Datacenter Networks

CPSC 433/533, Spring 2021

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What you should understand…

- **What is a datacenter network**
  - Scale, service-model, application characteristics
- **What makes it different?**
  - Characteristics, goals (w.r.t. Internet), degrees of freedom
- **How do we achieve goals by exploiting freedom?**
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Key Features of a DCN

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- Service model
  - *Public* clouds (jargon: SaaS, PaaS, DaaS, IaaS, …)
  - Multi-tenancy

- Application characteristics
  - Large-scale computations (“big data”)
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- Common Theme: **Parallelism**
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- **Two common paradigms (not exhaustive)**
  - Partition-Aggregate
  - Map-Reduce

Workload: Partition Aggregate

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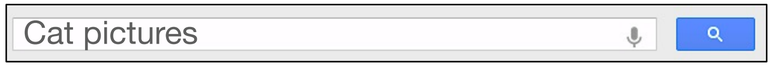
User query (from outside datacenter)



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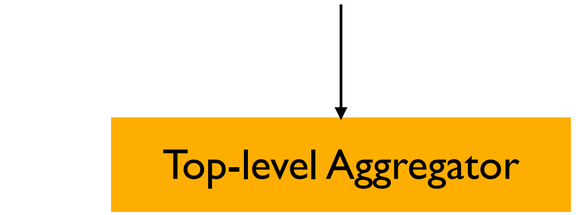

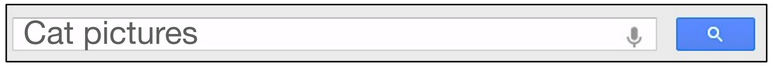

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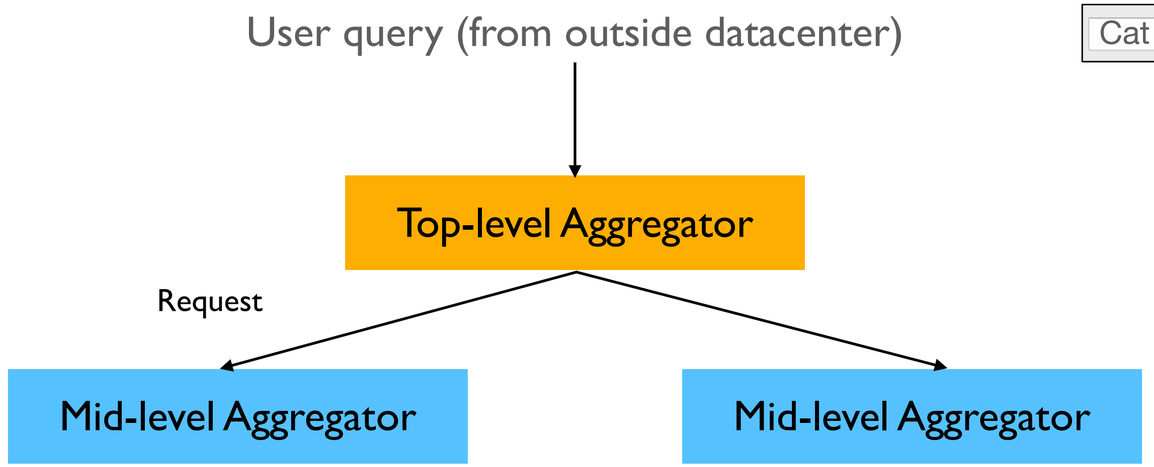

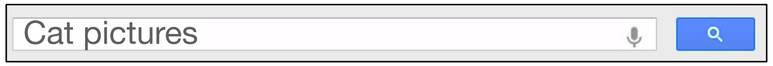

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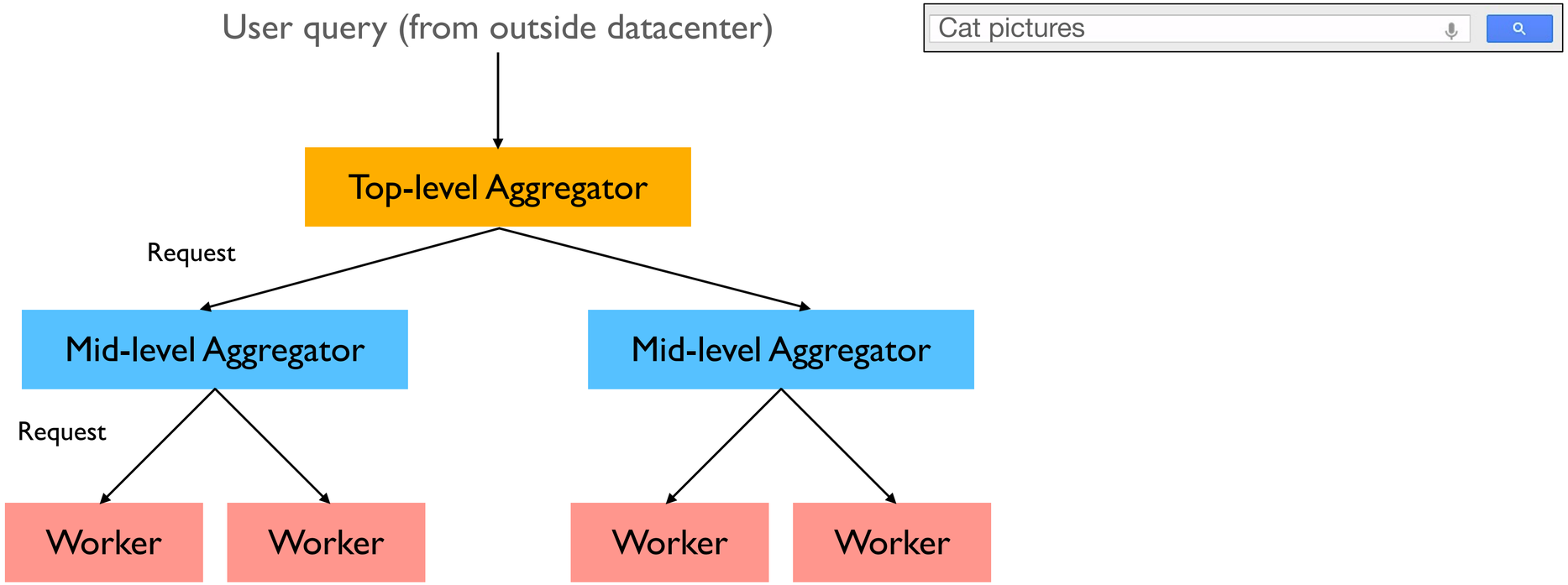

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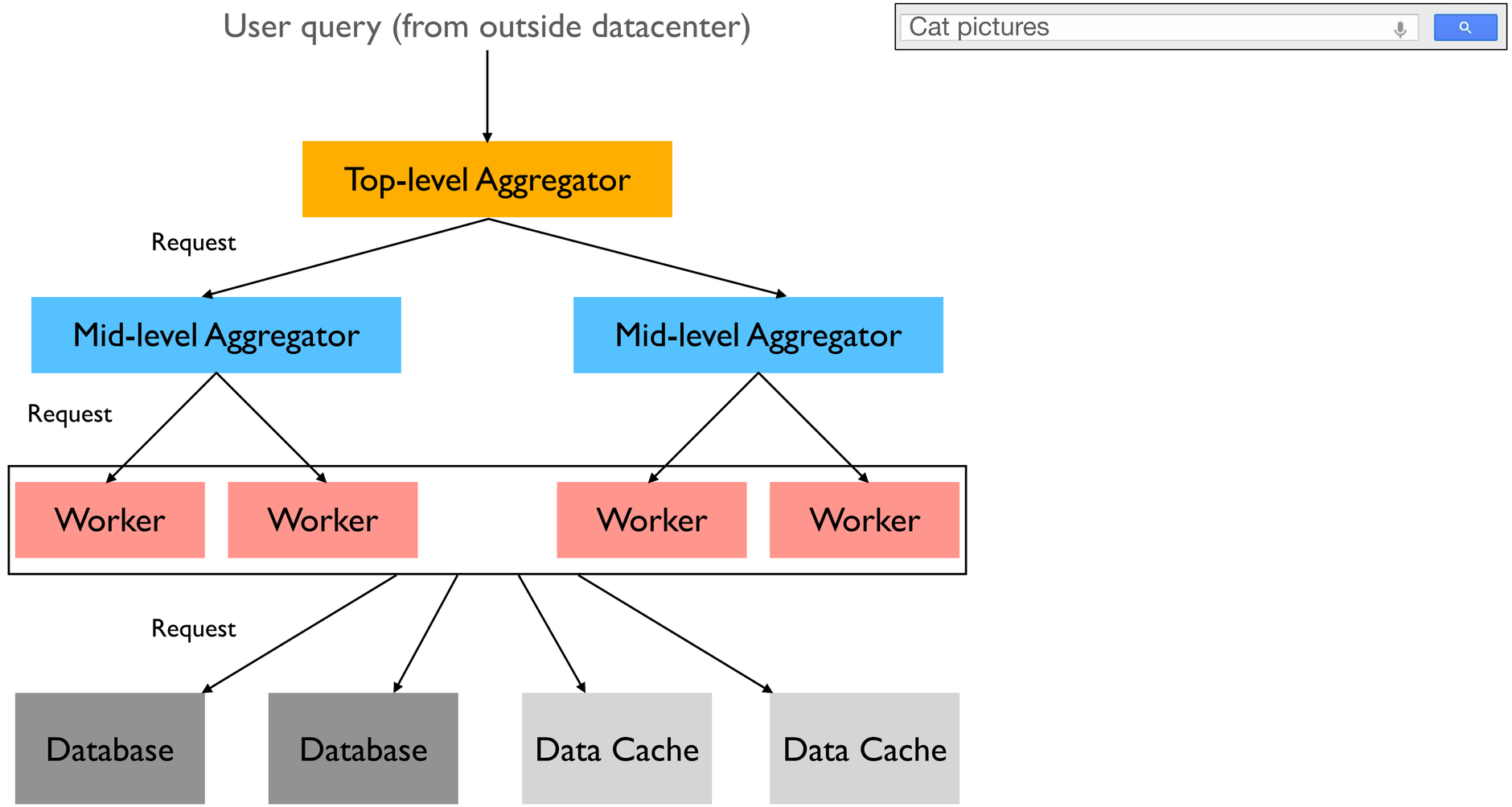

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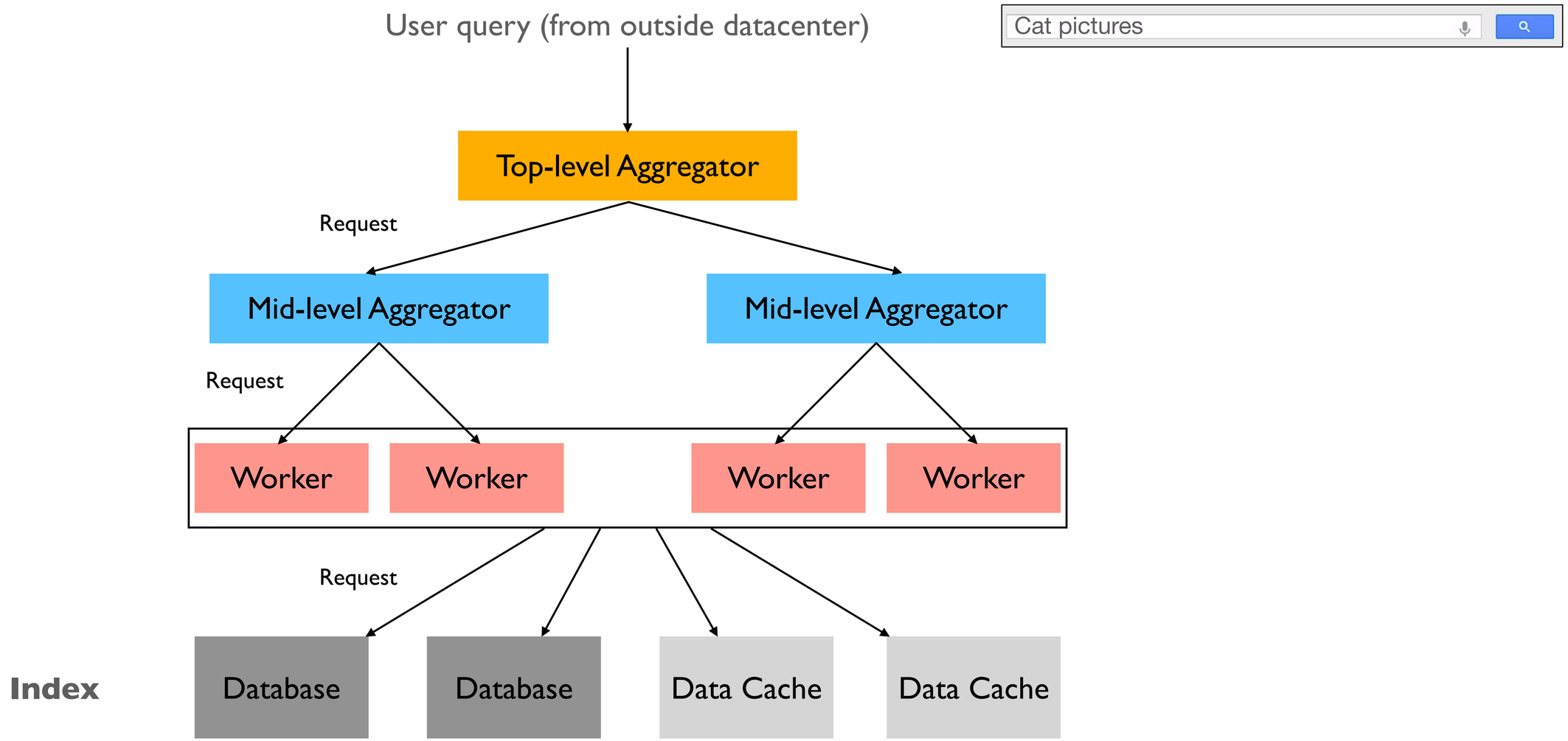

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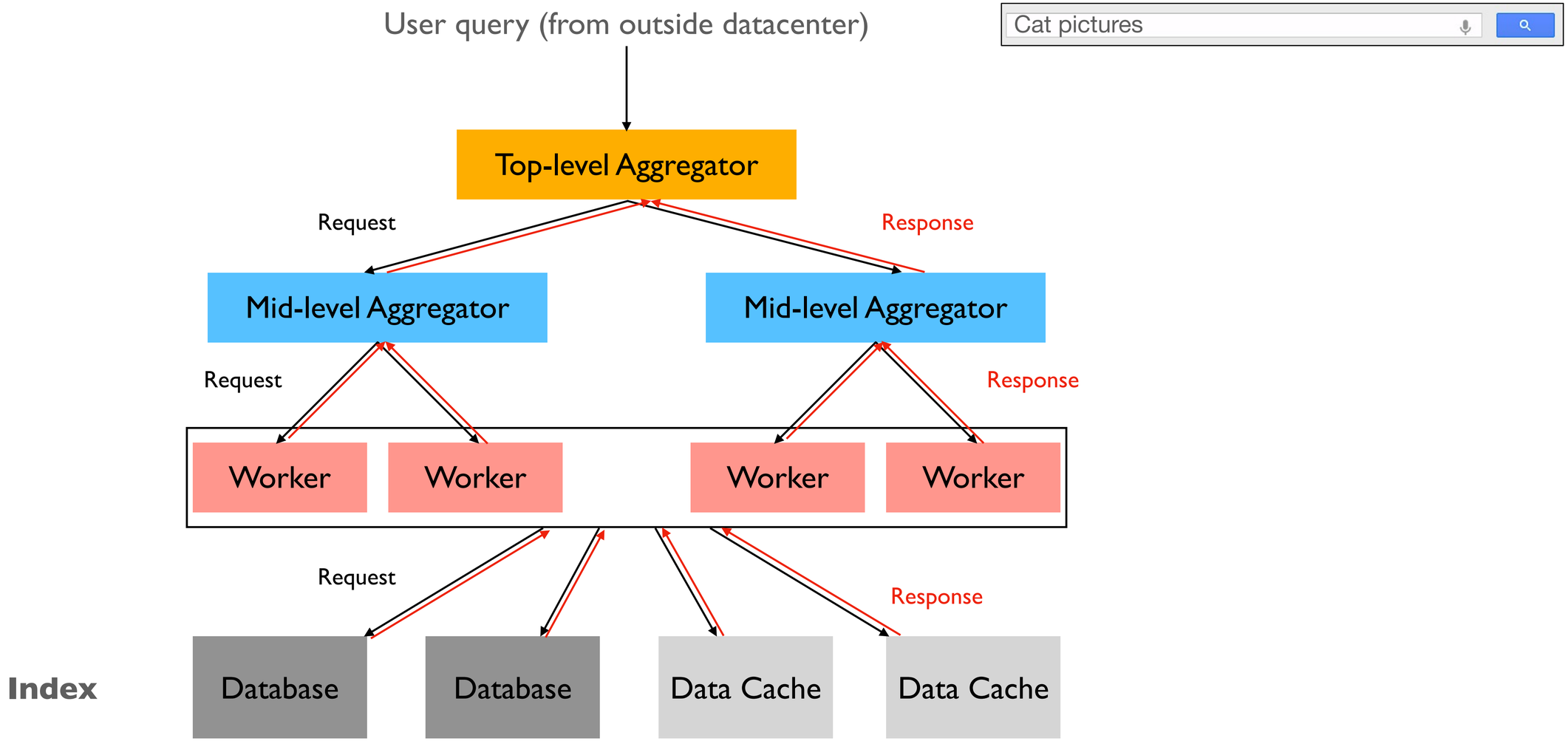

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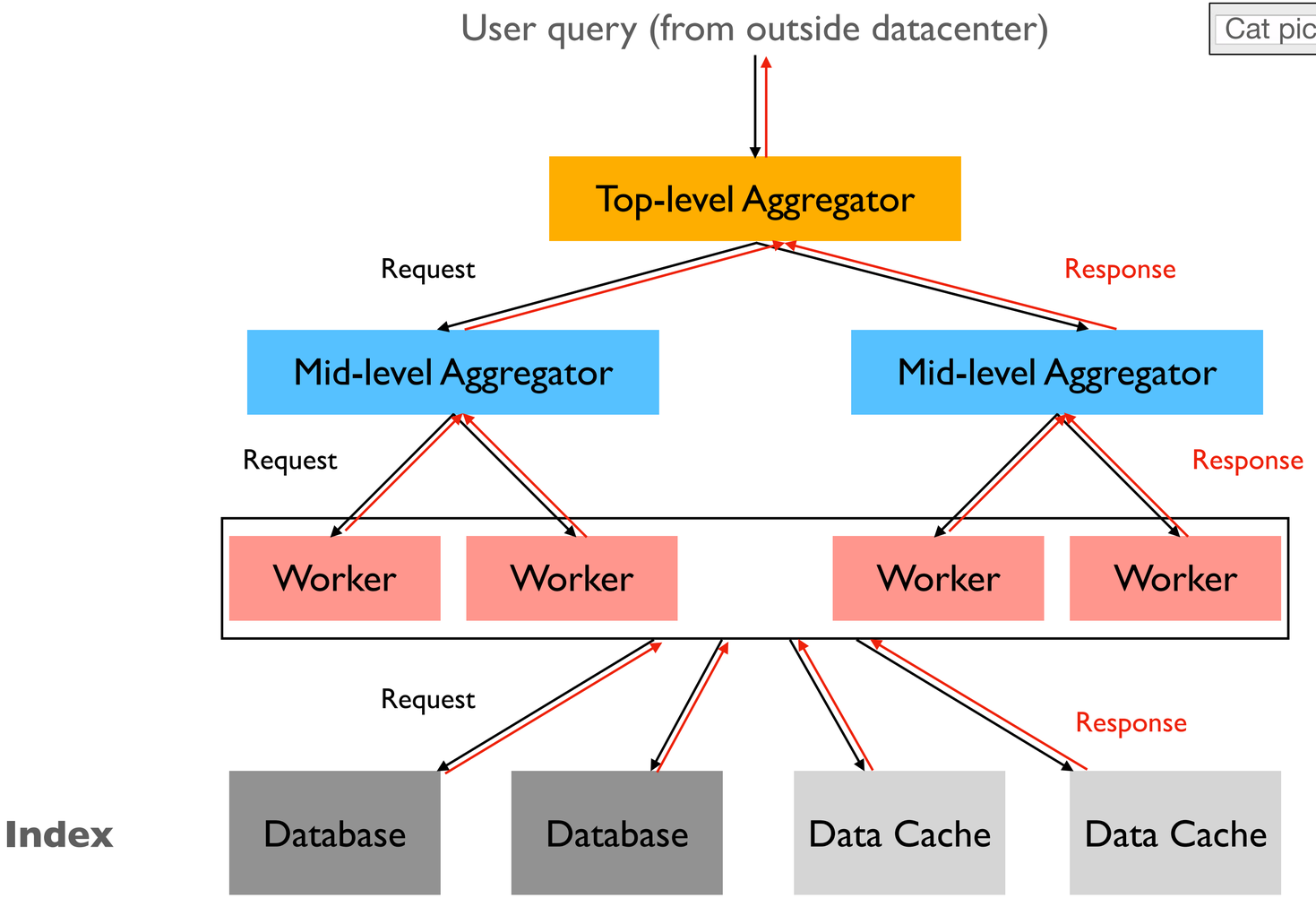
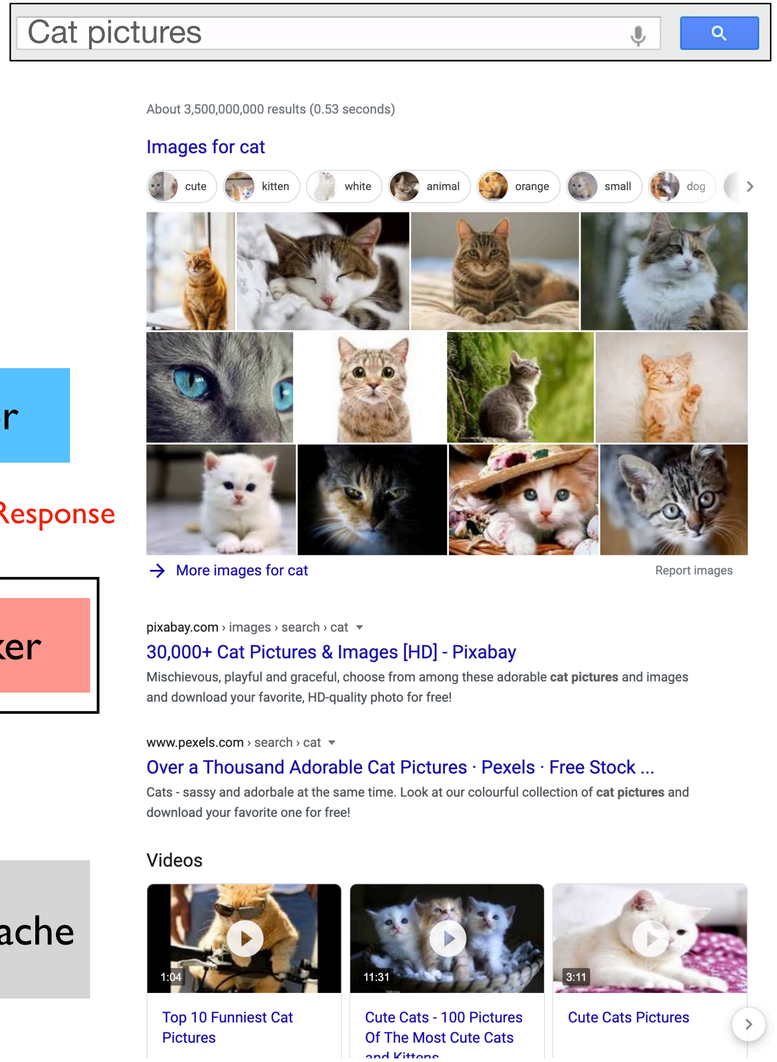
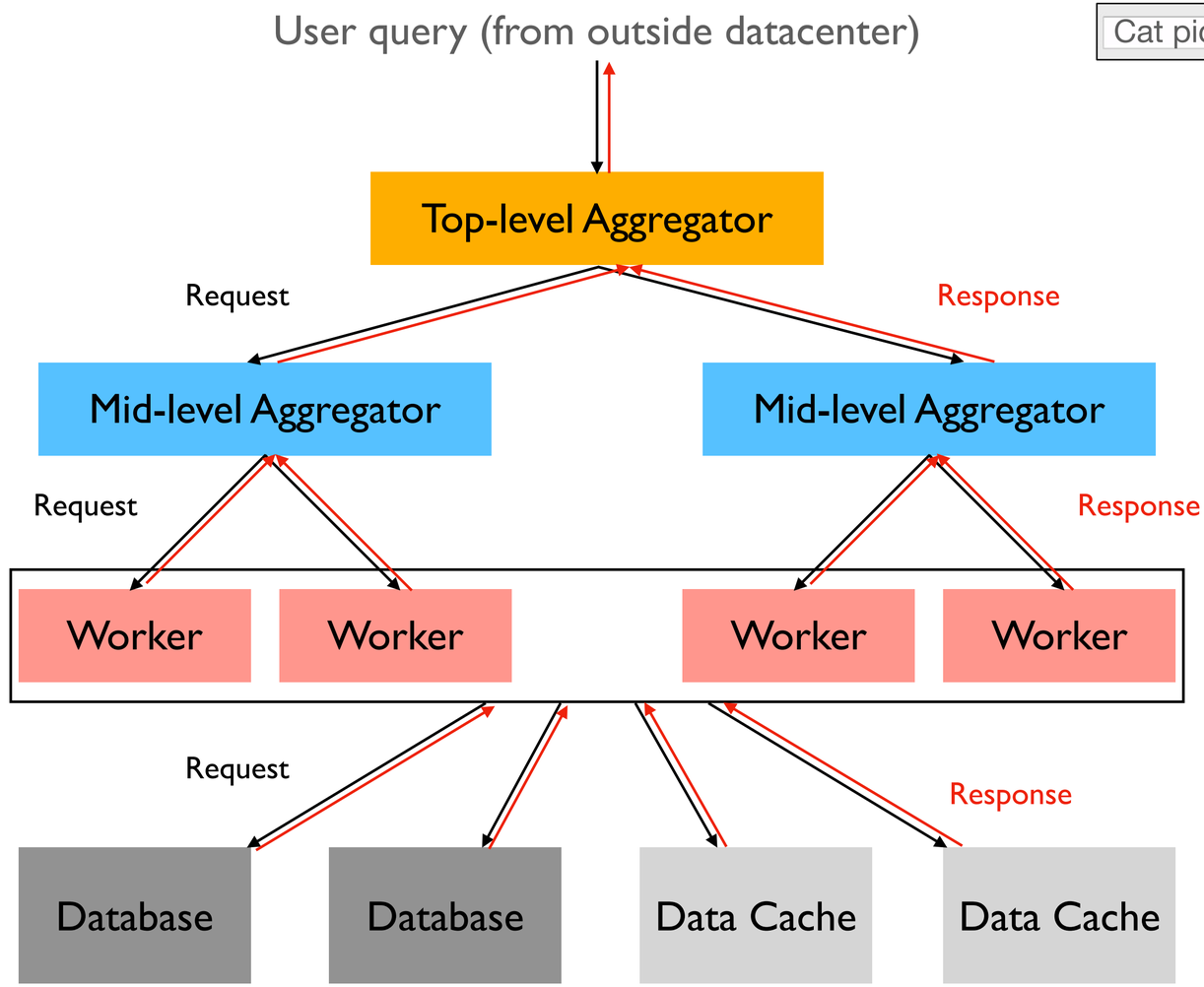
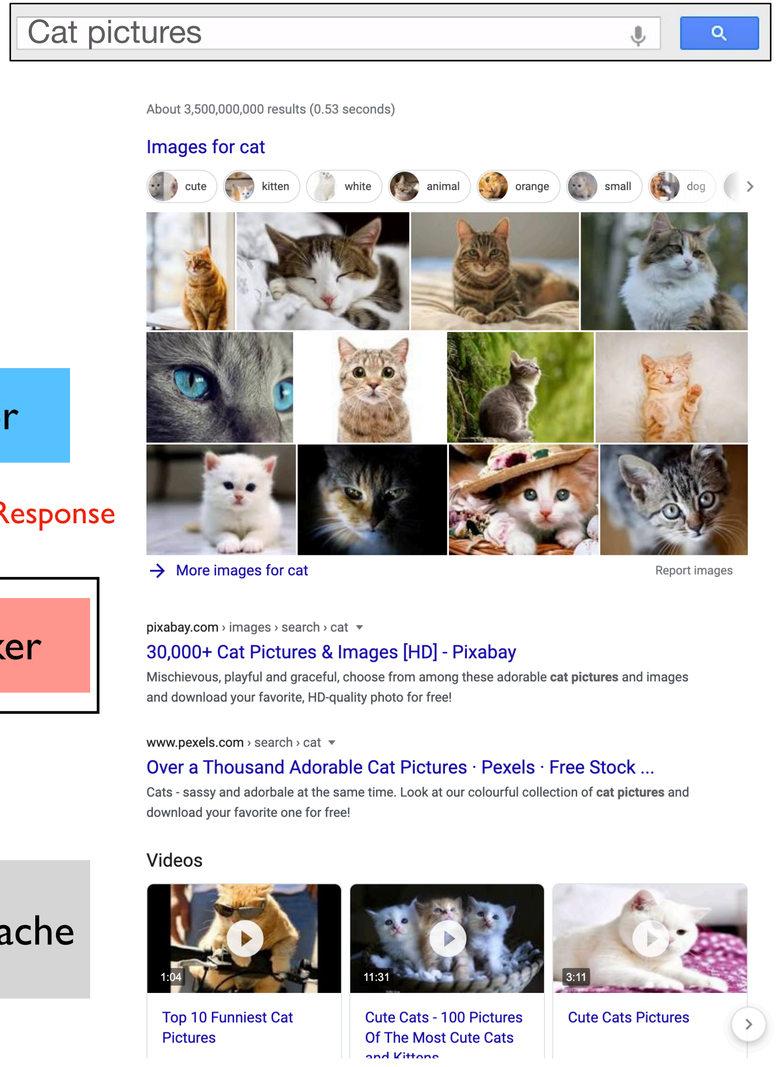




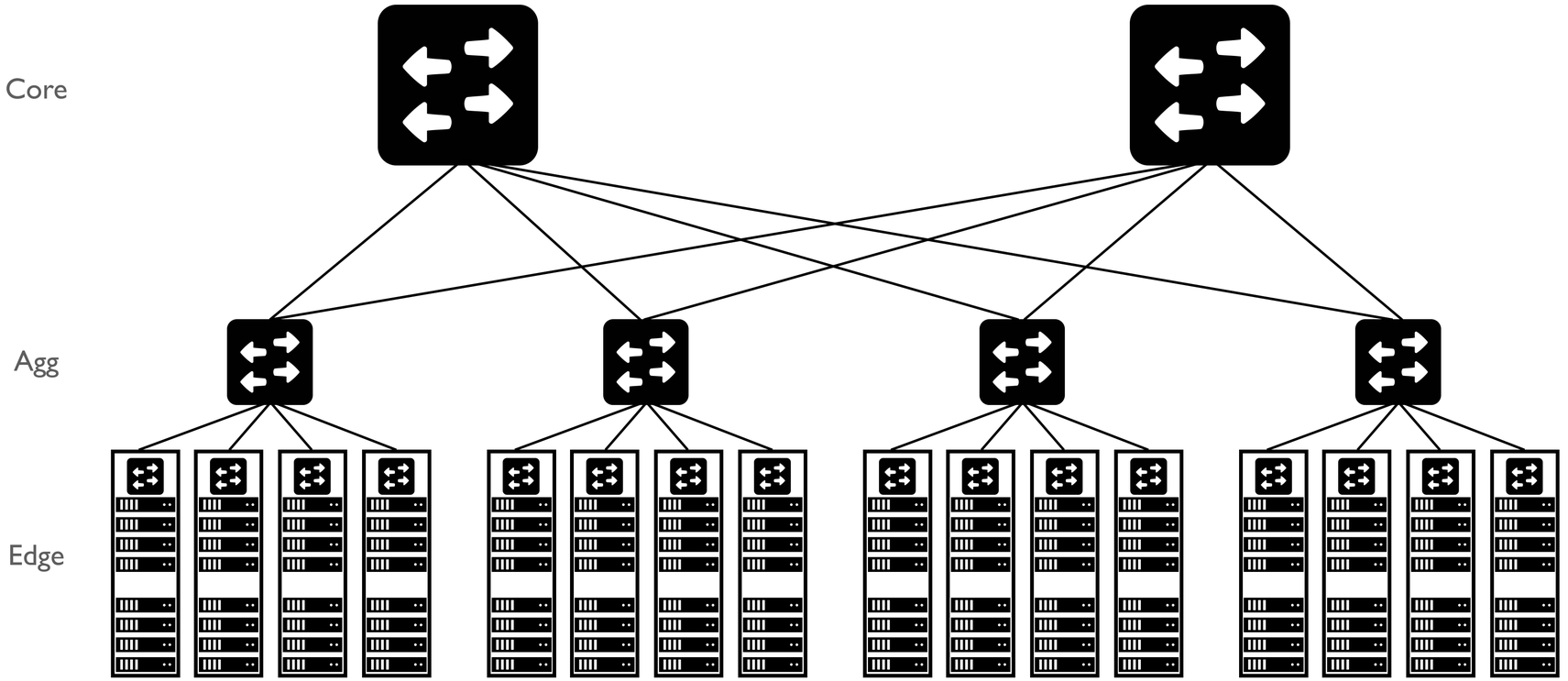
Workload: Partition Aggregate

Most communications over network





“North-South” Traffic



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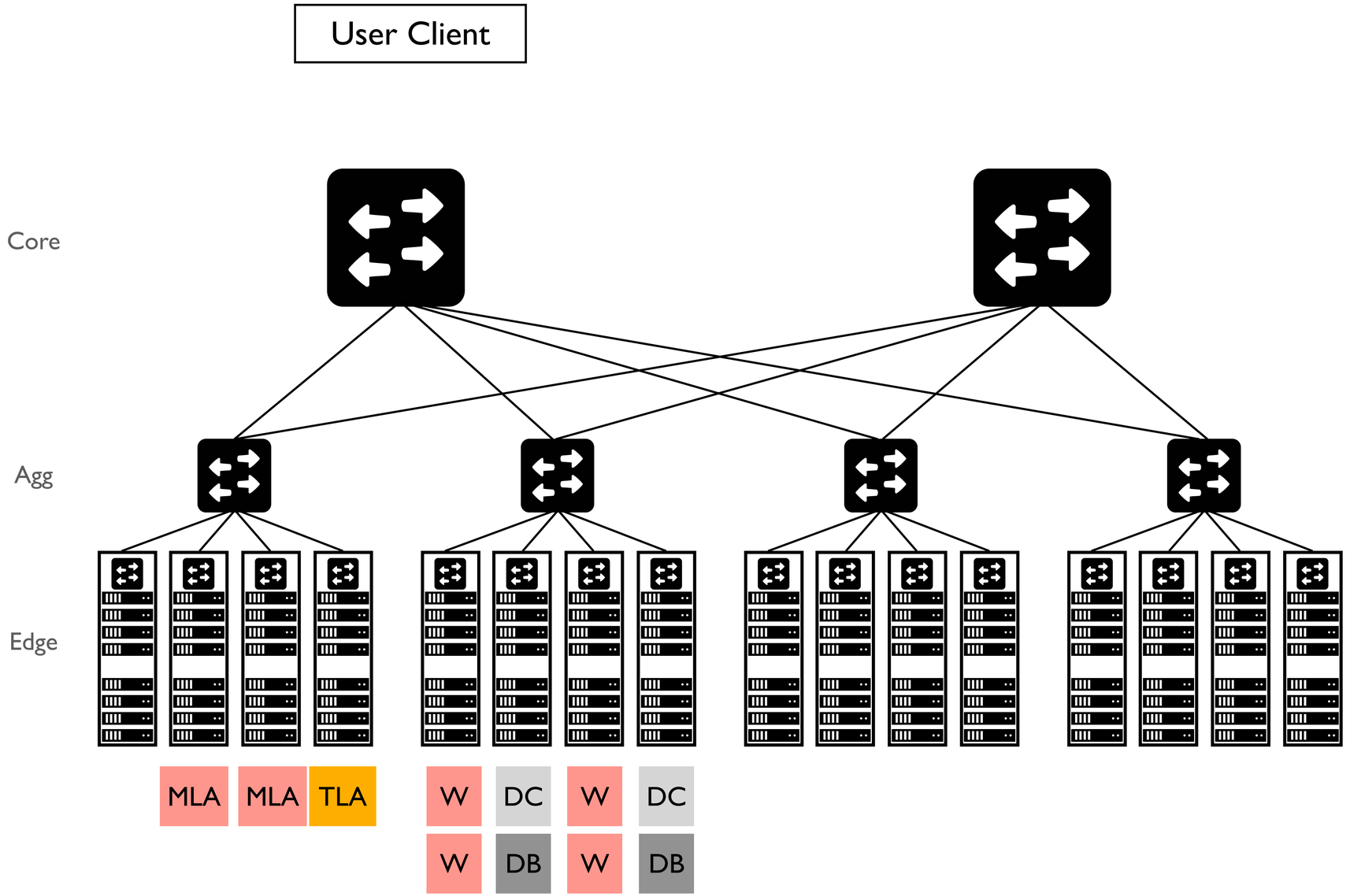

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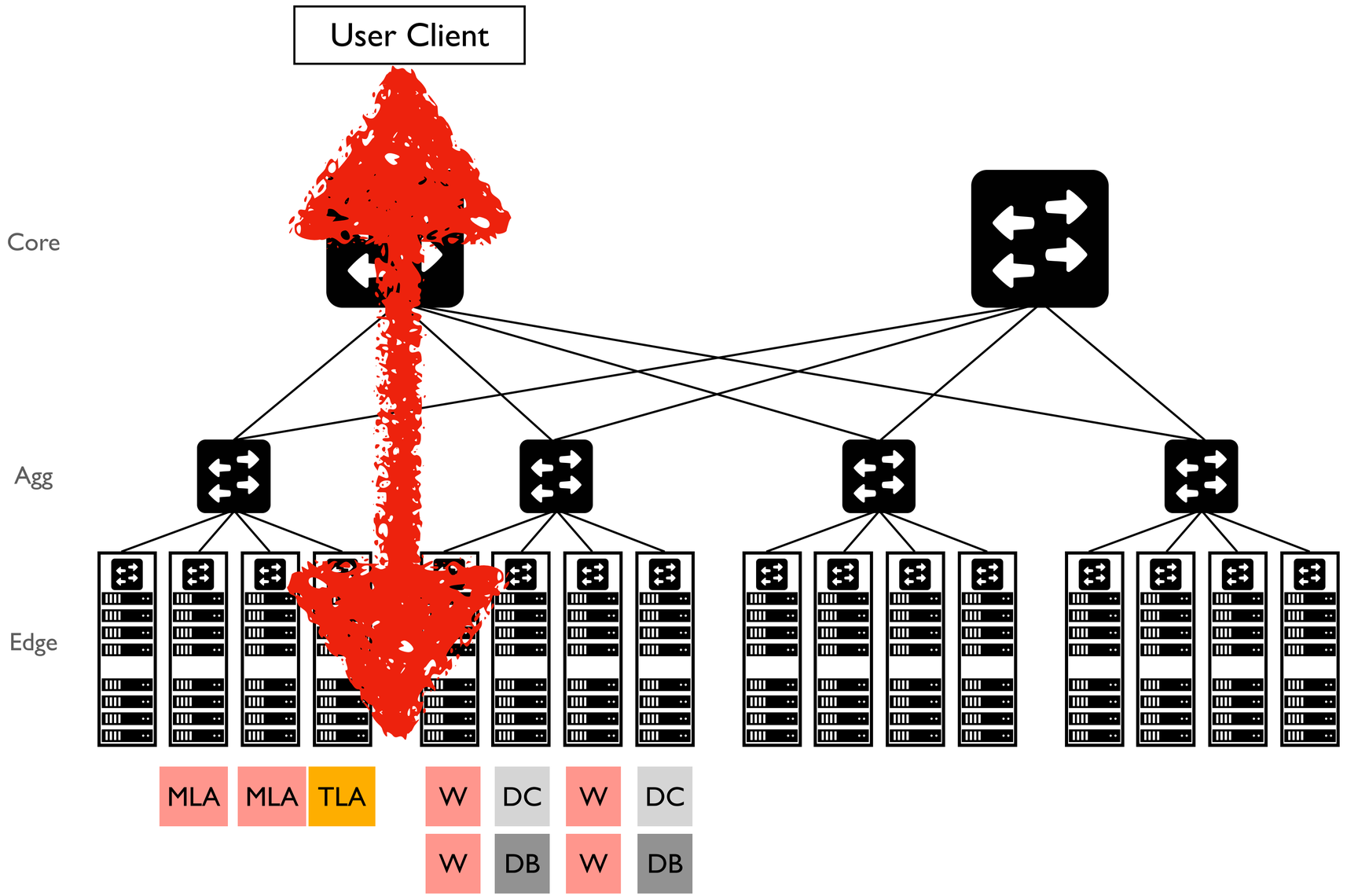

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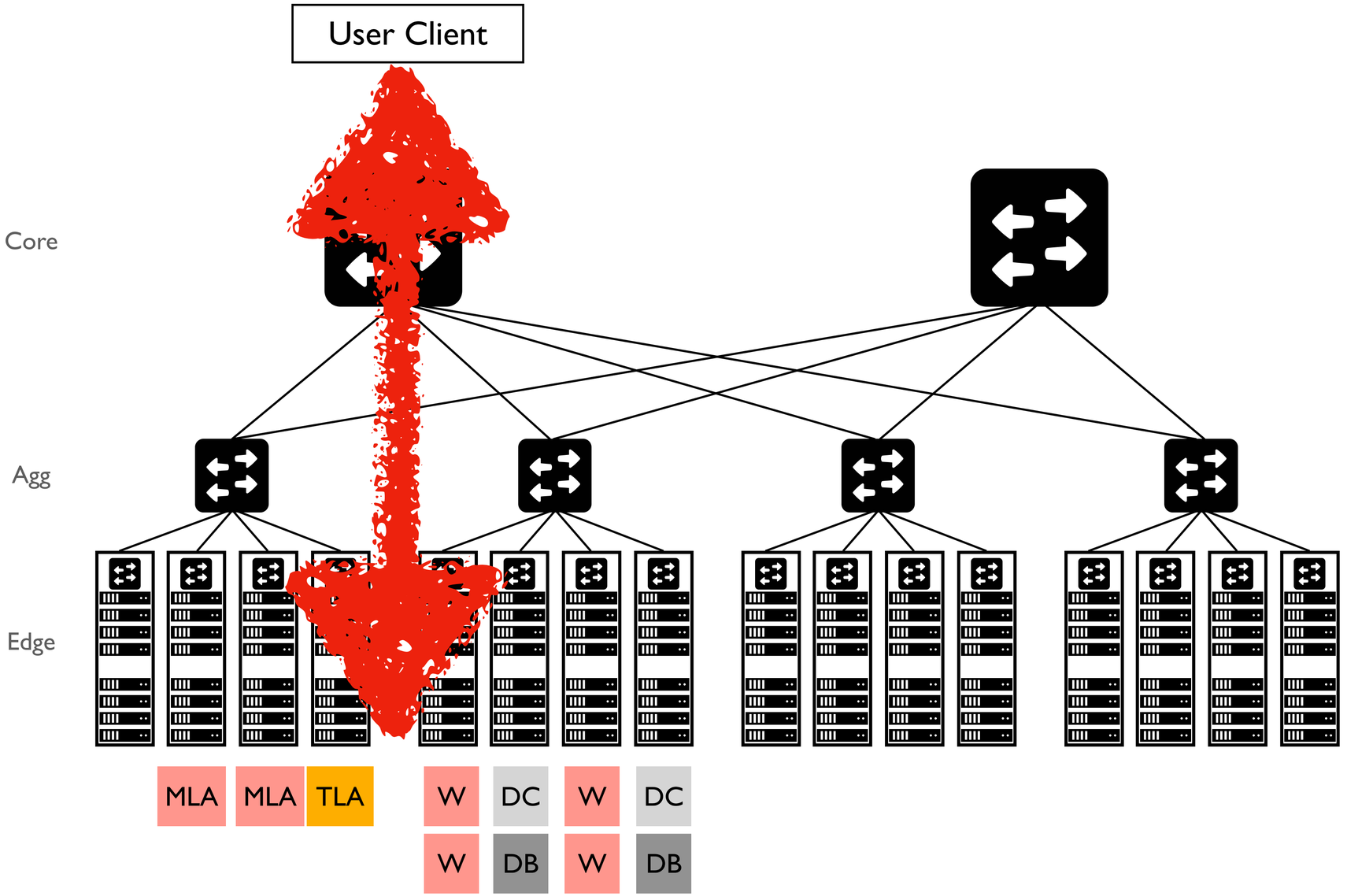

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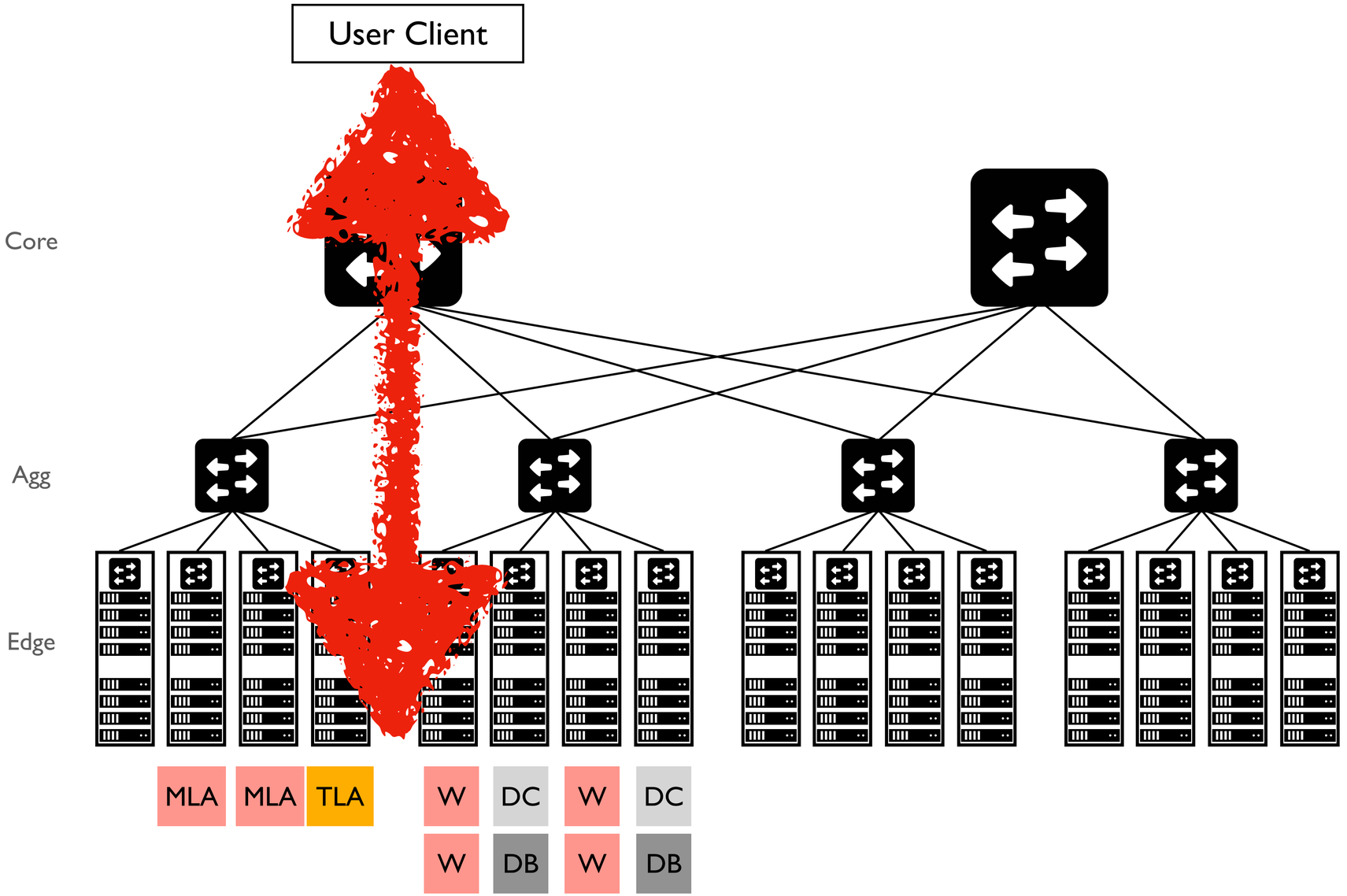

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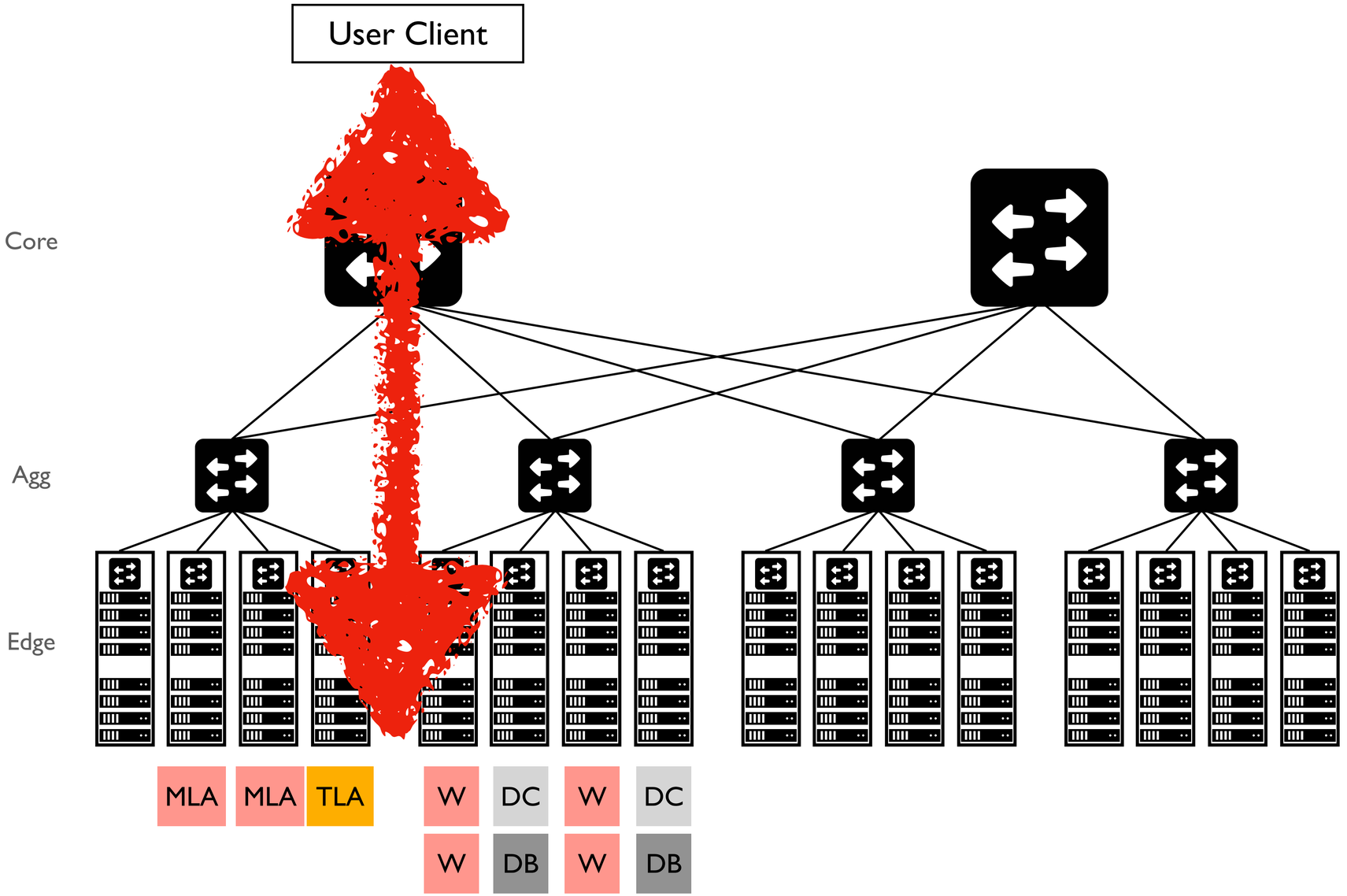

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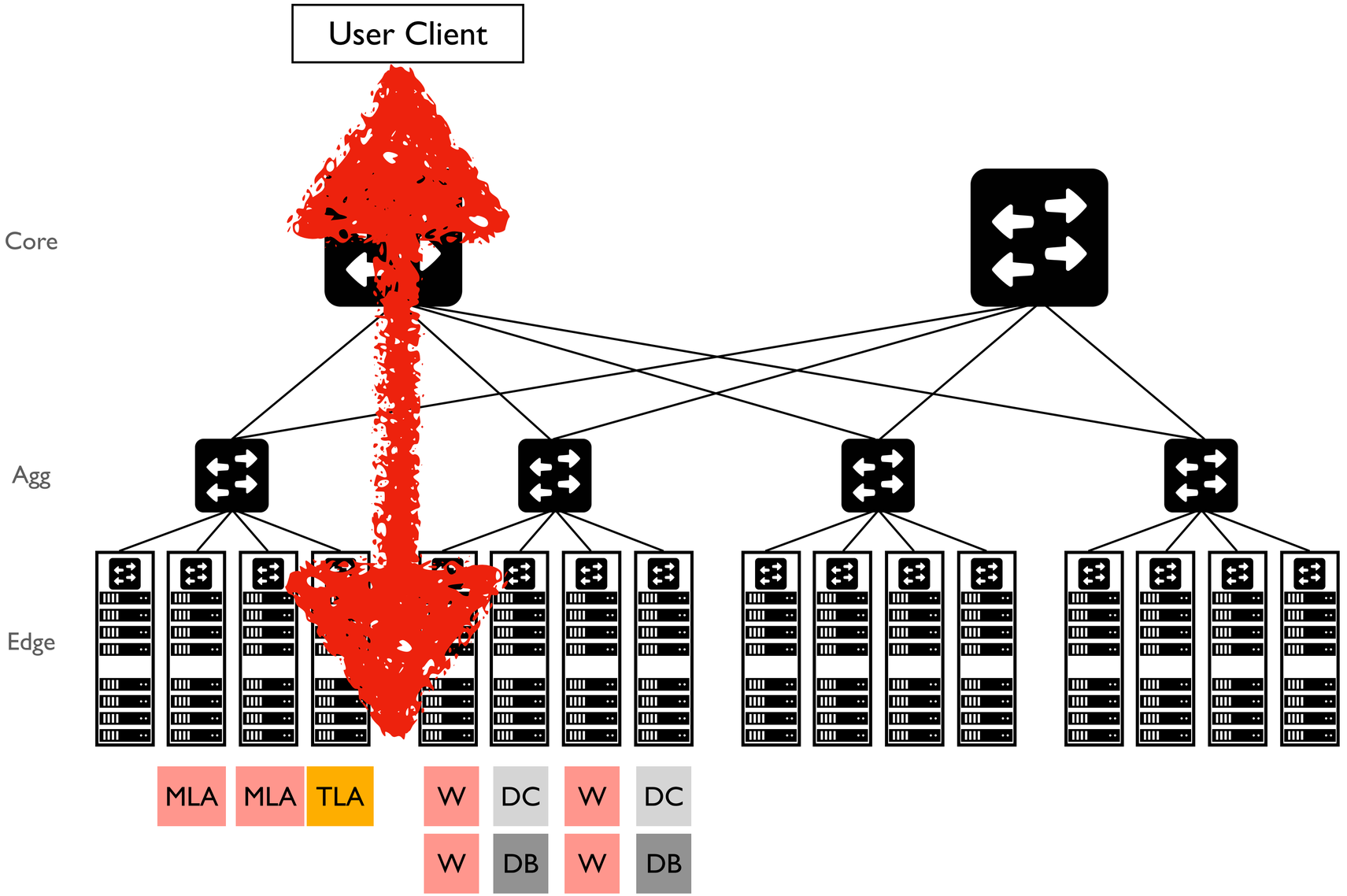

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- Handled by worker/aggregator tasks, databases & caches

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Distributed Storage

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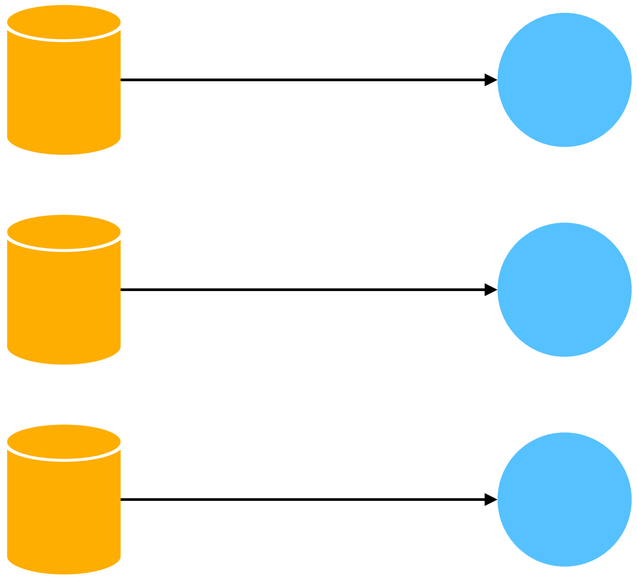
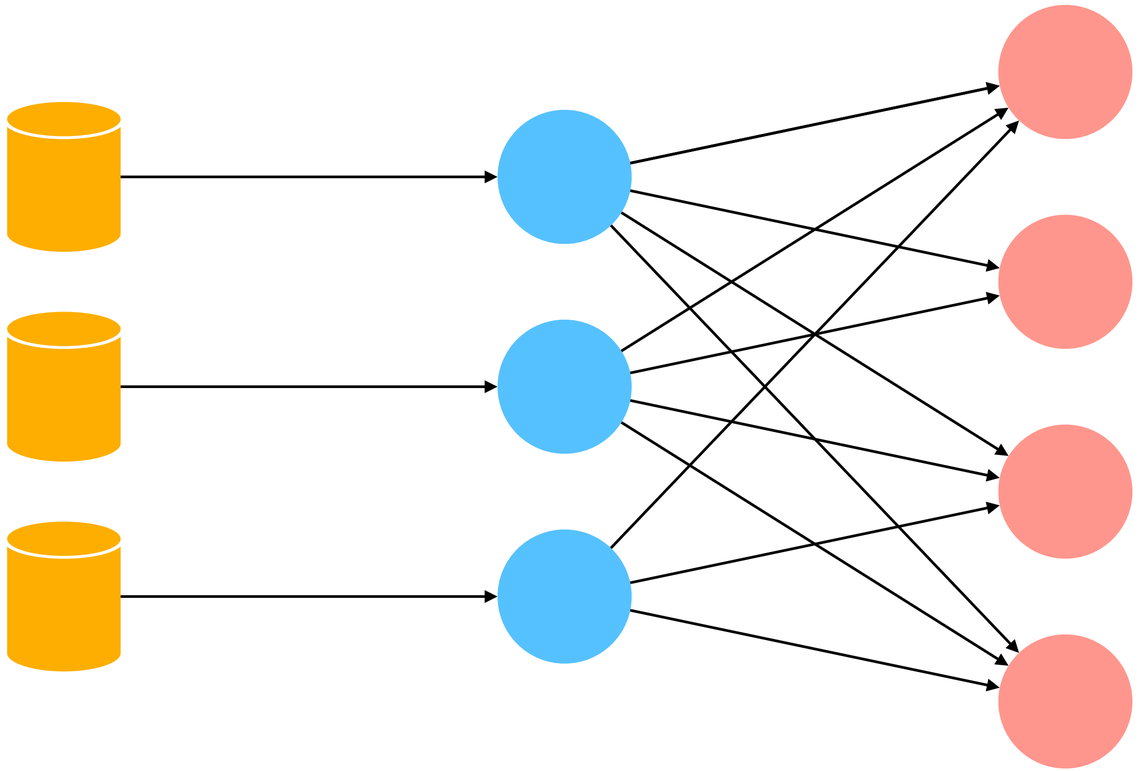


Distributed Storage

Map Tasks

Workload: Map Reduce



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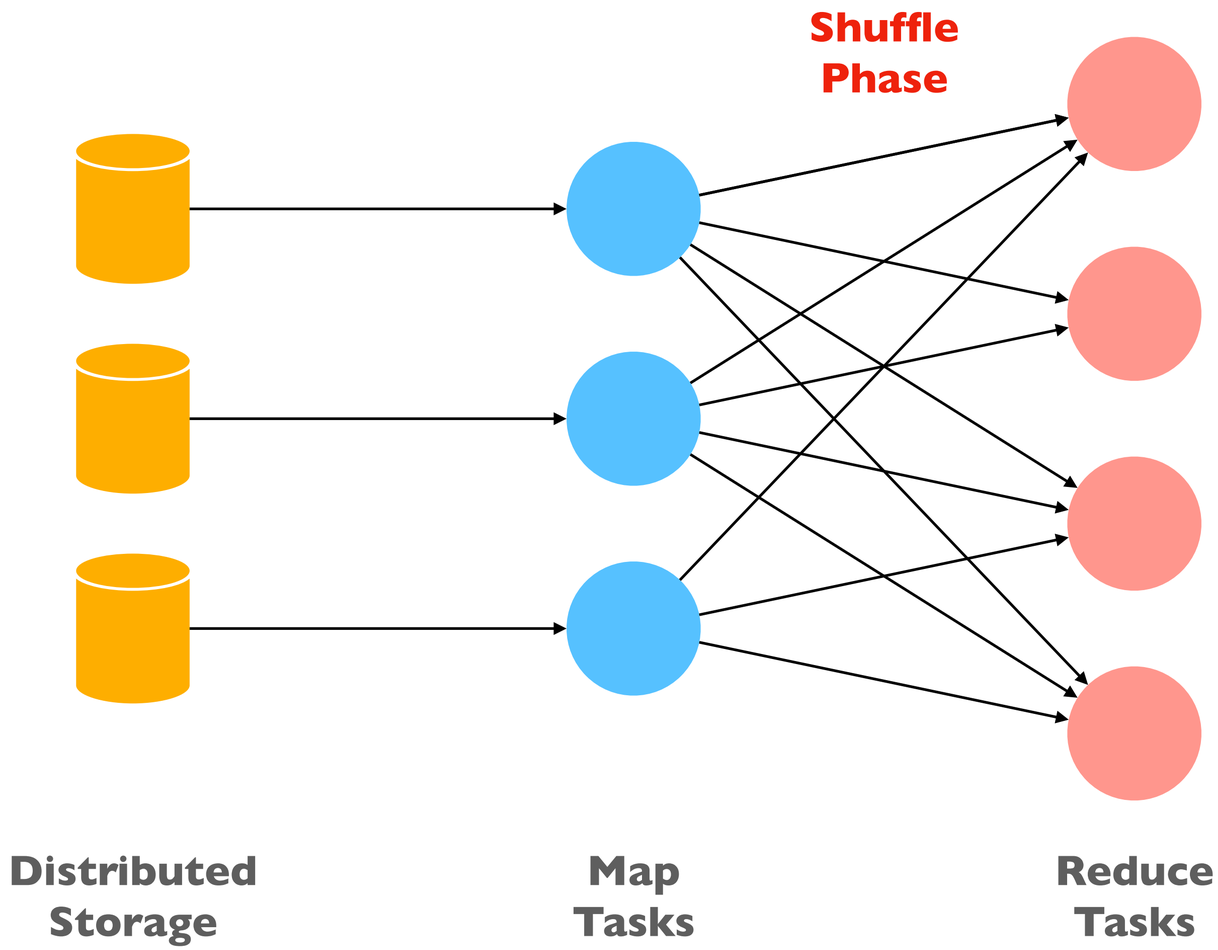

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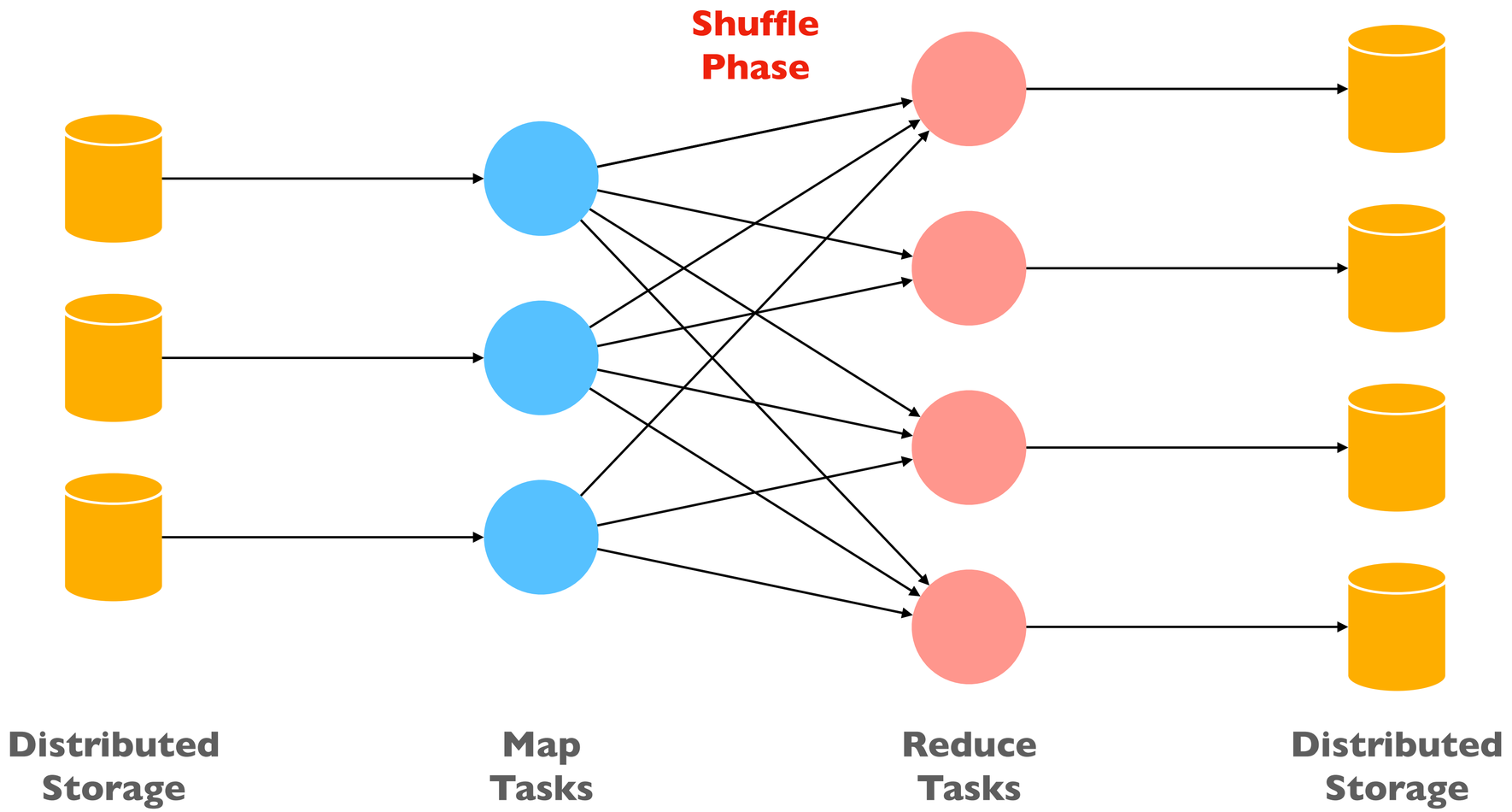

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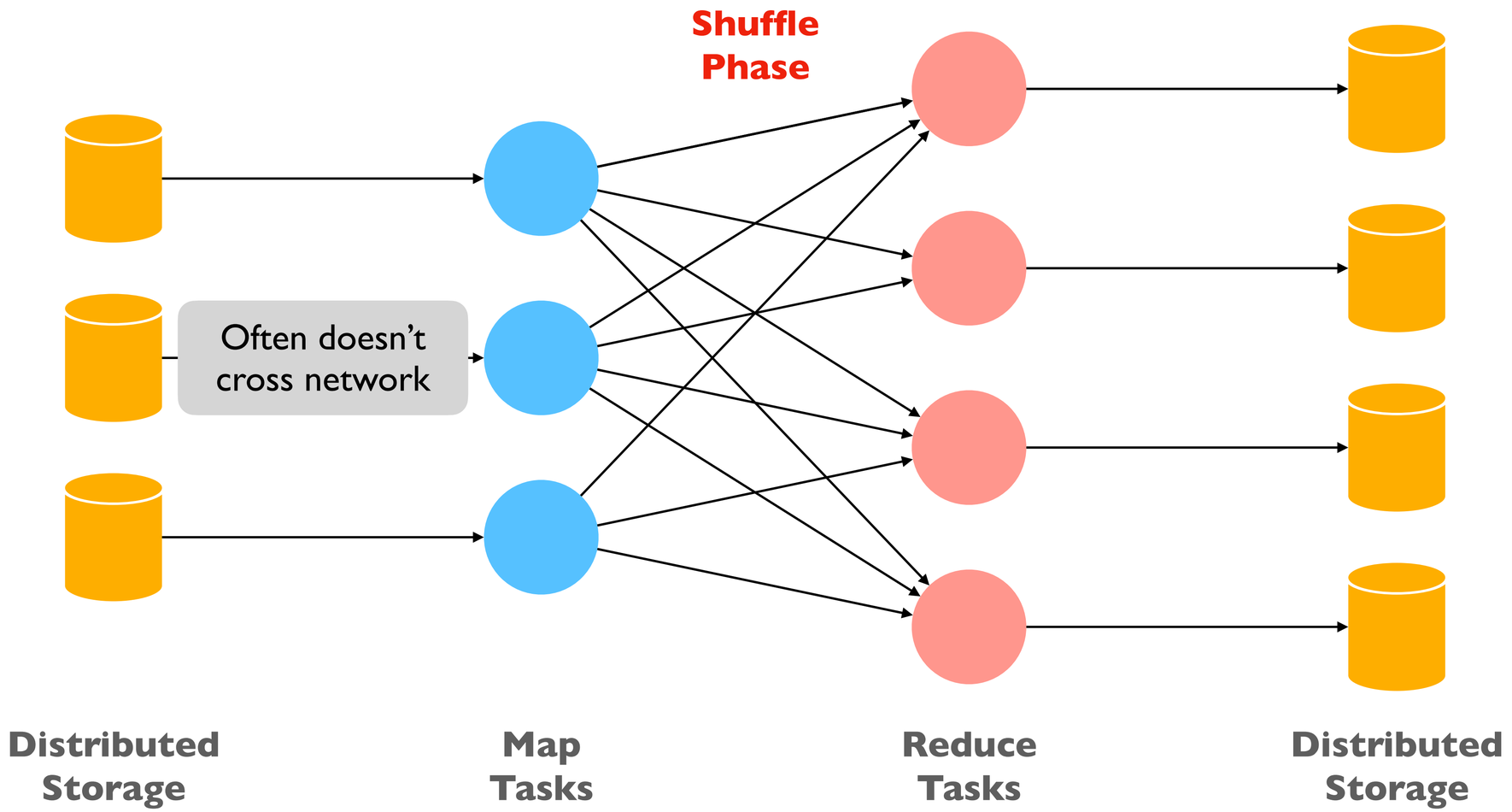

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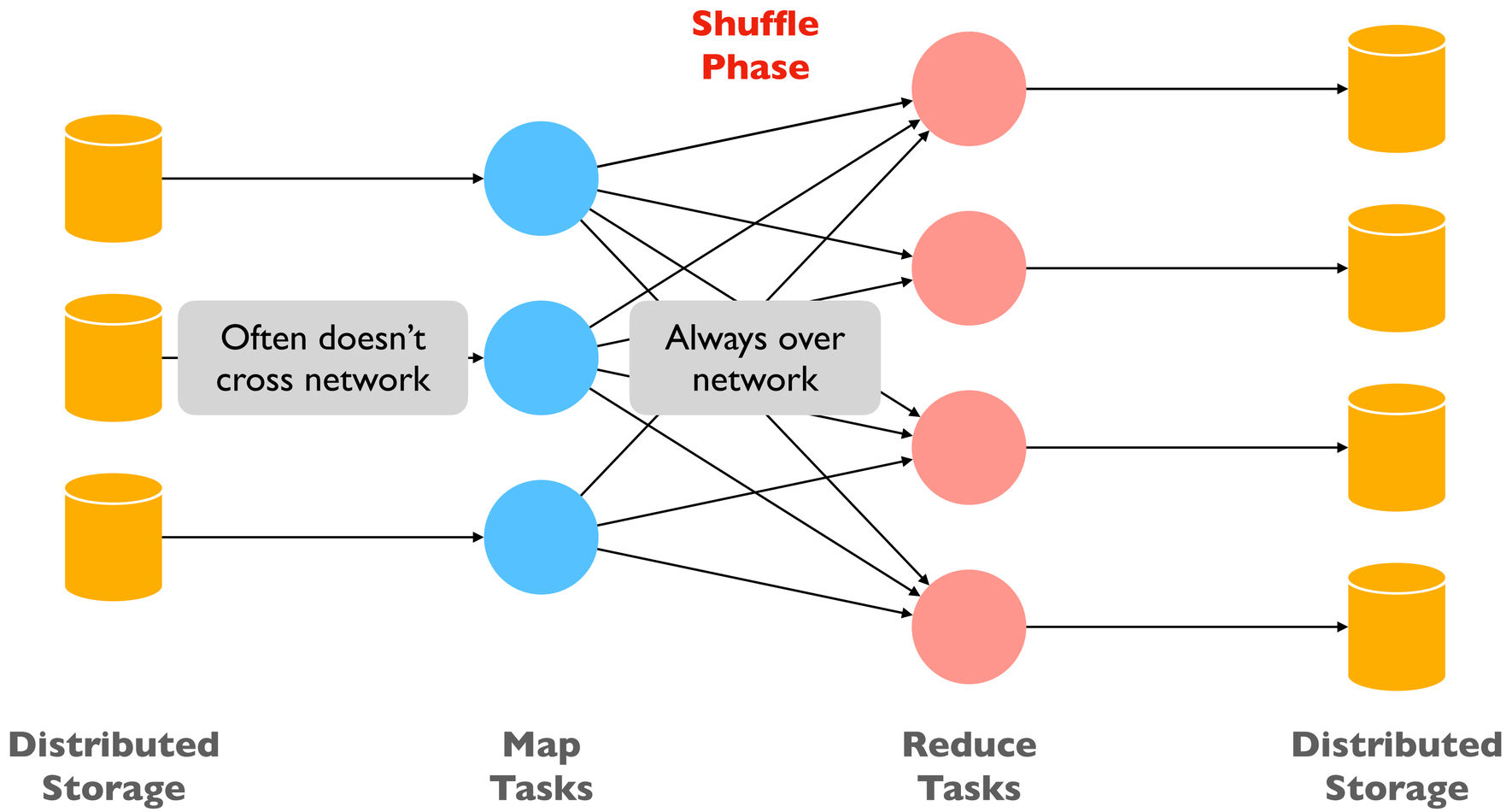

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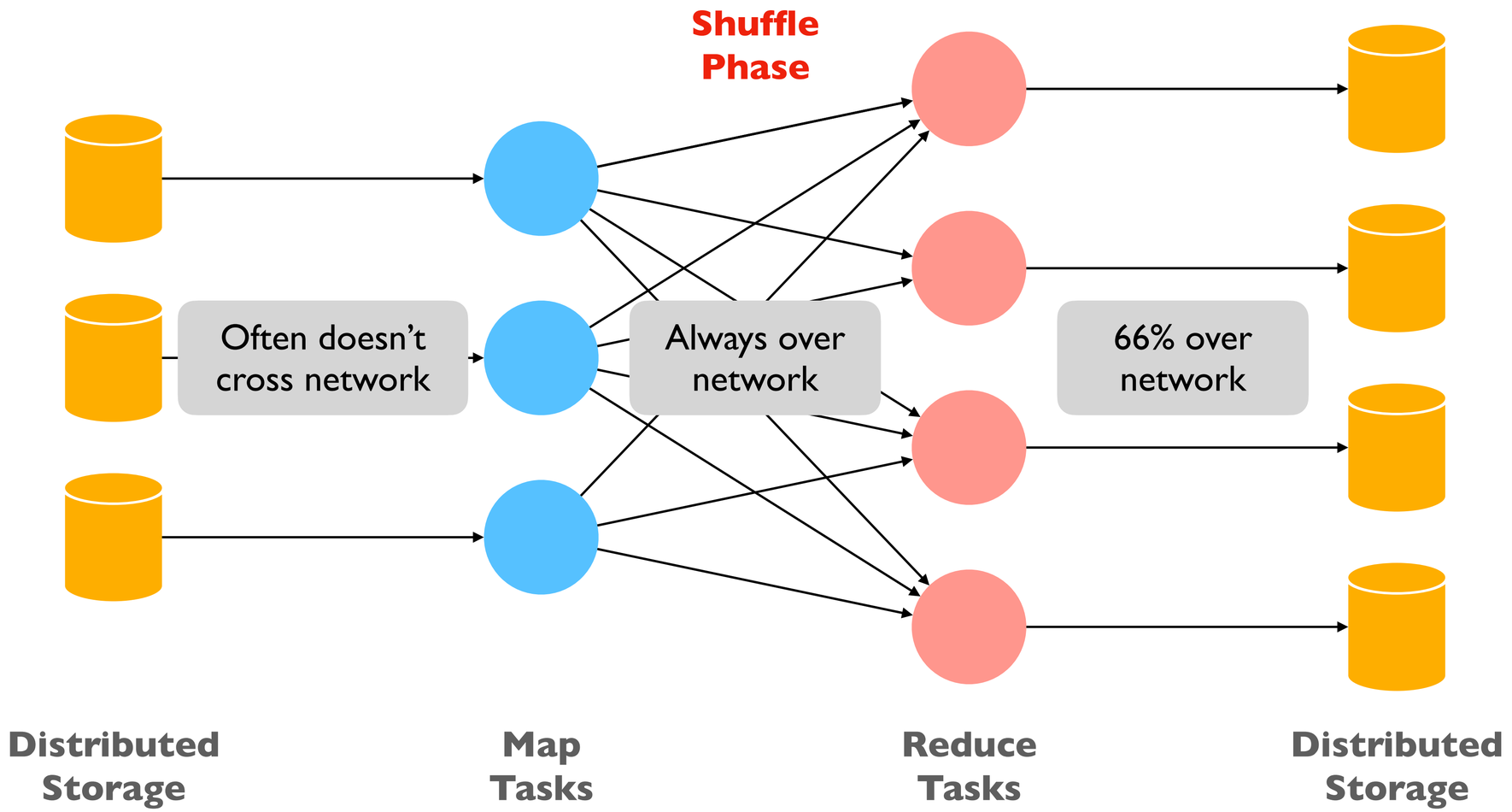
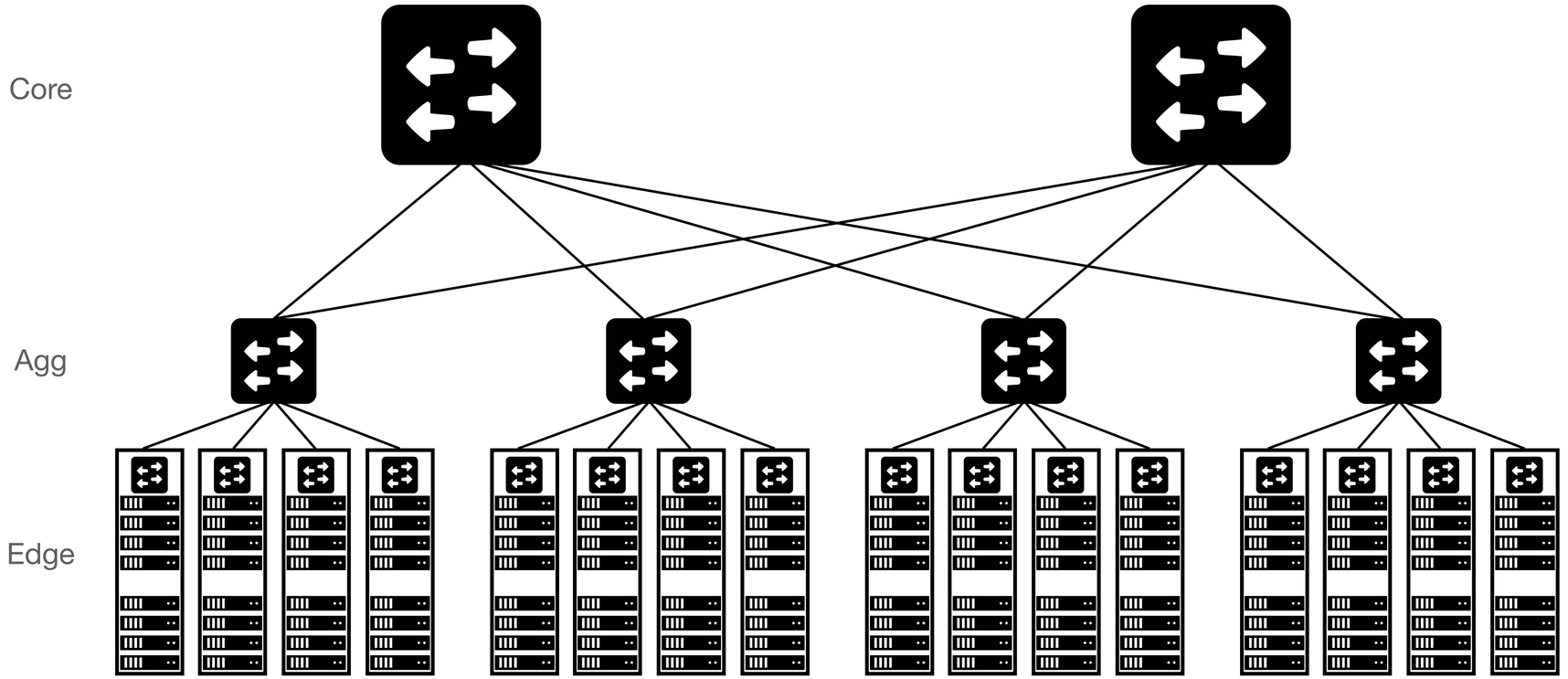


“East-west” Traffic



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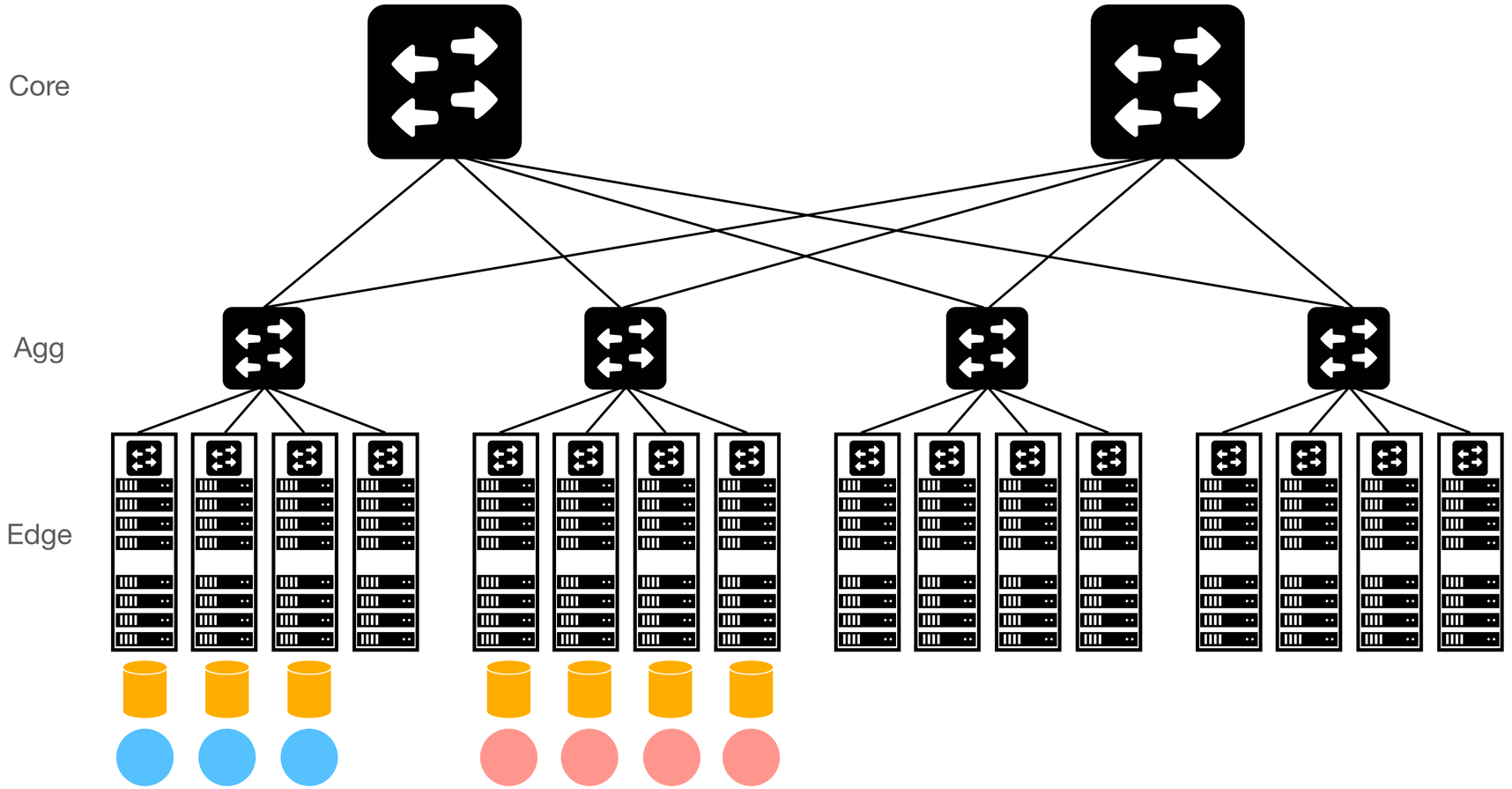

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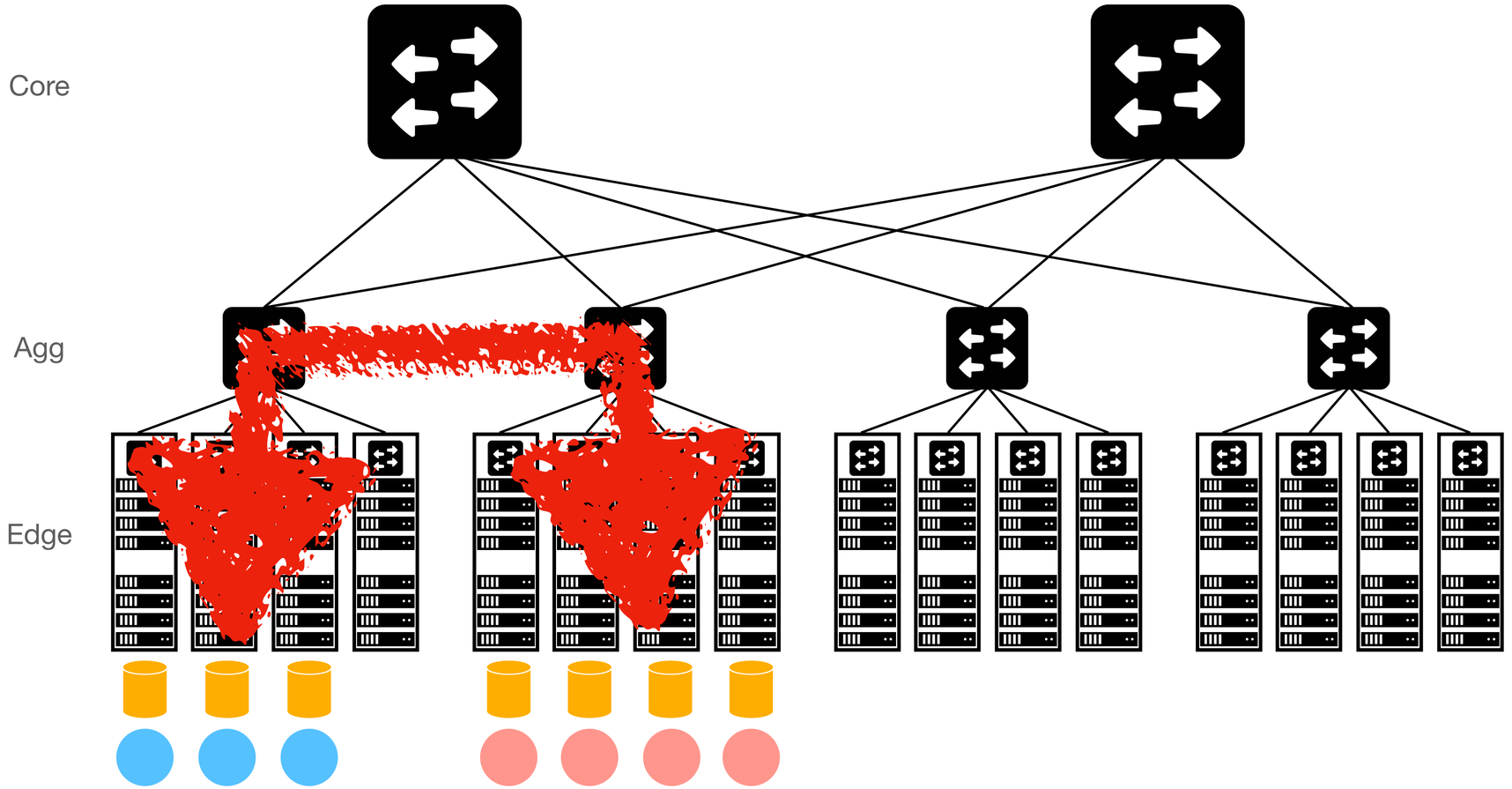

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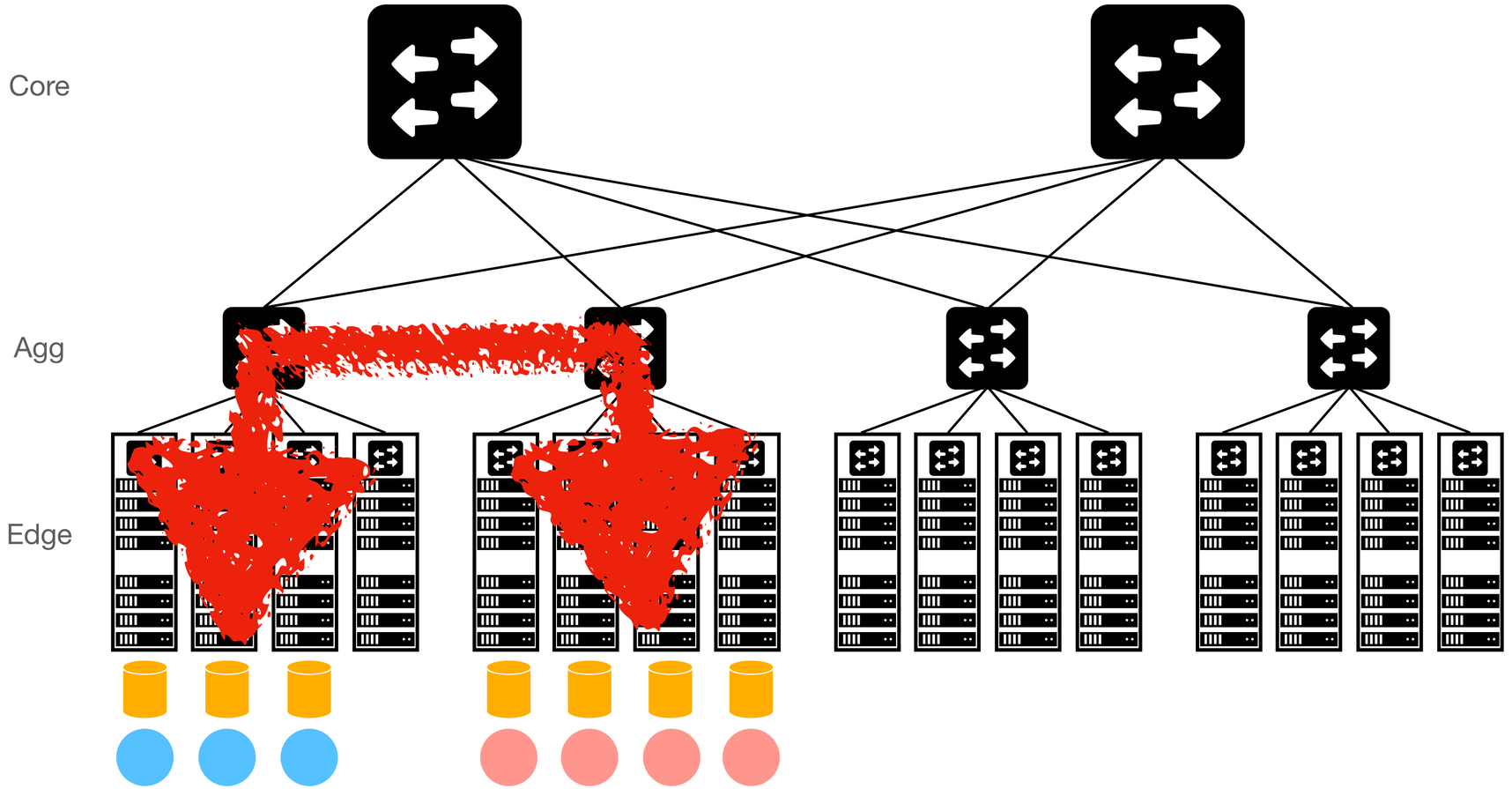

- Traffic between servers in the datacenter

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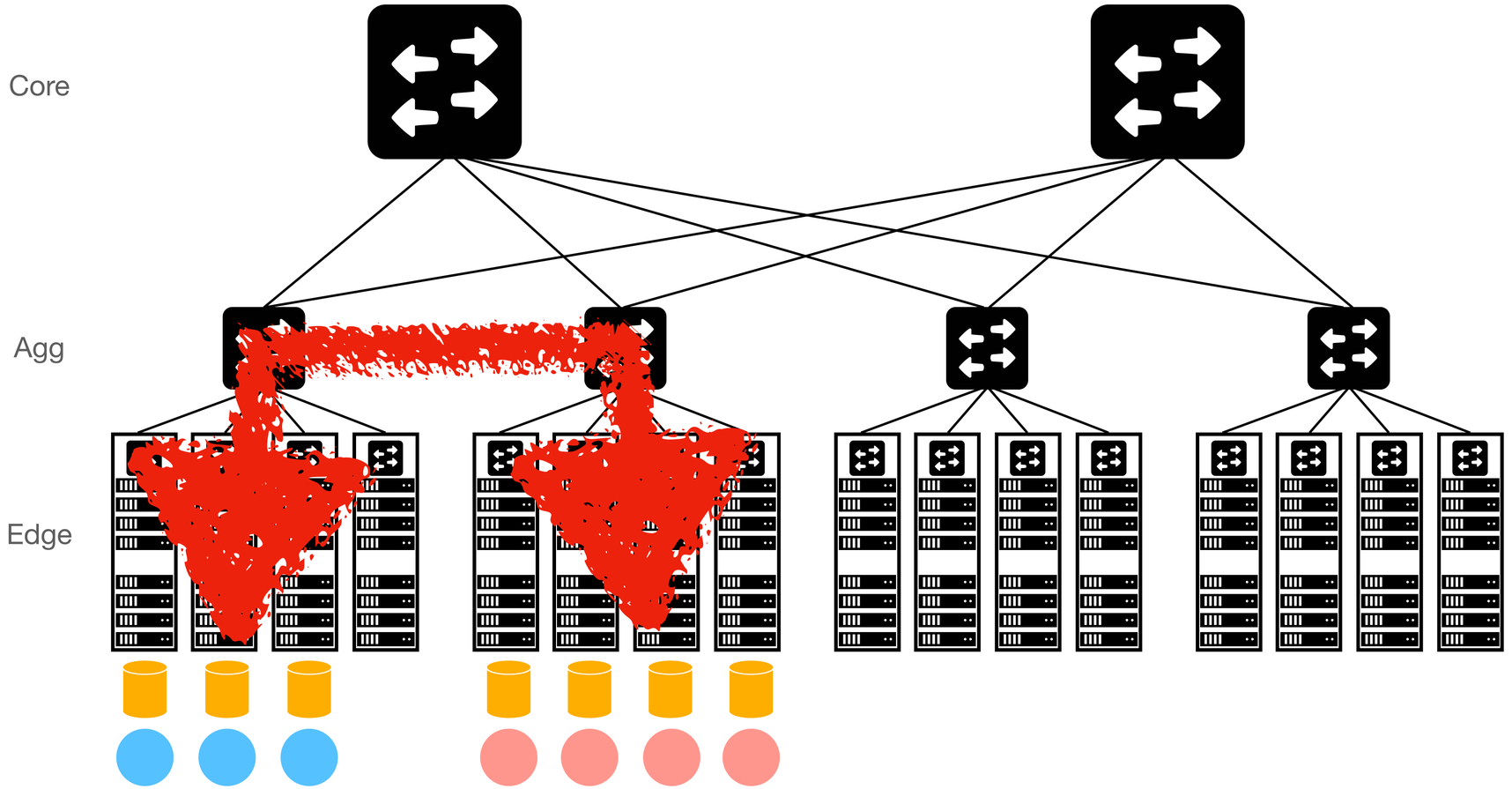

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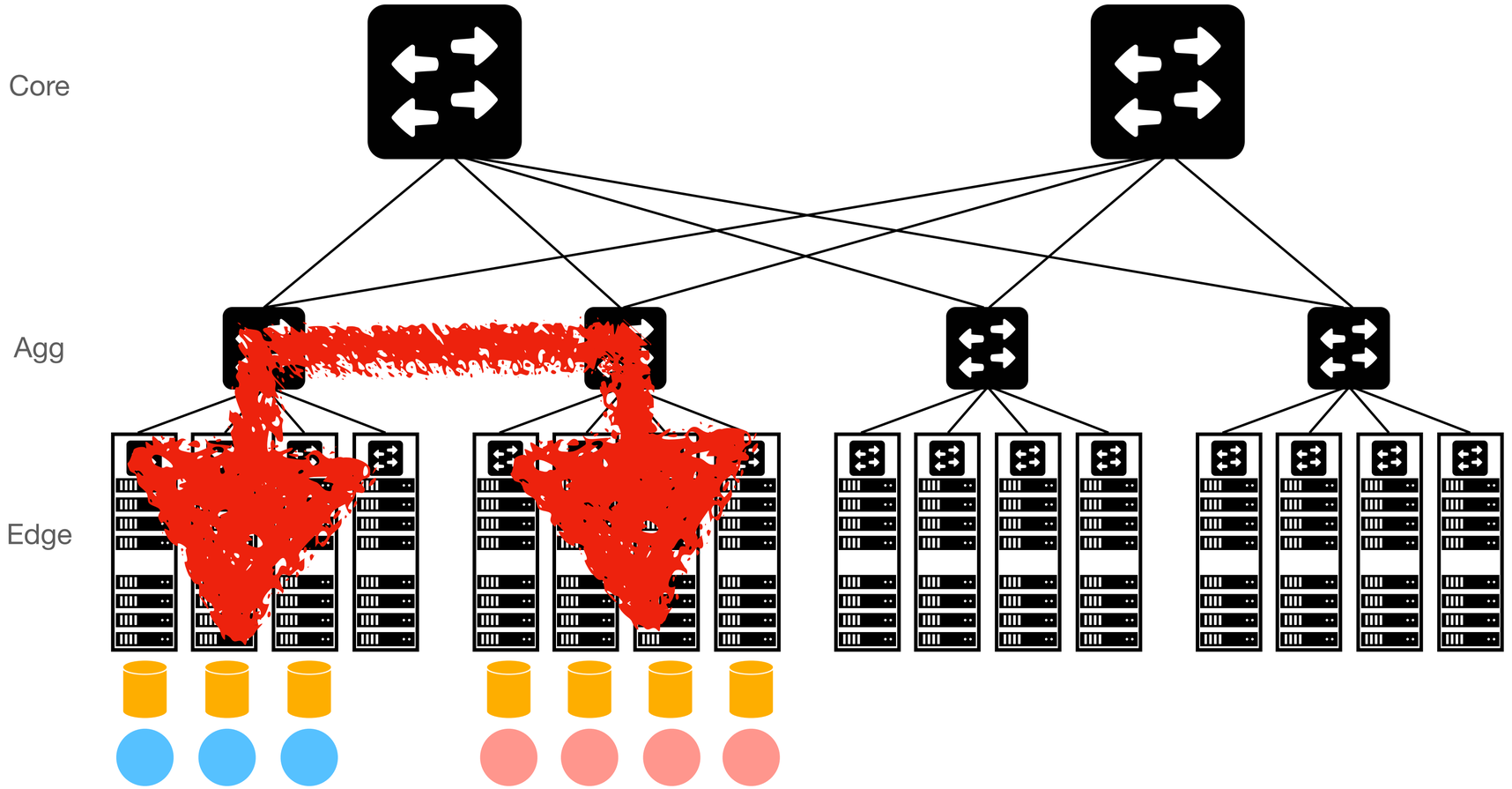

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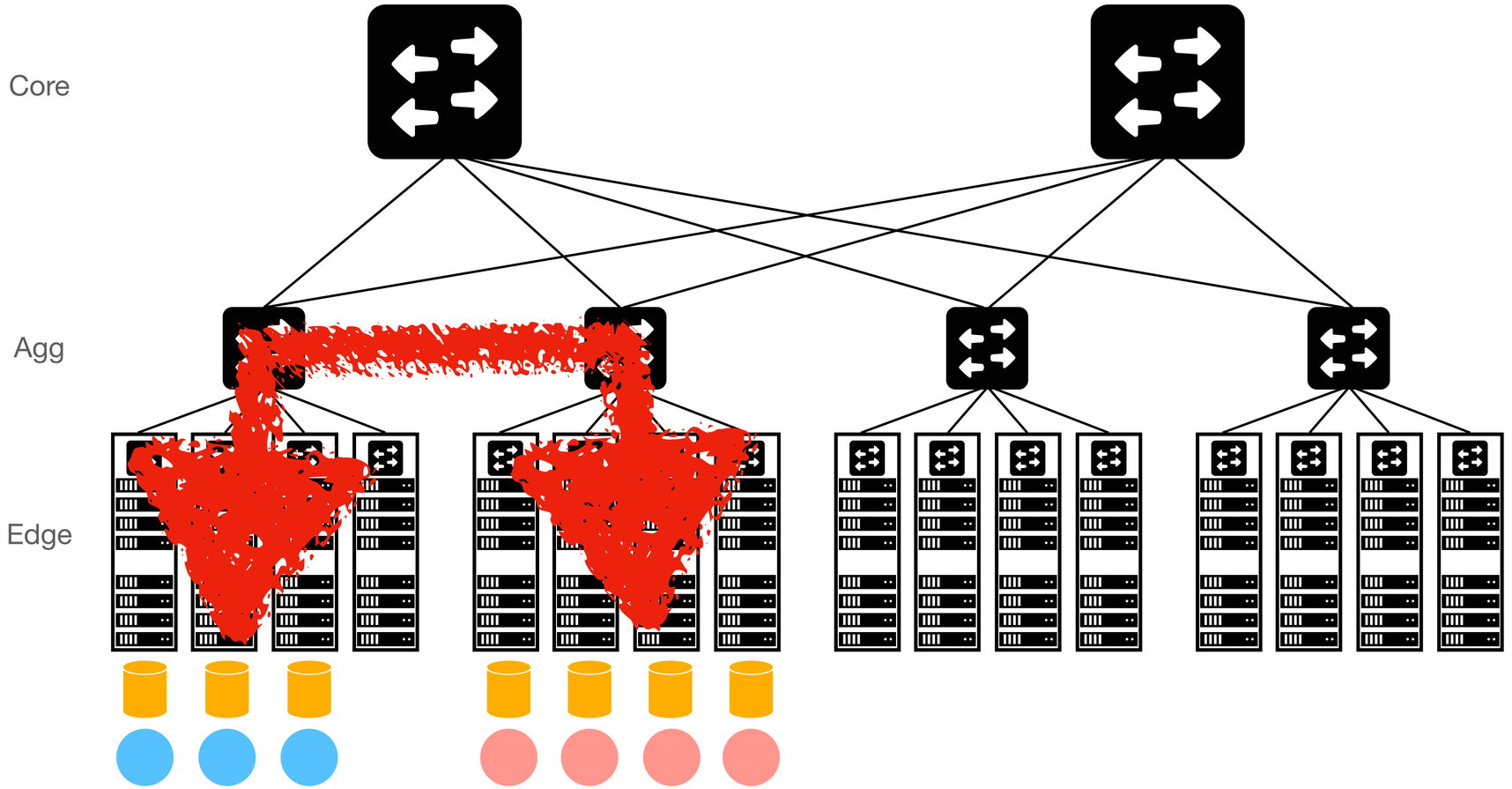

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- Handled by map/reduce tasks, distributed filesystem

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  - Web-search (north-south), data mining (east-west)

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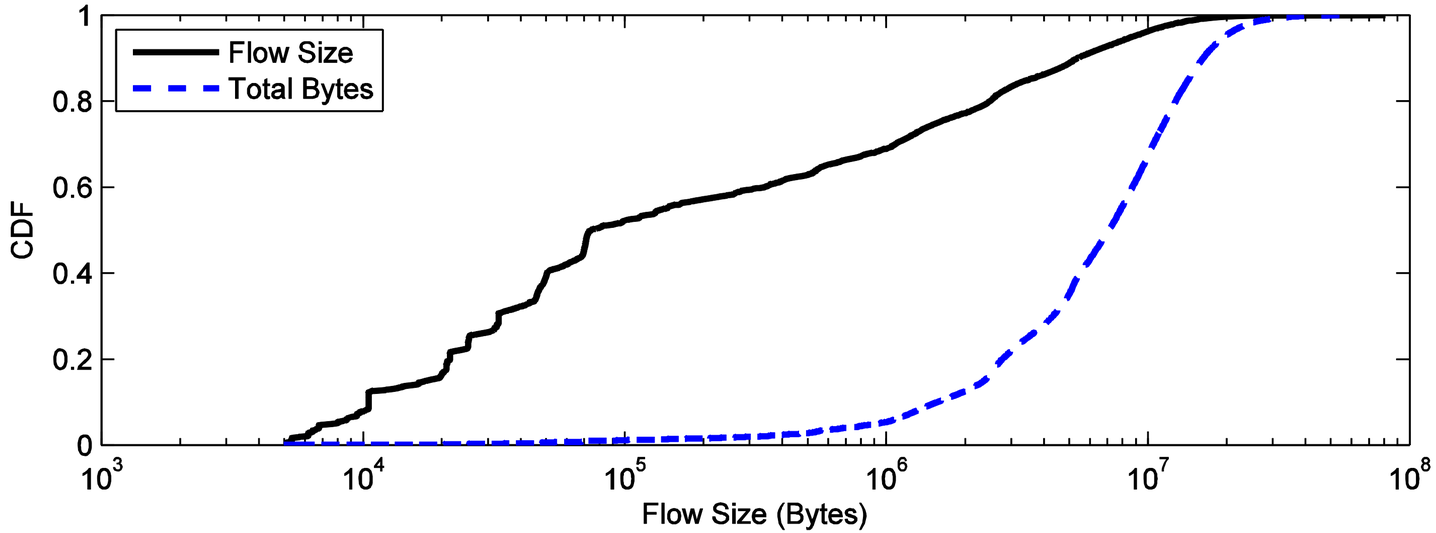

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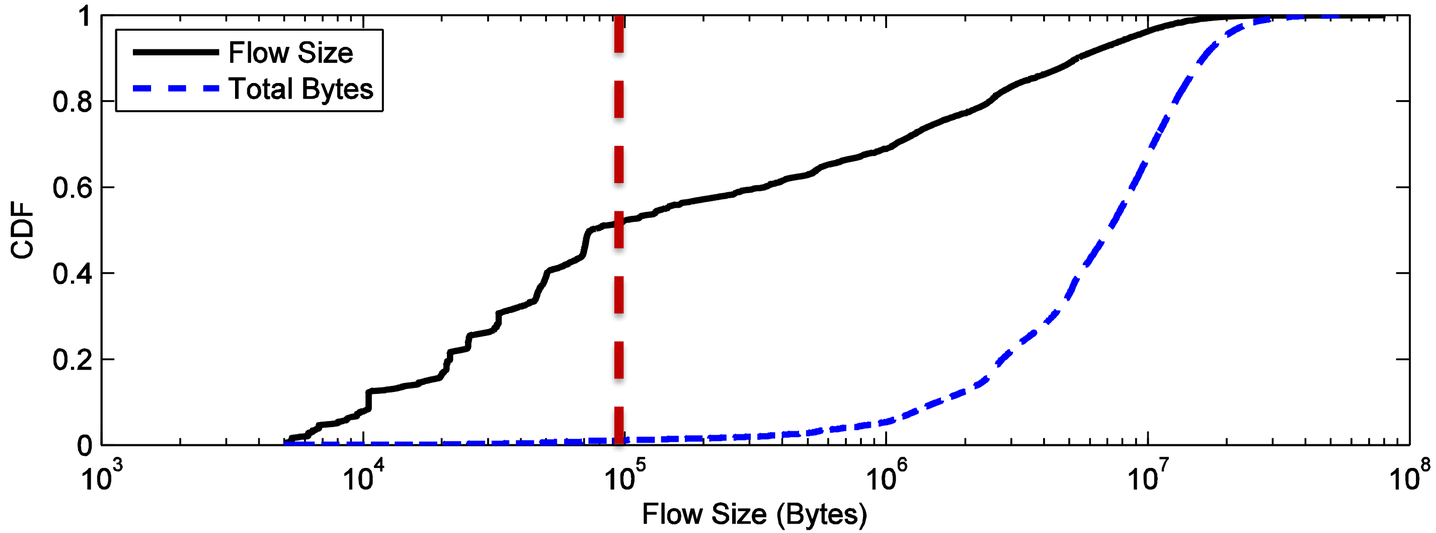

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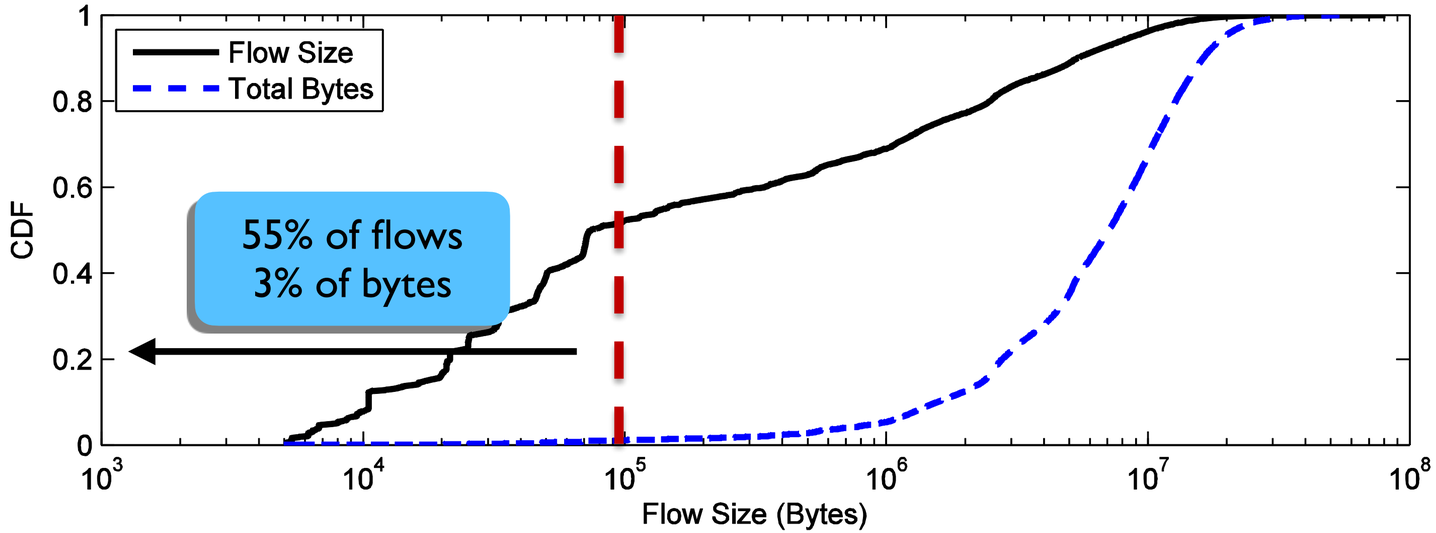

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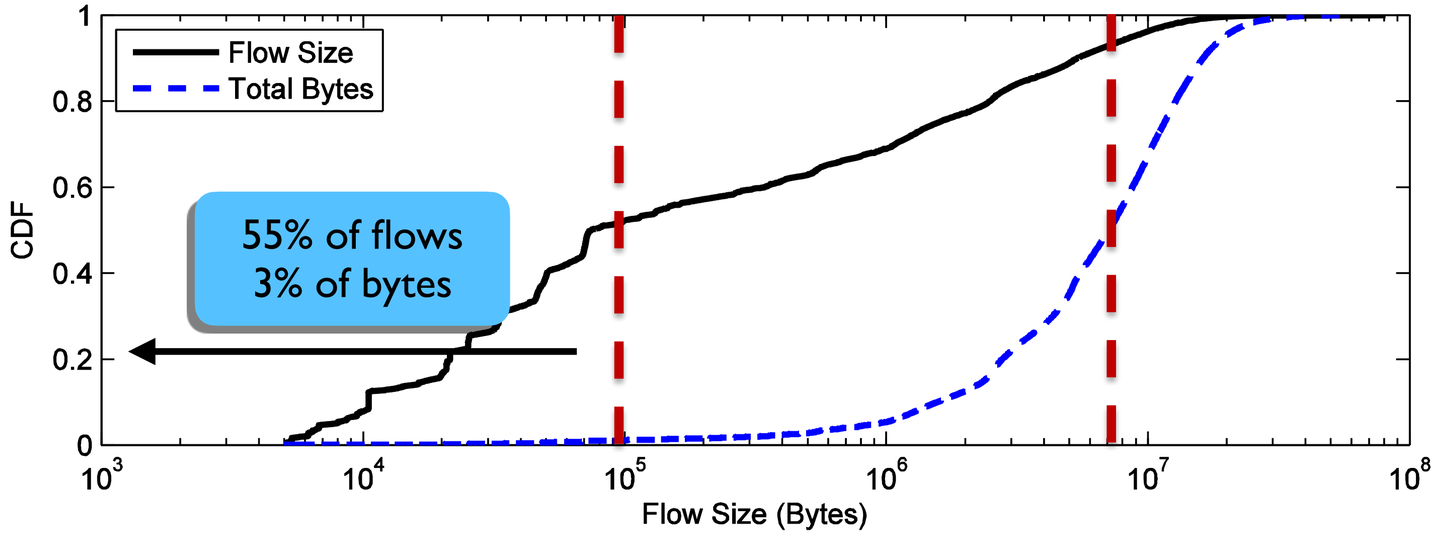

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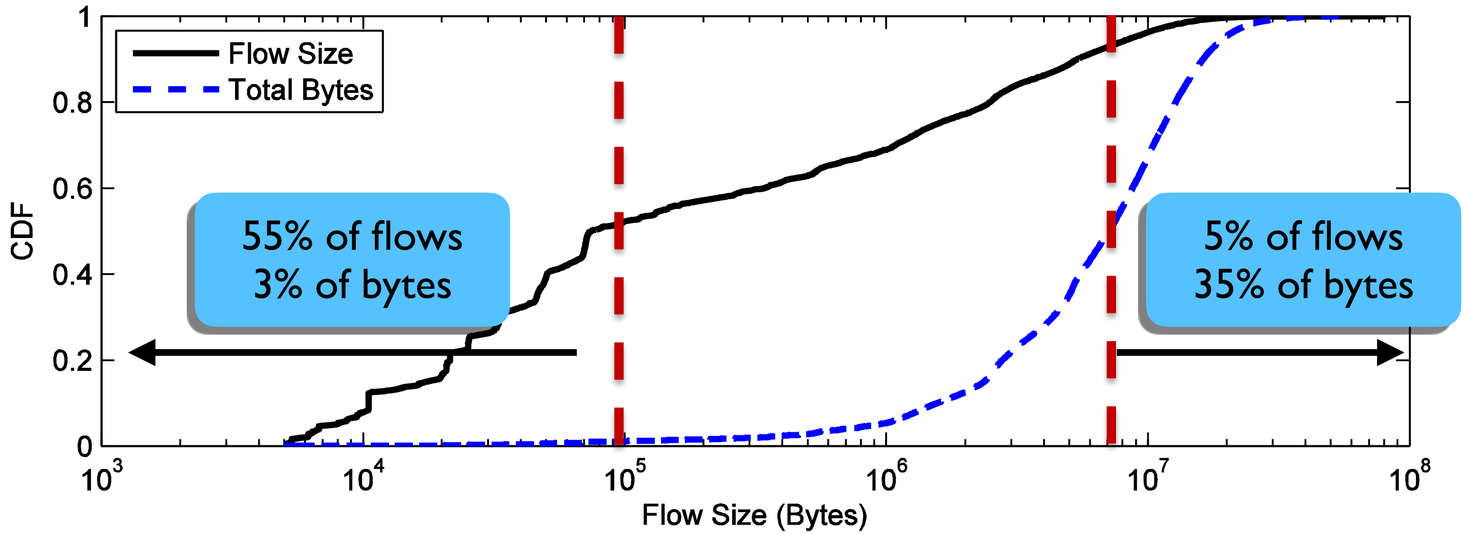

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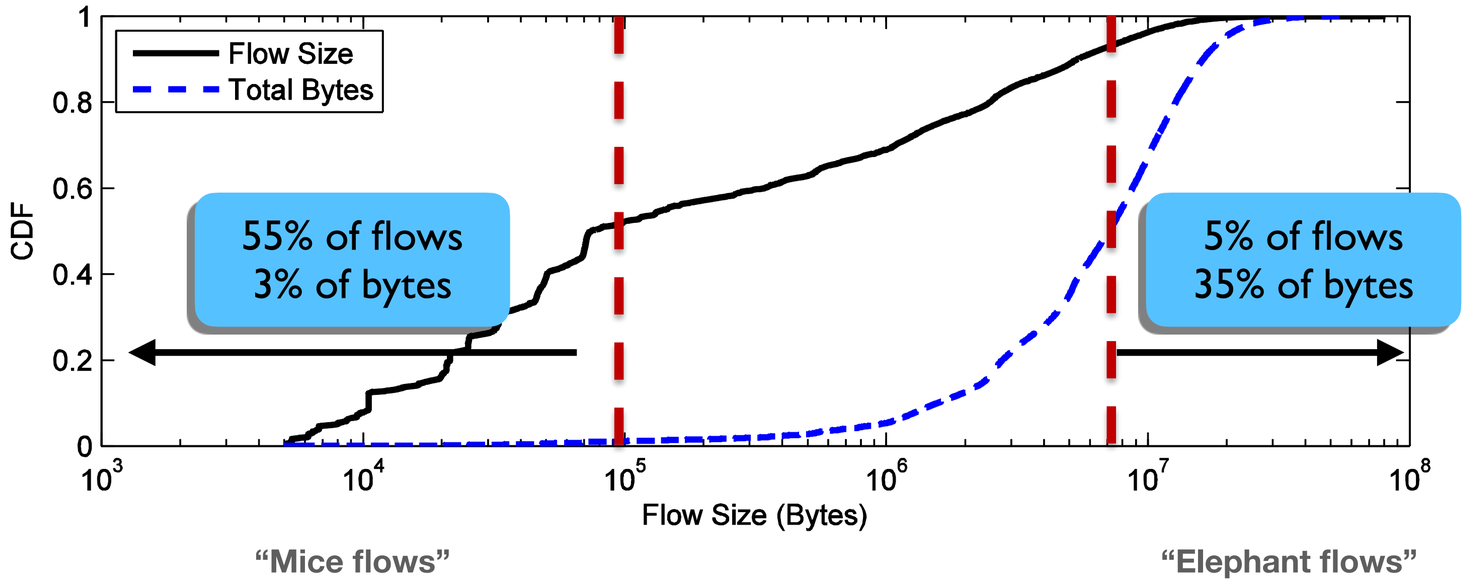

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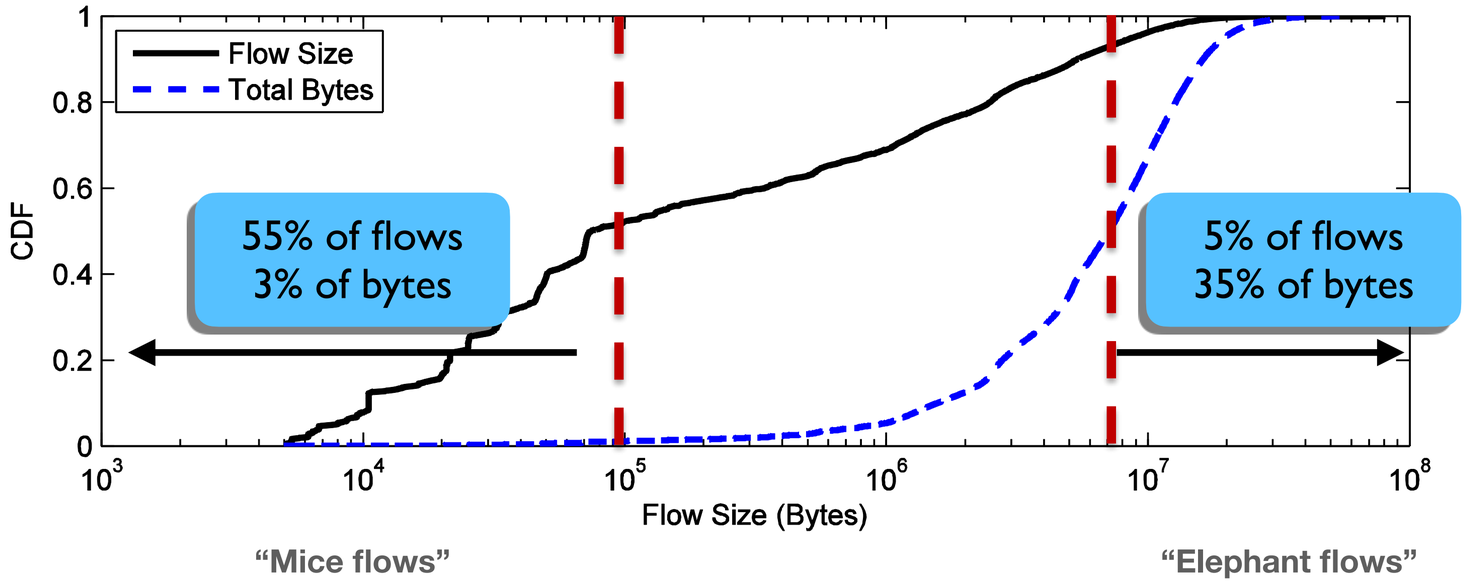

Research: How do you design the network protocols for such traffic?

Implications of Application Characteristics

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- **Low latency is critical (for north-south)**
  - Also worst-case ("tail") latency

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- **High bandwidth any-to-any communication (east-west)**
  - "Bisection bandwidth"

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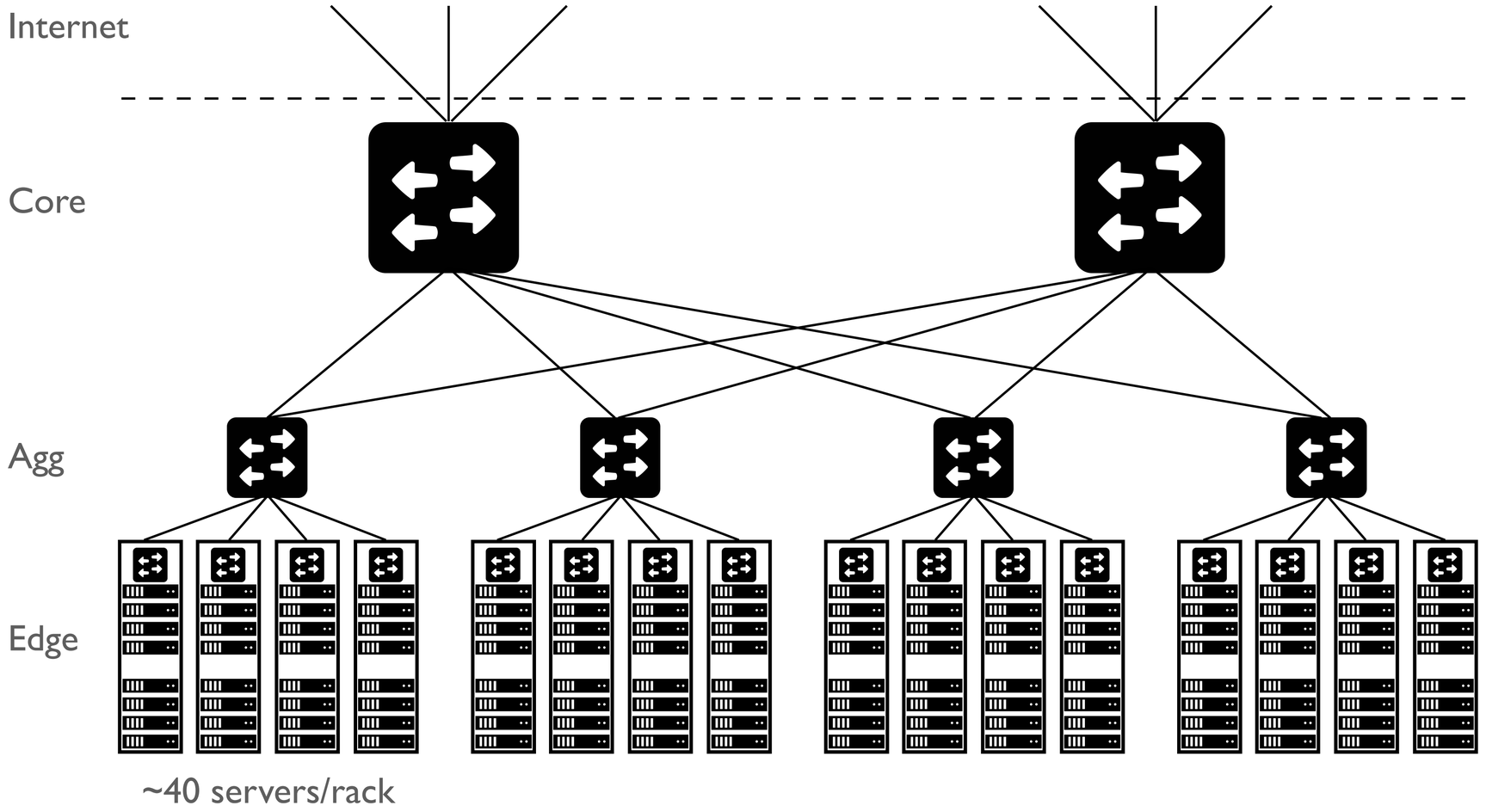
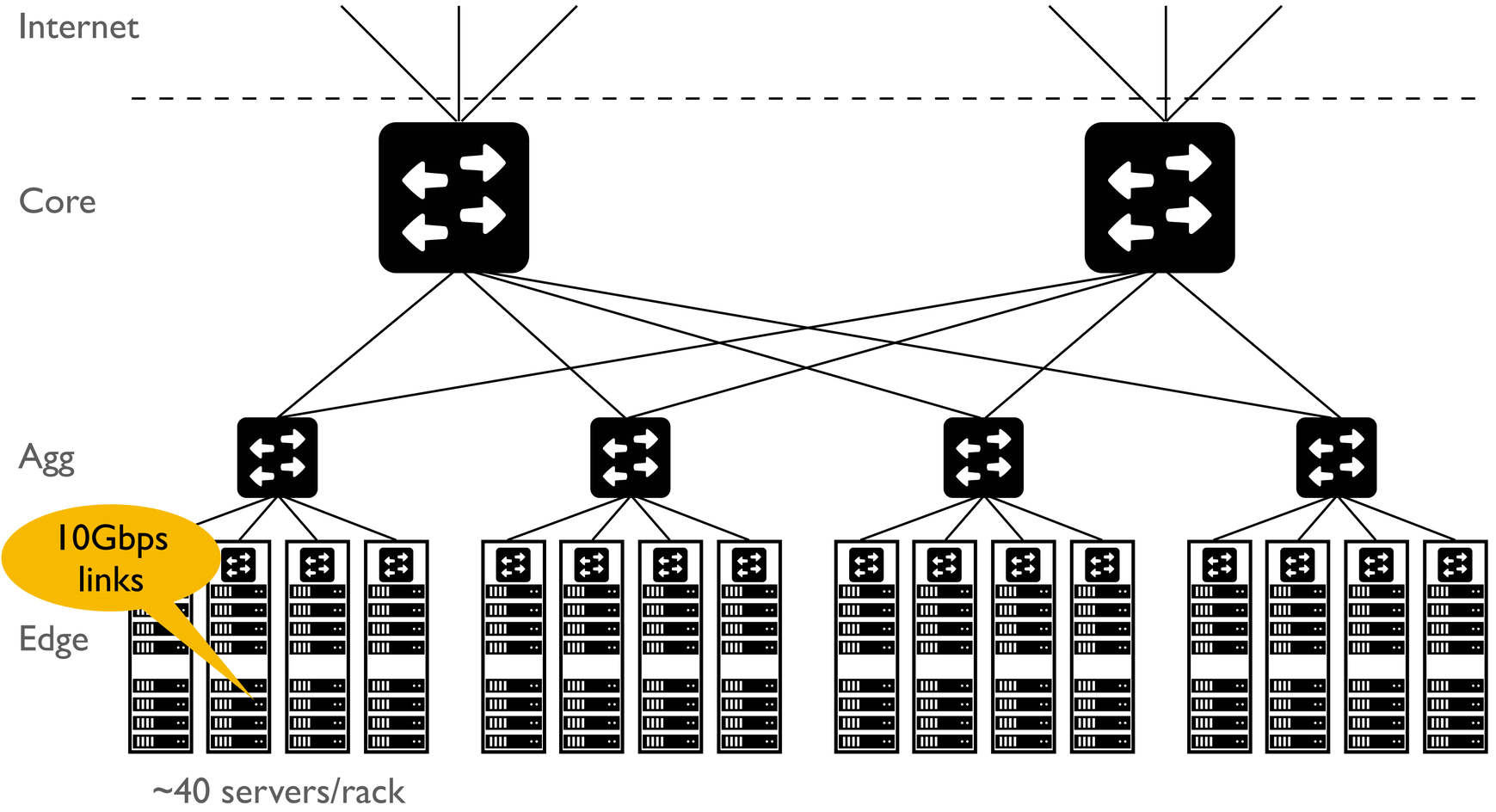
- *Full* bisection bandwidth: bisection bandwidth in an *N*-node network is N/2 times the bandwidth of a single access link
  - *Nodes of any two halves can communicate at full speed with each other*

Achieving Full Bisection Bandwidth



Achieving Full Bisection Bandwidth



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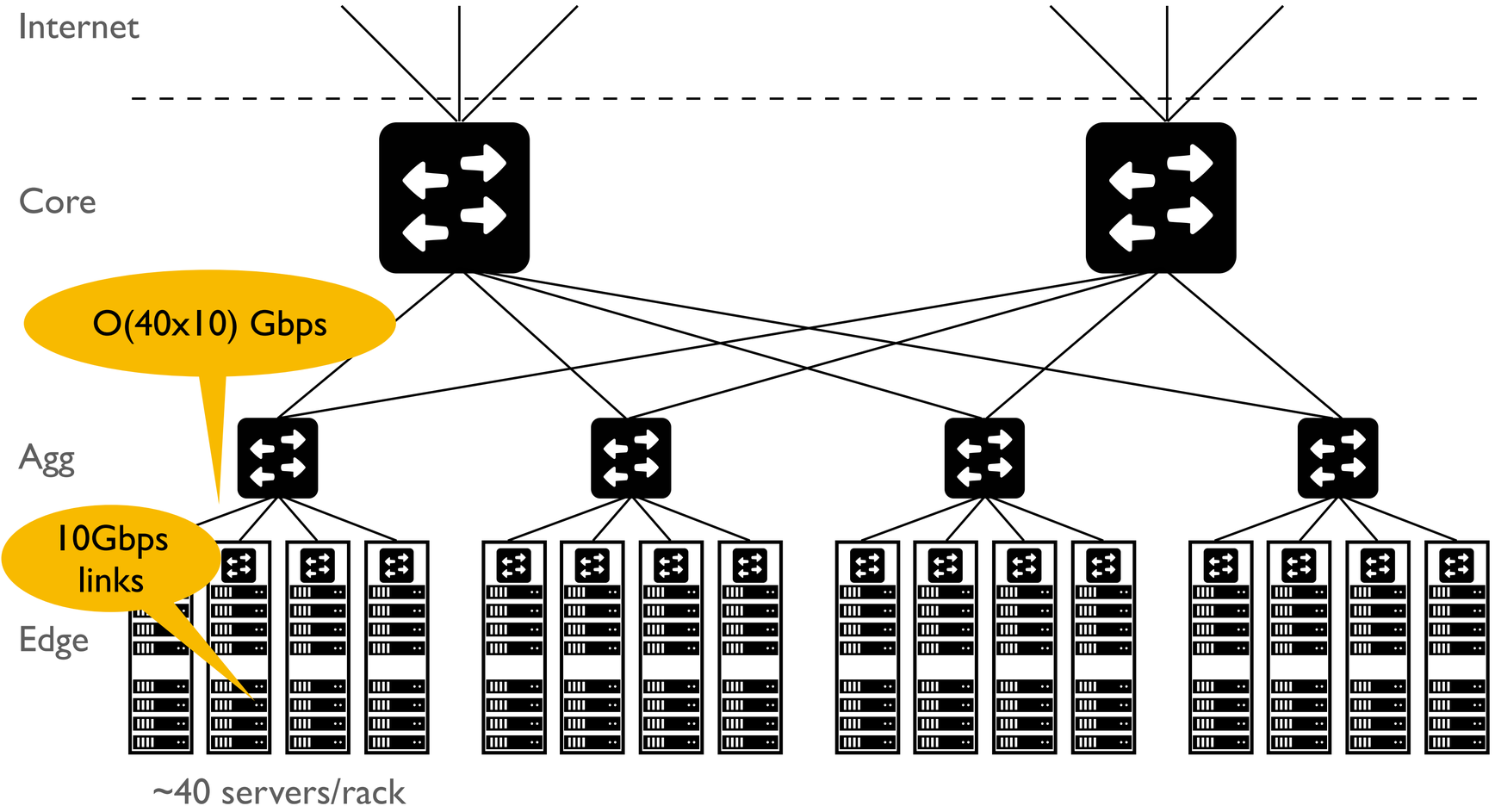

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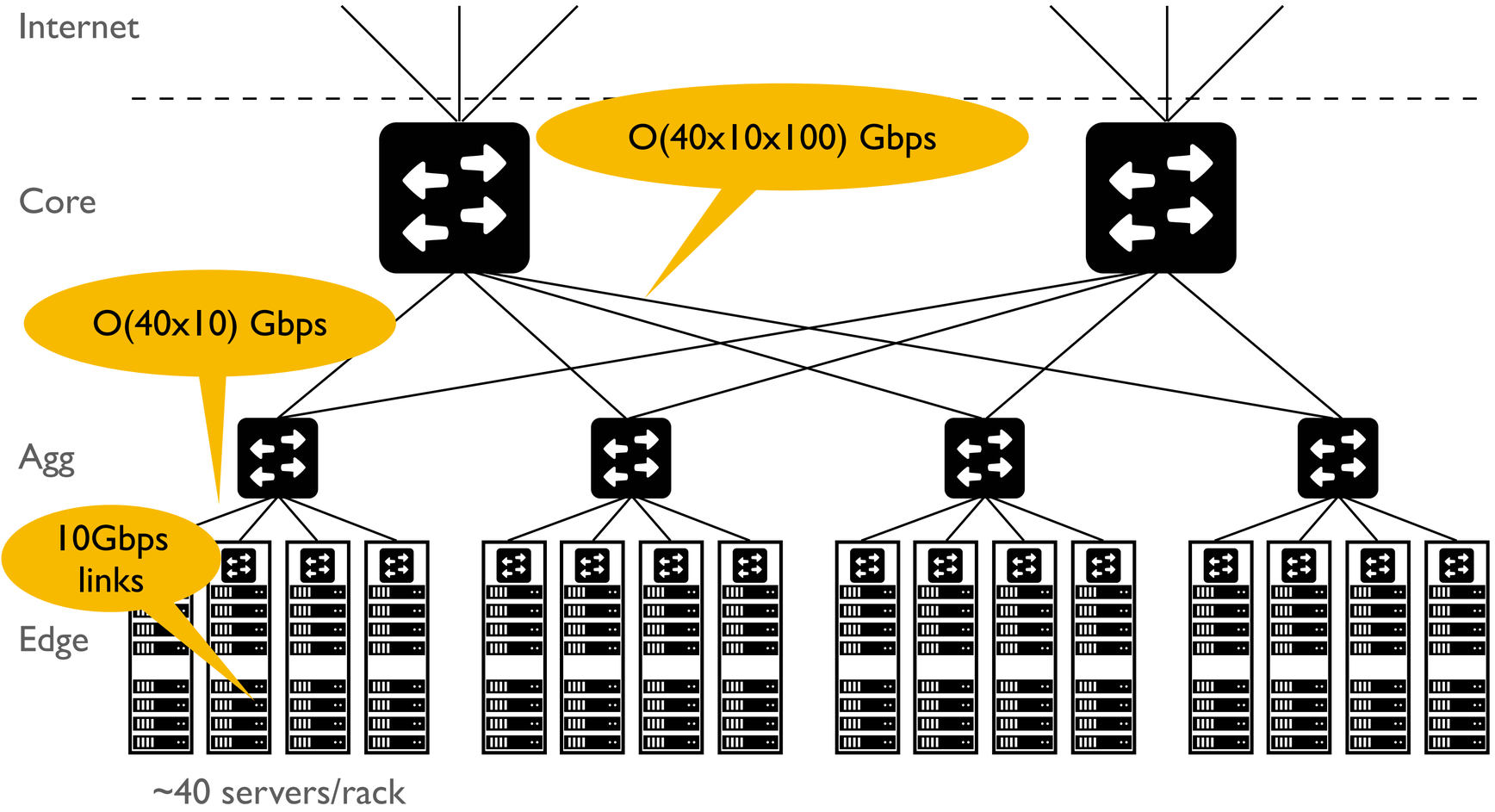

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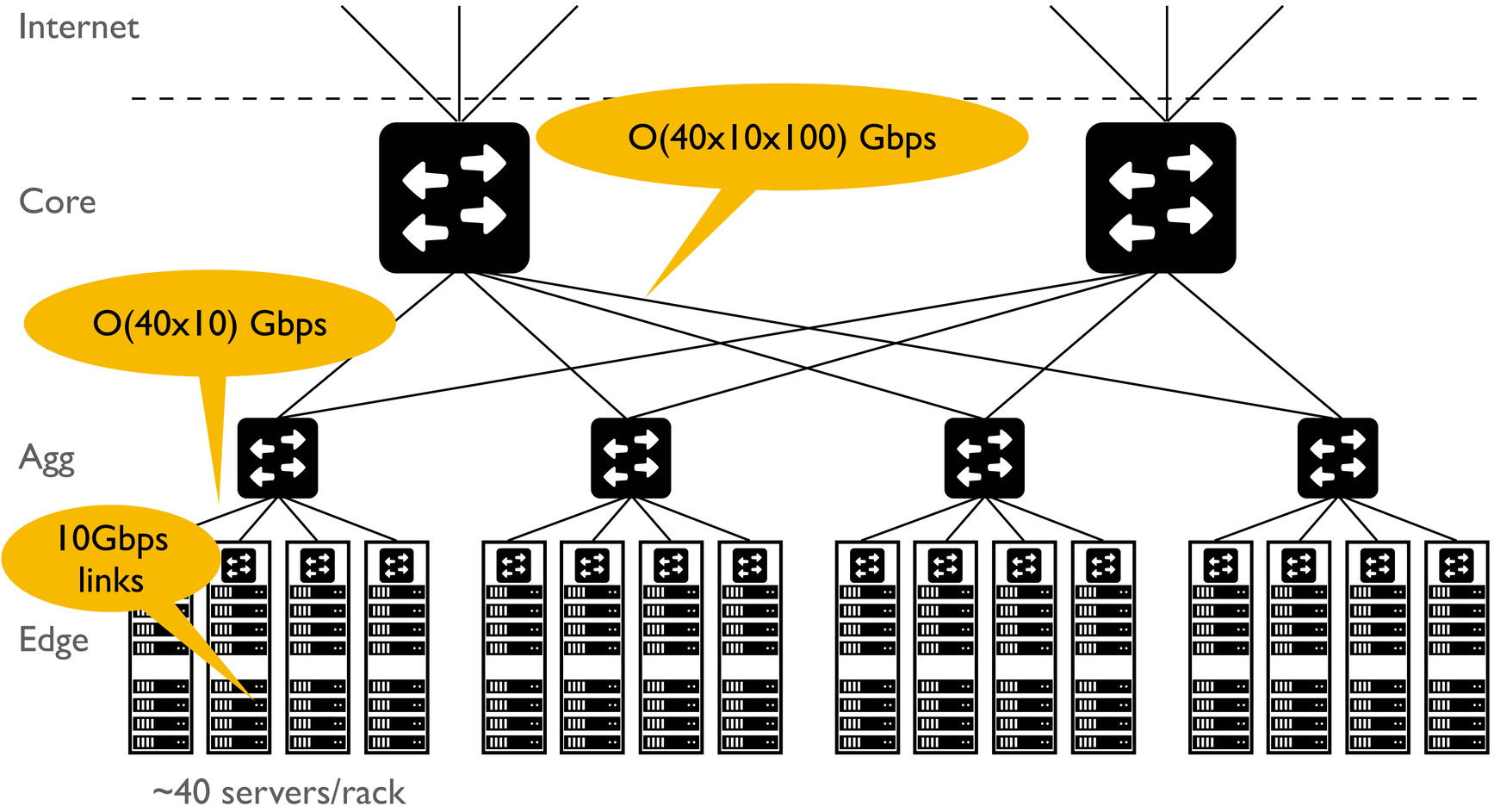

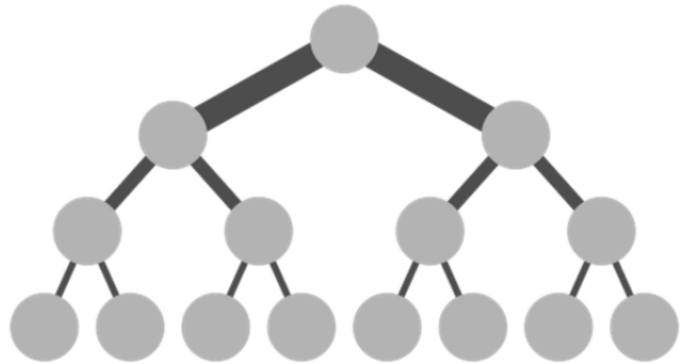

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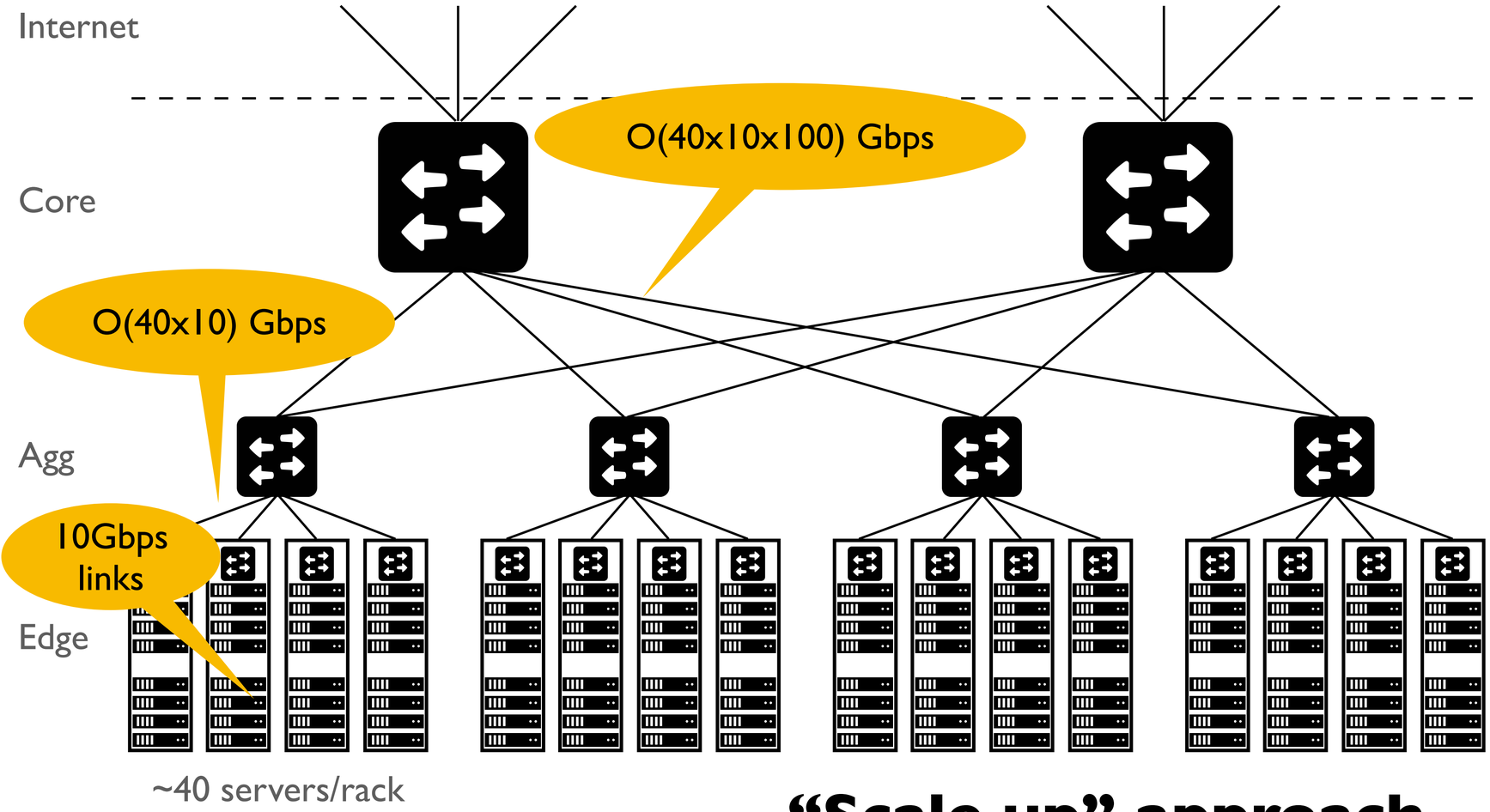

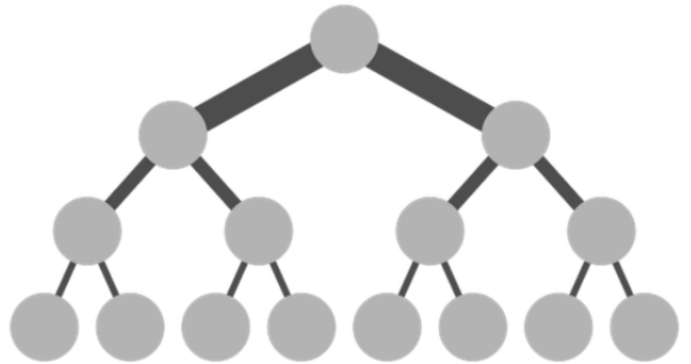

“Scale up” approach

Achieving Full Bisection Bandwidth

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- **Challenge: "Scaling up" a traditional tree topology is expensive!**
  - Requires non-commodity / impractical / link and switch components

Achieving Full Bisection Bandwidth

- **Challenge: "Scaling up" a traditional tree topology is expensive!**
  - Requires non-commodity / impractical / link and switch components

- **Solutions?**
  - Later…

Questions?

What you should understand…

- What is a datacenter network
  - Scale, service-model, application characteristics

- **What makes it different?**
  - Characteristics, goals (w.r.t. Internet), degrees of freedom

- How do we achieve goals by exploiting freedom?
  - Topology redesign, L2/L3 redesign, L4 redesign
  - We will look at some approaches, not all

What's different about DC Networks

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Characteristics

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Characteristics

- Huge scale
  - ~20,000 switches/routers
  - Contrast: AT&T ~500 routers

What's different about DC Networks

Characteristics

- Huge scale
- Limited geographic scope
  - High bandwidth: 10/40/100G (contrast: DSL/WiFi)
  - Very low RTT: 1-10s usecs (contrast: 100s msecs)

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Characteristics

- Huge scale
- Limited geographic scope
- Limited heterogeneity
  - Link speeds, technologies, latencies, …

What's different about DC Networks

Characteristics

- Huge scale
- Limited geographic scope
- Limited heterogeneity
- Regular/planned topologies (e.g., trees)
  - Contrast: ad-hoc evolution of wide-area topologies

What's different about DC Networks

Goals

- **Extreme bisection bandwidth requirements**
  - Recall: all that east-west traffic
  - Target: any server can communicate at its full link speed

What's different about DC Networks

Goals

- **Extreme bisection bandwidth requirements**
- **Extreme latency requirements**
  - Real money on the line
  - Current target: 1 us RTTs

What's different about DC Networks

Goals

- **Extreme bisection bandwidth requirements**
- **Extreme latency requirements**
- ***Predictable*, *deterministic* performance**
  - "Your packet will reach in X ms, or not at all"
  - "Your VM will always see at least Y Gbps throughput"
  - How is still an open question

What's different about DC Networks

Goals

- Extreme bisection bandwidth requirements
- Extreme latency requirements
- *Predictable*, *deterministic* performance
- Differentiating between tenants is key
  - e.g., "No traffic between VMs of tenant A and tenant B"
  - "Tenant X cannot consume more than X Gbps"
  - "Tenant Y's traffic is low priority"

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- Extreme bisection bandwidth requirements
- Extreme latency requirements
- *Predictable*, *deterministic* performance
- Differentiating between tenants is key
- Scalability (of course)
- Cost/efficiency
  - Focus on commodity solutions, ease of management

What's different about DC Networks

New degrees of (design) freedom

- Single administrative domain!
  - Can deviate from standards, invent your own, etc.
  - "Greenfield" deployment is still feasible

What's different about DC Networks

New degrees of (design) freedom

- Single administrative domain!
- Control over network *and* endpoint(s)
  - Can change (say) addressing, congestion control, *etc.*
  - Can add mechanisms for security/policy/etc. at endpoints (typically in the hypervisor)

What's different about DC Networks

New degrees of (design) freedom

- Single administrative domain!
- Control over network *and* endpoint(s)
- Control over the *placement* of traffic source/sink
  - e.g., map-reduce scheduler chooses where tasks run
  - Can control what traffic crosses which links

Questions?

What you should understand…

- What is a datacenter network
  - Scale, service-model, application characteristics
- What makes it different?
  - Characteristics, goals (w.r.t. Internet), degrees of freedom
- **How do we achieve goals by exploiting freedom?**
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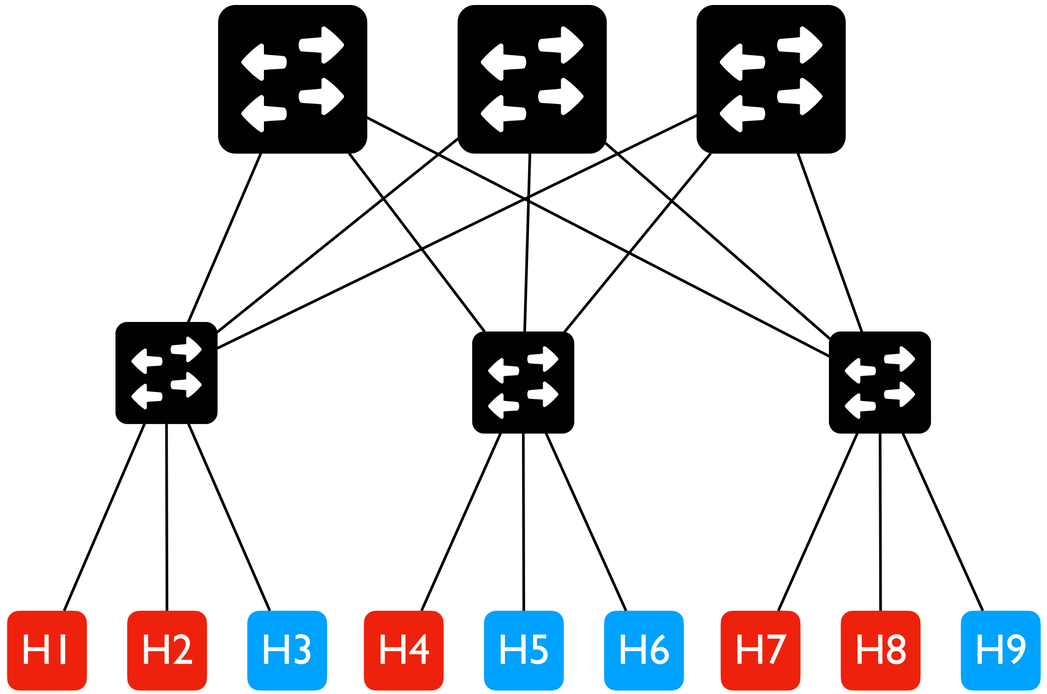
- **Conceptually: DC network as one giant switch!**

DC Network: Just a Giant Switch!



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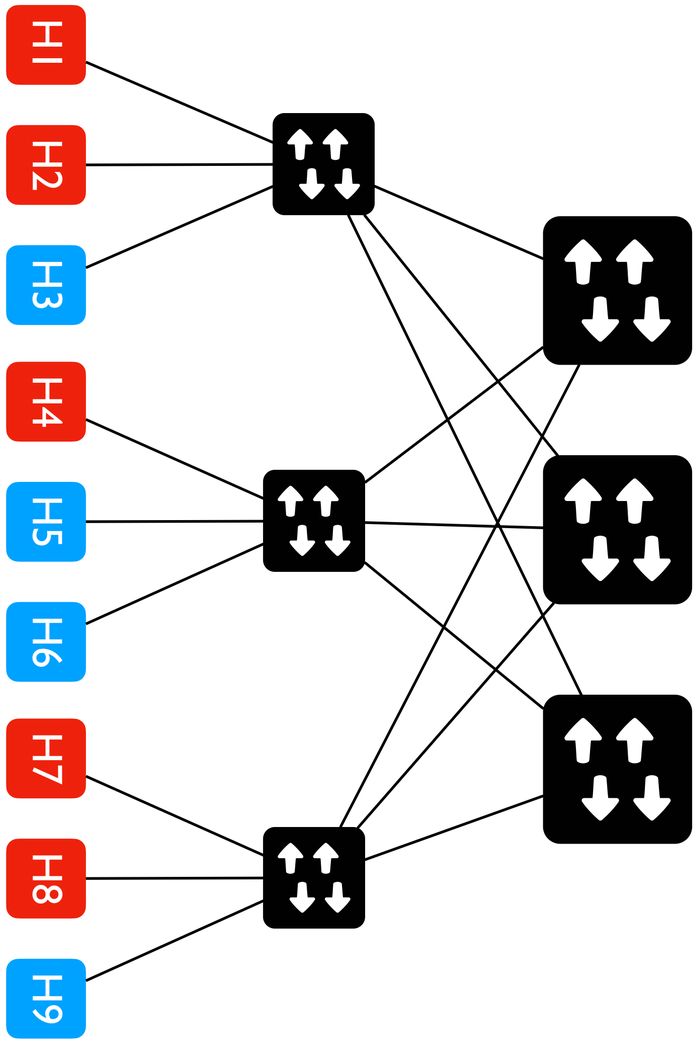

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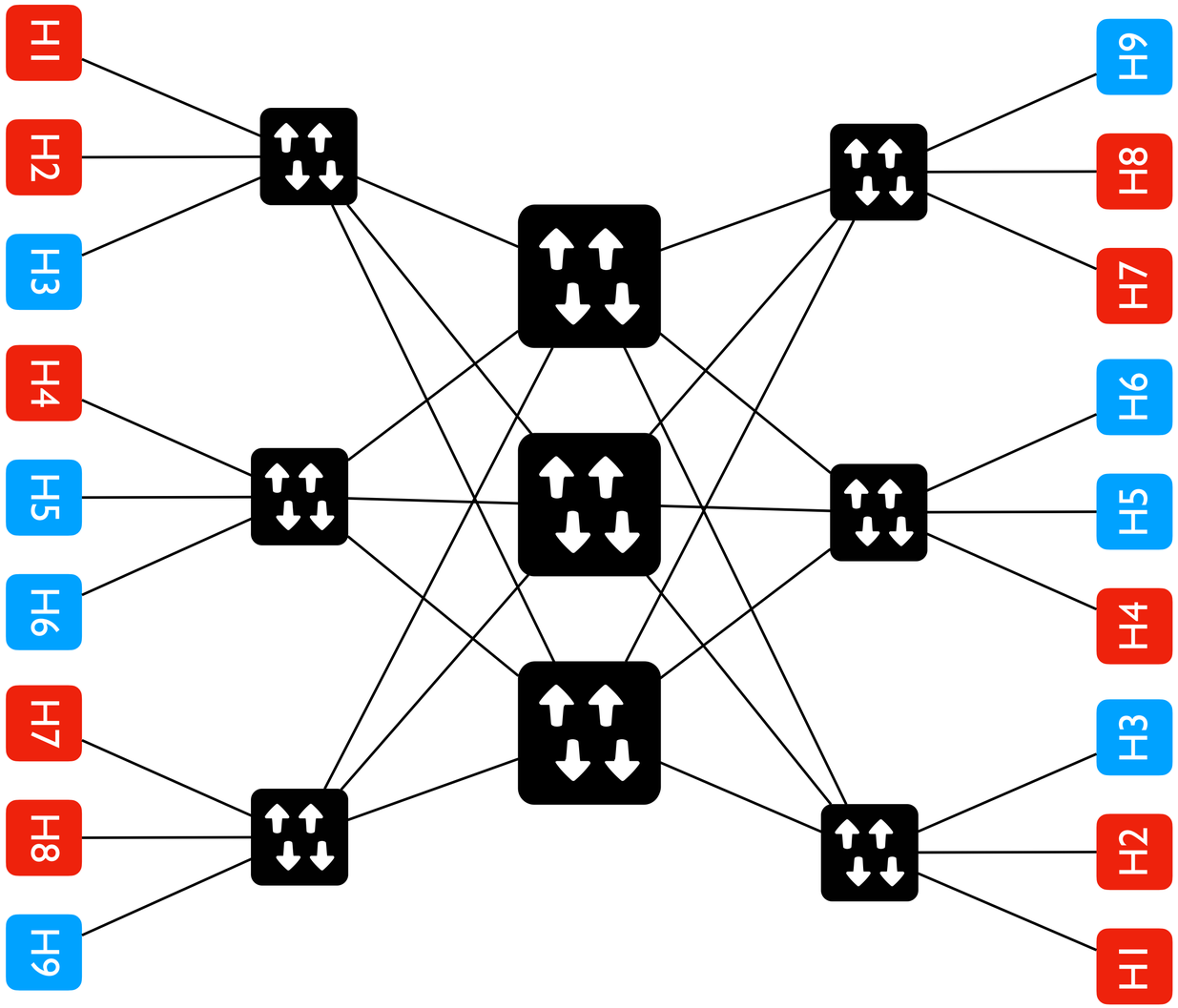

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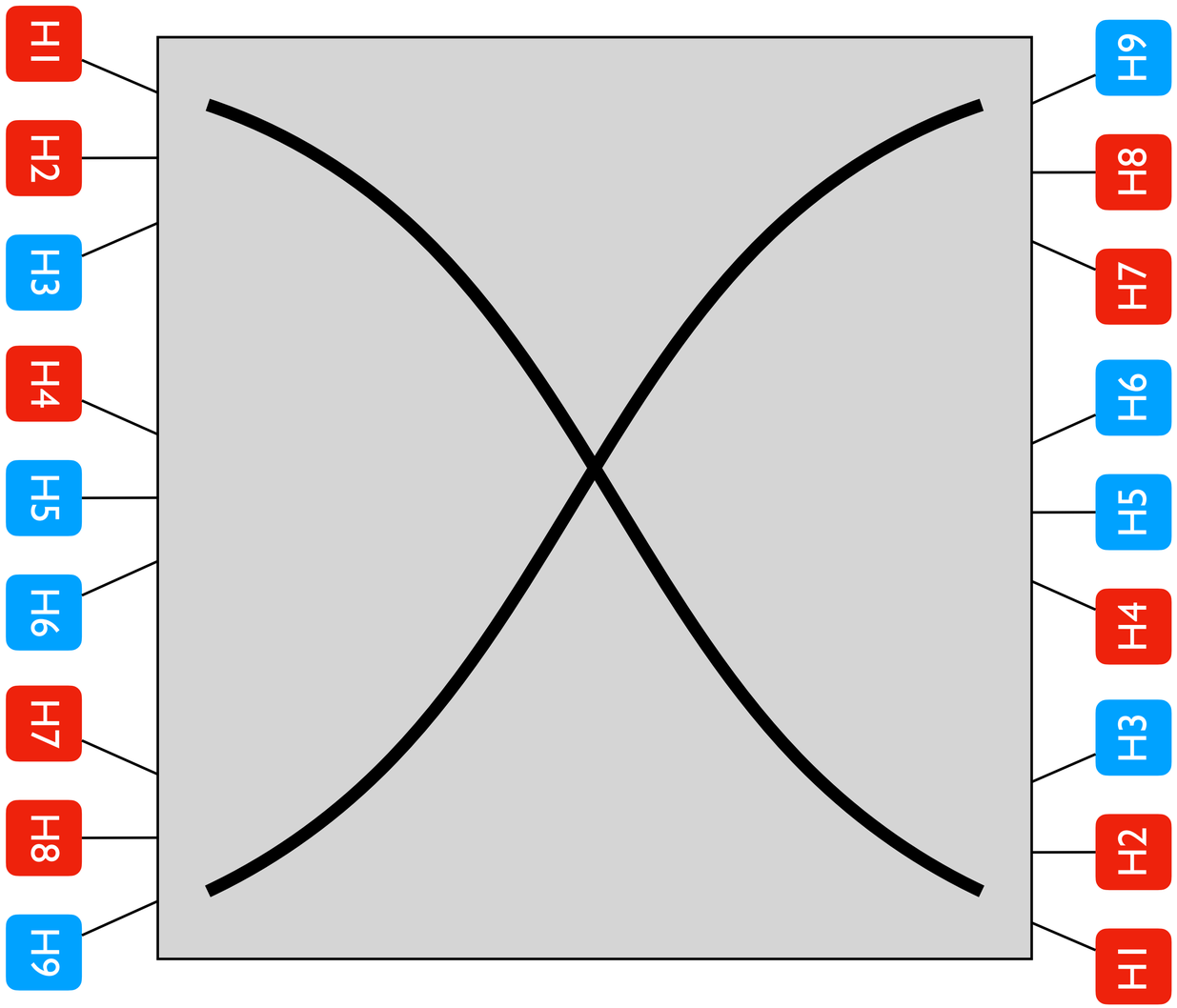

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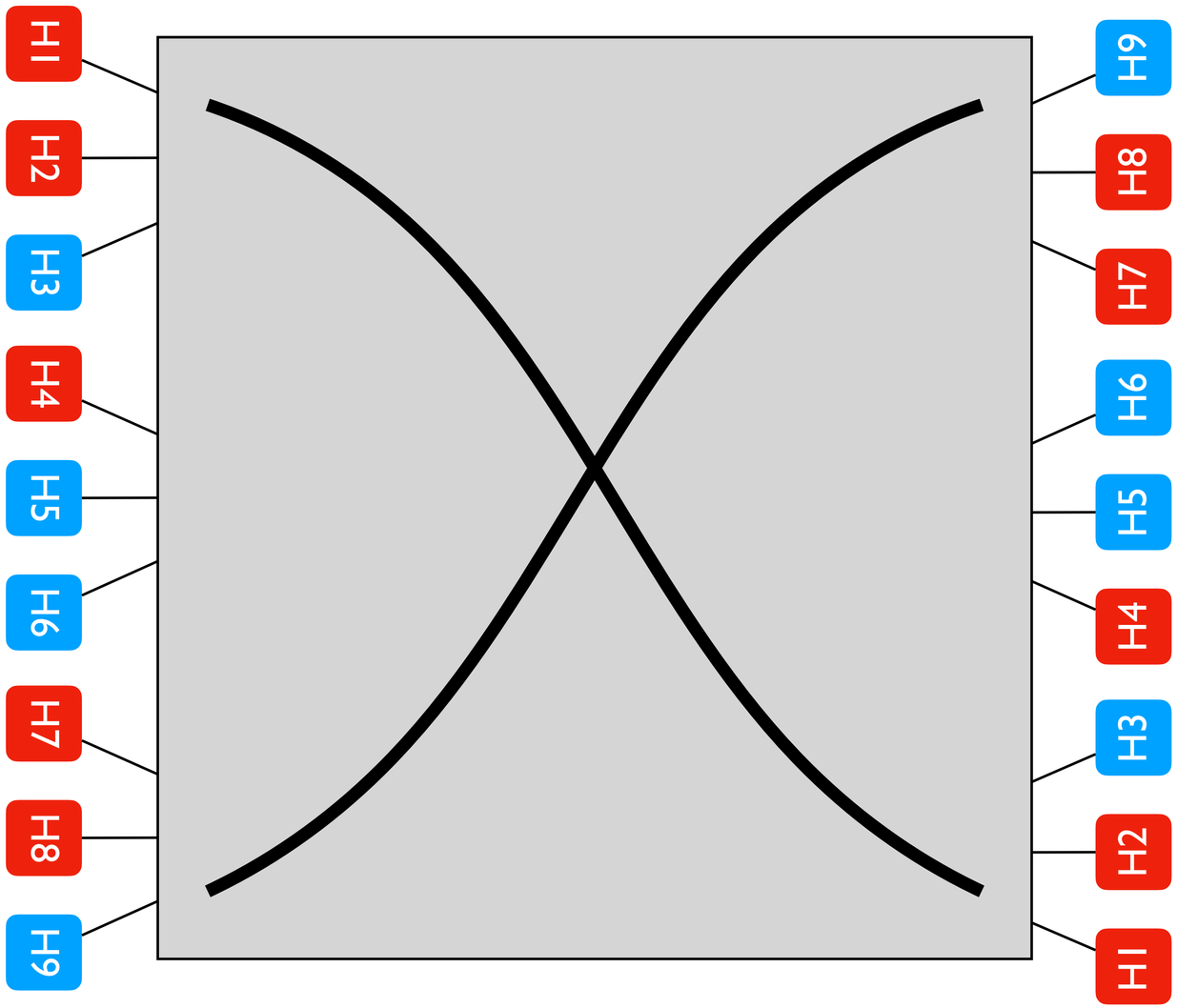

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  - Would require a 10 Pbits/sec switch!
    - 1M ports (one port per server)
    - 10 Gbps per port

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- **Conceptually: DC network as one giant switch**
  - Would require a 10 Pbits/sec switch!
    - 1M ports (one port per server)
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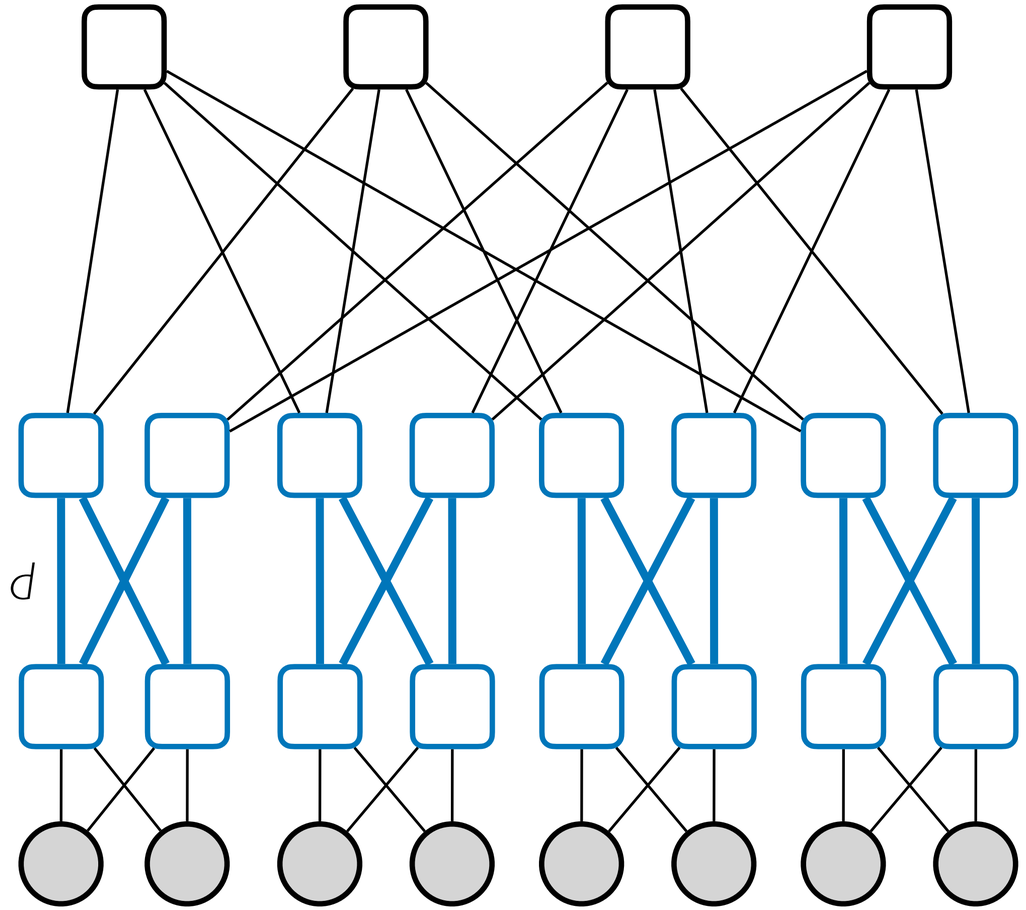
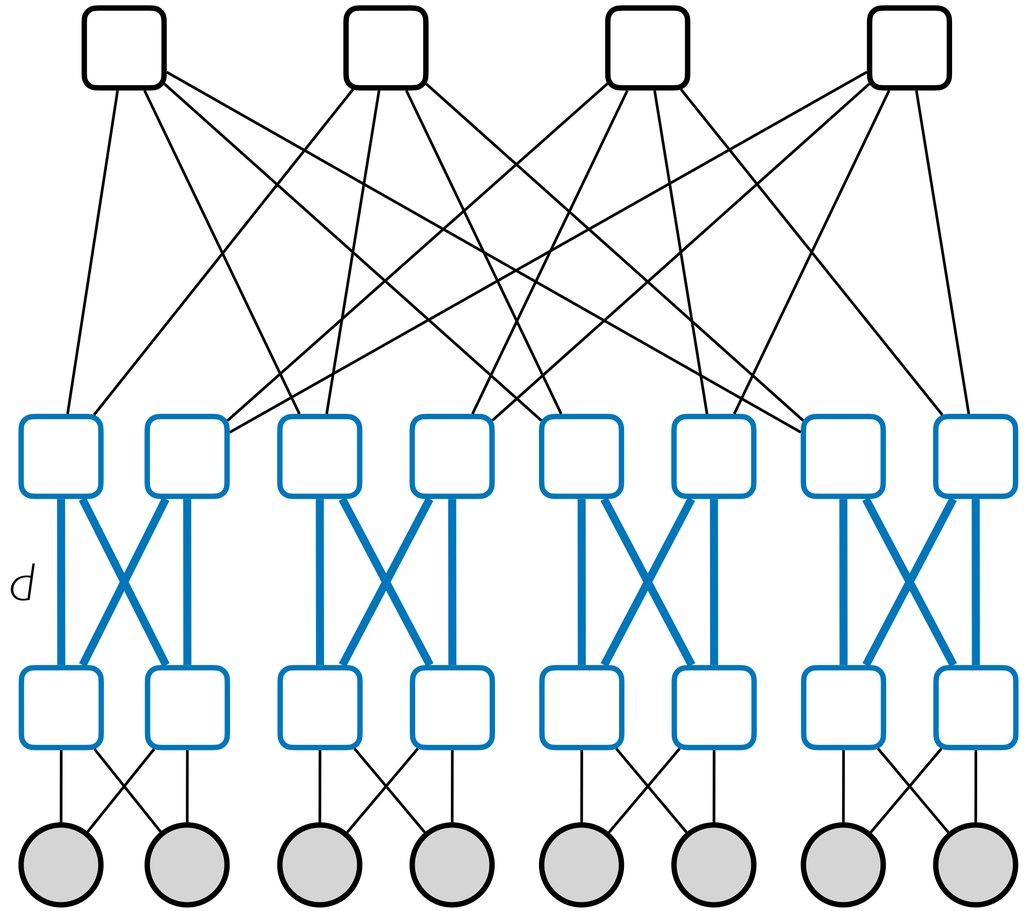
- **Practical approach: build a network of switches ("fabric") with high bisection bandwidth**
  - Each switch has practical #ports and link speeds

Architecting Better Topologies

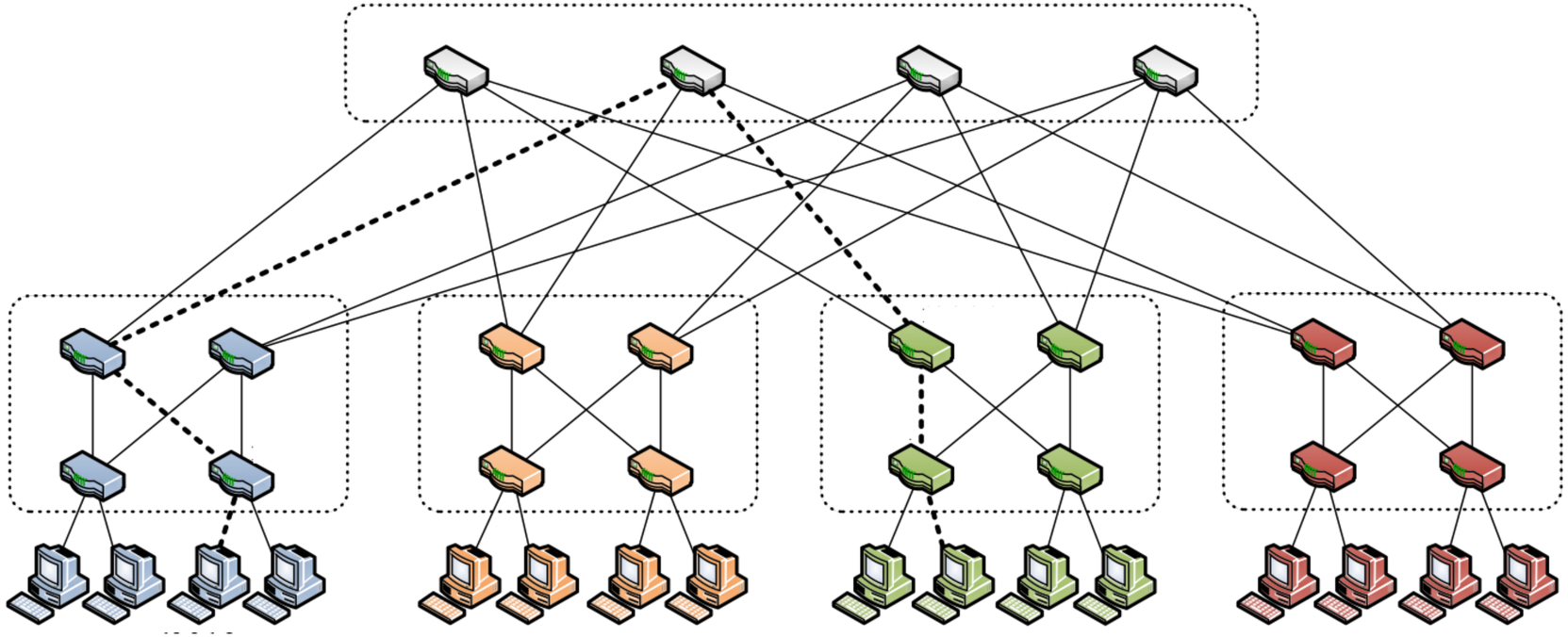


Architecting Better Topologies

- **E.g., 'Clos' topology**
  - Multi-stage network with L stages
  - All switches have k ports
  - k/2 ports up, k/2 down (except core)
  - *All links have same speed*
  - *Guarantees full bisection bandwidth*



“Fat Tree” Topology [SIGCOMM’08]



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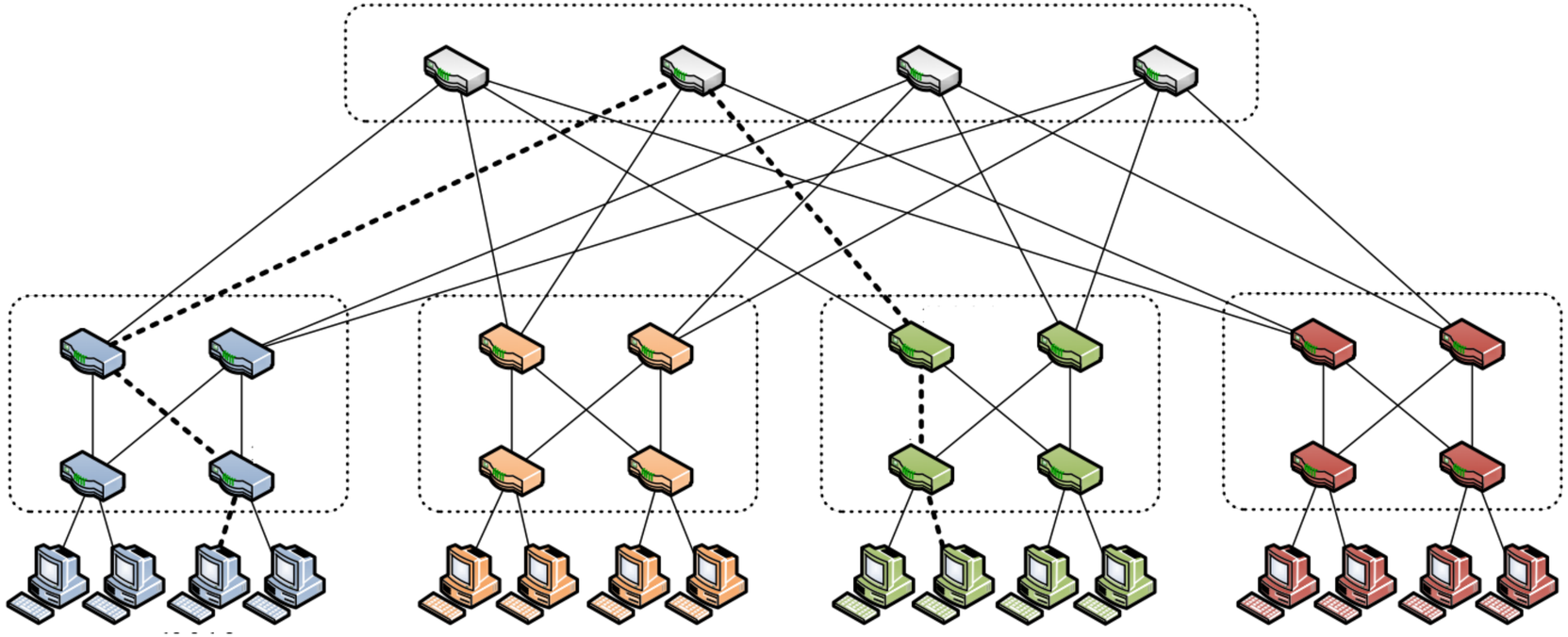

- **Few things to notice:**
  - Special case of Clos Topology with 3 stages (edge/aggregation/core)
  - All switches have the same number of ports (=4)
  - All links have same bandwidth
  - Many paths between any two end hosts

Bandwidth: Provisioning vs. Using

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- Topology offers high bisection bandwidth

Bandwidth: Provisioning vs. Using

- Topology offers high bisection bandwidth

- All other system components must be able to exploit this available capacity
  - Routing must use all paths
  - Transport protocol must fill all pipes (fast)

Questions?

How do we achieve DCN goals?

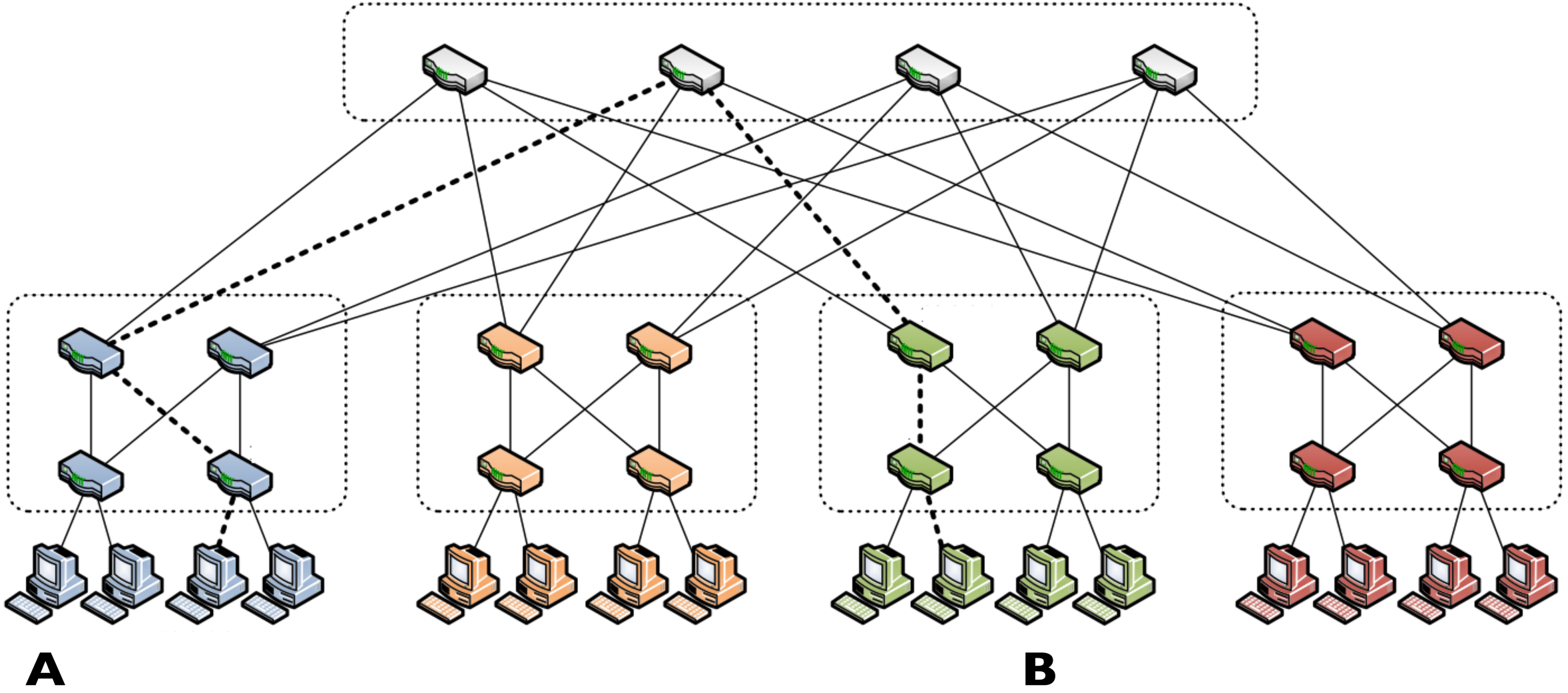
- **L2/L3 design:**
  - Addressing / routing / forwarding in the Fat-Tree

How do we achieve DCN goals?

- **L2/L3 design:**
  - Addressing / routing / forwarding in the Fat-Tree

- **Goals:**
  - Routing protocol must expose all available paths
  - Forwarding must spread traffic evenly all paths

Using multiple paths well



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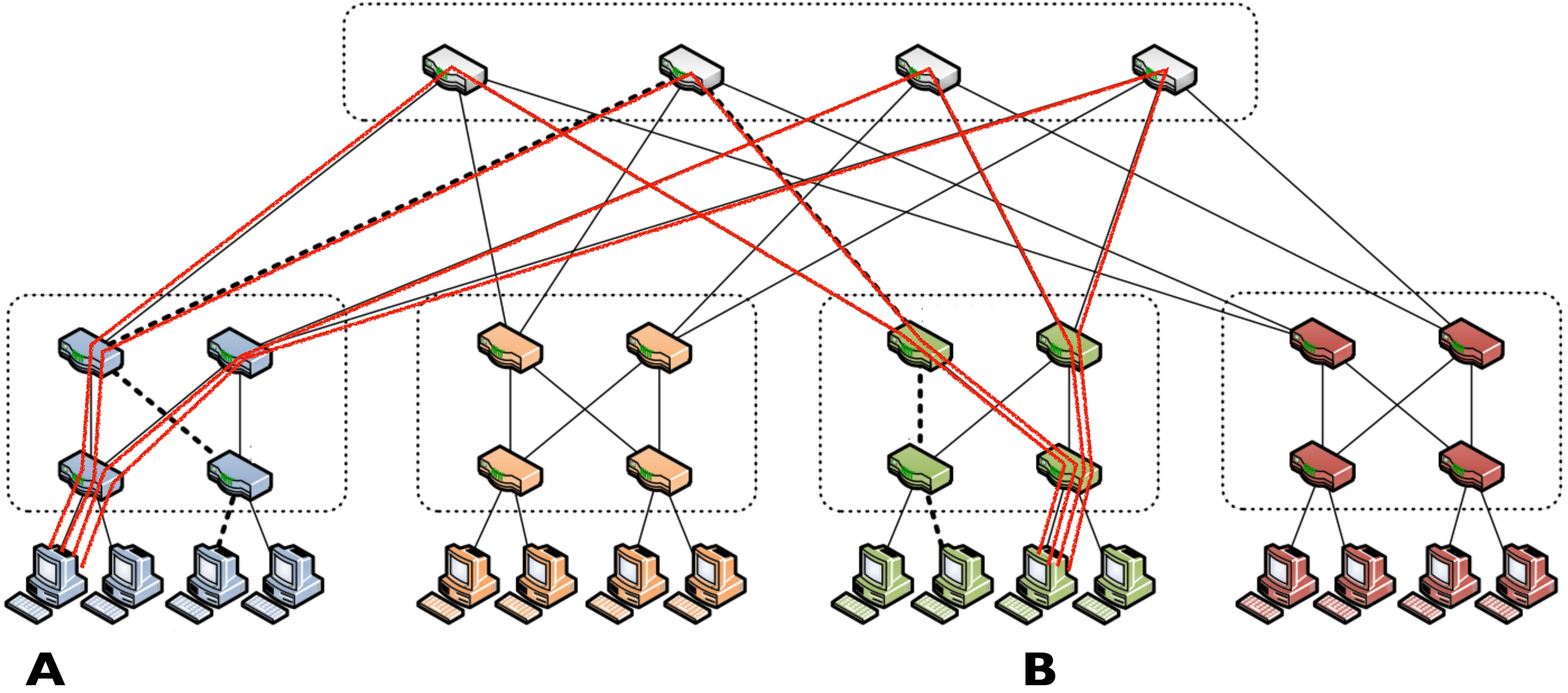

Extend DV/LS to exploit multi-paths

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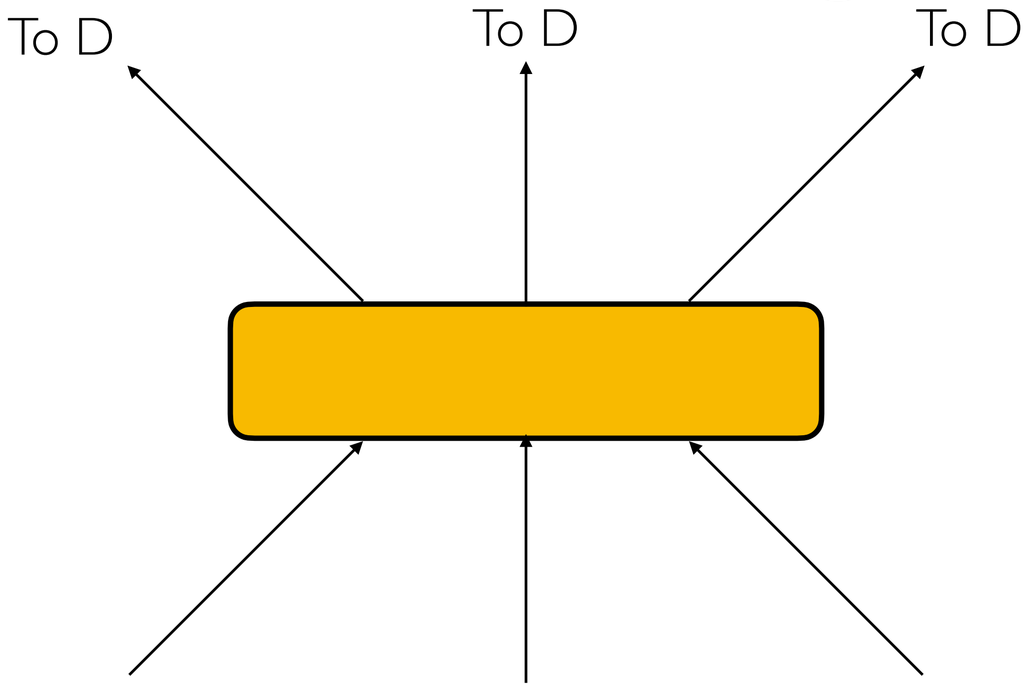
- **Forwarding: how to spread traffic across next hops?**

Forwarding

Forwarding



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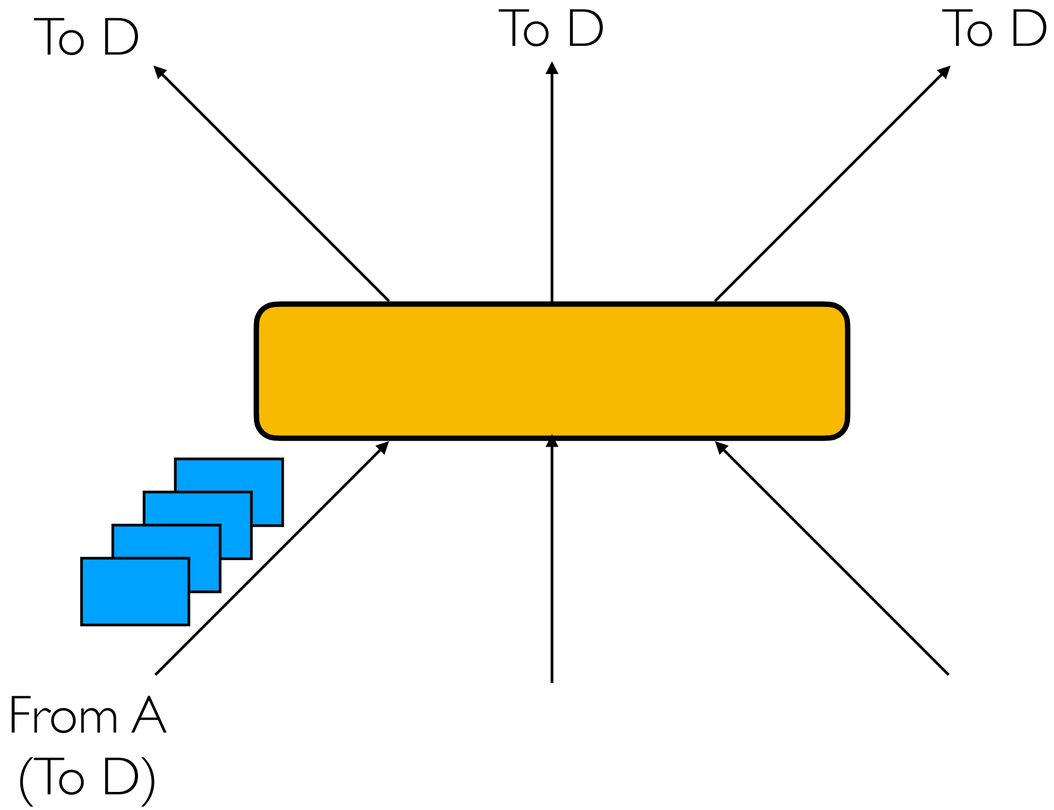

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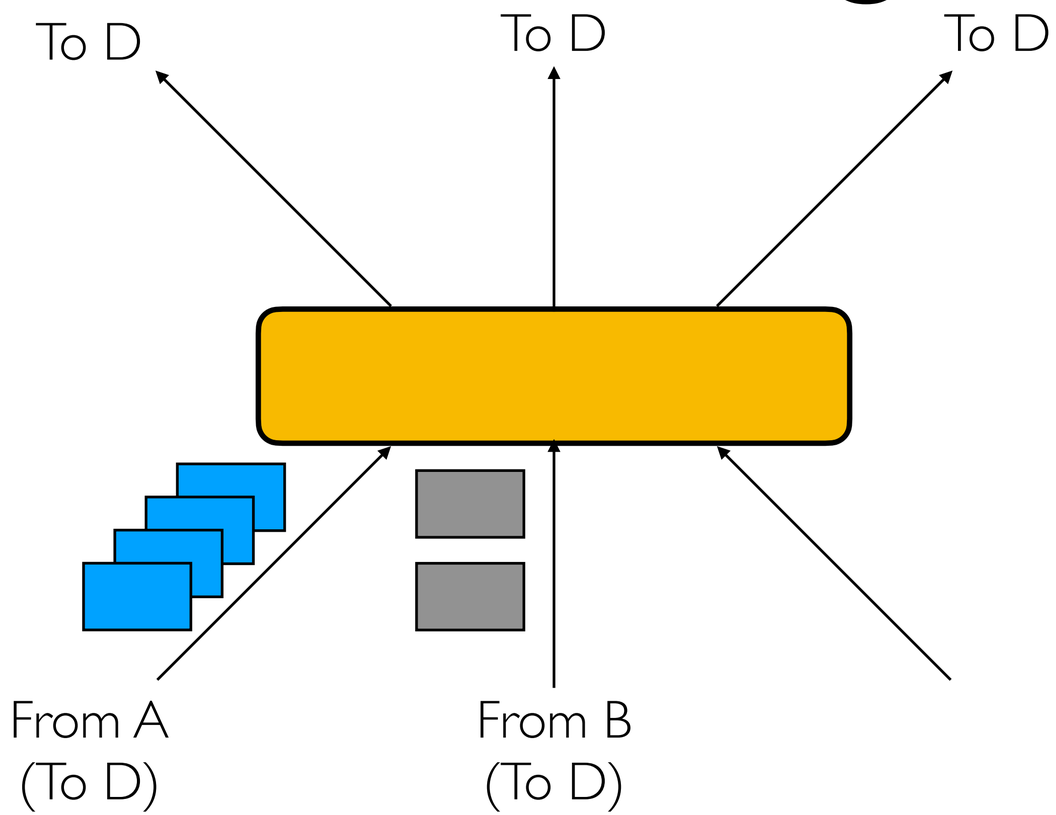

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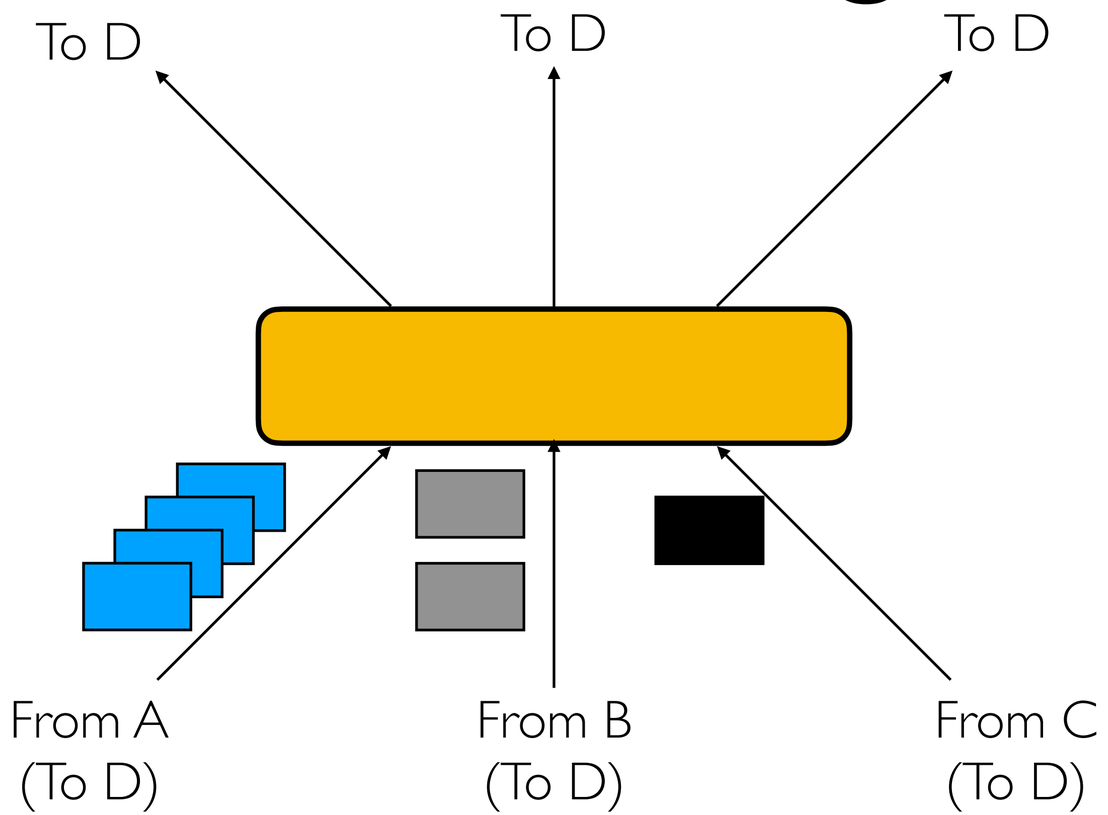

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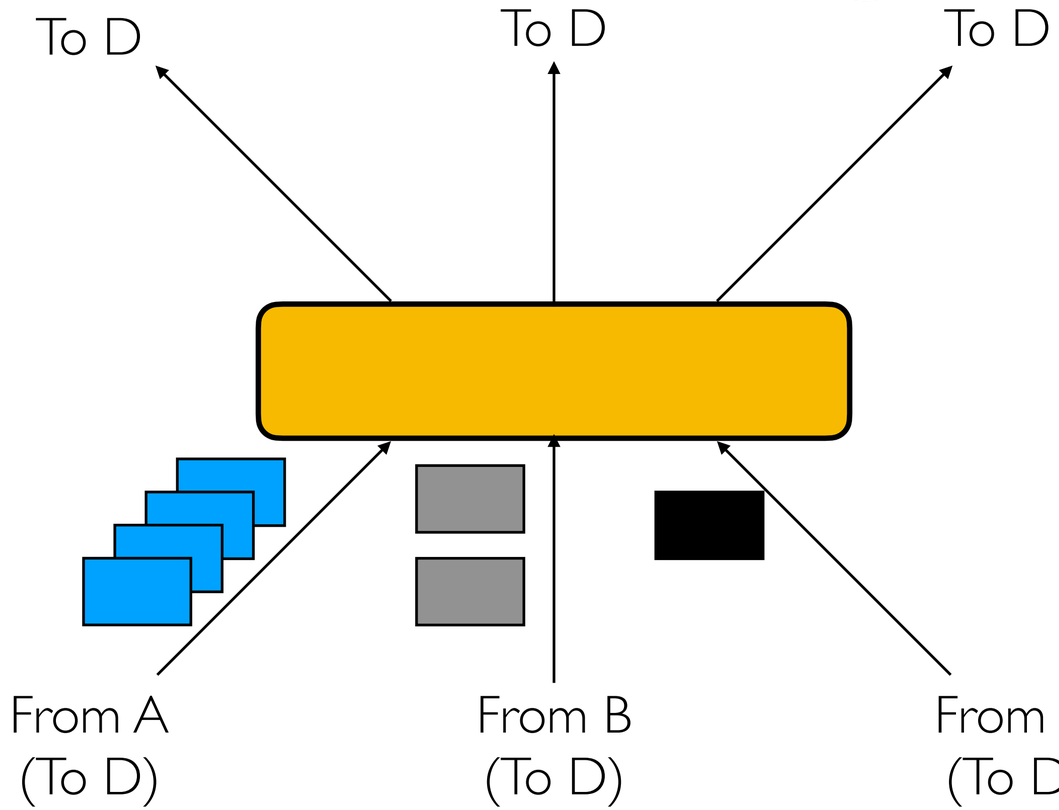
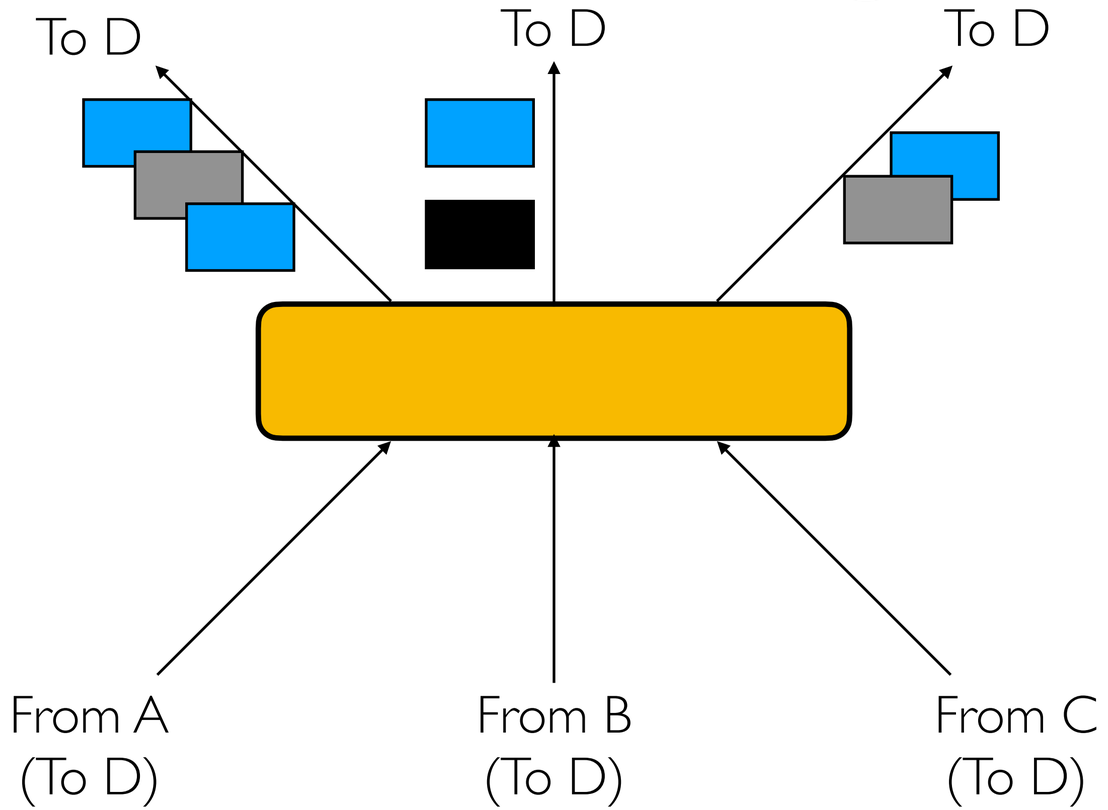


- Per-packet load balancing

Forwarding



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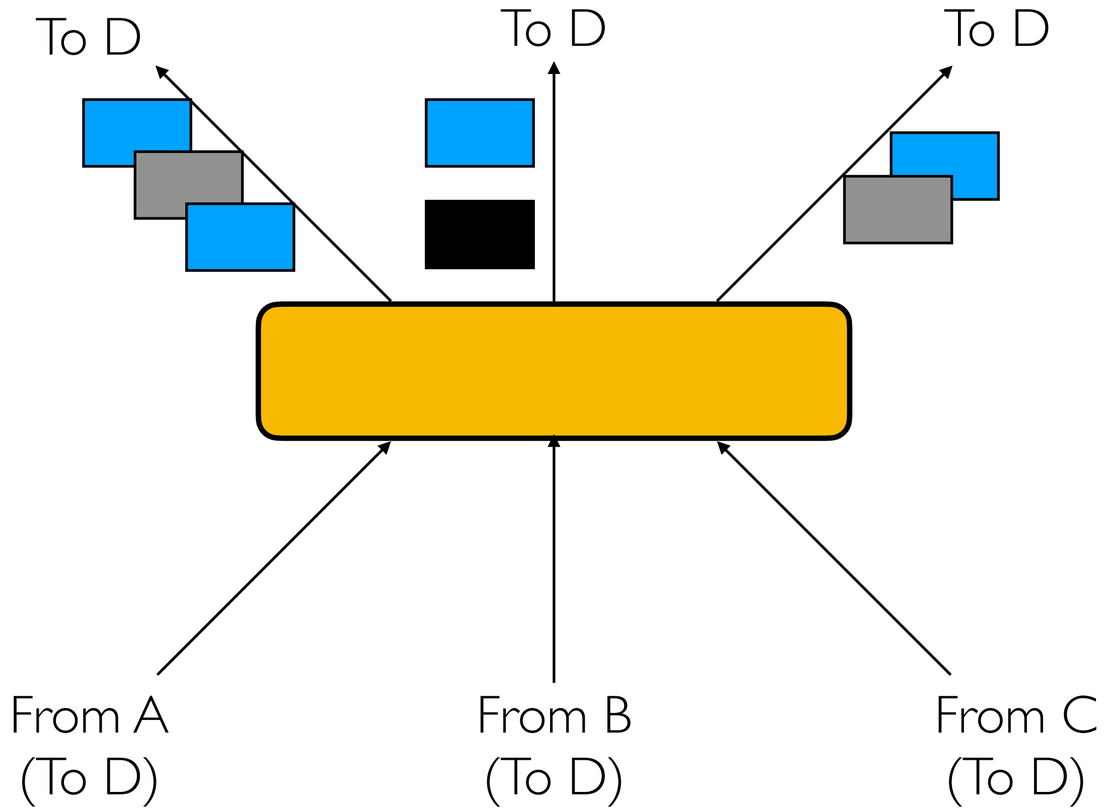

- Per-packet load balancing
  - Traffic well spread (even w/ elephant flows)

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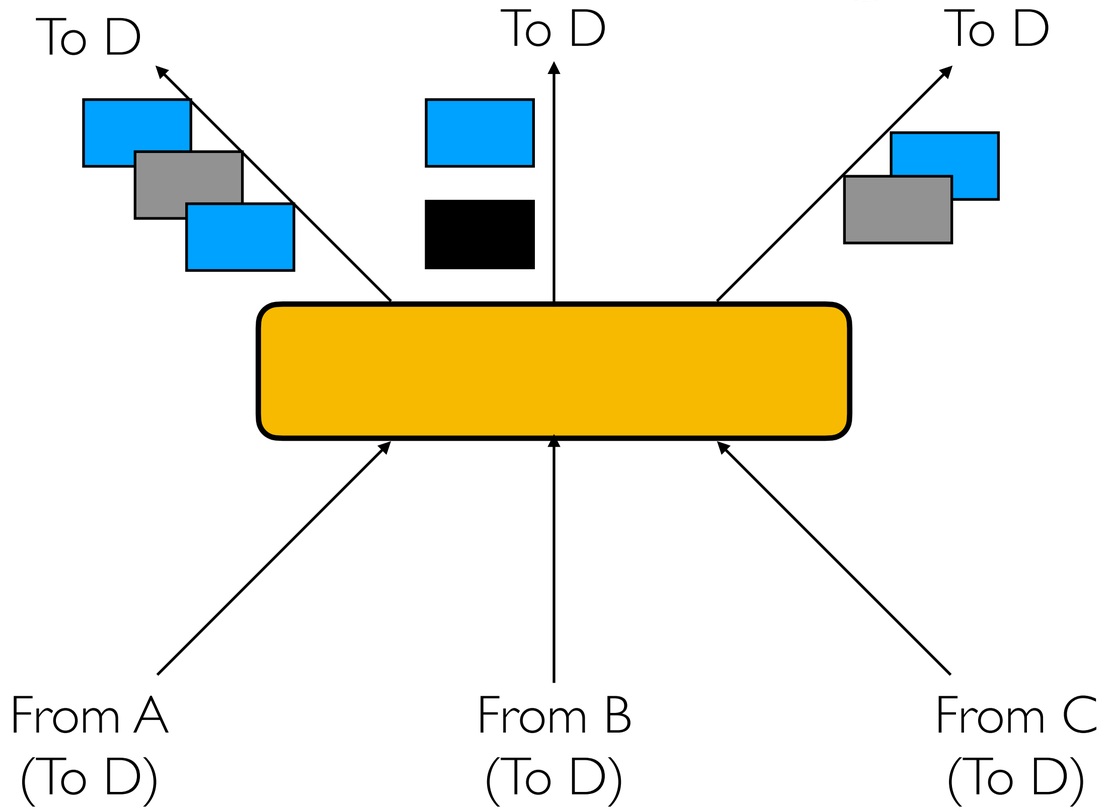

- Per-packet load balancing
  - Traffic well spread (even w/ elephant flows)
  - Interacts badly w/ TCP

TCP w/ per-packet load balancing

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- **Consider:**
  - Sender sends seq#: 1, 2, 3, 4, 5
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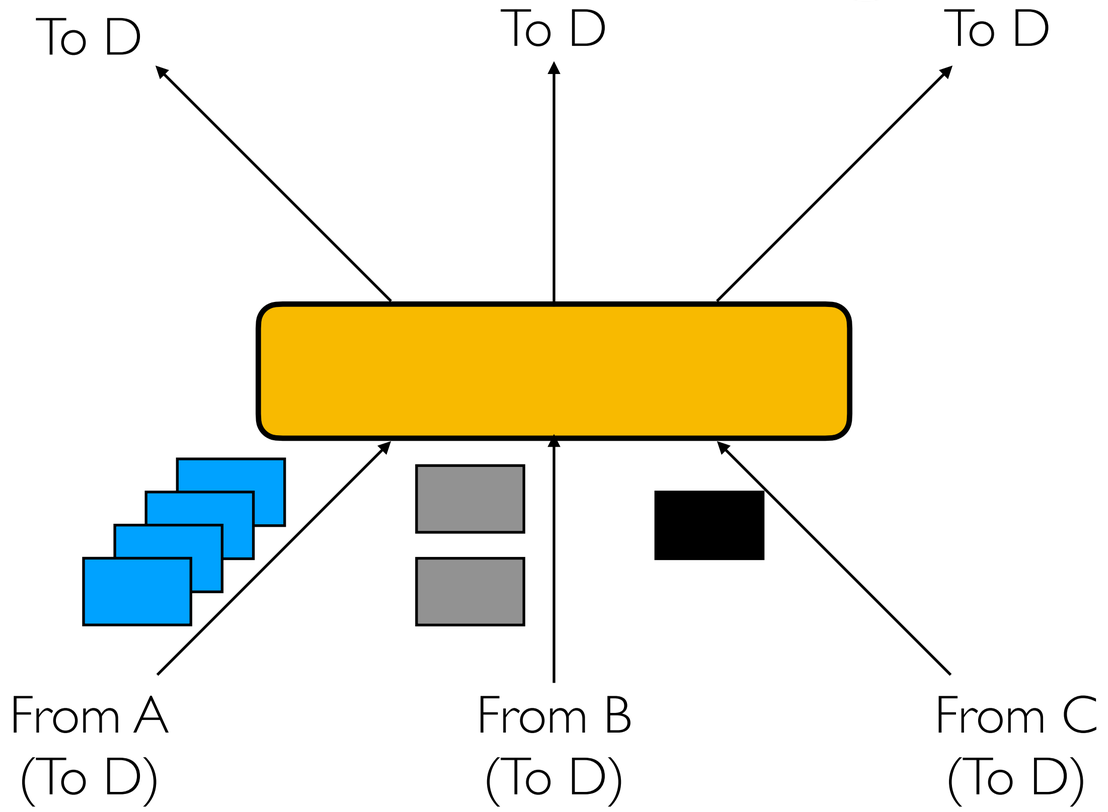
- **Multipath TCP (MP-TCP): Extend TCP with multi path routing**
  - Value beyond datacenters (e.g., spread traffic across WiFi and 4G access)

Forwarding



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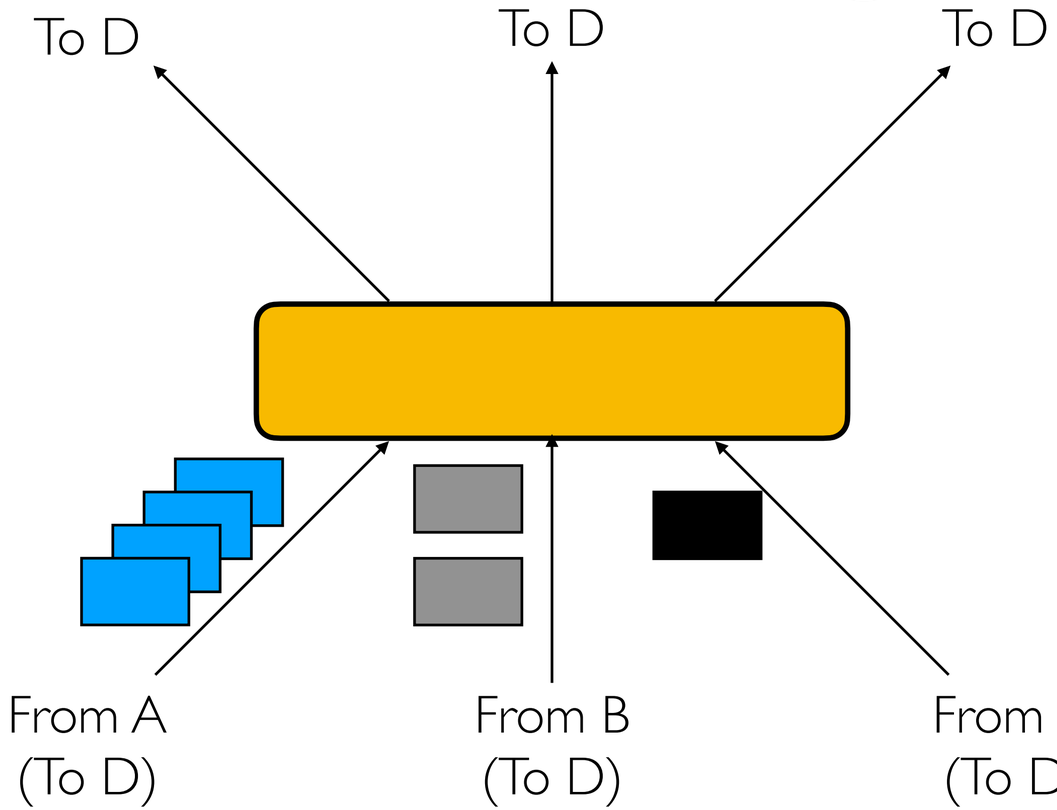
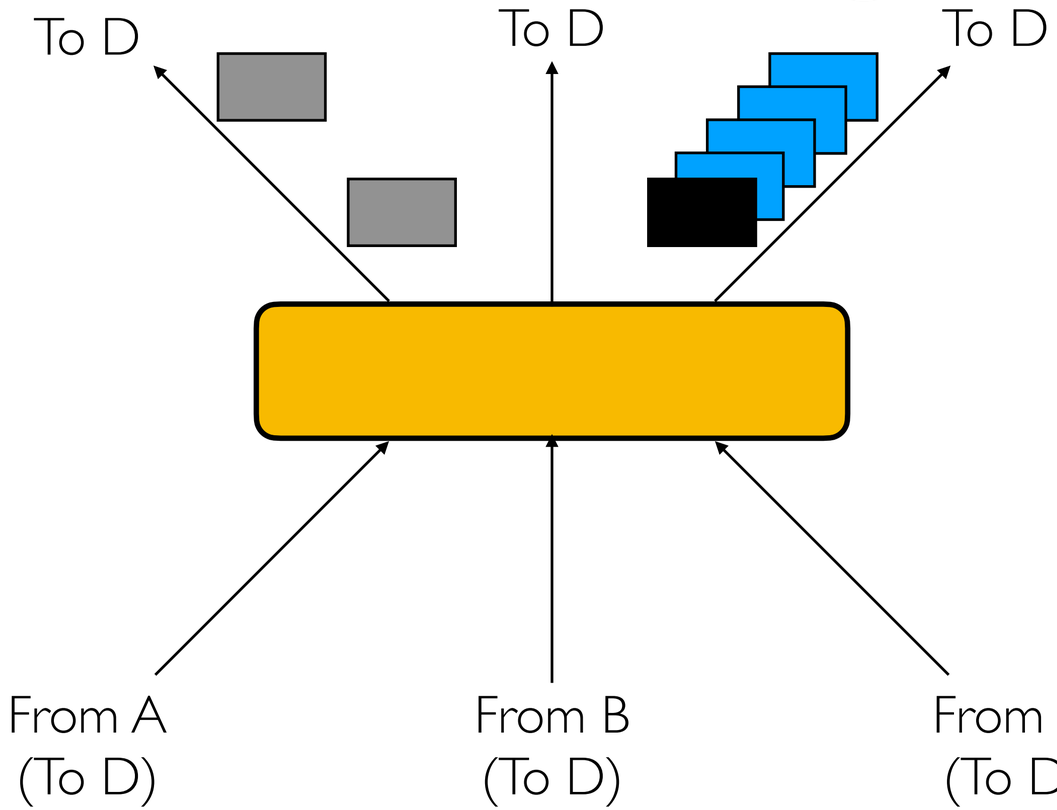


- **Per-*flow* load balancing (*ECMP, "Equal Cost Multi Path"*)**
  - E.g., based on HASH(srcAddr, dstAddr, srcPort, dstPort)

Forwarding



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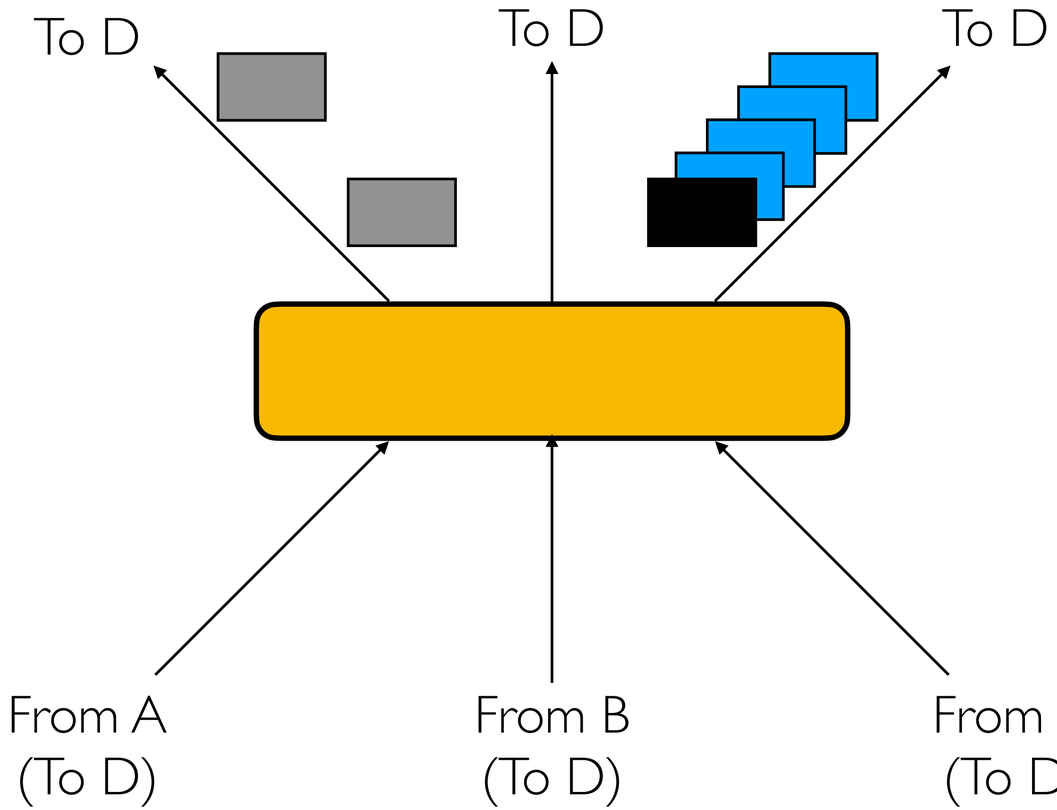

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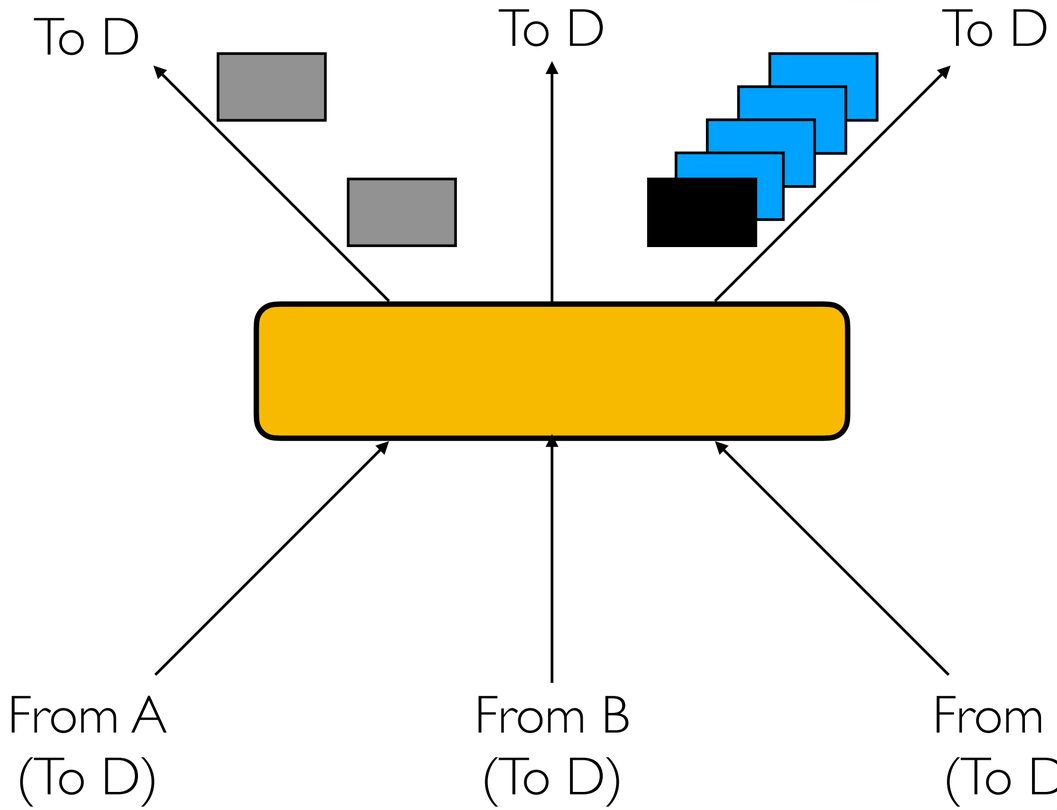

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  - Con: non-optimal load balancing; elephants are a problem

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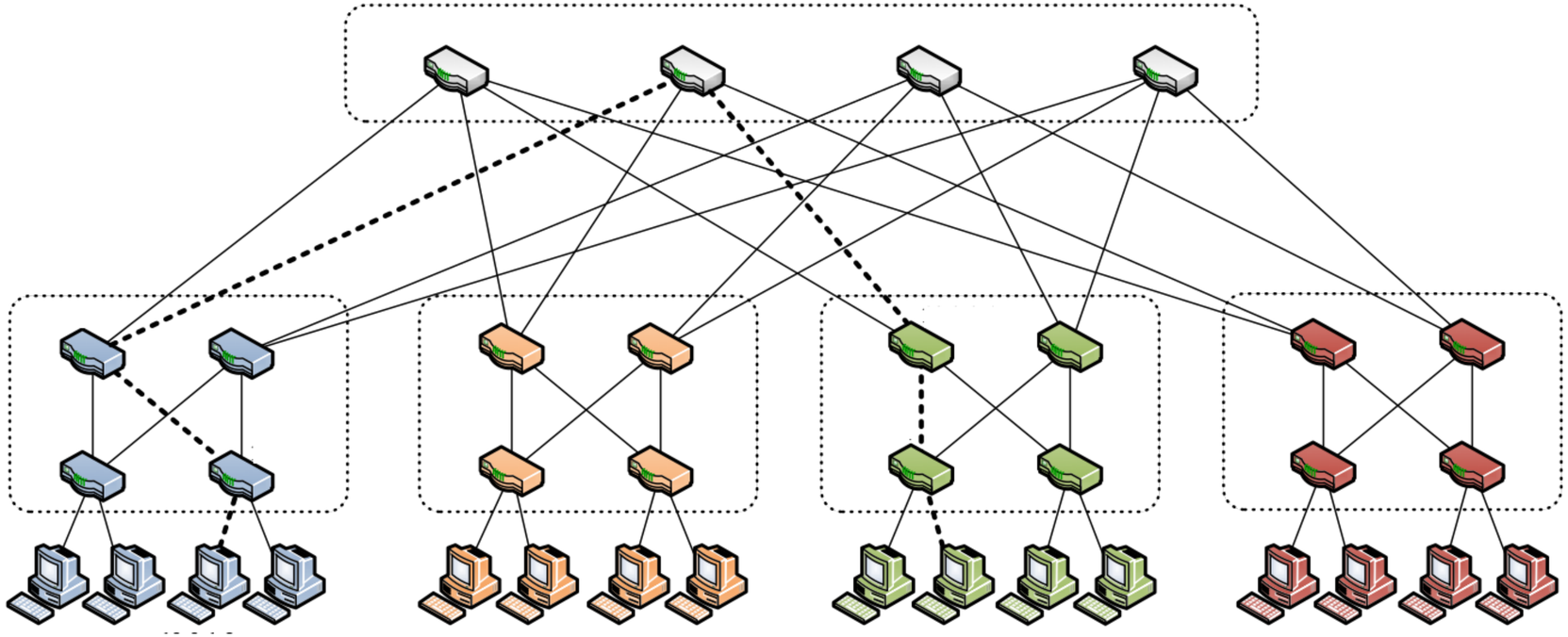
- **Problem: scales poorly**
  - With N destinations, O(N) routing entries and messages
  - N now in the millions!

Questions?

You: design a scalable routing solution

- Design for this specific topology



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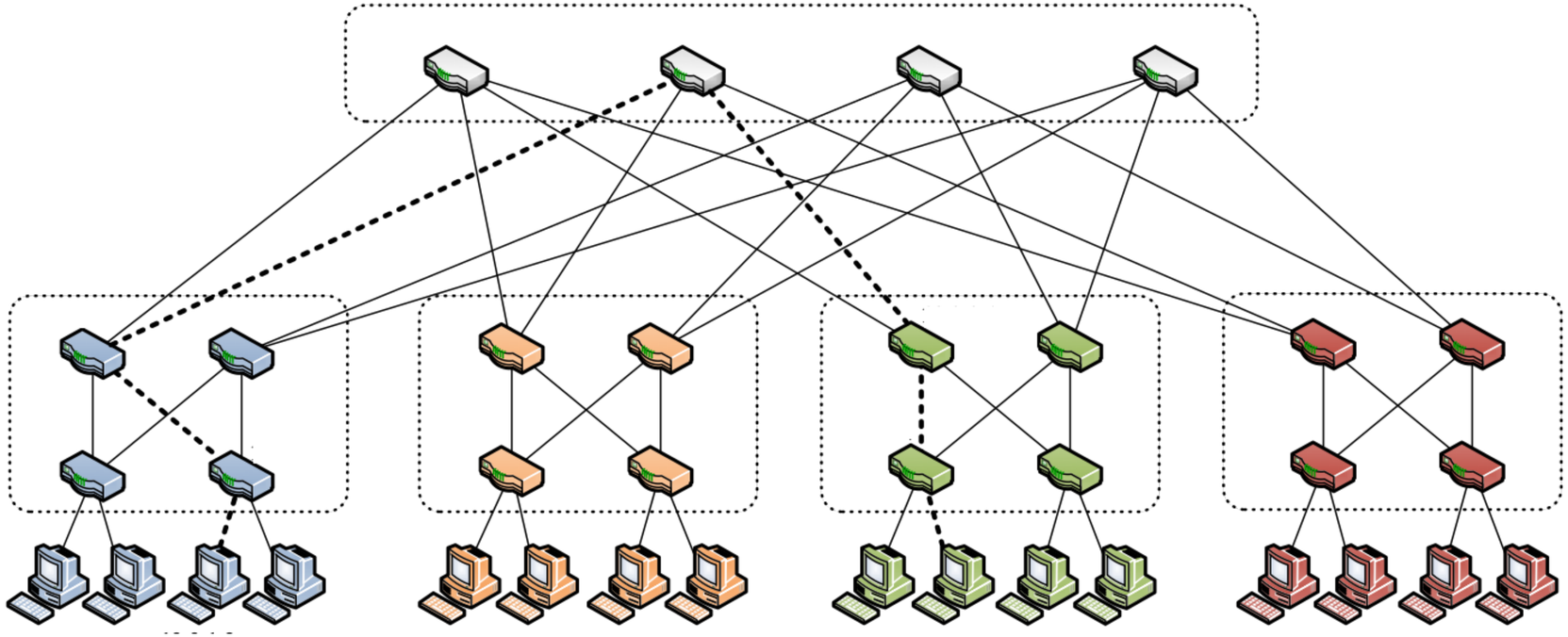
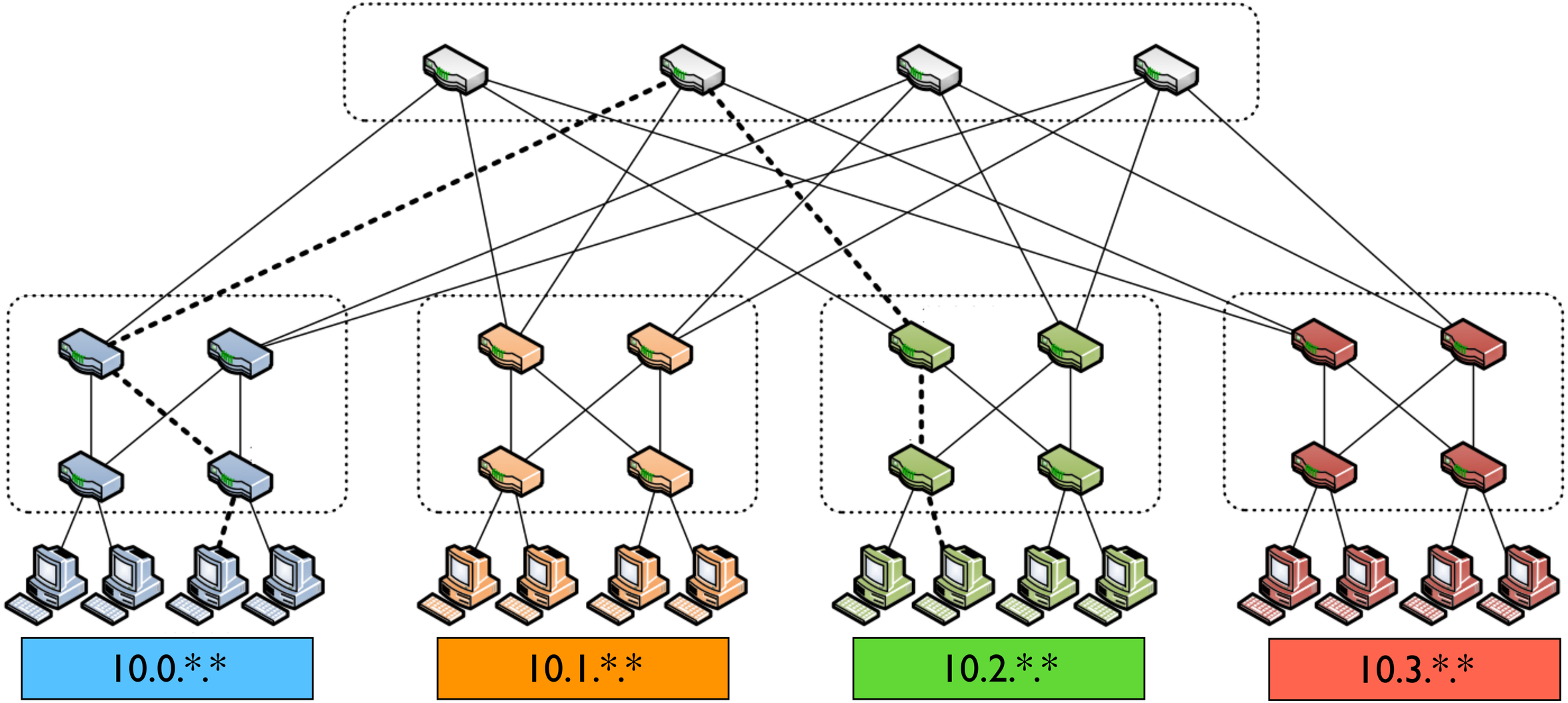


- **Take 3 minutes, then tell me:**
  - #routing entries per switch your solution needs
  - Many solutions possible; remember: you are now free from backward compatibility
    - Can redesign IP, routing algorithms, switch designs, etc.

Solution 1: Topology-aware addressing



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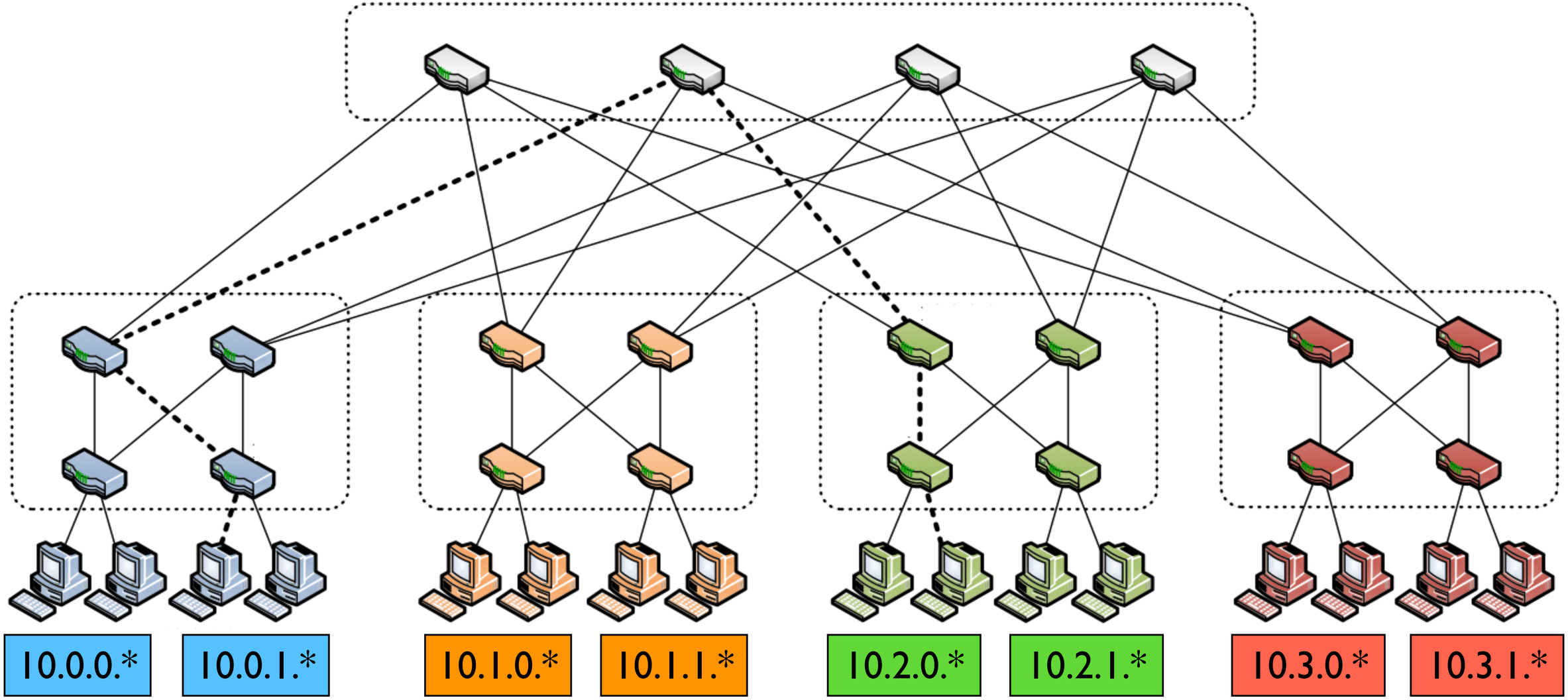

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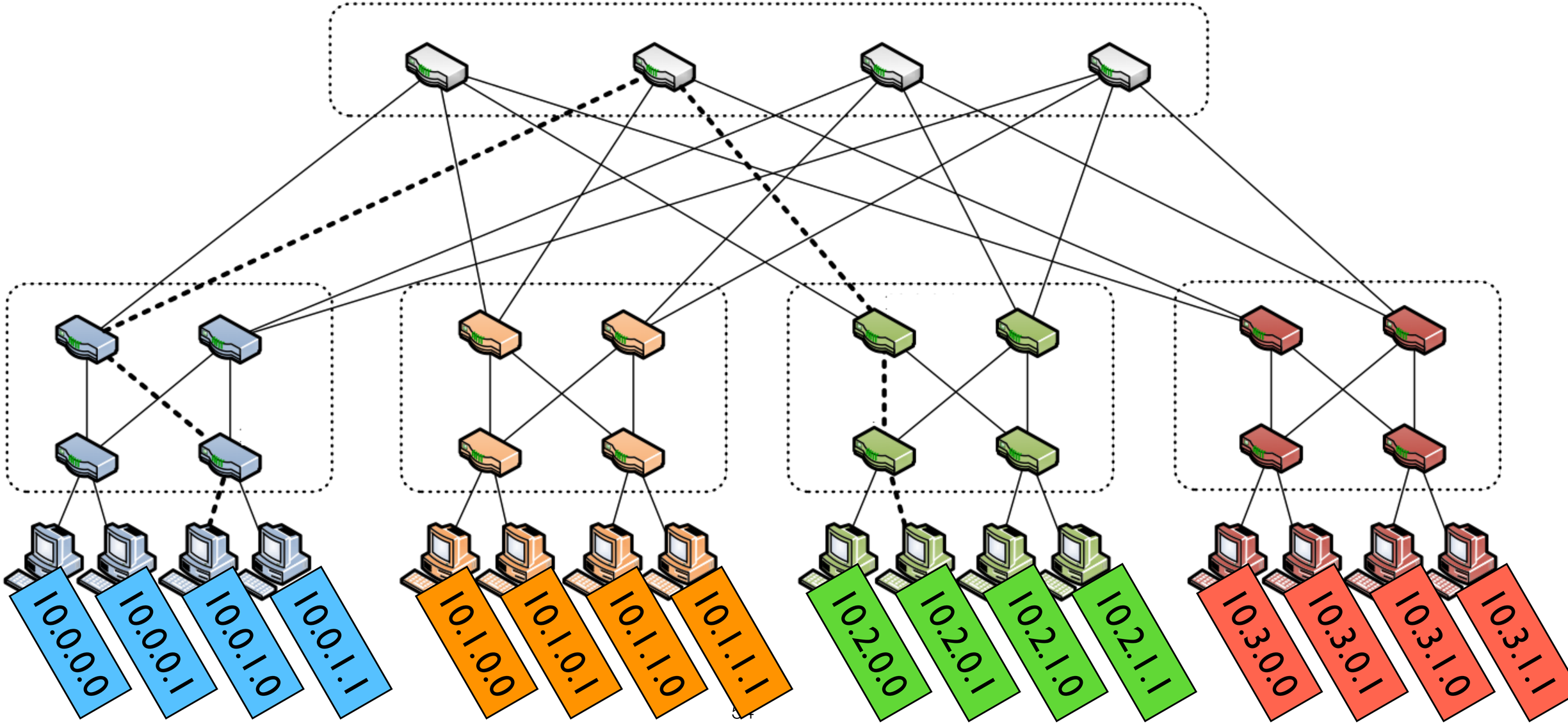

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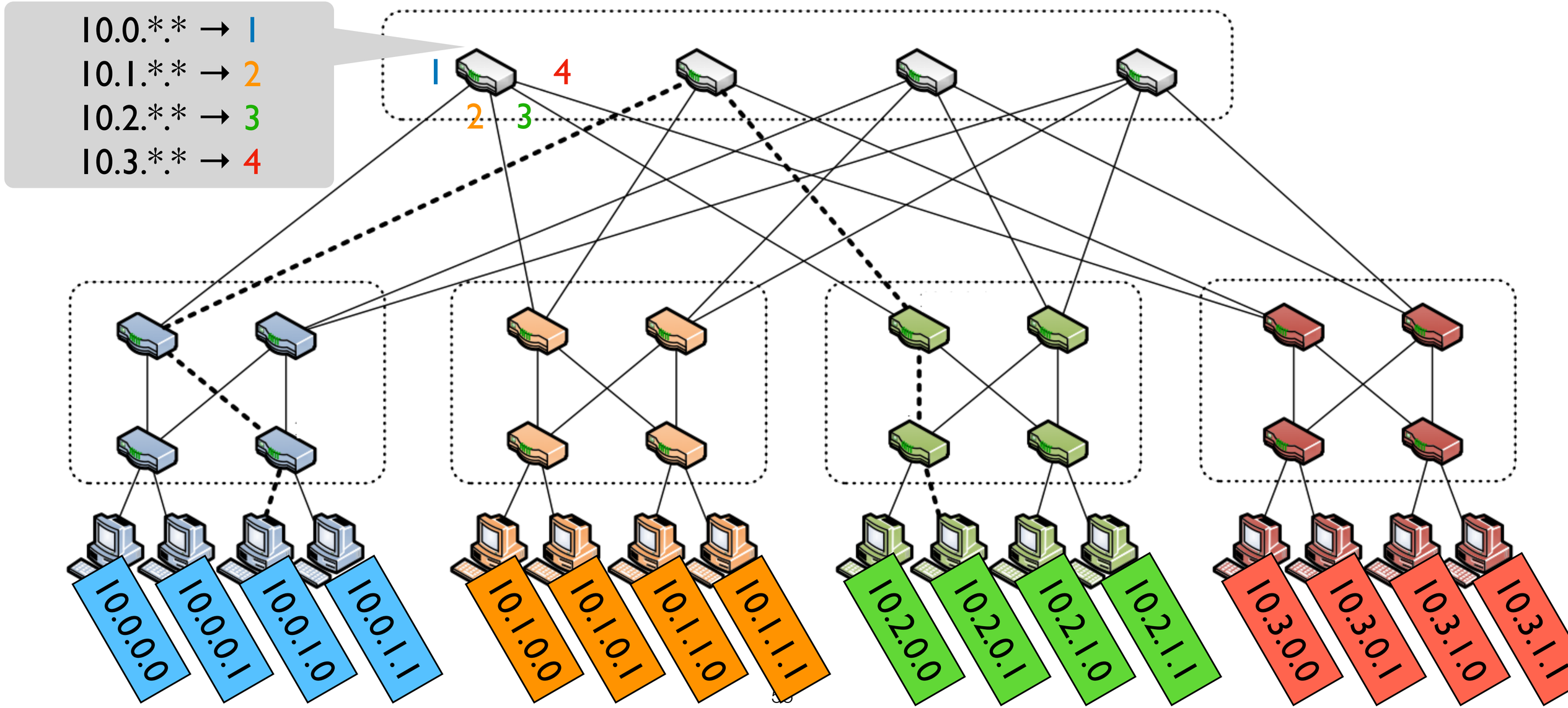

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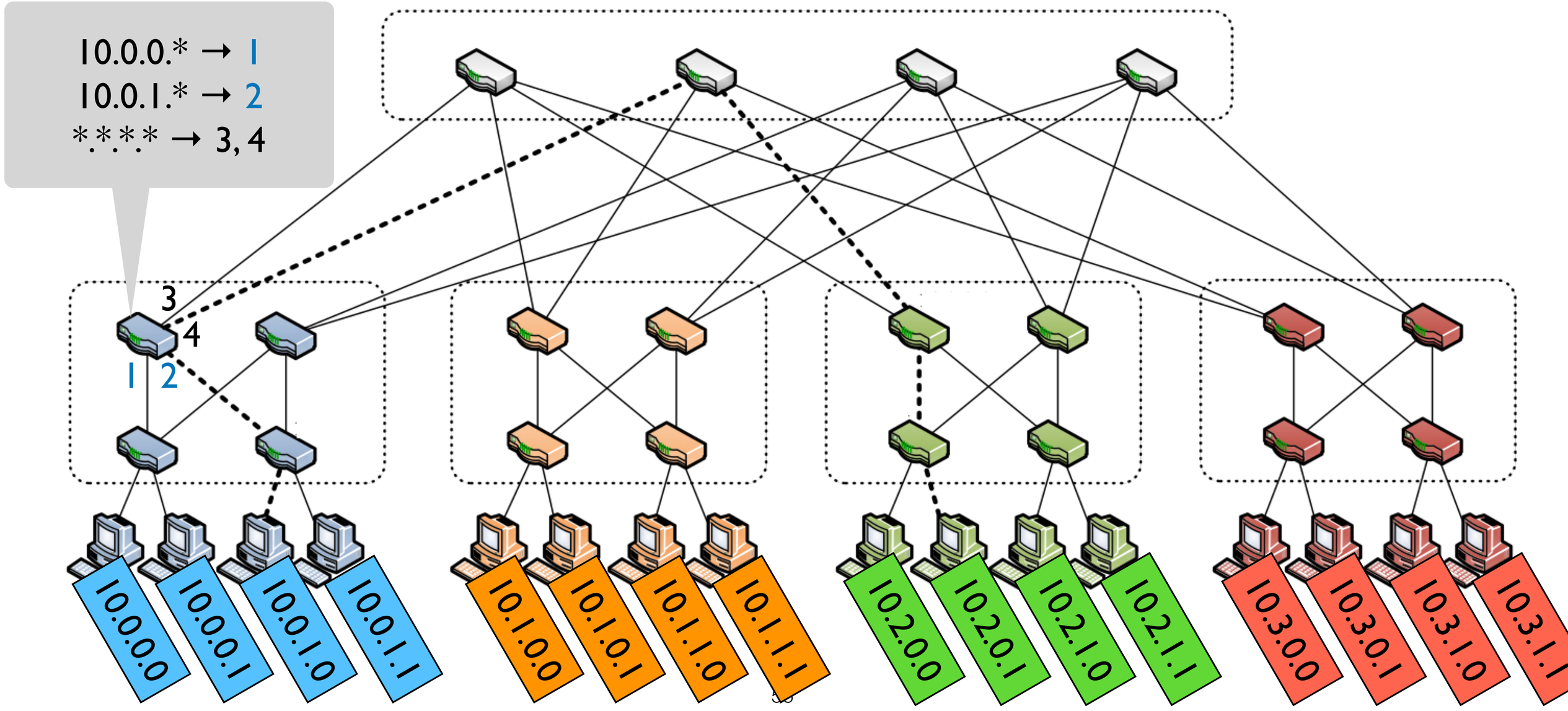

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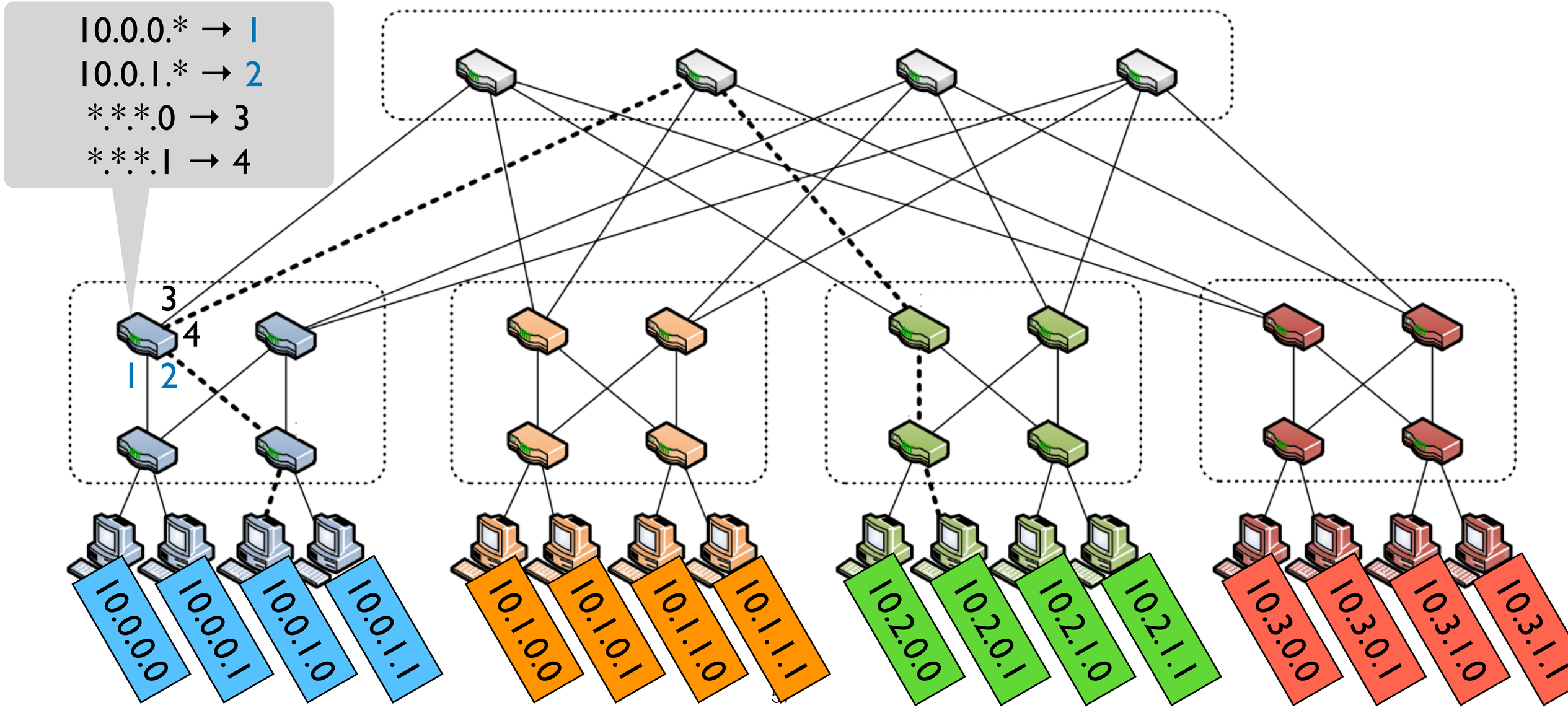

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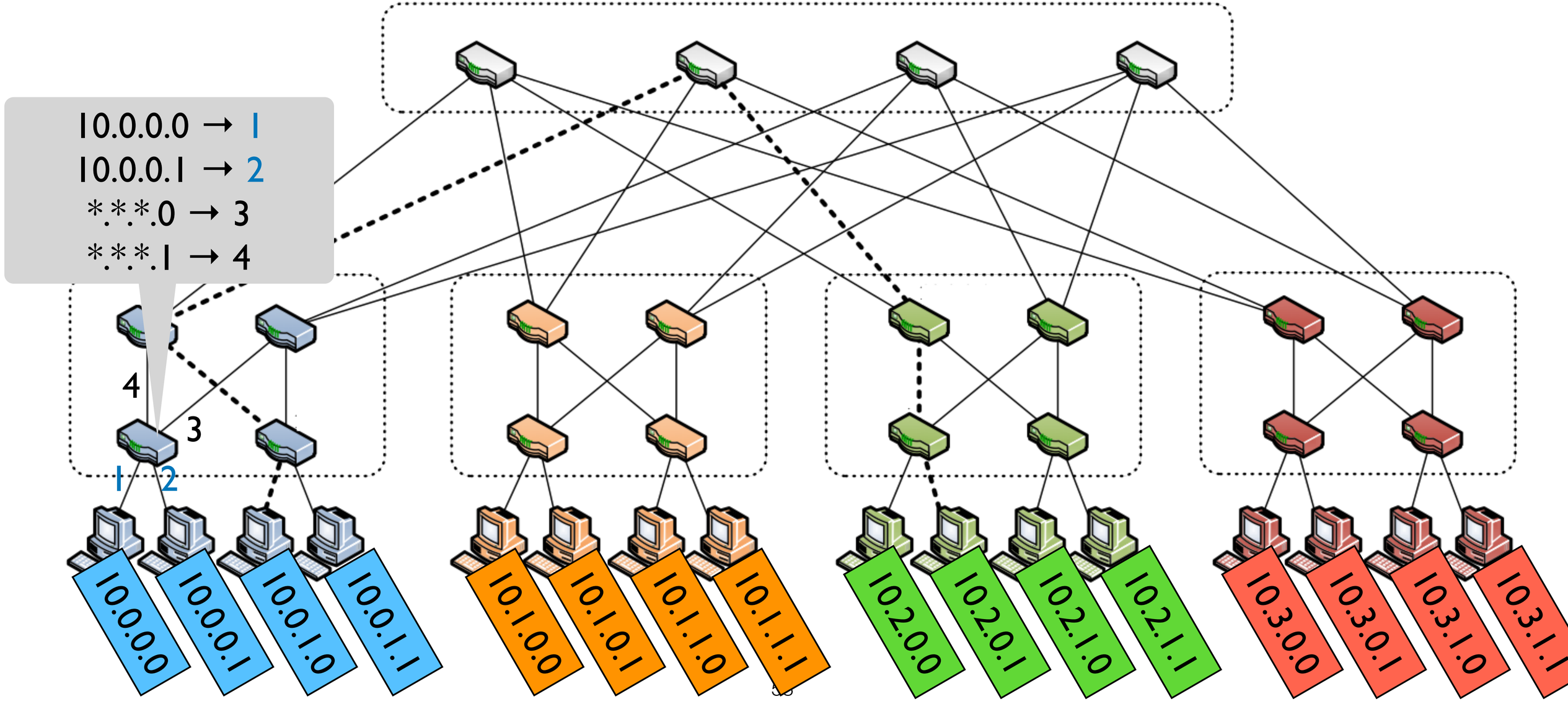

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- **Idea: addresses embed location in regular topology**
- **Maximum #entries/switch: *k* (=*4 in example*)**
  - Constant, independent of #destinations!
- **No route computation / messages / protocols**
  - Topology is "hard coded"
- **Problems?**
  - VM migration: ideally, VM keeps its IP address when it moves
  - Vulnerable to misconfiguration (in topology or addresses)

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  - E.g., header=[dst=D | index=0 | path={S5, S1, S2, S9}]
- Switch forwards based on packet header
  - index++; next-hop = path[index]

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- Cons:
  - Scalability / robustness of controller (SDN addresses this)
  - Clean-state design of everything

Questions?

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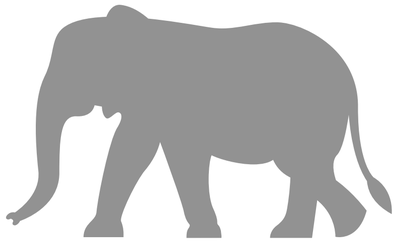
- **L4 design:**
  - Transport protocol design (w/ Fat-Tree)

Workloads

- **Partition/aggregate**
  - Query

- **Short messages [50KB-1MB]**
  - Coordination, control state

- **Large flows [1MB-50MB]**
  - Data update



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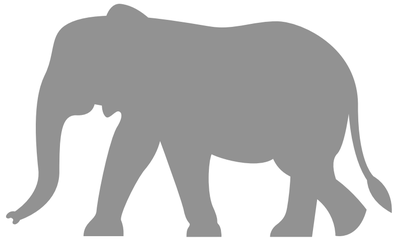

Throughput-sensitive

What's "Ideal"?

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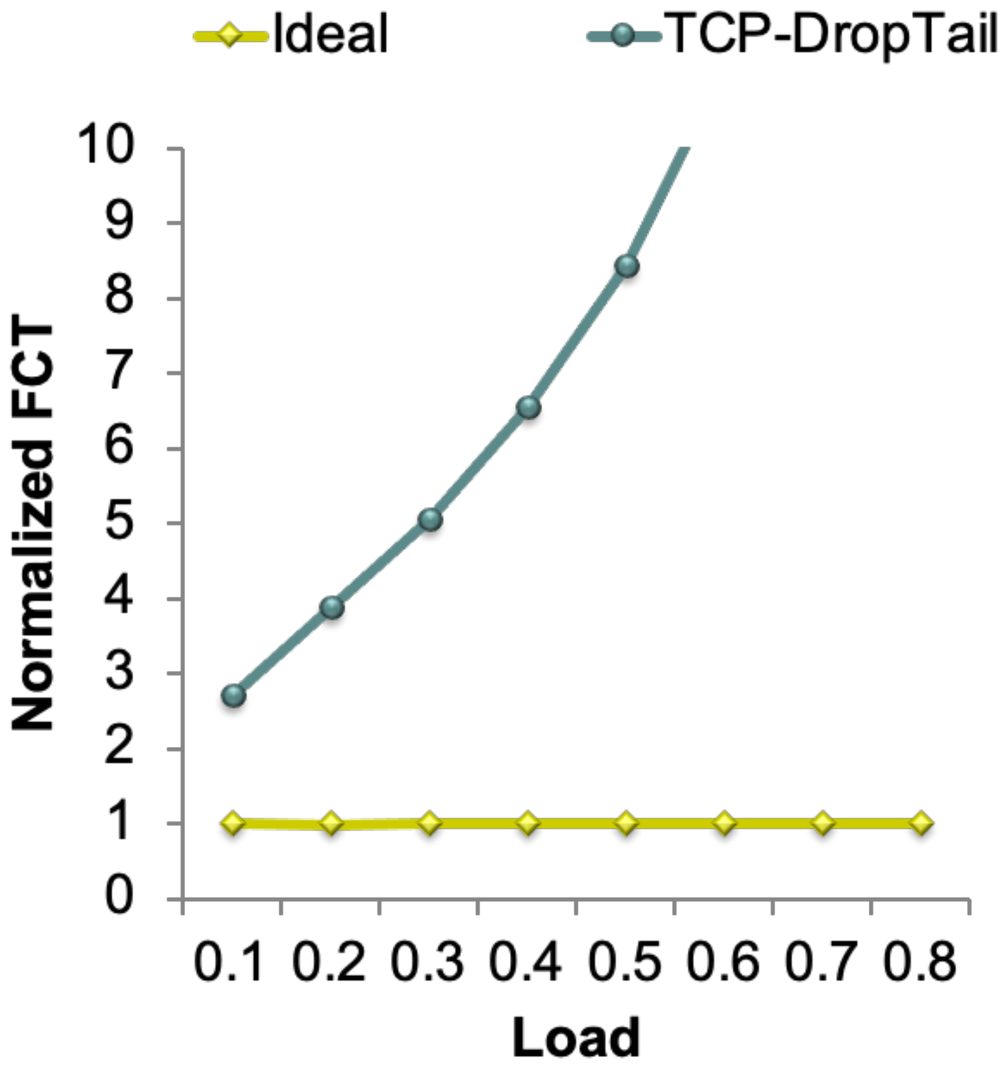
- **What is the best measure of performance for a data center transport protocol?**
  - When the flow is completely transferred?
  - Latency of each packet in the flow?
  - Number of packet drops?
  - Link utilization?
  - Average queue length at switches?

Flow Completion Time (FCT)

- Time from when flow started at the sender, to when all packets in the flow were at the receiver

FCT with TCP


Ideal
TCP-DropTail
Normalized FCT
10
9
8
7
6
5
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3
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1
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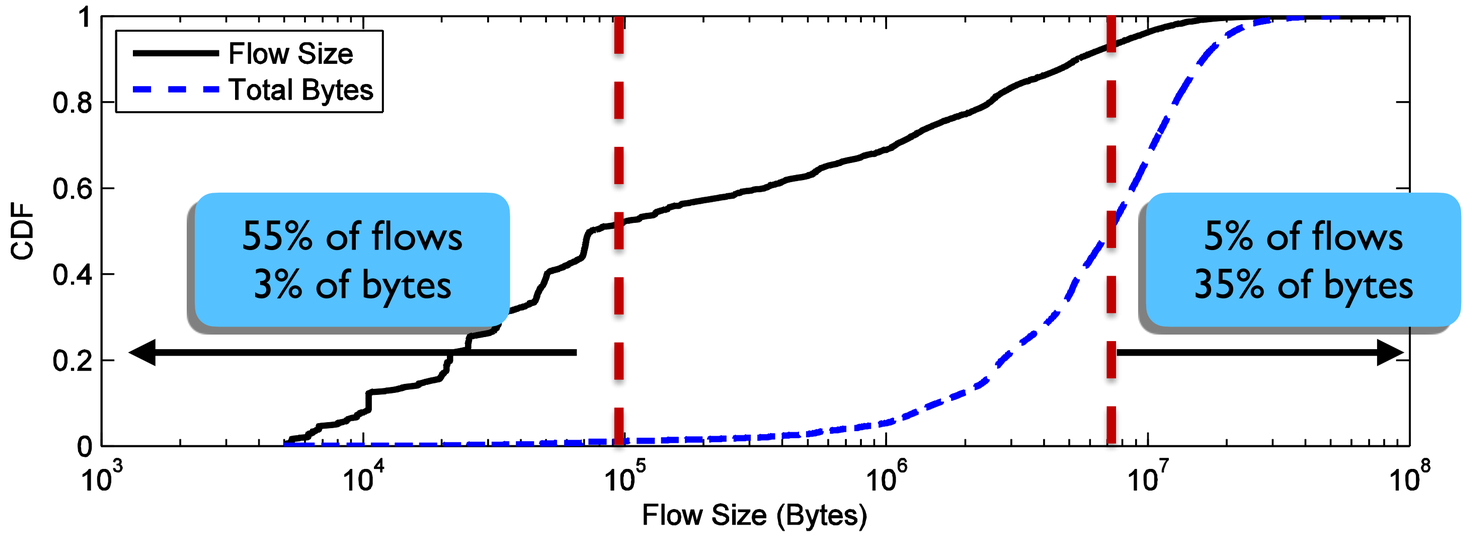
Load

Recall: "Elephants" and "Mice"

- Microsoft [Alizadeh et. al. 2010]
  - Web-search (north-south), data mining (east-west)



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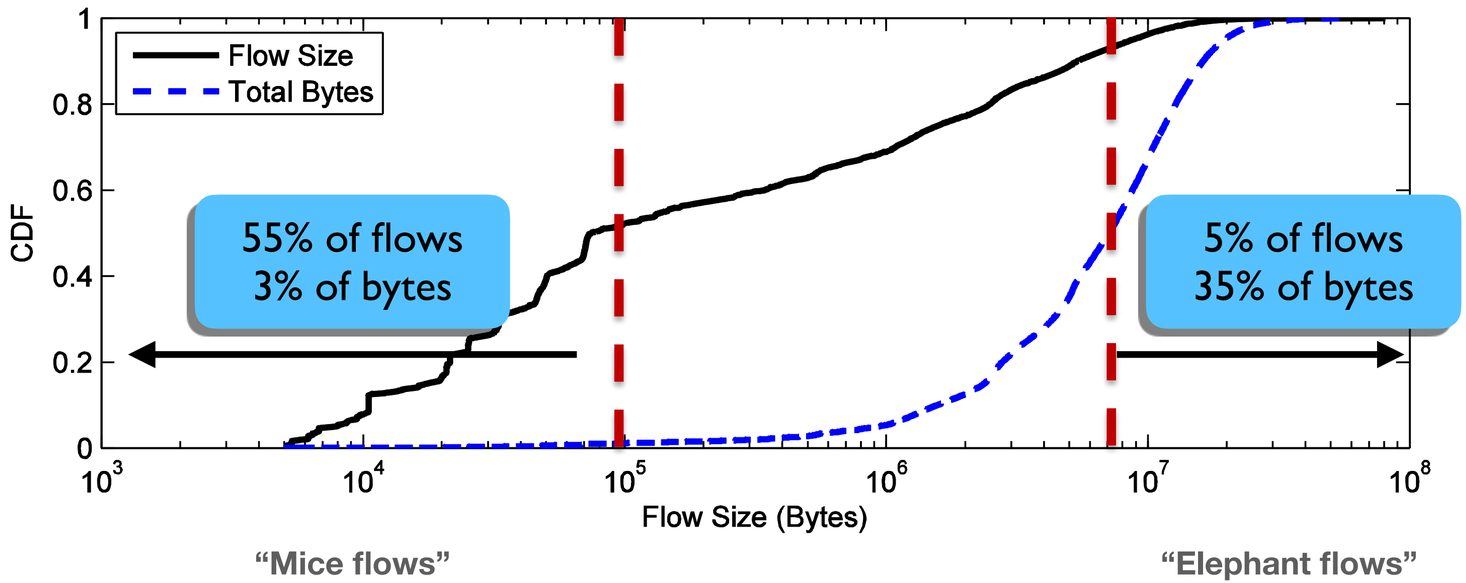

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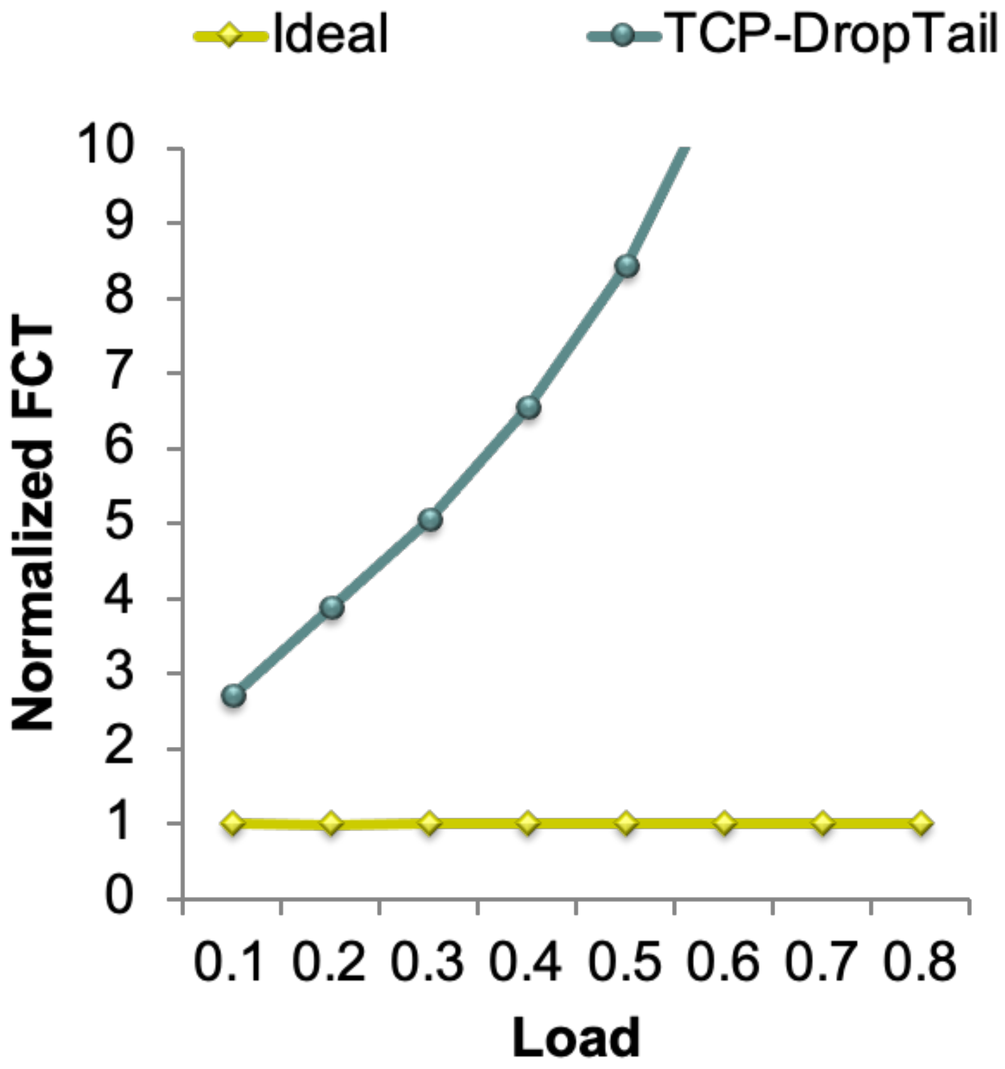

Problem: the mice are delayed by the elephants

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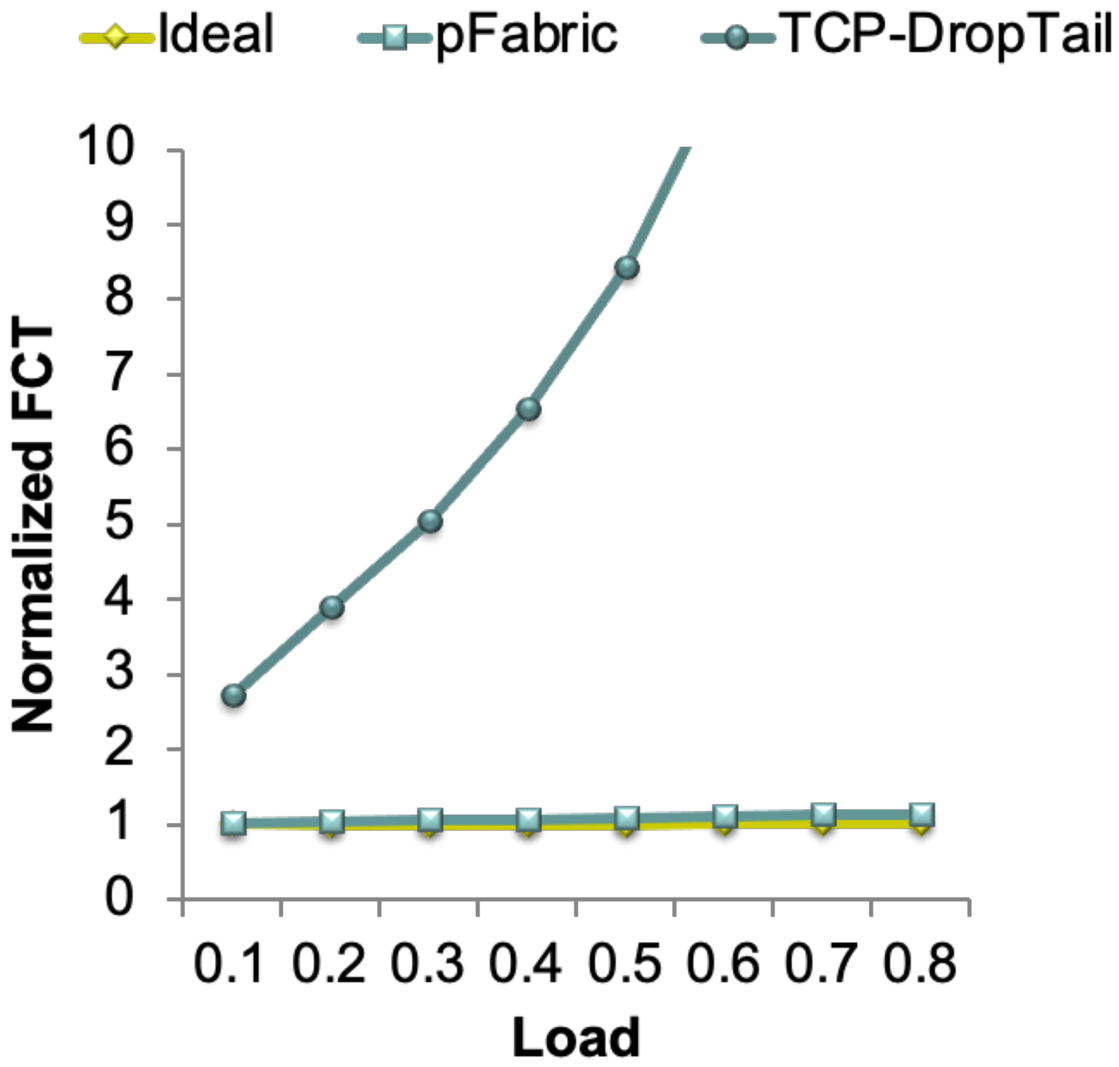
- **Servers**
  - Transmit/retransmit aggressively (at full link rate)
  - Drop transmission rate only under extreme loss (timeouts)

FCT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- Solution for a network of queues is NP-hard
- Setting priority=remaining flow size is a heuristic to approximate SJF

Questions?