Routing in Datacenters

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cs168.io

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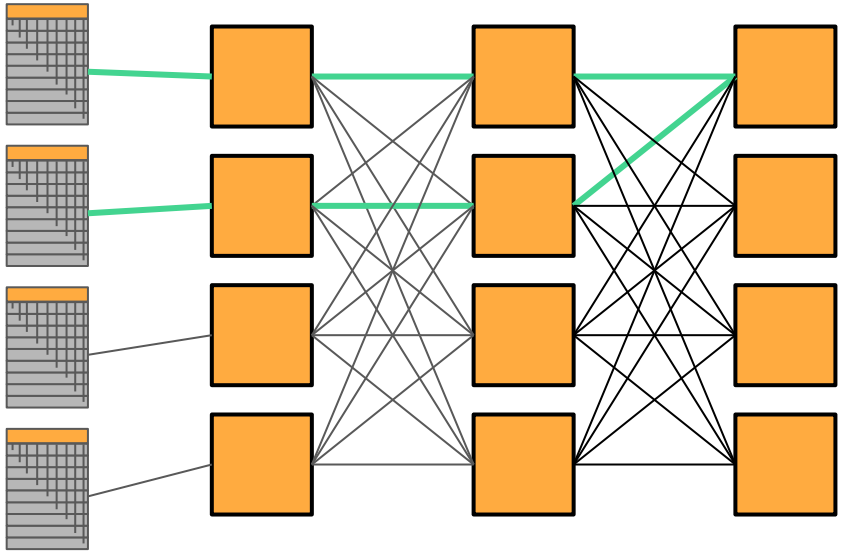
Thanks to Ankit Singla and Murphy McCauley for some of the material!

Recall

- Datacenter networks are single-organisation networks that are typically in a single location.

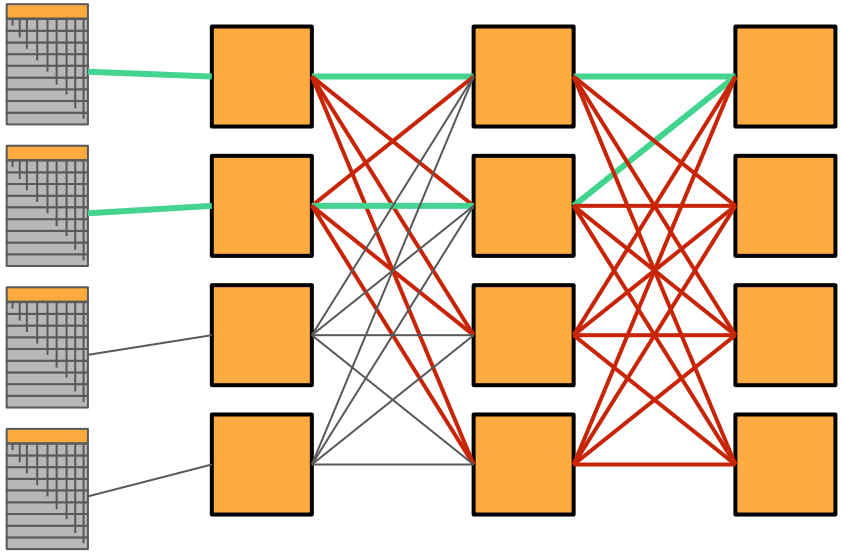
- Utilise meshy topologies (e.g., folded Clos) to be able to maximise bisection bandwidth.

Datacenter Topologies



Recall: previously, we assumed that a routing protocol will pick a single path between some source a destination.

Datacenter Topologies



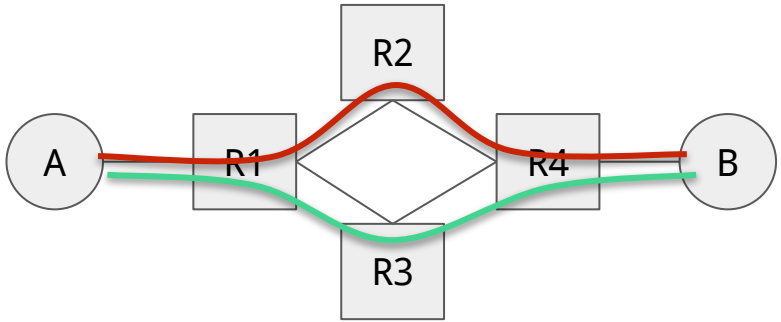
Picking only one path → not using all of the capacity available, and assuming coordinated selection of paths.

Equal Cost Multi-Path (ECMP)

- We, ideally, want to be able to use multiple paths between two sources.
- Why?

Equal Cost Multi-Path (ECMP)

- We, ideally, want to be able to use multiple paths between two hosts.
- Why? **Bandwidth.**



A → B bandwidth = link line rate
Red path unused.

Equal Cost Multi-Path (ECMP)

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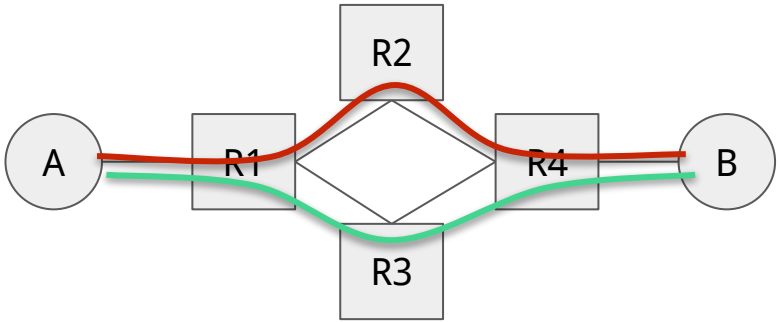

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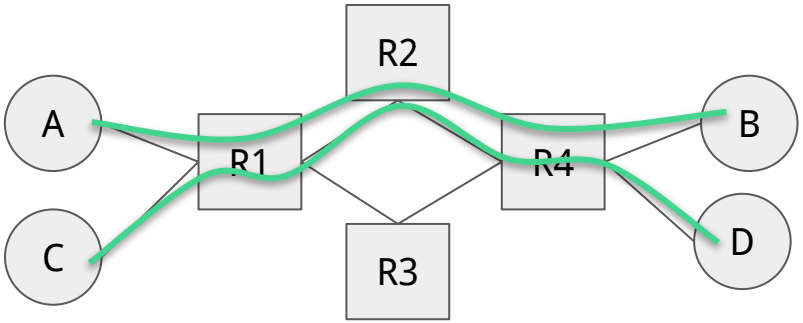

A → B + C → D compete.
< line rate available for A → B

Equal Cost Multi-Path (ECMP)

- Recall: previously, we assumed that we pick a single path between some source a destination when routing.

- We need to be able to use multiple paths within the network topology *where they are equal cost.*

- Equal Cost Multi-Path.
  - Select all the paths that are the same cost.
  - Load-balance packets across these links.

Questions?

ECMP - Hashing

- How do we choose how to load balance packets across different forwarding paths?

- We need *f(packet)* → *link.*
  - *f(packet)* can run at each point that we need to load-balance traffic.

ECMP - Hashing

- What's a good *f*?
- Just round-robin - send each packet to a different link.

ECMP - Hashing

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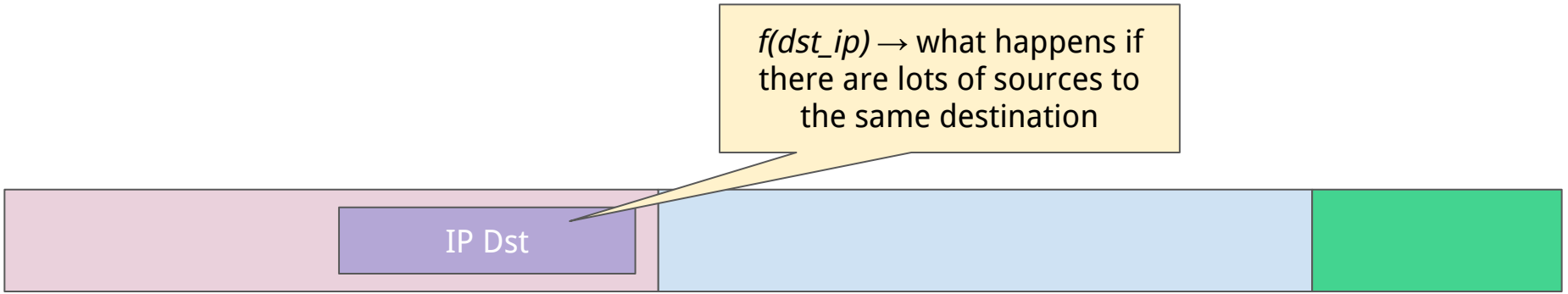
- Just round-robin - send each packet to a different link.

Ignores payload - does TCP care about re-ordering?

ECMP - Hashing

- What's a good *f*?



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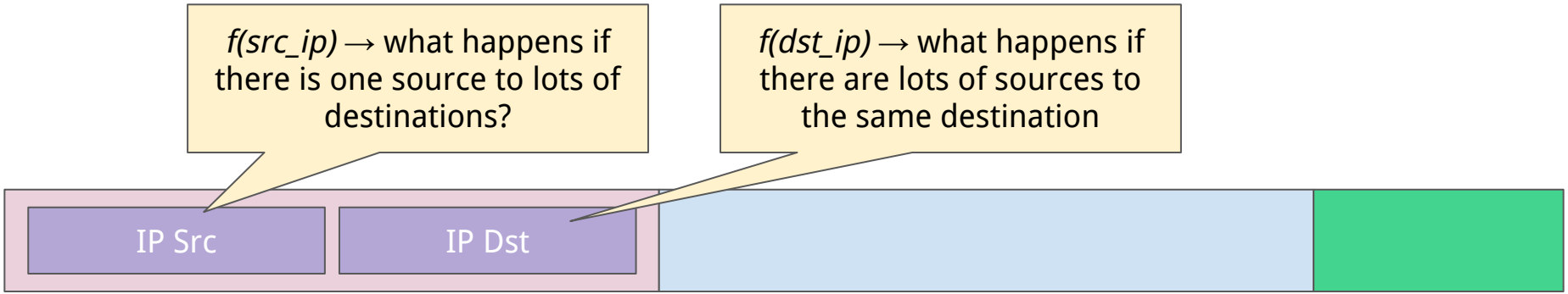

ECMP - Hashing

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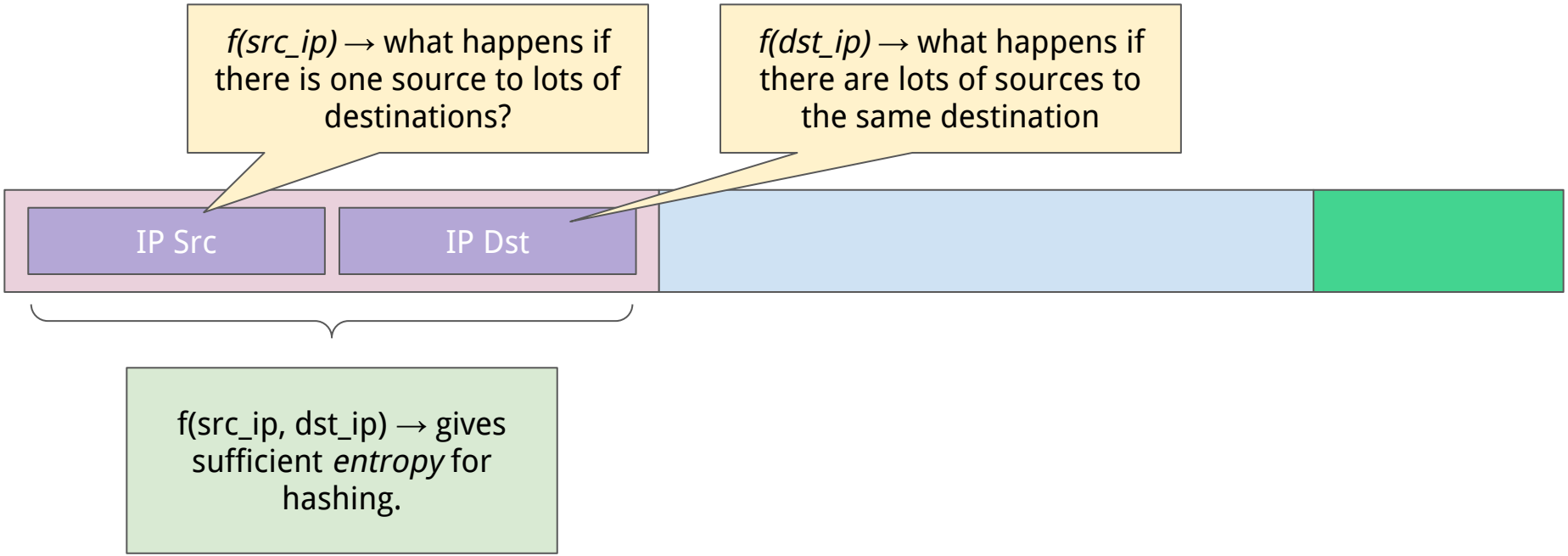

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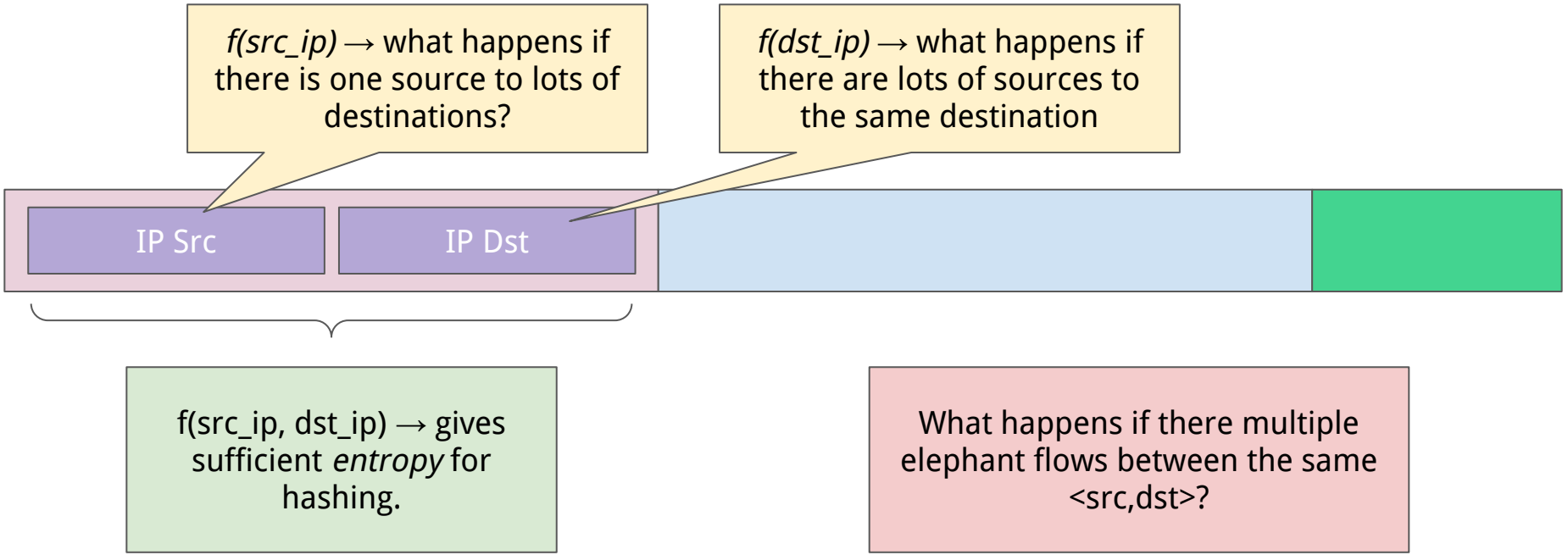

ECMP - Hashing

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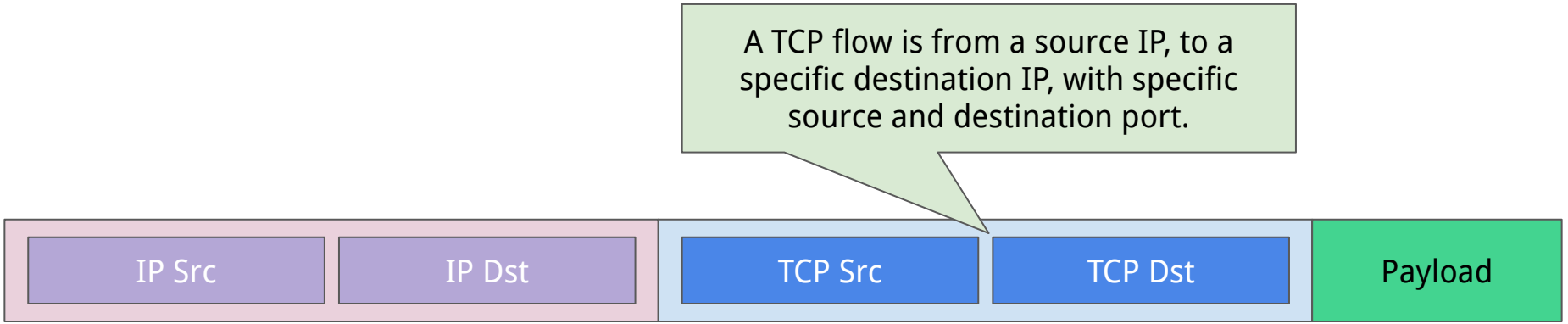


f(src_ip, dst_ip, src_port, dst_port)

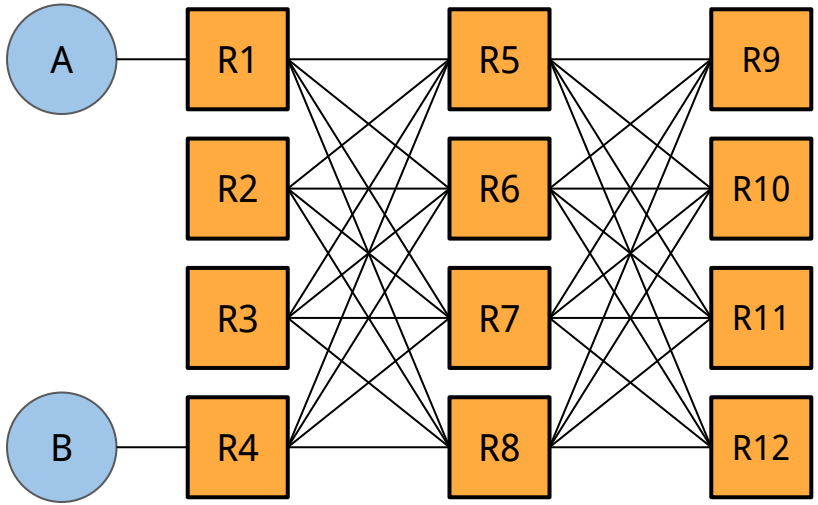
ECMP - Hashing

f(src_ip, dst_ip, proto, src_port, dst_port)

- This series of fields is referred to as a 5-tuple.
- Gives sufficient entropy for load-balancing whilst not resulting in re-ordering.
- We refer to this as *per-flow* load-balancing.

Questions?

Recall: Clos Topologies

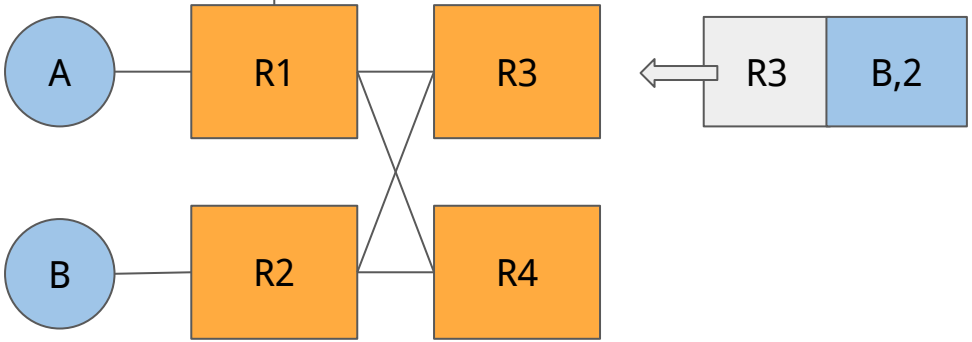


Routing in Clos Topologies

- How do we adjust our routing protocols to work in Clos topologies?

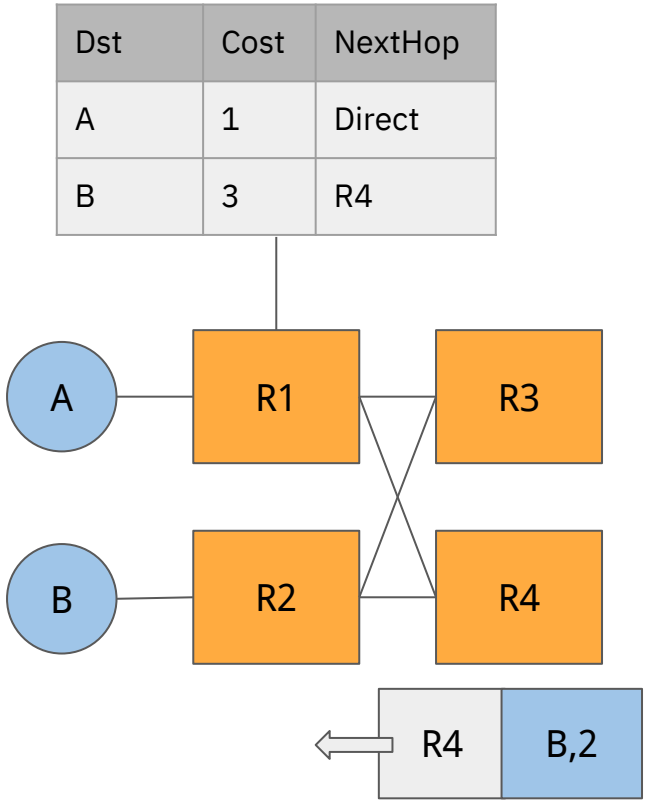
Routing in Clos Topologies - DV

Dst	Cost	NextHop
A	1	Direct
B	3	R4



- **Distance-Vector**

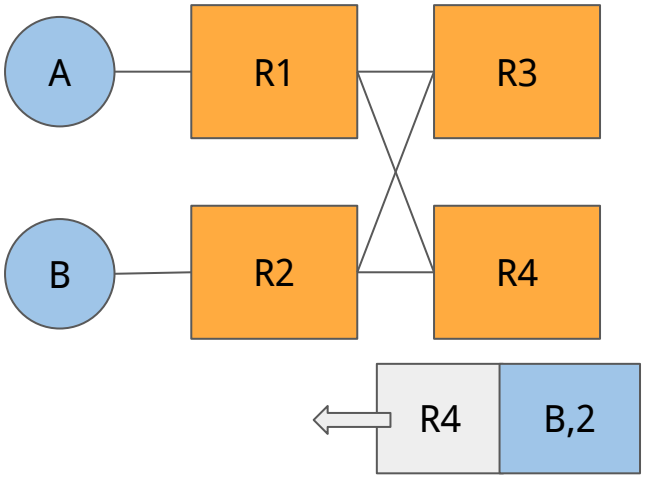
Routing in Clos Topologies - DV



- **Distance-Vector** – R1 receives advertisement from R4 with cost of 2 to B (R4-R2, R2-B).
- Cost is *the same* as existing route B via R4.
- Route is not accepted!

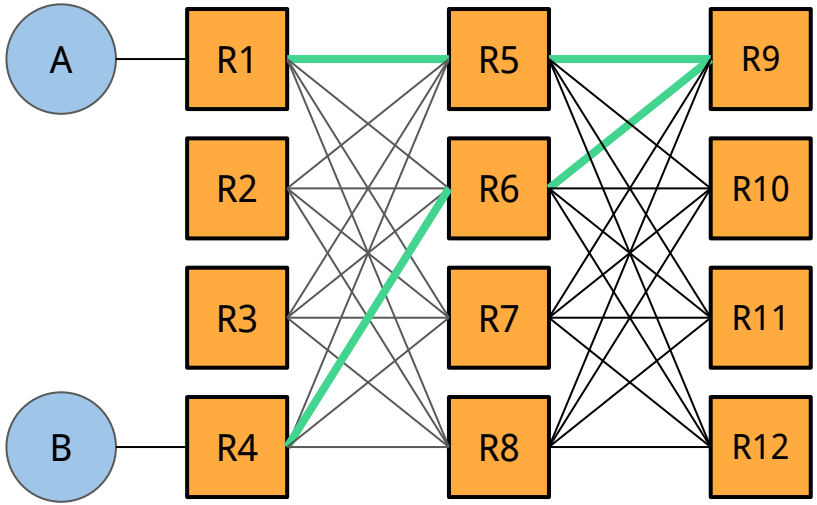
Routing in Clos Topologies - DV

Dst	Cost	NextHop
A	1	Direct
B	**3**	**R4**
	3	R3



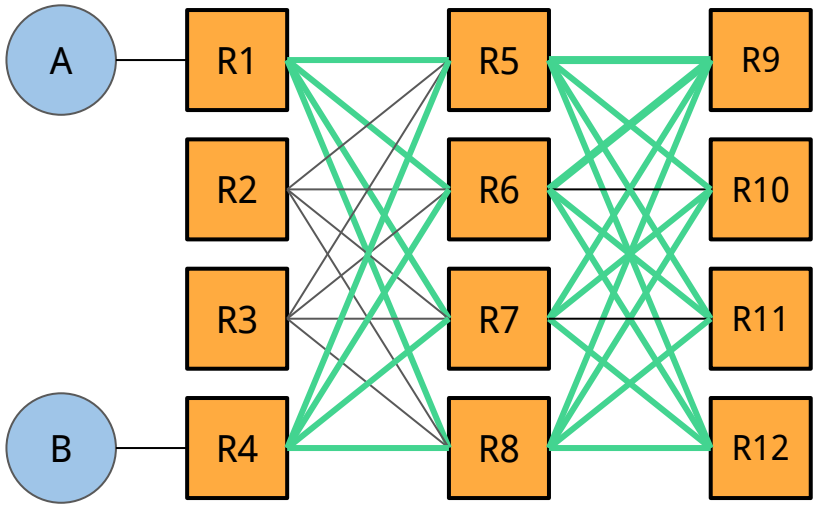
- Must extend routing table to store multiple next-hops per destination.
- Update logic – if the cost is the same, then add as an additional route.
- Forwarding can then have entries to allow for ECMP.

Routing in Clos Topologies - LS



- **Link State**
- Recall: each node stores the entire topology graph.
- Calculates shortest path to each destination through graph.

Routing in Clos Topologies - LS



- Must extend protocol to calculate all shortest paths between source and destination.
- Multiple paths now programmed into the forwarding table.

Questions?

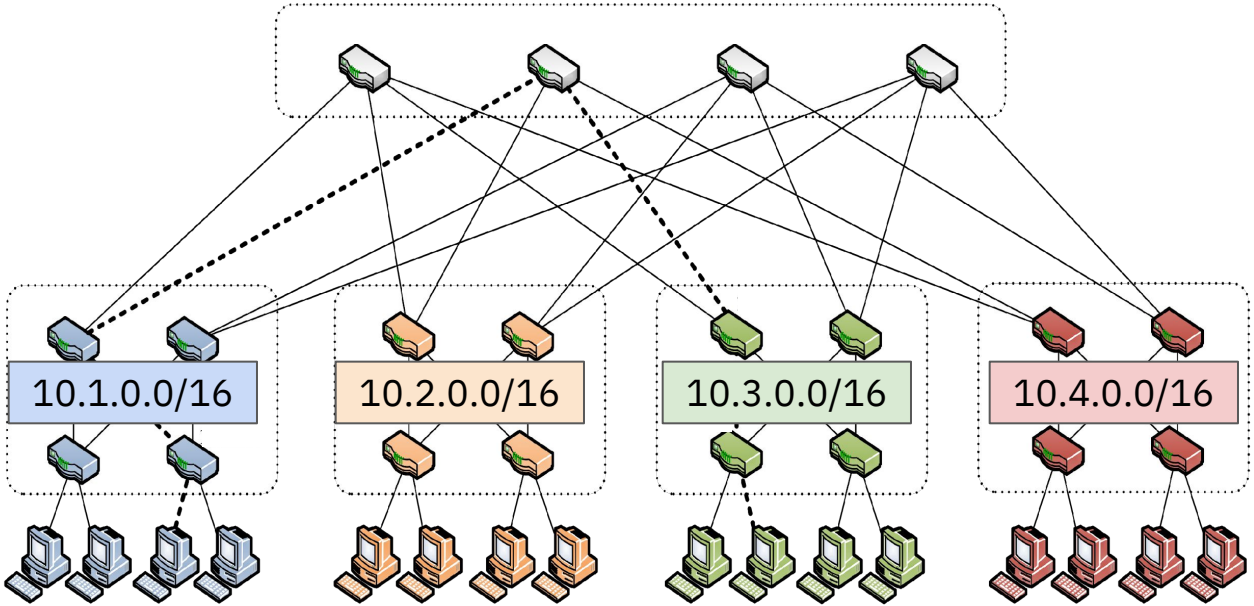
Routing in Clos - Scaling.

- Distance-Vector:
  - Per-destination advertisements means 100,000+ destinations being advertised.
- Link-State:
  - Many link state advertisements with 10,000+ links.
- Memory, CPU and forwarding table resources are limited on commodity switches.

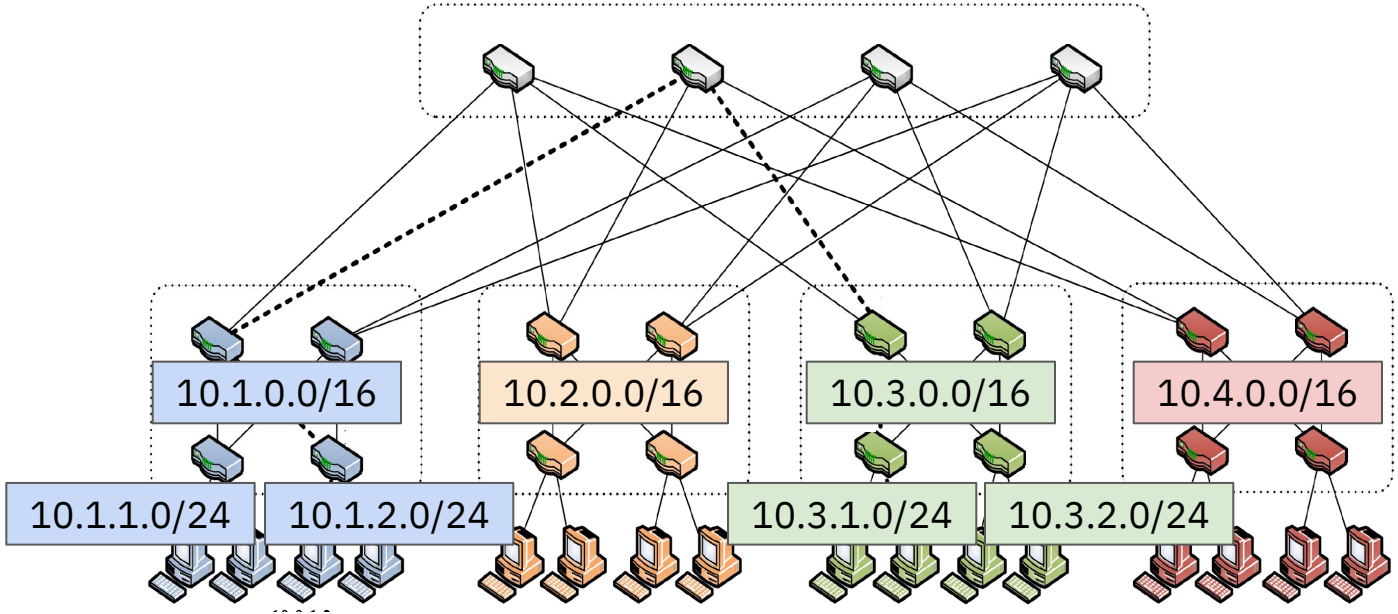
Topology-Aware Addressing and Routing

- Basic idea: the node (host) address tells us **where** in the topology it is.
- Exploits the idea that the topology is **regular**.

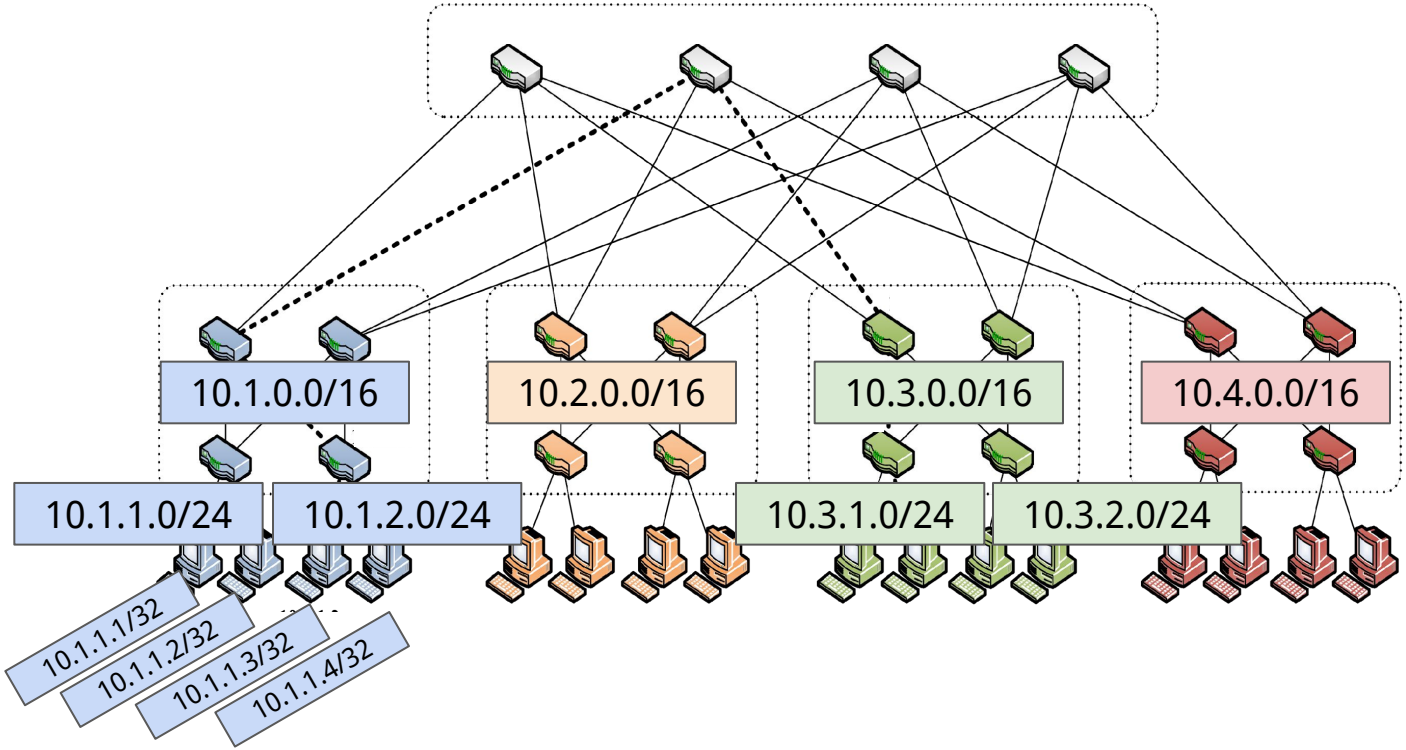
Topology-Aware Routing and Addressing



Topology-Aware Routing and Addressing

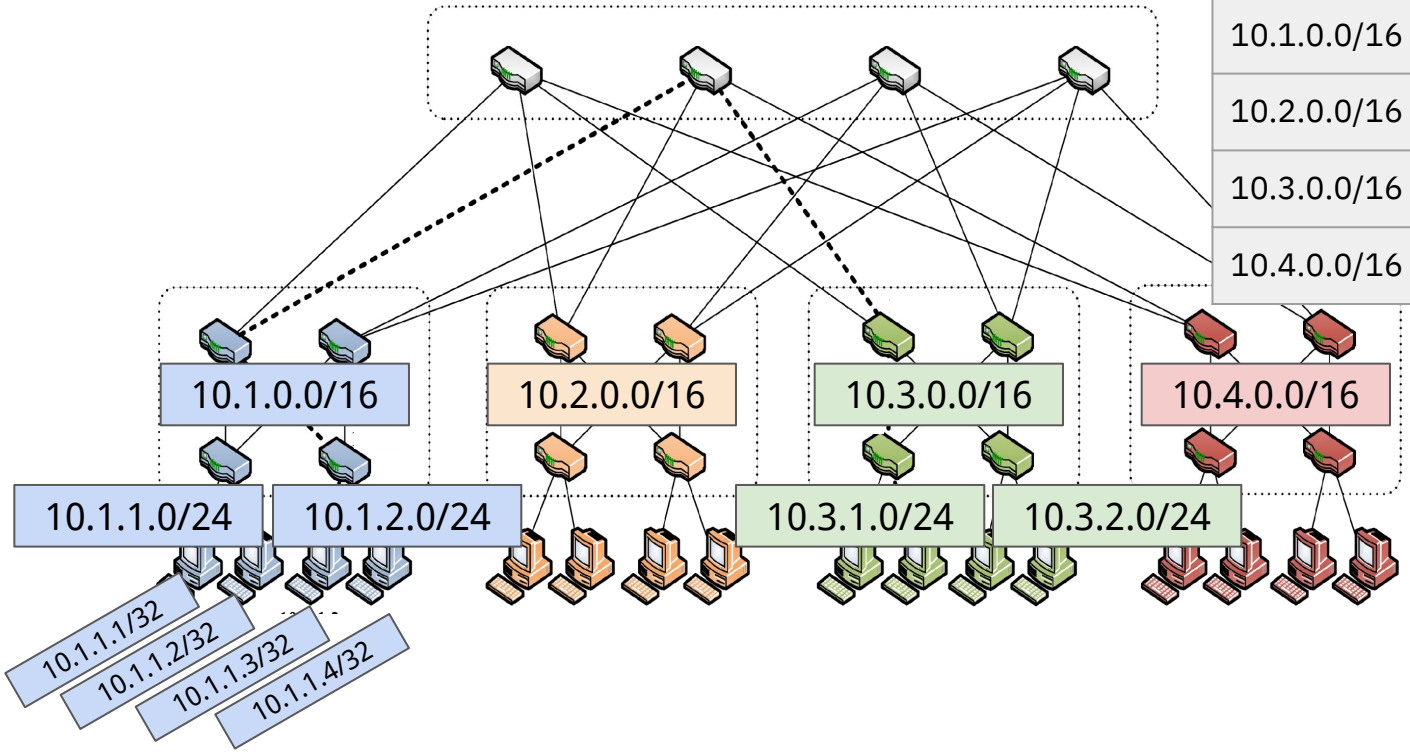


Topology-Aware Routing and Addressing



Topology-Aware Routing and Addressing

Dst	Port
10.1.0.0/16	1
10.2.0.0/16	2
10.3.0.0/16	3
10.4.0.0/16	4



Topology-Aware Addressing and Routing

- Routing aggregation (summarisation) results in:
  - Fewer entries.
  - More stability.
- Updates are generally to address link or switch failures.
  - No need to advertise when a host goes away.
- Nice example of what can be achieved in a controlled network.
  - But… we can’t deal with “random” addressing turning up!

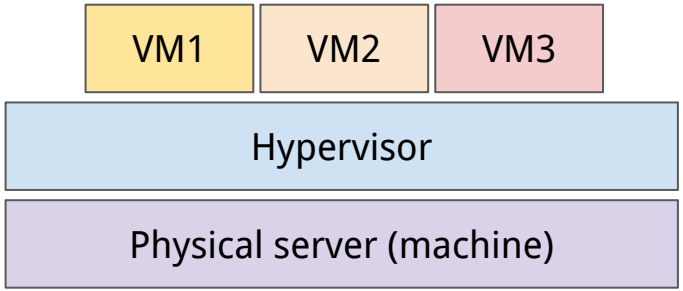
Questions?

A challenge to our datacenter routing approach…

- Traditional datacenters required servers to be installed or uninstalled to change routing requirements.
  - Machine was either there or it wasn't!
- Virtualisation (virtual machines, containers) means that hosts can move often and quickly.
- Introduces new network control-plane scaling considerations.
  - More updates.
  - More calculations.

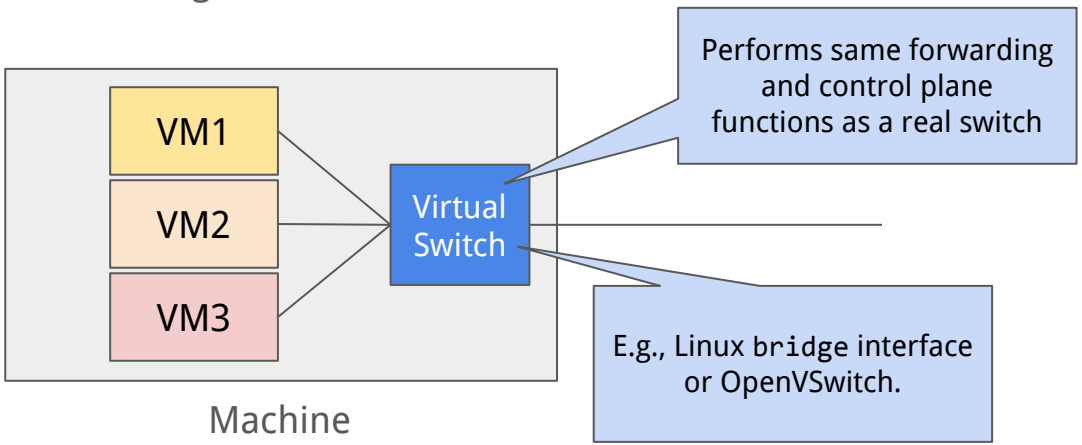
What is a virtual machine?

- A way of running a host inside another host.
- Allows for separation of environments whilst making efficient use of compute resources.
  - Allows for different administrators.
  - Allows for separation for security.
- Numerous hypervisors available.
  - e.g., VMWare, KVM.



Virtual Switches

- Virtual machines need network connectivity.
- This means our routers/switches might have multiple hosts connected per port.
- We need our machines to have some form of switch.
  - A virtual switch running in software.



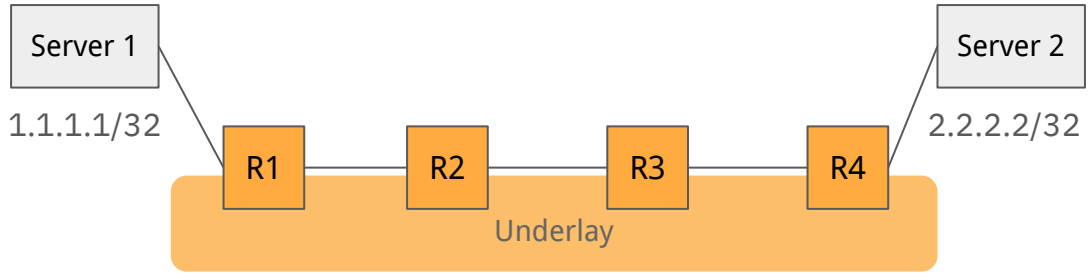
Questions?

What do virtual machines mean for our DC?

- More hosts!
- Hosts that exist independently of the number of ports on our “leaf” switches.
- We need some way to refer to, and reason about, networking with this new virtual layer.

The Underlay Network

- The underlay network handles routing between physical machines.
  - We can exploit our addressing tricks to reduce scale.

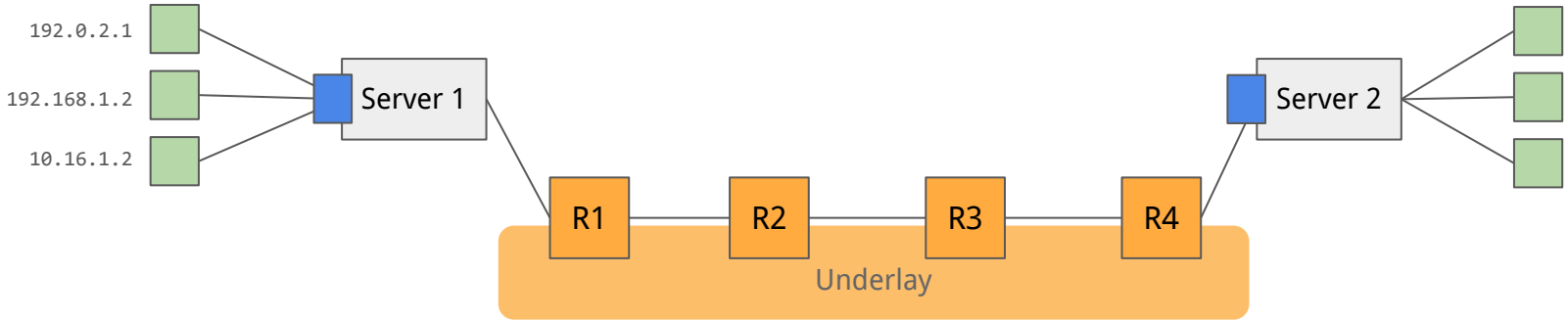


Dst	NextHop
2.0.0.0/8	R2
1.0.0.0/8	Direct

Dst	NextHop
2.0.0.0/8	Direct
1.0.0.0/8	R3

Impact of Virtual Machines

- We now have new hosts that turn up into our network rapidly!
- They may not be constrained to our “scalable” addressing scheme.



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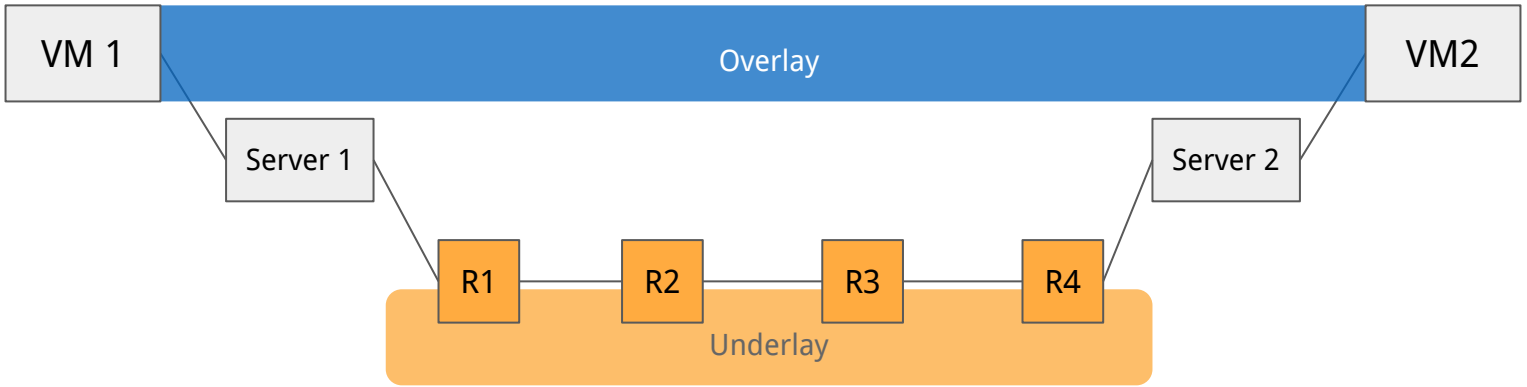
Scaling Concern

- Each virtual machine is one /32.
  - We can't necessarily guarantee that we can aggregate.
- Aggregation was our scaling trick.

Dst	NextHop
2.0.0.0/8	R2
1.0.0.0/8	Direct
192.0.2.1/32	**1.1.1.1**
192.0.2.2/32	**R2**

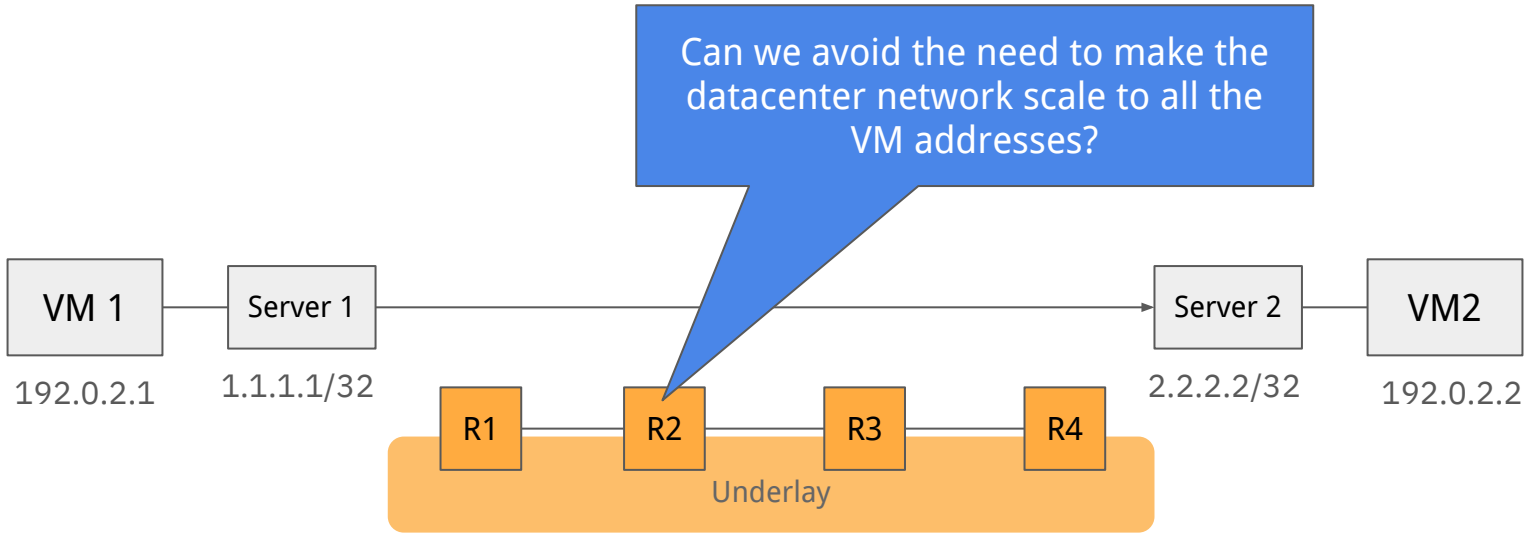
Dst	NextHop
2.0.0.0/8	Direct
1.0.0.0/8	R3
192.0.2.1/32	**R3**
192.0.2.2/32	**2.2.2.2**

Overlay and Underlay Networks



Concept: overlay network – a network topology that exists on top of the physical topology.

How can we scale and support overlay networks?



Dst	NextHop
2.2.2.2/32	R2
1.1.1.1/32	Direct

Dst	NextHop
2.2.2.2/32	Direct
1.1.1.1/32	R3

Questions?

How can we scale and support overlay networks?

- VM1 → VM2 is a flow that is from 192.0.2.1 to 192.0.2.2.
- With destination based forwarding – we only look at the IP destination.
- Problem: The underlay network needs to understand every address in the overlay network.
  - Defining overlay networks didn't help us scale!

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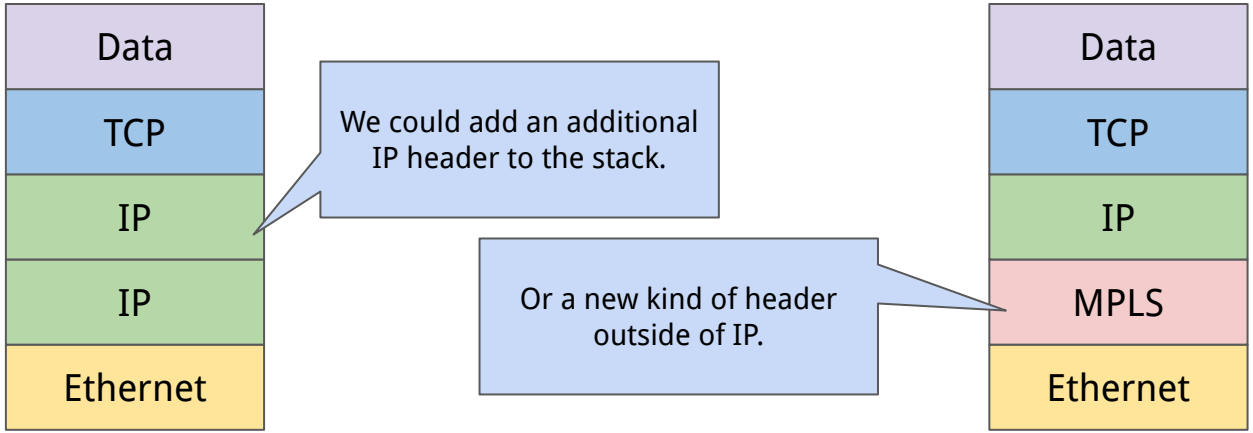
- Problem: The underlay network needs to understand every address in the overlay network.
  - Defining overlay networks didn't help us scale!
- **Is there some way we can avoid needing to think about the VM address and rather just care about the physical machine?**
  - We'd like to keep *destination-based forwarding*.

Encapsulation

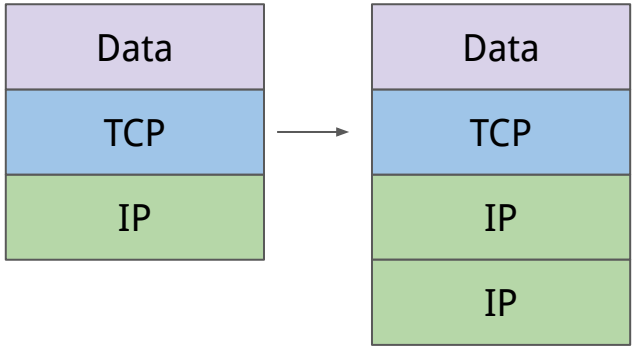
- Thus far, we have just used one header per layer.
  - One L2 (Ethernet), one L3 (IP), one L4 (TCP).
- What happens if we add additional headers into the stack?



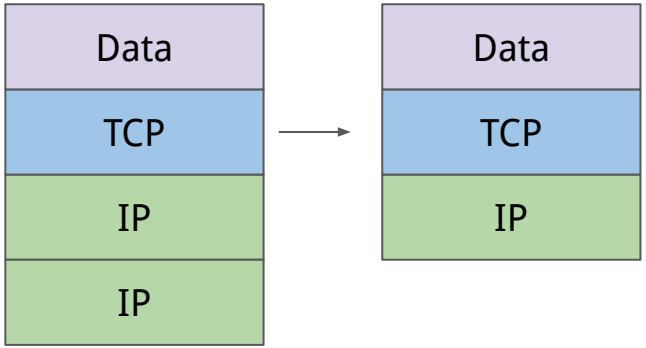
What does encapsulation allow us to do?

- Tell part of the network to forward based on one destination.
- At some later point in the network - remove the “outer” encapsulation, and let the network forward based on the “inner” encapsulation.
- This allows us to hide some complexity from the underlay network.

Encapsulation Actions

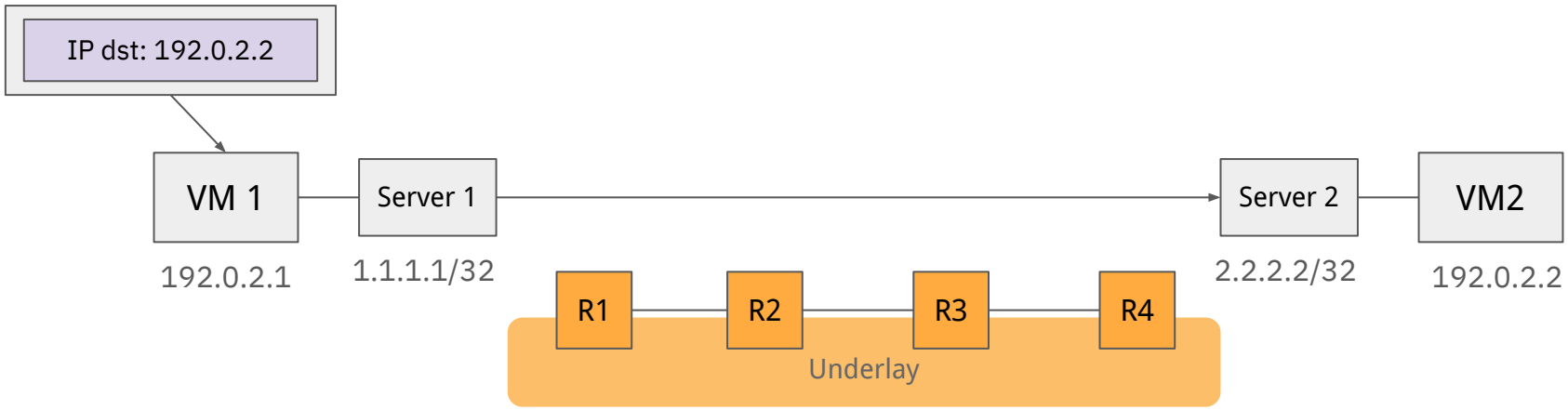


Encapsulate packet - add another header to the original headers.



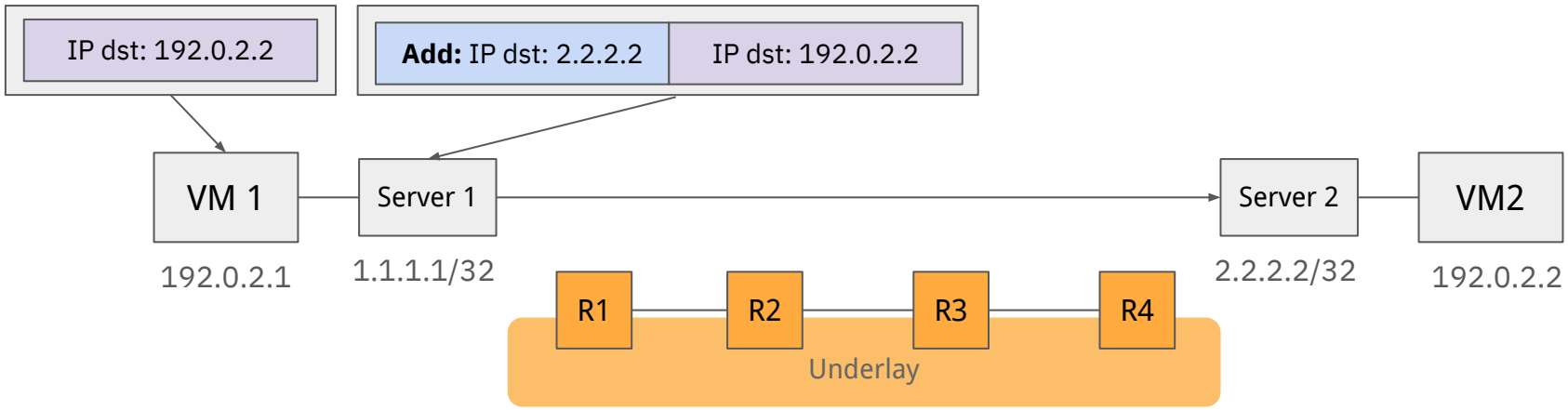
Decapsulate packet - remove a header to expose the header underneath.

Encapsulating Packets



Using an *encapsulation* allows us to hide the “inner” overlay packet from the underlay.

Encapsulating Packets



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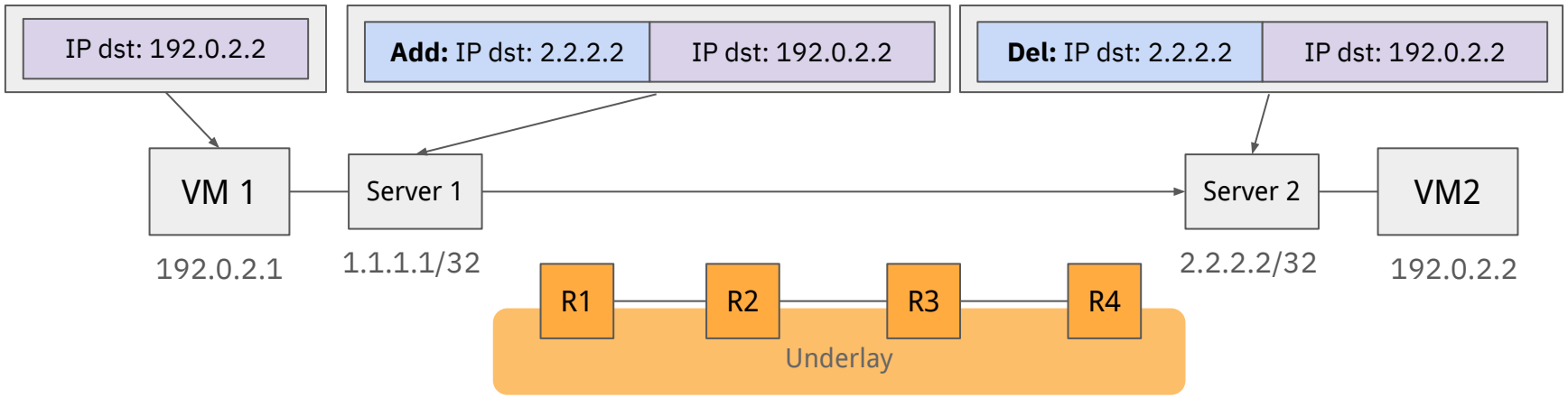
Encapsulating Packets



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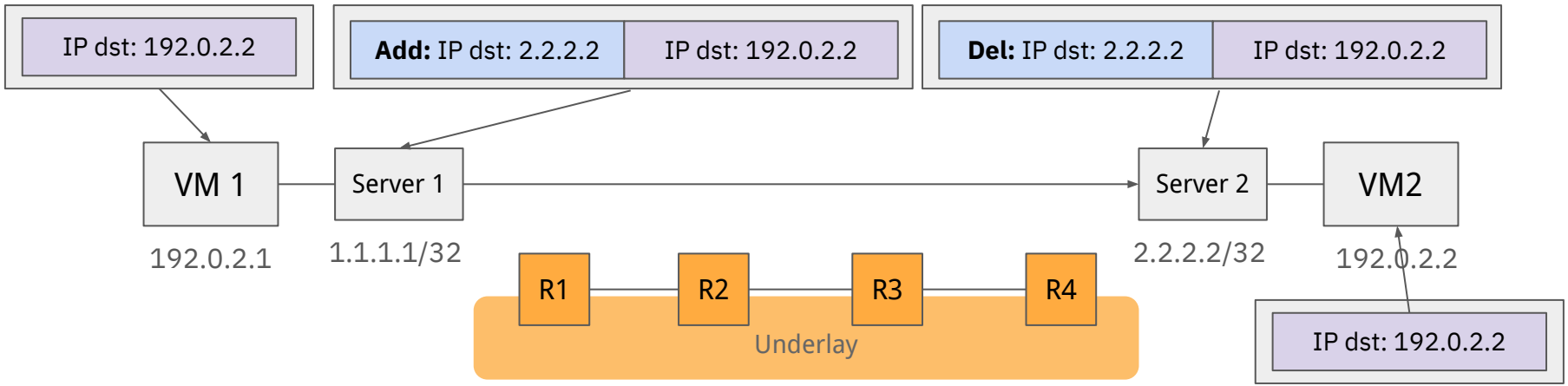
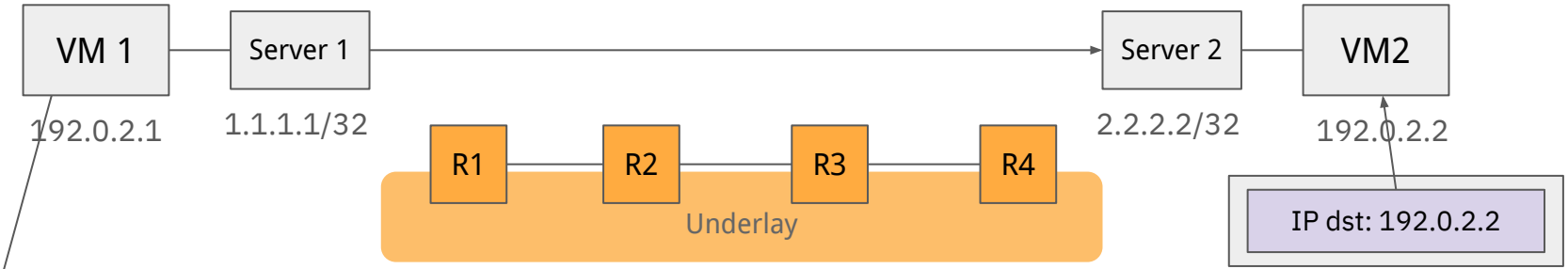
Encapsulating Packets



Using an *encapsulation* allows us to hide the “inner” overlay packet from the underlay.

Scaling routing with encapsulation

- Encapsulation allows us to separate routing in the underlay and overlay.
- Underlay:
  - Knows only about reachability to physical machines in the datacenter (same scaling as before).
- Overlay:
  - Knows about routing to each virtual machine that it needs to forward traffic to.



Dst	NextHop
0.0.0.0/0	Server 1

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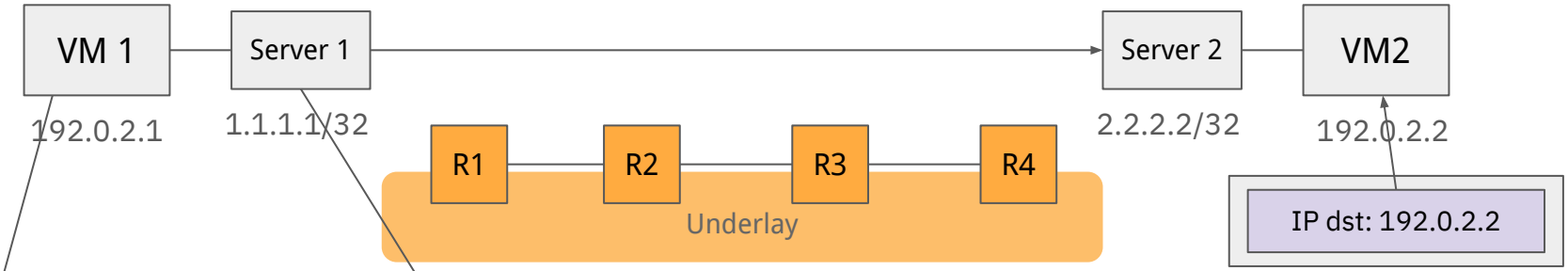

Dst	NextHop
0.0.0.0/0	Server 1

Dst	NextHop
192.0.2.2/32	Encap (dst: 2.2.2.2) && R1
0.0.0.0/0	R1

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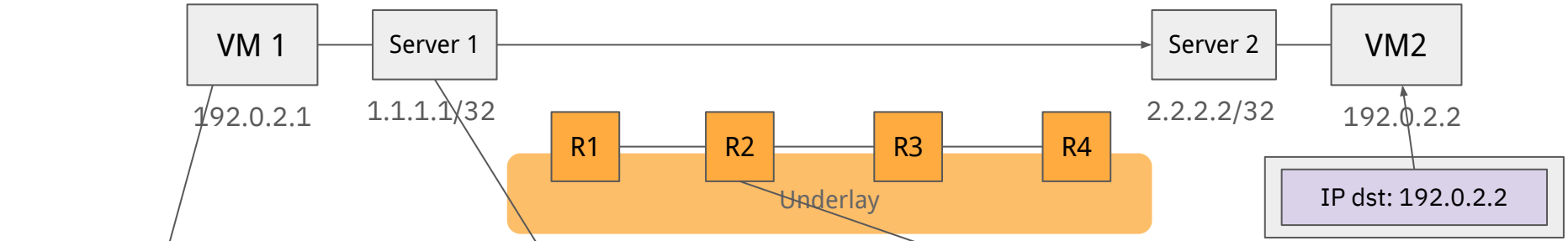

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0.0.0.0/0	Server 1

Dst	NextHop
192.0.2.2/32	Encap (dst: 2.2.2.2) && R1
0.0.0.0/0	R1

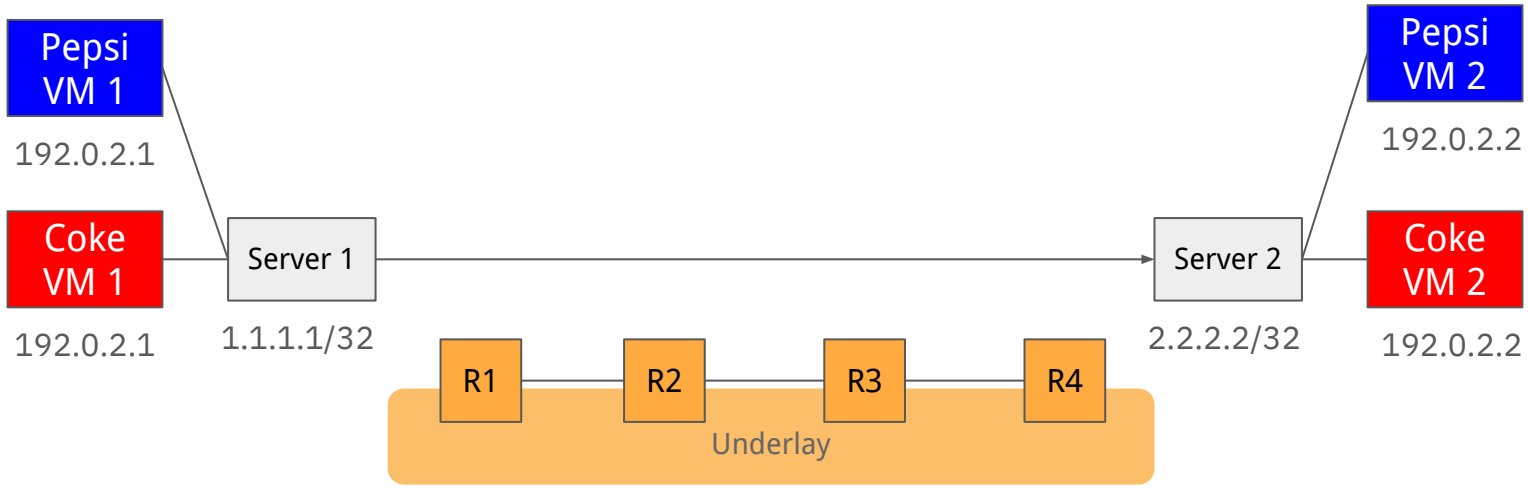
Dst	NextHop
2.0.0.0/8	R3

Questions?

Multi-tenancy

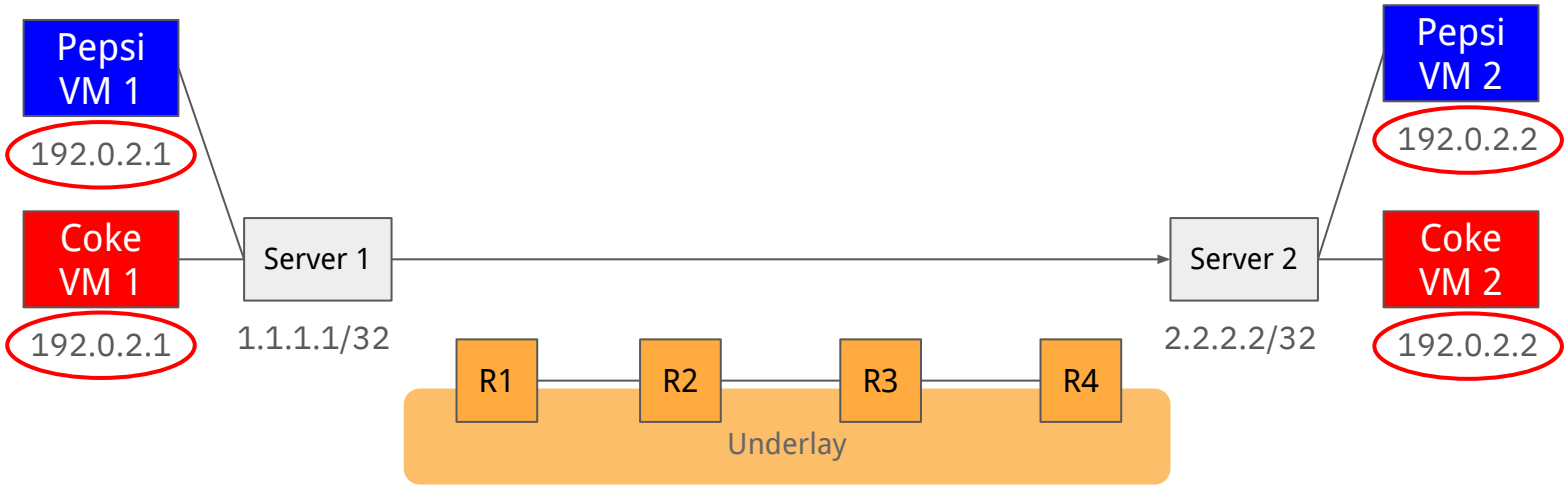
- Datacenter networks are single owner, but multi-tenant.
- This means that there can be different companies/departments running on the same infrastructure.
  - Again, allows for efficient use of resources.
- Large case: Cloud provider.
  - Many customers with their virtual machines running inside a single datacenter.
  - e.g., Azure, AWS, GCP.

Multi-tenancy in a Datacenter



Our datacenter networks need to support multiple tenant networks - who don't coordinate with each other.

Multi-tenancy in a Datacenter



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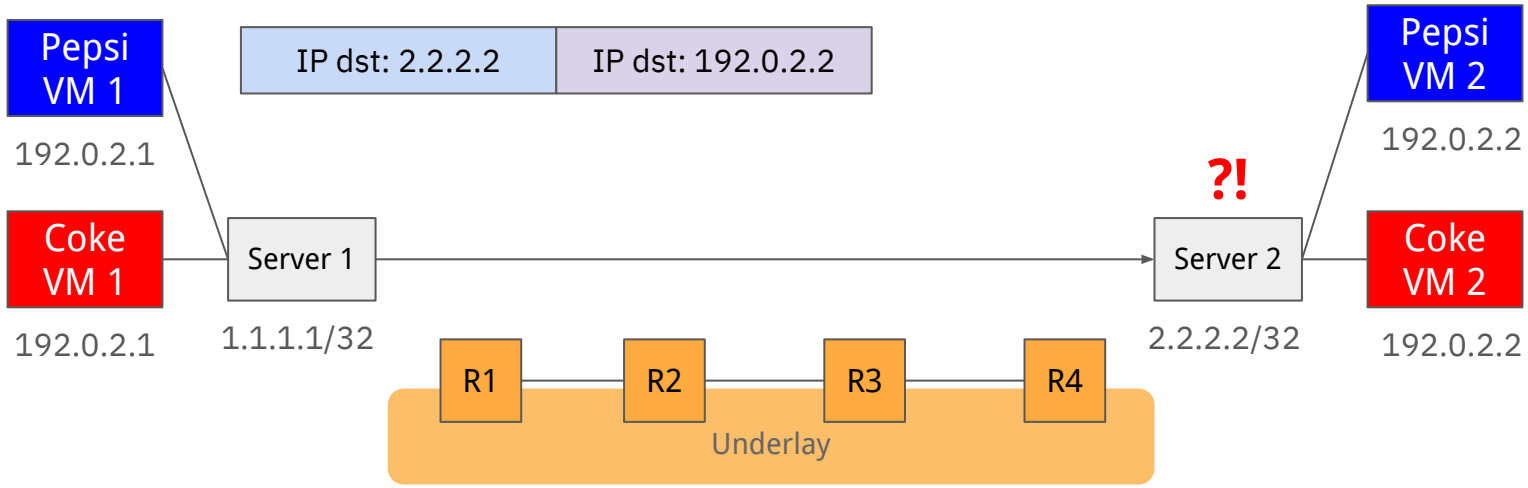
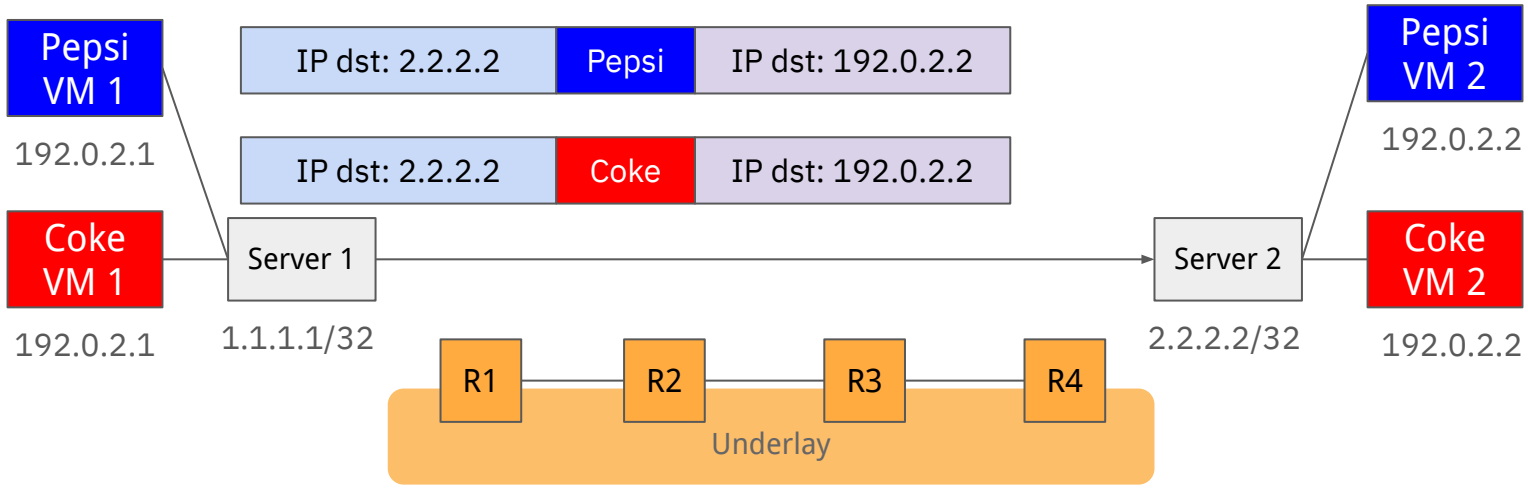


Our encapsulation just told us where to go - not who the packet was for.

Multi-tenancy in a Datacenter



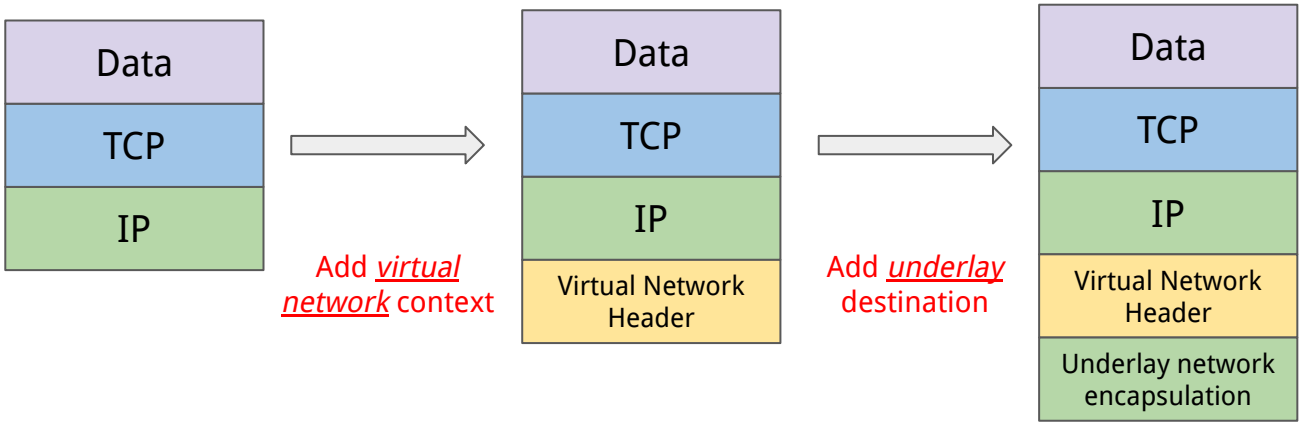
Using encapsulations that allow specification of a *virtual network ID* allows multi-tenancy.

Encapsulations for Multi-Tenancy

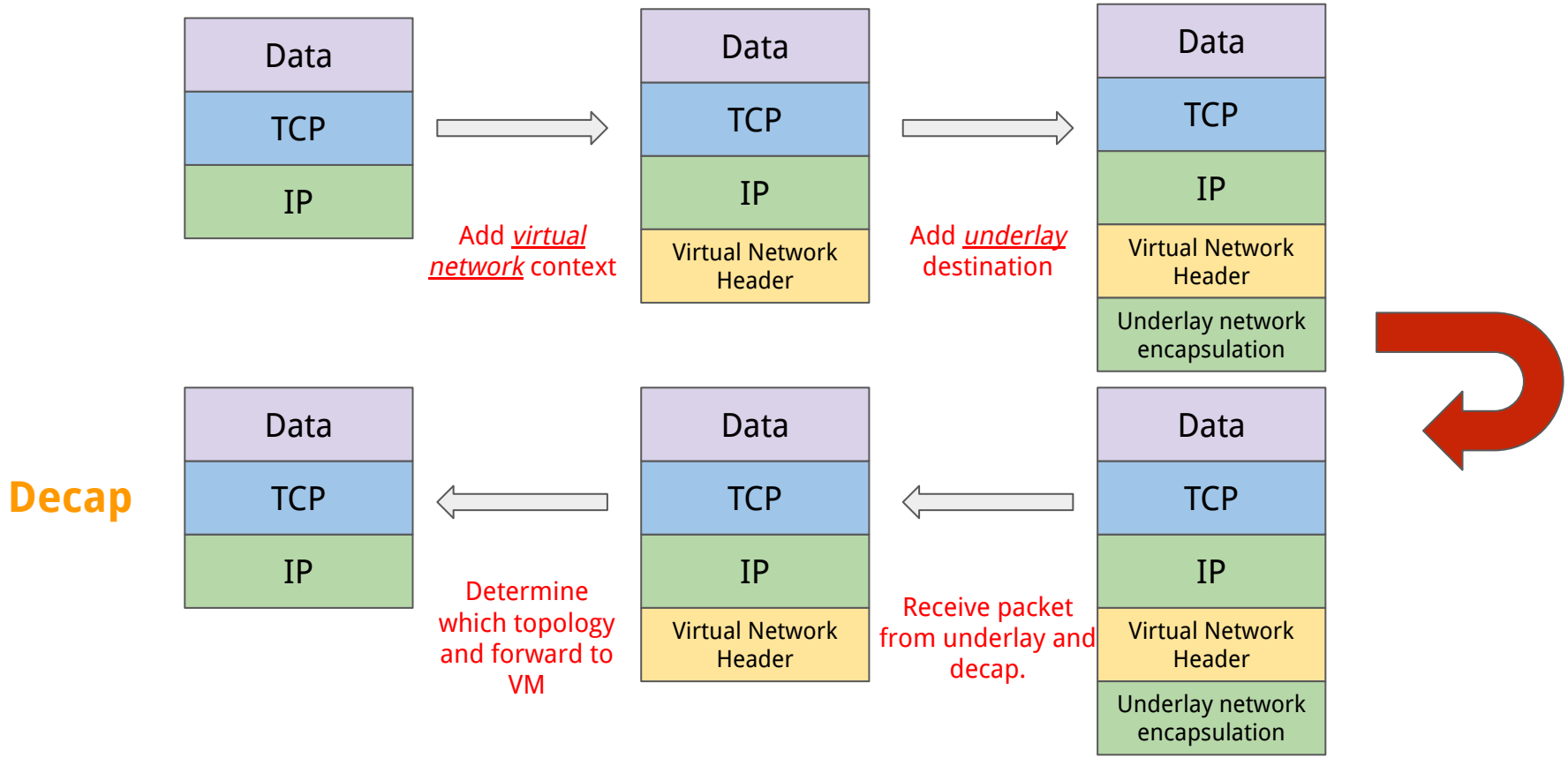
- Carries information that isn’t directly forwarding information in the packet header.
- Allows for a packet to be resolved into a specific *virtual network*.
- Each virtual network is assigned a *virtual network ID.*

Putting it together - stacking encapsulations

Encap



Putting it together - stacking encapsulations



What headers do we use?

- Traditional encapsulation for multi-tenancy in telco networks has been MPLS.
  - A specific 20-bit label that identifies a service.
  - Historically not encapsulated in IP (but can be!)
- Many old and new(er) options as datacenters like this have grown.
  - Most work over IP (i.e., IP is the “outer” packet header that the underlay looks at).
  - e.g., GRE, VXLAN, GENEVE…
- Don’t worry about the details – mainly just understand that the idea of encapsulation exists.

Questions?

Summary

- Datacenter networks need different treatment in routing protocols.
  - Both Link State and Distance Vector.
- We can design addressing in our datacenters to improve scalability.
- As more dynamic, virtual servers arrived - routing could not scale!
- We use an overlay network to separate VM-to-VM networking from server-to-server.
  - This is achieved through encapsulating packets.
- Packet encapsulation also allows us to separate different tenants in a datacenter.