing tables, L2 isolation, sockets and IPTABLE rules.
- Containers use iproute2 to interact with network namespaces.
- Network namespaces are stored in /var/run/netns
- Two types of network namespaces:
  - Root namespace (ip link)
  - Non-root namespace (ip netns, ip link)

A container network interface belongs to only one network namespace. Multiple containers require multiple interfaces or using pseudo-interfaces like:

- **Virtual bridge**, using Virtual Ethernet device (veth) pairs as a tunnel between container and root namespace, and a Linux bridge or OpenvSwitch (OVS) for connectivity between containers and external (real) interfaces.
- **Multiplexing**, using a network device with multiple virtual interfaces and packet forwarding rules (MACVLAN, IPVLAN),
- **Hardware networks** like SR-IOV (supported by most Network Interface Controllers (NIC)).

Container Networking

Docker networking uses pluggable drivers. Several drivers exist by default and provide core networking functionality.

Bridge networks
Default Docker networking mode, a Link Layer device which forwards traffic between network segments, using a software bridge, which allows containers on the same bridge network on the same host to communicate. The Docker bridge driver automatically installs rules in the host machines.
Docker0: a Linux bridge created by docker daemon

- 1 interface to host namespace
- All containers on the host are attached to docker0 via *veth-pair*
- Container gets private IP address assignment, with random MAC generation to avoid MAC collissions and ARP problems.

```
docker run –d –P –net=bridge training/webapp python app.py
docker ps
docker exec <containerid> ip a
```

Host networks
Use host's network and share the host's networking namespace. Container does not get its own IP-address.
Basic port mapping on host network to reach services

```
ifconfig | grep –A 2 eth0
docker run –d –net=host training/webapp python app.py
docker ps
docker exec <containerid> ip a | grep –A 2 eth0
```

Container Networking

Overlay
Creates a distributed network across multiple hosts to connect multiple containers. When you initialize a container host, two new networks are created:

- An overlay network called ingress
- A bridge network called docker_gwbridge

All pods on the host are attached to docker0 via *veth-pair*

Macvlan
Connect directly to physical network, assigning a MAC address to a container's virtual network interface, making it appear as a physical device on the network. You can also use ipvlan, which uses L3 and L2 mode, and use an L2 bridge.

No Networking
Disable all networking, usually in conjunction with a custom network driver.

Container Network Interface (CNI)

CNI is a vendor-neutral interface between container runtimes and networks, independent of the Container Orchestration (CO) platform, e.g. Kubernetes, OpenShift, Docker, rkt, Mesos, CloudFoundry, podman, CRI-O, Kurma, Amazon ECS. CNI (*Container Network Interface*) originates at CoreOS as part of rkt. Now a CNCF project.

CNI is responsible for network connectivity of containers and removing allocated resources when the container is deleted. It consists of a specification and libraries for writing plugins to configure network interfaces. CNI defines a basic execution flow and JSON-based configuration format for network operations. Plugins are executables in the host, and Kubelet is the runtime on the node.

The container runtime creates the Network Namespace, identifies the network to attach containers, and invokes the plugin.
The CNI plugin or bridge program implements:

1. Create veth Pairs
2. Create Bridge Network/Interface
3. Attach vEth to Namespace
4. Attach other vEth to Bridge
5. Assign IP address
6. Bring up interfaces
7. Enable NAT

Basic plugin commands:

- ADD
- DEL
- CHECK
- VERSION

E.g. the container runtime invokes `bridge add <cid> <namespace>` to add a container to a network.

Container Network Interface (CNI)

Container Networking is based for a large part on Linux networking.

Multi-networking
CNI supports multi-networking, but Kubernetes by default does not: a Kubernetes pod is exposed only to 1 interface (and loopback). Multus by Intel supports multi-networking using CRD-based network objects.

Reference plugins: bridge, loopback, vlan, macvlan, ipvlan, host-device, ptp (point-to-point), Windows bridge, Windows overlay.
IPAM (IP Address Management): host-local, DHCP, static
Meta (chained) plugins: bandwidth, firewall, flannel, portmap, source-based routing, tuning
3rd Party plugins: Calico, Weave, Cilium, Multus, Romana, SR-IOV (Single Root I/O Virtualization), Nuage, Amazon ECS, Linen, Silk (CF)

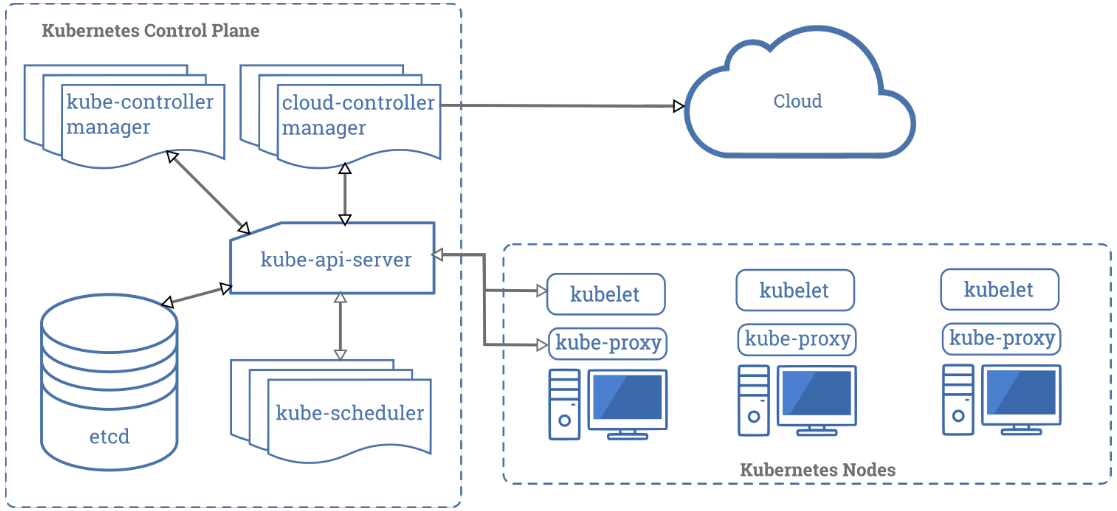
* IBM Cloud Kubernetes implements Calico
* OpenShift supports using SR-IOV hardware on nodes

Container Network Model (CNM)

Aka Libnetwork supported by Docker
https://github.com/docker/libnetwork

Kubernetes Architecture

- At its core, Kubernetes is a database (etcd) with "watchers" and "controllers" that react to changes in etcd, etcd is a consensus database using Raft
- The kube-api-server is an API server that exposes the Kubernetes API, all traffic goes through the API Server
- The kube-scheduler watches for new Pods not assigned to a node and selects a node to run the Pod on,
- The kube-controller-manager runs the controller loops that make Kubernetes,
- The cloud-controller-manager interacts with the underlying cloud provider,
- The etcd key-value store represents the user defined desired state of the objects,
- The kubelet makes sure that containers are running in a Pod,
- The kube-proxy is a network proxy that maintains network rules on nodes,

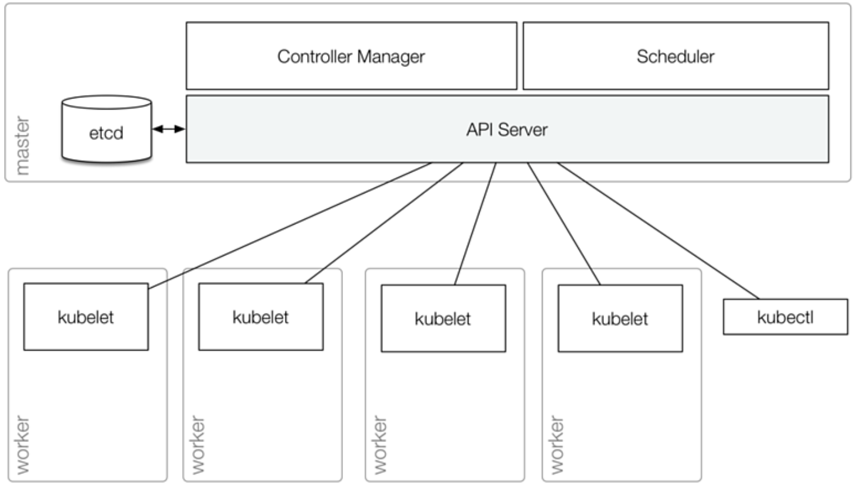


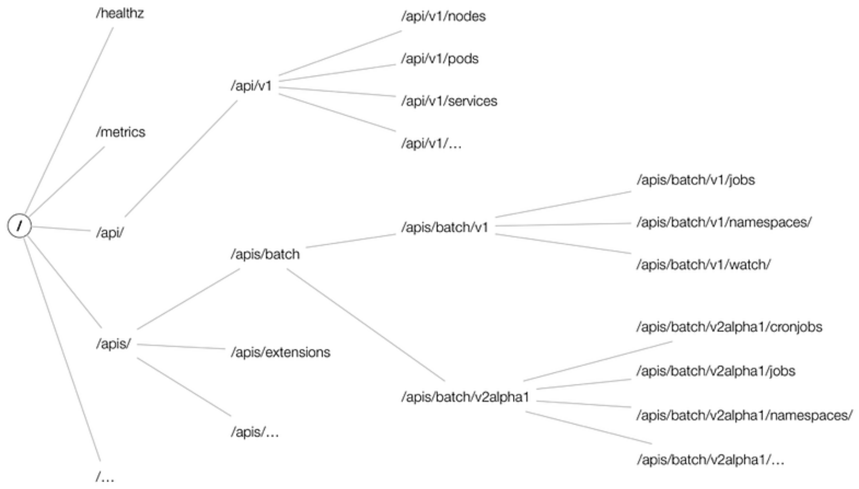
API Server

The control plane on the master node(s) consists of the API Server, the Controller Manager and Schedulers. The *API Server* is the only component that talks directly to *etcd* and is a gateway to *etcd*, which is the consensus database for the state of your application cluster.

The API Server:

- Serves the Kubernetes API,
- Proxies cluster components such as the Kubernetes UI,
- Allows manipulation of the state of objects,
- Persists the state of objects in etcd.





https://www.openshift.com/blog/kubernetes-deep-dive-api-server-part-1

API Server

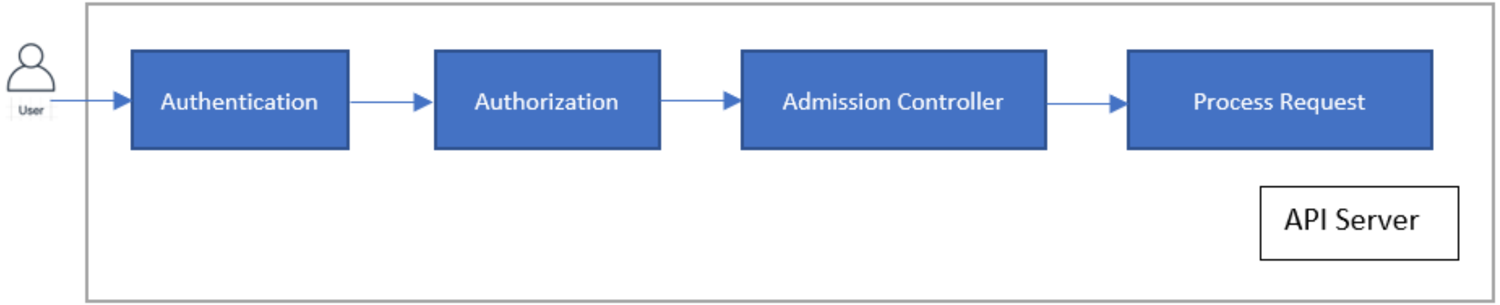
Workflow:

1. **Transport security**: API Server is accessed via port 443 protected by TLS and it presents a certificate.

2. **Authentication**: running 1 or more authentication modules (client certificates, password, plain tokens, bootstrap tokens, JSON web tokens)

3. **Authorization**: request must include username, action and target object, and is verified against a policy. Multiple authorization modules are supported: ABAC, RBAC, Webhook.

4. **Admission Controller**: modify or reject requests, does not effect reads.

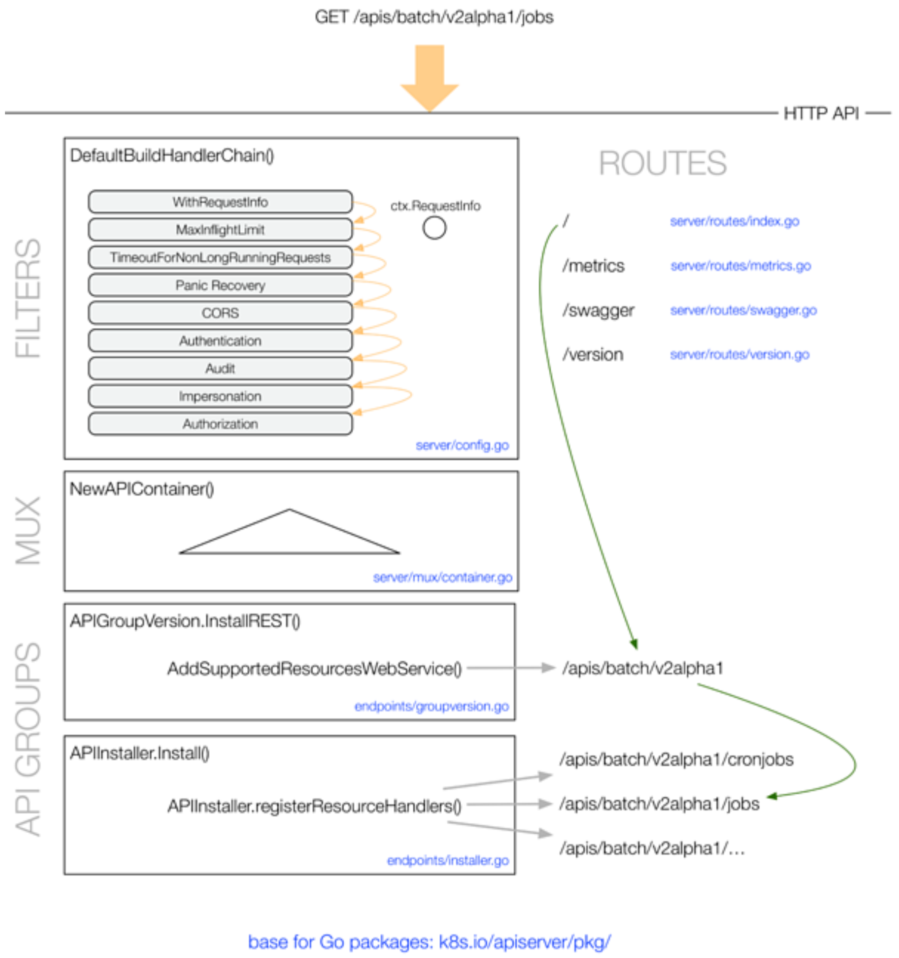


source: https://kubernetes.io/docs/concepts/security/controlling-access/

Request Flow

The API Server handles requests from within and to outside the cluster. When an HTTP request hits the Kubernetes API:

- HTTP request is processed by a chain of **Filters** registered in **DefaultBuildHandlerChain()**. Either the filter passes and attaches respective info to **ctx.RequestInfo**, such as authenticated user or returns an appropriate HTTP response code.
- Next, the **Multiplexer or MUX** routes the HTTP request to the respective handler, depending on the HTTP path.
- The **Routes** (as defined in routes/*) connect handlers with HTTP paths.
- The handler takes the HTTP Request and Context (like user, rights, etc.) and delivers the requested object from storage.



https://www.openshift.com/blog/kubernetes-deep-dive-api-server-part-1

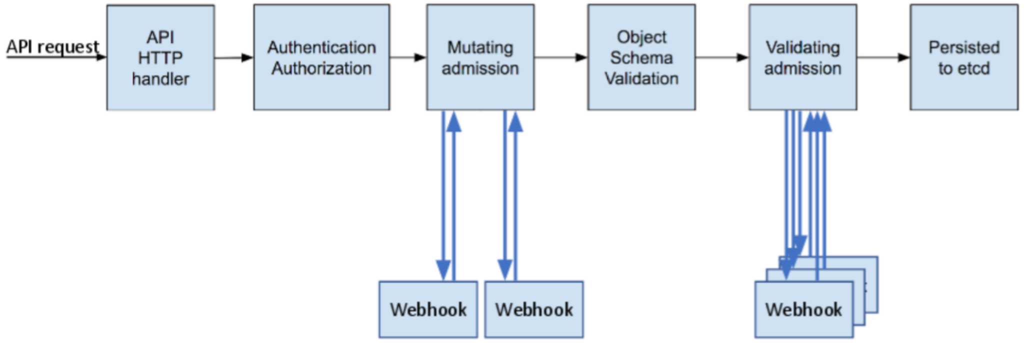
Admission Controller

An **admission controller** is a piece of code that intercepts requests to the Kubernetes API server prior to persistence of the object, but after the request is authenticated and authorized. The admission control process has two phases: a ***mutating* phase and *validating* phase**. The controllers are compiled into the kube-apiserver binary.

Examples of **default admission controllers**: AlwaysAdmit, AlwaysPullImages, AlwaysDeny, CertificateApproval, CertificateSigning, DefaultStorageClass, EventRateLimit, NameSpaceLifecycle, NodeRestriction, PodNodeSelector, PersistentVolumeClaimResize, PodSecurityPolicy, ResourceQuota, ServiceAccount among more than 30, and **2 webhooks with a special role**: **MutatingAdmissionWebhook and ValidatingAdmissionWebhook**.

The **webhooks** do not implement any policy logic themselves, but is obtained from a REST endpoint. This approach decouples the admission controller logic from the Kubernetes API server, allowing **custom logic** to be executed whenever resources are created, updated, or deleted in a Kubernetes cluster. The webhook handles an **AdmissionReview** request sent by the API Server and sends back a decision in the same AdmissionReview it received.

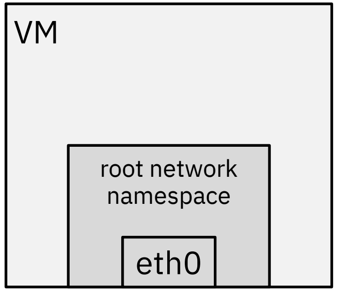
OpenShift Container Platform (OCP) has a default set of admission plug-ins enabled for each resource type.



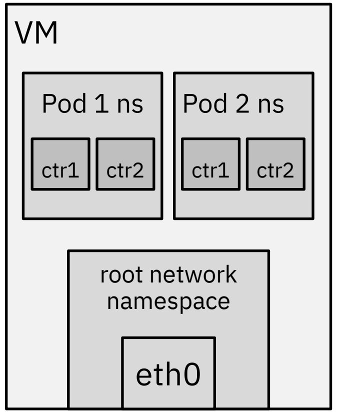
Kubernetes Networking

- All pods can communicate with all pods without NAT
- All nodes can communicate with all pods without NAT
- The IP of the pod is the same for itself as it is for others

4 networking problems remain:
- Container to container
- Pod to pod
- Pod to service
- Internet to service



VM
Typically, network communication on a VM interacts with an Ethernet device. In Linux, that network communication runs within a network namespace with its own logical networking stack with its own routes, firewall rules, and network devices.



Container to container
A pod is *a group of containers that share a network namespace*, they all have the same IP address and port space assigned and can find each other via localhost. Containers join the network namespace with the --net=container: function. Containers within a pod also can access shared volumes, which are part of the pod and available to be mounted into the applications filesystem. A pod exists in its own Ethernet namespace.

Kubernetes Networking

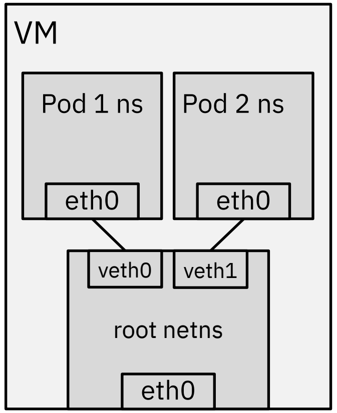
Pod to pod
A pod exists in its own Ethernet namespace that needs to communicate with other network namespaces on the same node. *Pods or Namespaces can be connected using* a ***Linux Virtual Ethernet Device*** *or* ***veth pair****, consisting of two virtual interfaces* across multiple namespaces. One side of the veth pair is connected to the root network namespace, and the other side to the Pod's network namespace. This setup can be replicated for all pods on the VM. The veth connects a pod namespace to the root namespace.

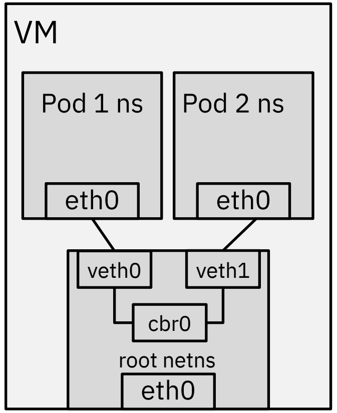
A **bridge** connects pod namespaces. A Linux Ethernet bridge is a virtual Layer 2 (L2) networking device to connect two networks by maintaining a forwarding table between sources and destinations by examining the destination of the data packets and looking at the MAC-address of each Ethernet device in the network.

Bridges implement the ARP protocol to discover the link-layer MAC address associated with an IP address. The bridge broadcasts the data frame out to connected devices except the sender and the device that responds to the frame is stored in a lookup table. But the Kubernetes networking model dictates that pods can reach pods by their IP address across nodes.

Generally, every Node in your cluster is assigned a CIDR block specifying the IP addresses available to Pods running on that Node. Once traffic destined for the CIDR block reaches the Node it is the Node's responsibility to forward traffic to the correct Pod. *On failure* to find the correct MAC address, the bridge sends the packet out the default route — the root namespace's eth0 device. At this point the route leaves the Node and enters the network. The network routes the packet to the correct Node based on the CIDR block assigned to the Node. How this is done is network specific.

The **Container Networking Interface (CNI)** provides a common API for connecting containers to the outside network.





Service

The connection for **Pod to service** and **Internet to service** is handled by Kubernetes Service types.

The **Service** object is an abstraction of a logical set of Pods exposed through **Endpoints** that are updated whenever the set of Pods in a Service change. Every Service defined in the cluster is assigned a DNS name that maps to the ClusterIP of the Service. Kubelets on nodes in the cluster are configured to use the IP of the DNS Service to resolve DNS names for **Service Discovery.** The Endpoints for a set of pods are determined using a **Selector**. **Labels** are key/value pairs that are attached to objects can be used to organize and select subsets of objects. The label selector is the core grouping primitive in Kubernetes.

Service types:

- **ClusterIP**, default Service type that exposes the service on a cluster-internal IP only.
- **NodePort**, exposes the service on each Node's IP at a static port (the NodePort). A ClusterIP service, to which the NodePort service will route, is automatically created.
- **LoadBalancer**, on top of a NodePort and ClusterIP, exposes the service externally using a cloud provider's load balancer.
- **ExternalName**, maps the service to the externalName field (e.g. foo.bar.example.com) by returning a CNAME record with its value.
- **Ingress**
- **Route**

Ingress

An **Ingress** resource manages external access to the services in a cluster, typically HTTP/HTTPS. Ingress can also provide load balancing, TLS termination and name-based virtual hosting. Ingress consists of an Ingress API object and the Ingress Controller. The Ingress Controller implements the Ingress API. The Ingress Controller is usually a load balancer for routing external traffic to your Kubernetes cluster and is responsible for L4-L7 Network Services.

Ingress consists of three components:

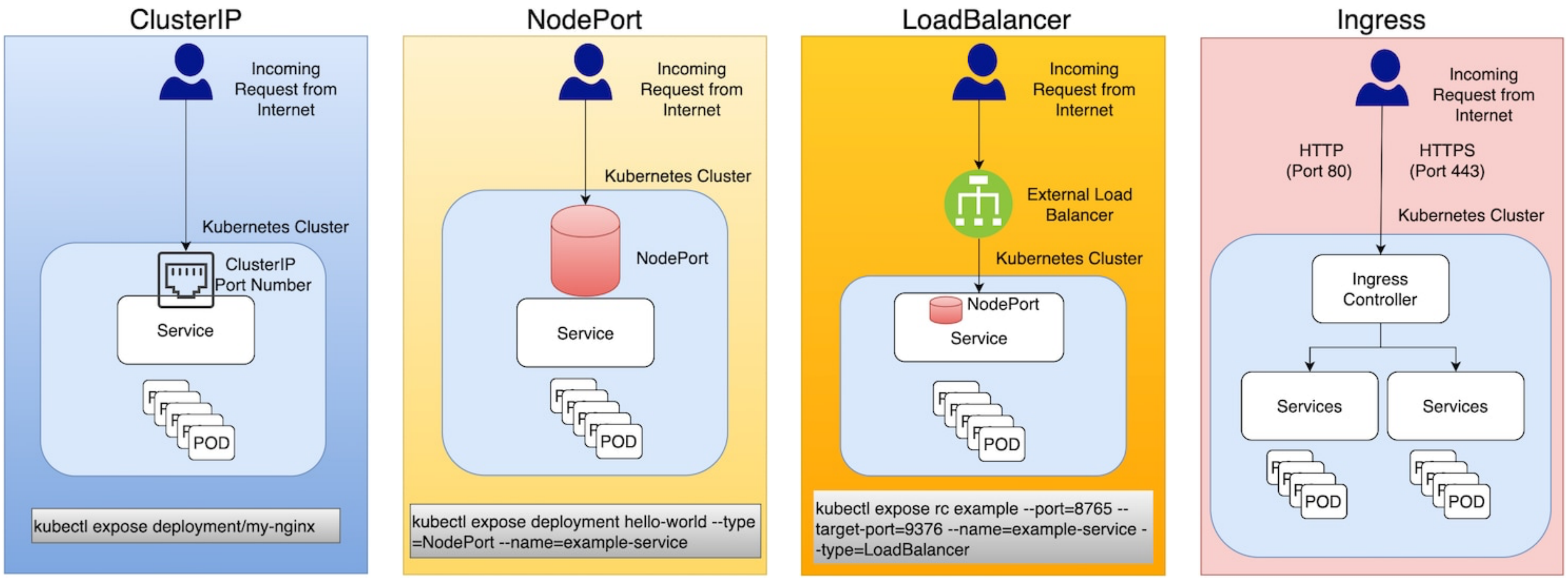
- Ingress resources,
- L7 Application Load Balancer (ALB),
- An external L4 load balancer to handle incoming requests across zones, depending on the provider.

To expose an app by using Ingress, you must create a Kubernetes service for your app and register this service with Ingress by defining an Ingress resource. The Ingress resource is a Kubernetes resource that defines the rules for how to route incoming requests for apps.

```
apiVersion: networking.k8s.io/v1beta1
kind: Ingress
spec:
  backend:
    serviceName: helloworld
    servicePort: 8080
```

source: https://cloud.ibm.com/docs/containers?topic=containers-ingress-about

Service



```
kubectl expose deployment/my-nginx
```

```
kubectl expose deployment hello-world --type
=NodePort --name=example-service
```

```
kubectl expose rc example --port=8765 --
target-port=9376 --name=example-service -
-type=LoadBalancer
```

Ingress Application Load Balancer (ALB)

The Ingress Application Load Balancer (ALB) is a layer 7 (L7) load balancer which implements the NGINX Ingress controller. A layer 4 (L4) LoadBalancer service exposes the ALB so that the ALB can receive external requests that come into your cluster.

The Application Load Balancer (ALB) is an external load balancer that listens for incoming HTTP, HTTPS, or TCP service requests. The ALB then forwards requests to the appropriate app according to the rules defined in the Ingress resource.

When you create a standard cluster, IBM Cloud Kubernetes Service automatically creates a highly available ALB in each zone where you have worker nodes. In classic clusters, the Ingress subdomain for your cluster is linked to the public ALB IP addresses. For classic clusters, the ALB is a **Multi-Zone Load Balancer (MZLB)** that IBM Cloud Kubernetes Service creates for you.

In a VPC cluster, one public VPC load balancer is automatically created outside of your cluster in your VPC. The public VPC load balancer *puts the public IP addresses of your public ALBs behind one hostname*. In VPC clusters, a hostname is assigned to the ALBs because the ALB IP addresses are not static. This ALB hostname is different than the Ingress subdomain. The services that expose your ALBs on public or private IP addresses are formatted as public-abc12 in the kube-system namespace.

The Kubernetes Ingress image is built on the community Kubernetes project's implementation of the **NGINX Ingress** controller. The Kubernetes Ingress controller image is now supported for Ingress ALBs, and all new ALBs run the Kubernetes Ingress image by default.

source: https://cloud.ibm.com/docs/containers?topic=containers-ingress-about

Ingress Application Load Balancer (ALB)

```
ibmcloud ks ingress secret create --cluster <cluster_name> --cert-crn <CRN> --name <secret_name> --
namespace <namespace>

apiVersion: networking.k8s.io/v1beta1 # For Kubernetes version 1.19, use networking.k8s.io/v1 instead
kind: Ingress
metadata:
  name: community-ingress-resource
  annotations:
    kubernetes.io/ingress.class: "<public|private>-iks-k8s-nginx"
spec:
  tls:
  - hosts:
    - <domain>
    secretName: <tls_secret_name>
rules:
  - host: <domain>
    http:
      paths:
      - path: /<app1_path>
        backend:
          serviceName: <app1_service>
          servicePort: 80
      - path: /<app2_path>
        backend:
          serviceName: <app2_service>
          servicePort: 80

kubectl apply -f ingress-resource.yaml -n <namespace>
```

Route

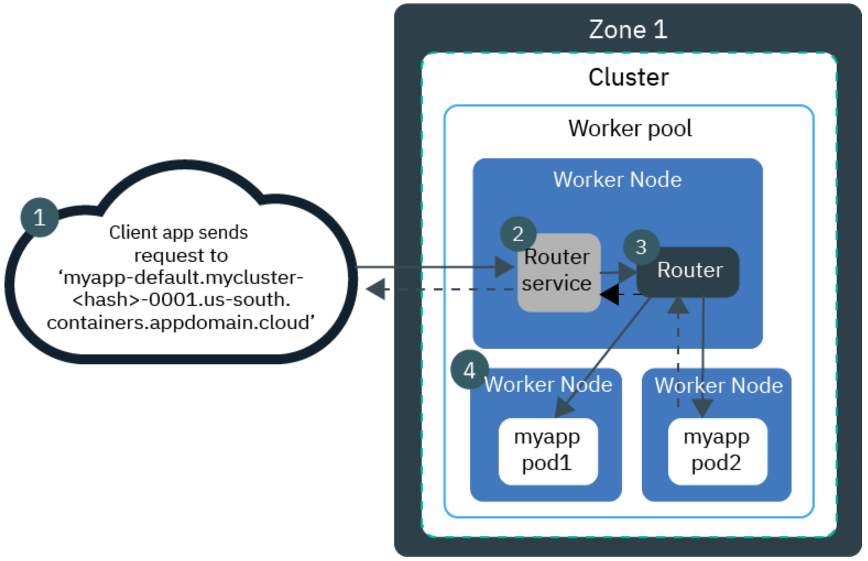
The Route is an OpenShift resource that was created before the Ingress was added to Kubernetes. Route also enables external access to services with additional capabilities like splitting traffic between multiple backends, sticky sessions. Route principles heavily influenced the Ingress design.

When a Route object is created on OpenShift the built-in *HAProxy* load balancer exposes the requested service and makes it externally available.

Routes are assigned a hostname from the router subdomain that external clients can use to send requests to your app.

OpenShift offers 4 types of routes:

- Simple, to handle non-encrypted HTTP traffic,
- Passthrough, to pass TLS connections without interruption to the pod, no TLS termination,
- Edge, to handle encrypted HTTPS traffic for non-encrypted HTTP endpoints,
- Re-encrypt, uses TLS termination and new TLS connection between router and pod.


1
Client app sends request to 'myapp-default.mycluster-<hash>-0001.us-south.containers.appdomain.cloud'
Zone 1
Cluster
Worker pool
Worker Node
2
Router service
3
Router
4
Worker Node
myapp pod1
Worker Node
myapp pod2

source: https://cloud.ibm.com/docs/openshift?topic=openshift-openshift_routes

DNS Server

The Kubernetes DNS server watches the Kubernetes API for new Services and changes. It creates a set of DNS records for each service. Kubernetes DNS schedules a DNS Pod and Service on the cluster, and configures the kubelets to tell individual containers to use the DNS Service's IP to resolve DNS names. Pods can resolve Services by their DNS name.

In Kubernetes version 1.11 and later, CoreDNS is recommended and installed by default with kubeadm. CoreDNS is a DNS server written in Go. There are currently about 30 plugins included in the default CoreDNS install, as well as external plugins.

When a query is processed by CoreDNS, the following steps are performed with the request:
- Route request to the closest zone and port,
- Route request through the static plugin chain,
- Each plugin inspects the request and determines if it should process the request, processing means responding to client.

Kubernetes also supports DNS SRV (DNS Service) records for named ports. If the `*my-service.my-ns*` Service has a port named "http" with the protocol set to TCP, you can do a DNS SRV query for `*_http._tcp.my-service.my-ns*` to discover the port number for `*http*` as well as the IP address.

The Kubernetes DNS server is the only way to access ExternalName Services.

DNS policies can be set per pod via the `**dnsPolicy**` field: *Default* (inherit from node), *ClusterFirst* (default, forward to upstream nameserver), *ClusterFirstWithHostNet, None*. The `**dnsConfig**` field on a Pod, allows you control on DNS settings for a Pod: *nameservers, searches, options*.

Network Policy

By default, pods are non-isolated and accept traffic from any source. Network isolation and traffic control at the IP address or port level, OSI layer 3 or 4 (L3 or L4), in a cluster is implemented by using a Container Network Interface (CNI) plug-in that supports Kubernetes network policy. A **NetworkPolicy** is a set of rules applied to a collection of endpoints that match a label selector within a namespace. For non-namespaced network policies, use a **GlobalNetworkPolicy**.

There are *four kinds of selectors* in an ingress from section or egress to section:

- podSelector,
- namespaceSelector,
- podSelector and namespaceSelector,
- ipBlock for IP CIDR ranges.

Every IBM Cloud Kubernetes Service cluster is set up with a network plug-in called Calico. When a Kubernetes network policy is applied, it is automatically converted into a Calico network policy.

Network Policy

```yaml
apiVersion: networking.k8s.io/v1
kind: NetworkPolicy
metadata:
  name: helloworld-deny-all
spec:
  podSelector: {}
  policyTypes:
    - Ingress
    - Egress
```

```yaml
apiVersion: networking.k8s.io/v1
kind: NetworkPolicy
metadata:
  name: allow-helloworld
spec:
  policyTypes:
    - Ingress
  podSelector:
    matchLabels:
      app: helloworld
  ingress:
    - {}
```

Security Context

A security context defines privilege and access control settings for a Pod or Container. Security context settings include, but are not limited to:

- Discretionary Access Control (DAC),
- Security Enhanced Linux (SELinux),
- Linux Capabilities,
- Seccomp,
- SecurityContextConstraint (SCC), ServiceAccount (SA), and Role Based Access Control (RBAC),

Pod Security Policy

Pod Security Policies enable fine-grained authorization of pod creation and updates. A *Pod Security Policy* is a cluster-level resource that controls security of the pod specification. The **PodSecurityPolicy** object defines a set of conditions that a pod must run. PodSecurityPolicies are implemented as an **admission controller**.

IBM