EECS 489
Computer Networks

Winter 2025

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Material with thanks to Aditya Akella, Sugih Jamin, Philip Levis, Sylvia Ratnasamy, Peter Steenkiste, and many other colleagues.

Agenda

- Datacenter networking

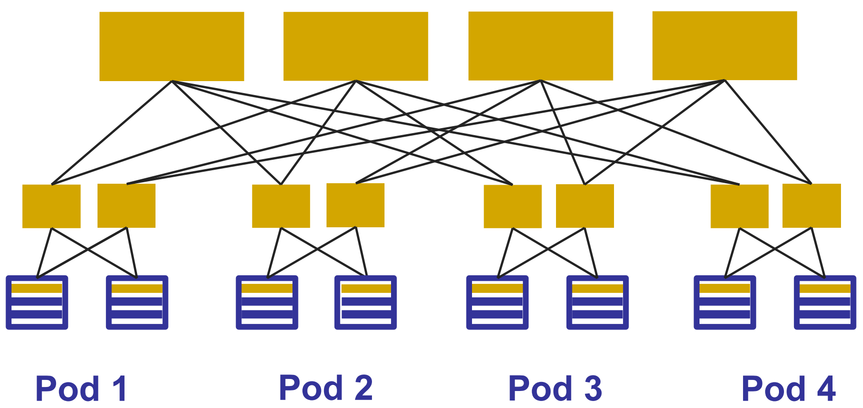
Recap: Datacenter network requirements

- High “bisection bandwidth”
- Low latency, even in the worst-case
- Large scale
- Low cost

Recap: Clos topology

- Multi-stage network
- k pods, where each pod has two layers of k/2 switches
  - k/2 ports up and k/2 down
- All links have the same b/w
- At most $k^3/4$ machines

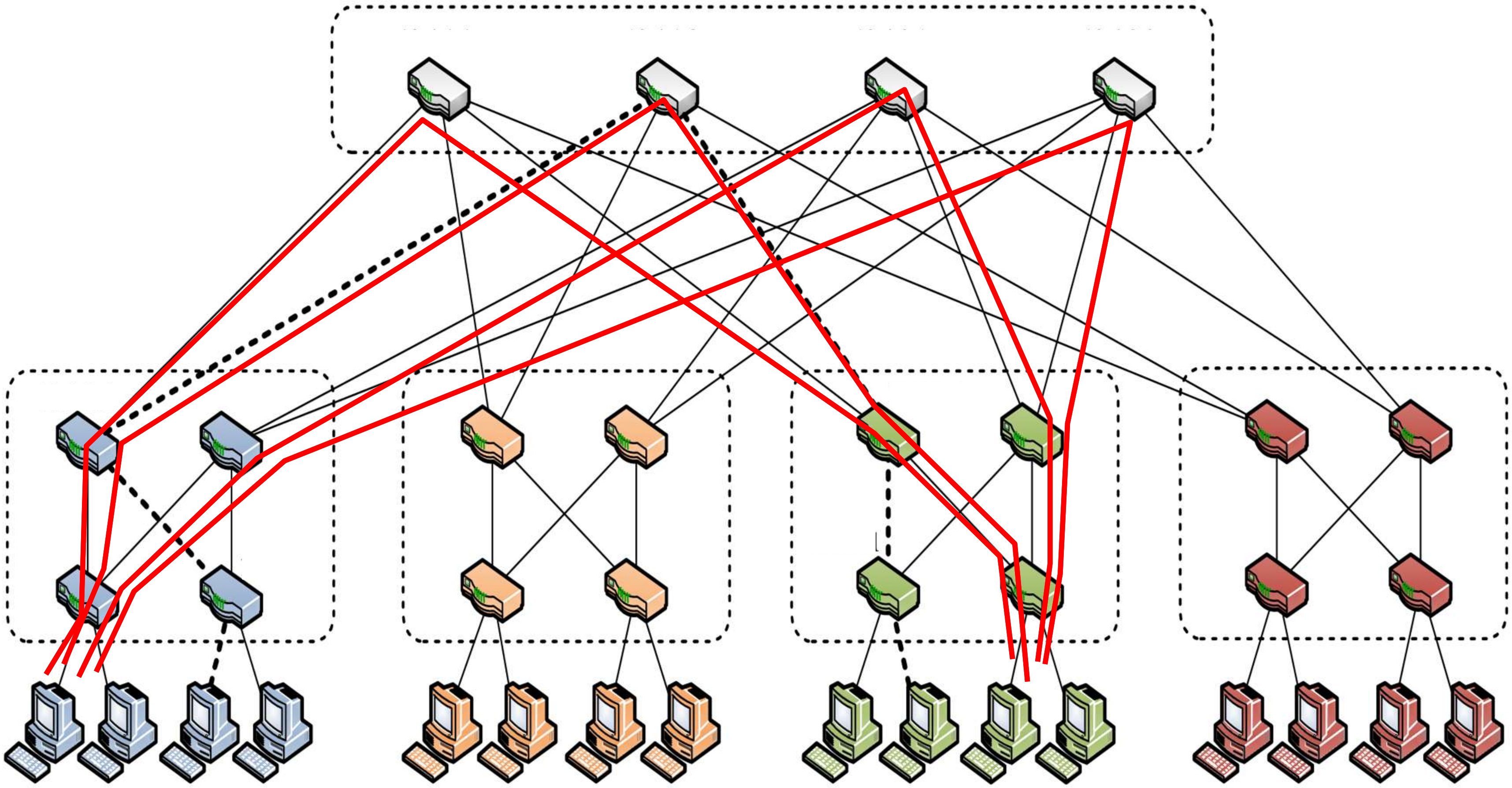
- Example
  - k = 4
  - 16 machines
- For k=48, 27648 machines



Agenda

- Networking in modern datacenters
  - L2/L3 design
    - Addressing / routing / forwarding in the Fat-Tree
  - L4 design
    - Transport protocol design (w/ Fat-Tree)
  - L7 design
    - Exploiting application-level information (w/ Fat-Tree)

Using multiple paths well



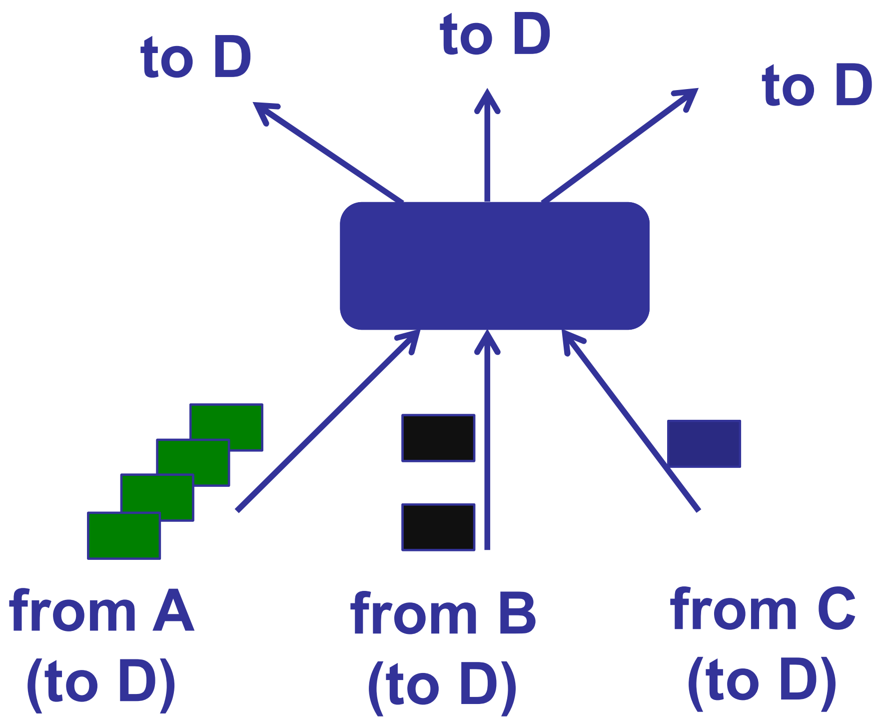
L2/L3 design goals

- Routing protocol must expose all available paths
- Forwarding must spread traffic evenly over all paths

Extend DV / LS ?

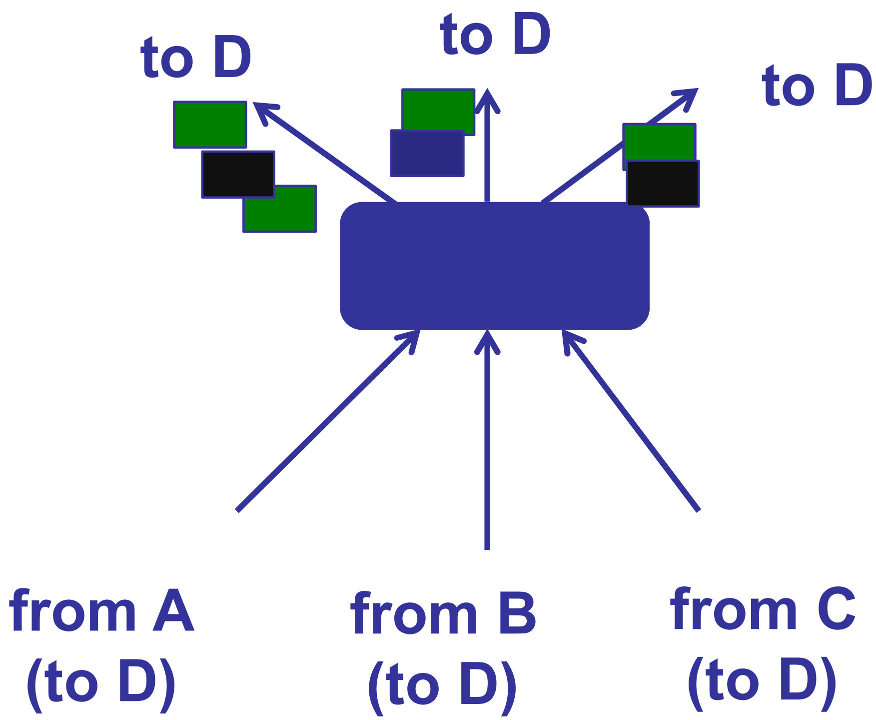
- Routing
  - Distance-Vector: Remember all next-hops that advertise equal cost to a destination
  - Link-State: Extend Dijkstra’s to compute all equal cost shortest paths to each destination
- Forwarding: how to spread traffic across next hops?

Forwarding



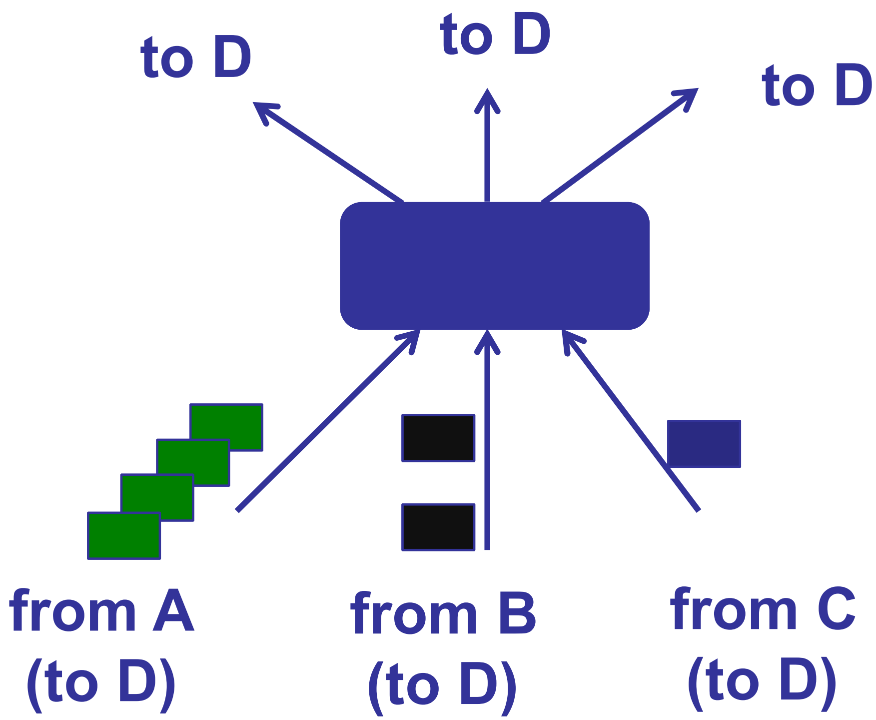
- Per-packet load balancing

Forwarding



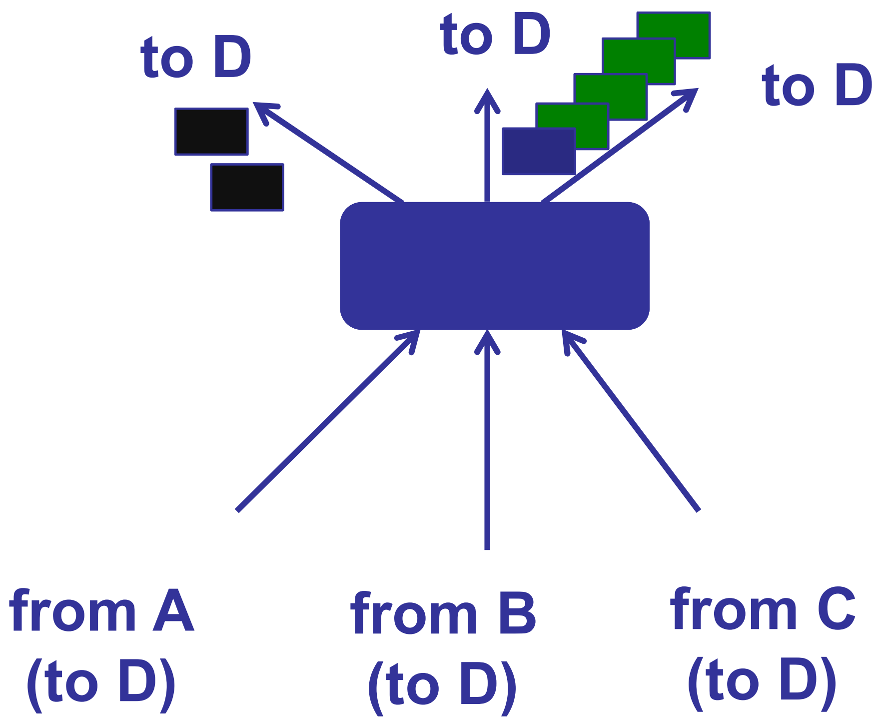
- Per-packet load balancing
  - Traffic well spread (even w/ elephant flows)
  - BUT Interacts poorly w/ TCP

Forwarding



- Per-flow load balancing (ECMP, “Equal Cost Multi Path”)
  - E.g., based on (src and dst IP and port)

Forwarding

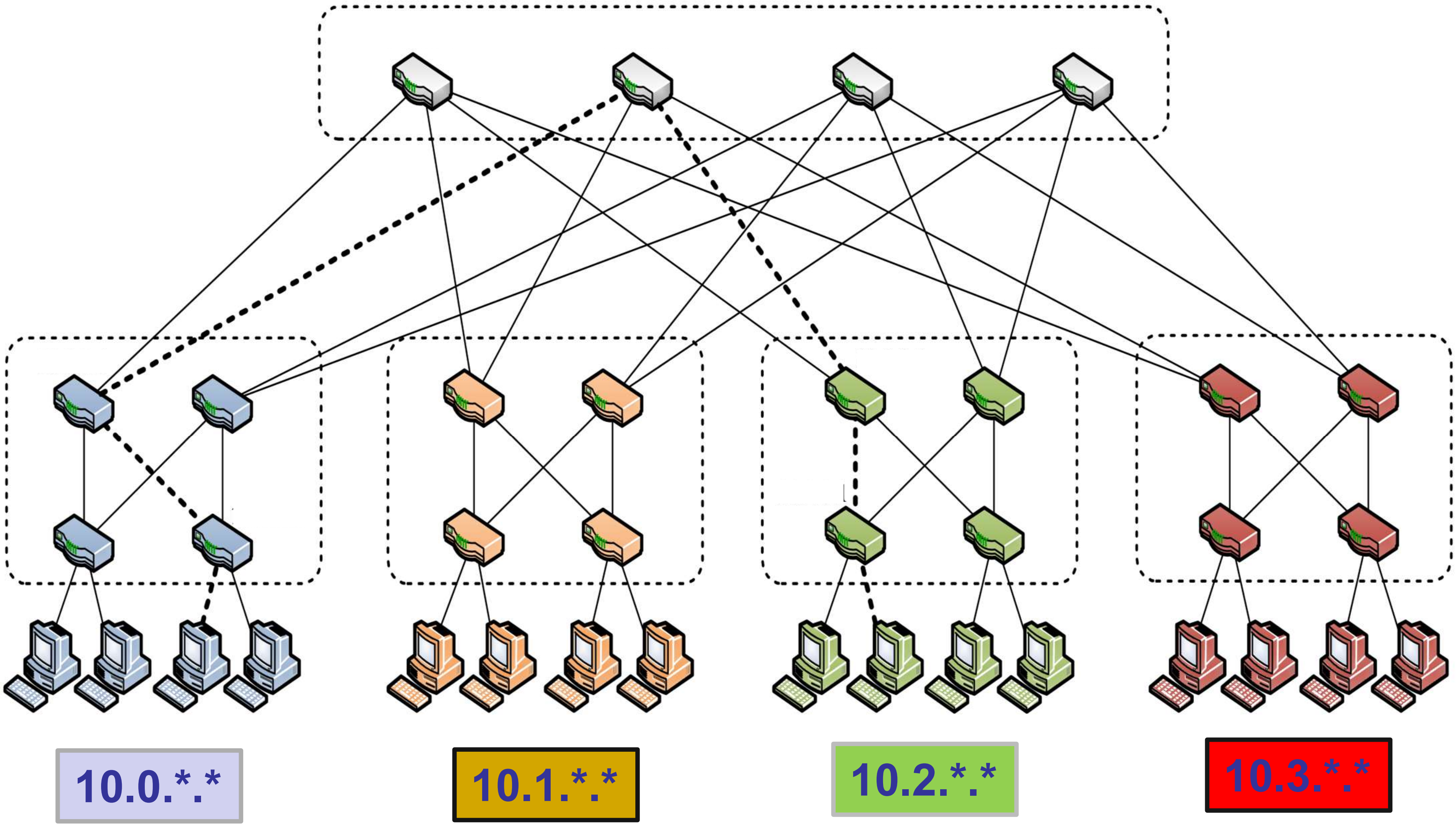


- Per-flow load balancing (ECMP)
  - A flow follows a single path (→ TCP is happy)
  - Suboptimal load-balancing; elephants are a problem

Extend DV / LS ?

- How:
  - Simple extensions to DV/LS
  - ECMP for load balancing
- Benefits
  - Simple; reuses existing solutions
- Problem: poor scaling
  - With N destinations, O(N) routing entries and messages
  - N now in the millions!

Solution 1: Topology-aware addressing



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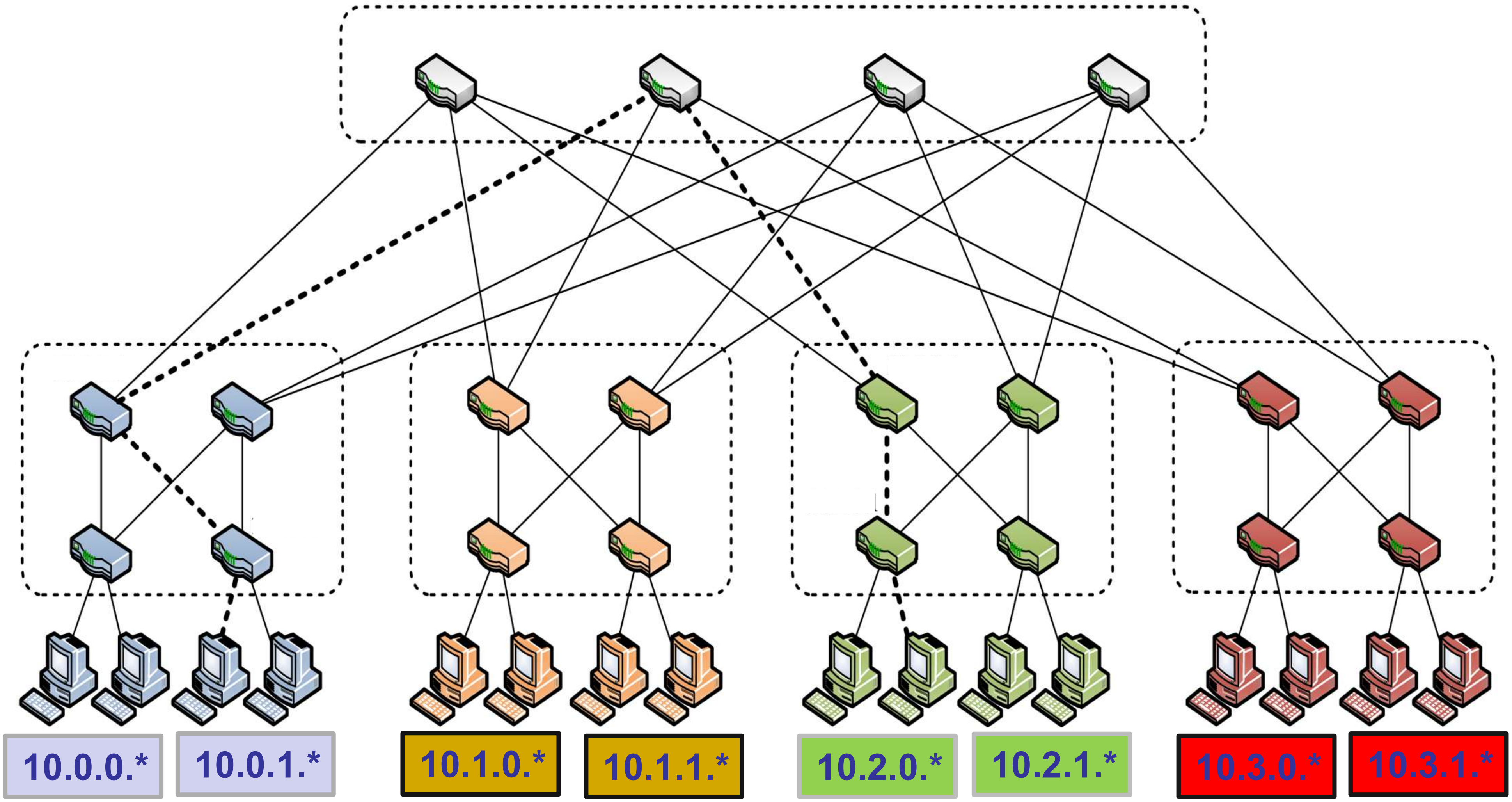

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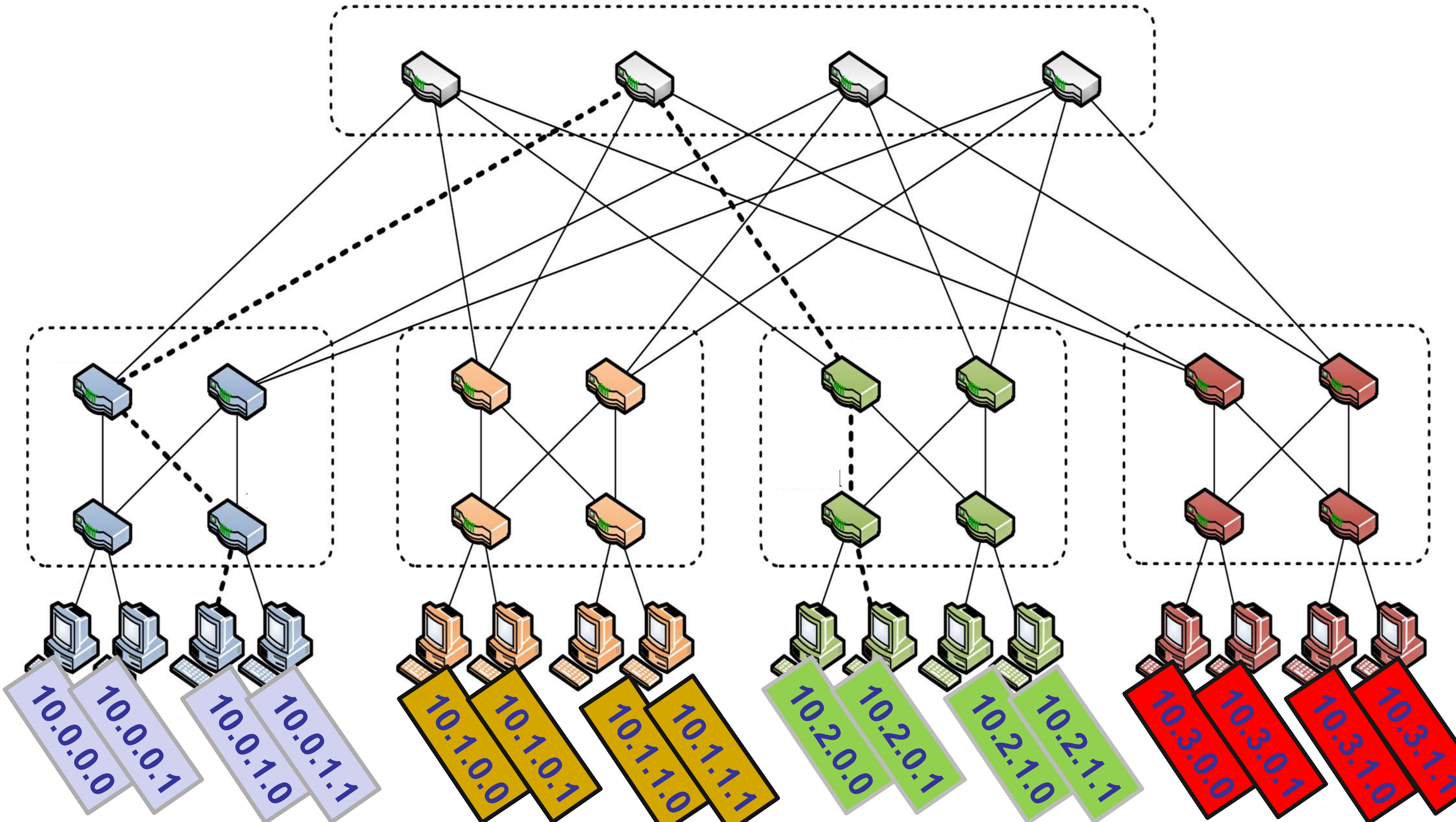

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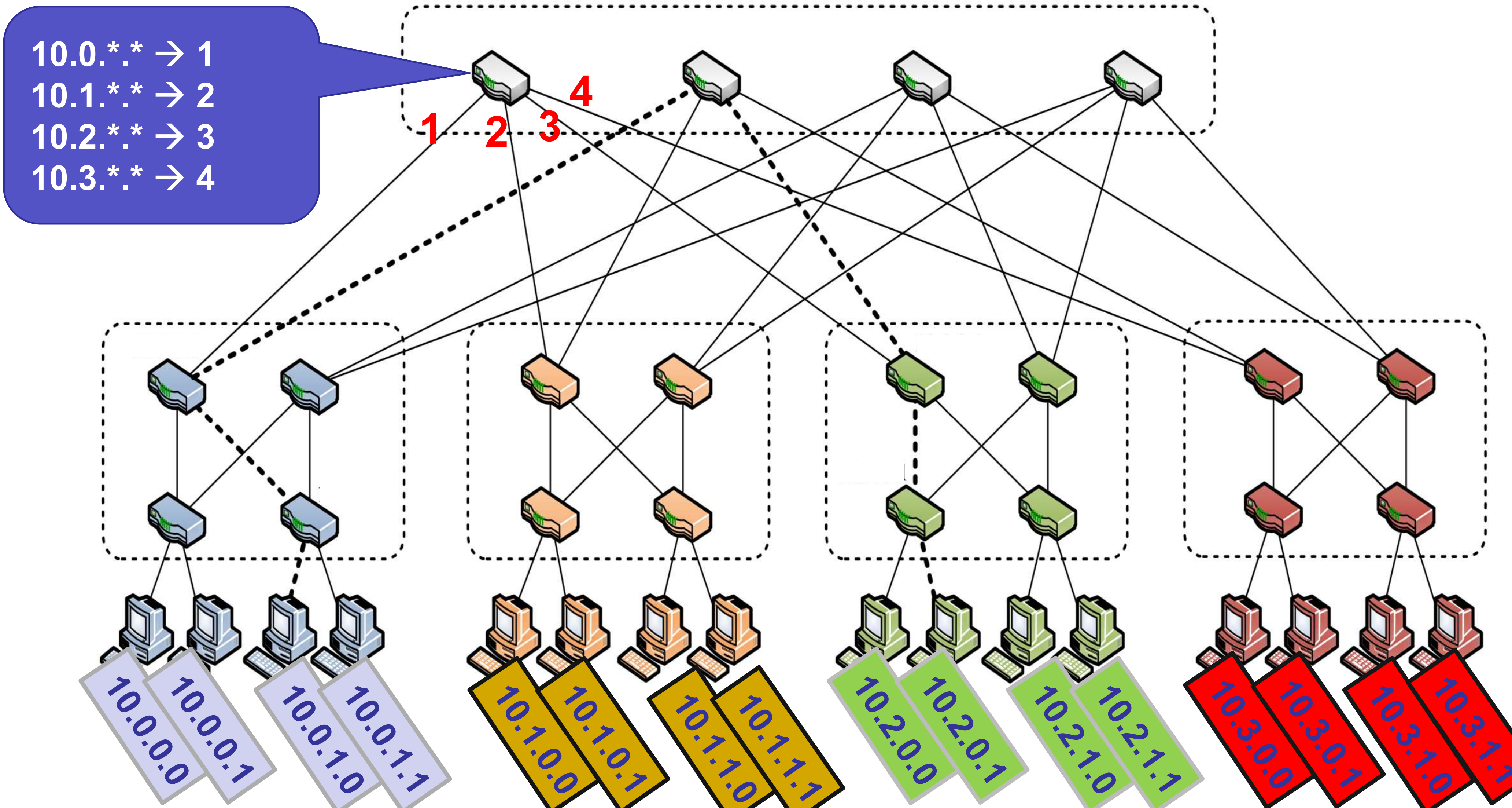

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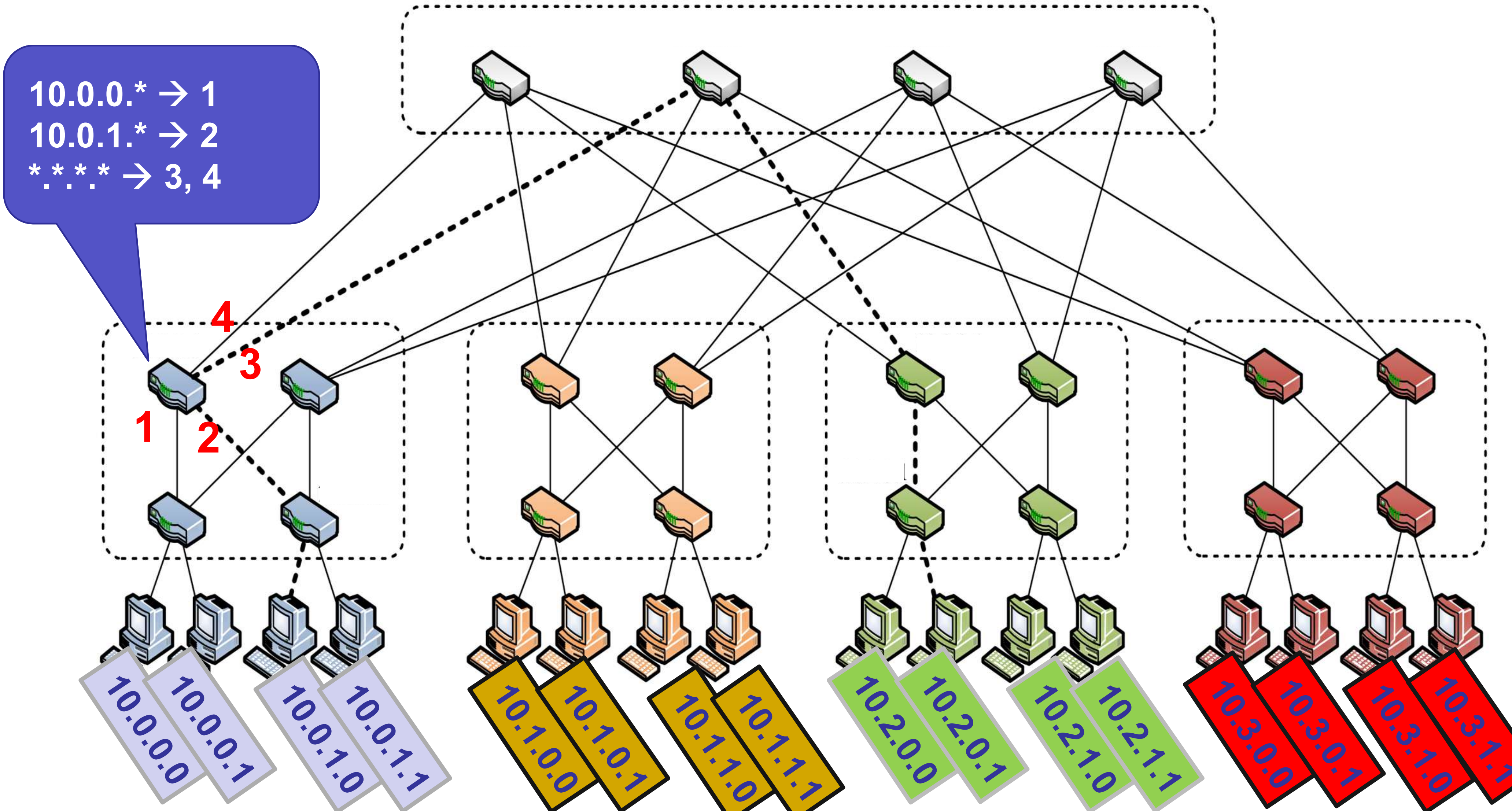

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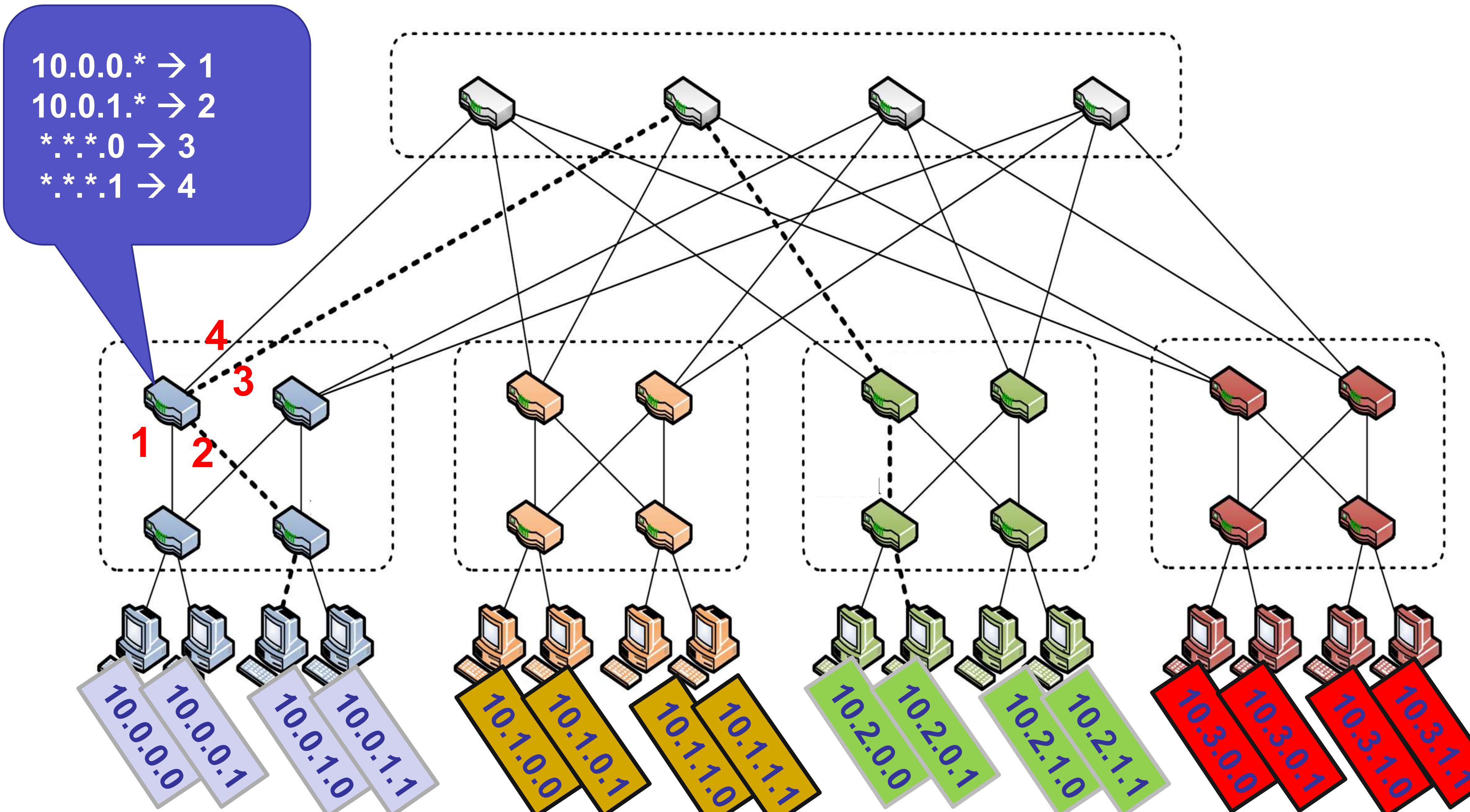

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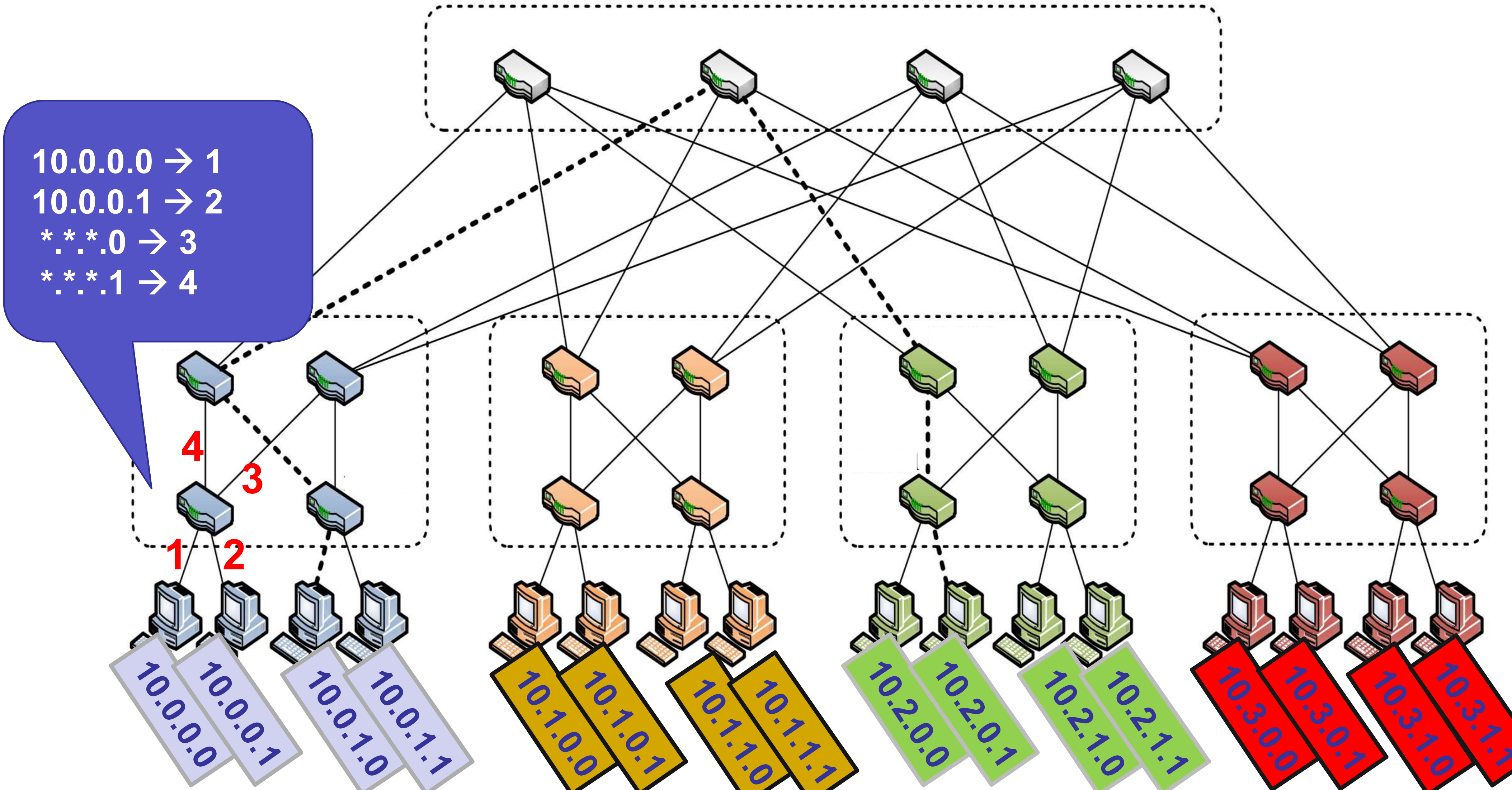

Solution 1: Topology-aware addressing

- 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, but still need localized link failure detection
- Problems?
  - VM migration: ideally, VM keeps its IP address when it moves
  - Vulnerable to (topology/addresses) misconfiguration

Solution 2: Centralize + Source routes

- Centralized "controller" server knows topology and computes routes
- Controller hands server all paths to each destination
  - O(#destinations) state per server, but server memory cheap (e.g., 1M routes x 100B/route=100MB)
- Server inserts entire path vector into packet header ("source routing")
  - E.g., header=[dst=D | index=0 | path={S5,S1,S2,S9}]
- Switch forwards based on packet header
  - index++; next-hop = path[index]

Solution 2: Centralize + Source routes

- #entries per switch?
  - None!
- #routing messages?
  - Akin to a broadcast from controller to all servers
- Pro:
  - Switches very simple and scalable
  - Flexibility: end-points control route selection
- Cons:
  - Scalability / robustness of controller (SDN issue)
  - Clean-slate design of everything

5-MINUTE BREAK!

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Workloads

- Partition-Aggregate traffic from user-facing queries
  - Numerous short flows with small traffic footprint
  - Latency-sensitive
- Map-Reduce traffic from data analytics
  - Comparatively fewer large flows with massive traffic footprint
  - Throughput-sensitive

Tension between requirements

High throughput

- Deep queues at switches
  - Queueing delays increase latency

Low latency

- Shallow queues at switches
  - Bad for bursts and throughput

Objective:
Low Queue Occupancy & High Throughput

Data Center TCP (DCTCP)

- Proposal from Microsoft Research, 2010
  - Incremental fixes to TCP for DC environments
  - Deployed in Microsoft datacenters (~rumor)
- Leverages Explicit Congestion Notification (ECN)

Recap: Explicit Congestion Notification (ECN)

- Defined in RFC 3168 using ToS/DSCP bits in the IP header
- Single bit in packet header; set by congested routers
  - If data packet has bit set, then ACK has ECN bit set
- Routers typically set ECN bit based on average queue length
- Congestion semantics exactly like that of drop
  - I.e., sender reacts as though it saw a drop

DCTCP: Key ideas

- React early, quickly, and with certainty using ECN
- React in proportion to the extent of congestion, not its presence

ECN Marks	TCP	DCTCP
1 0 1 1 1 1 0 1 1 1	Cut window by 50%	Cut window by 40%
0 0 0 0 0 0 0 0 0 1	Cut window by 50%	Cut window by 5%

Actions due to DCTCP

- At the switch
  - If instantaneous queue length > k
    - Set ECN bit in the packet
- At the receiver
  - If ECN bit is set in a packet, set ECN bit for its ACK
- At the sender
  - Maintain an EWMA of the fraction of packets marked (α)
  - Adapt window based on α: $W \leftarrow (1 - \alpha/2)\, W$
  - $\alpha = 1$ implies high congestion: $W \leftarrow W/2$ (like TCP)

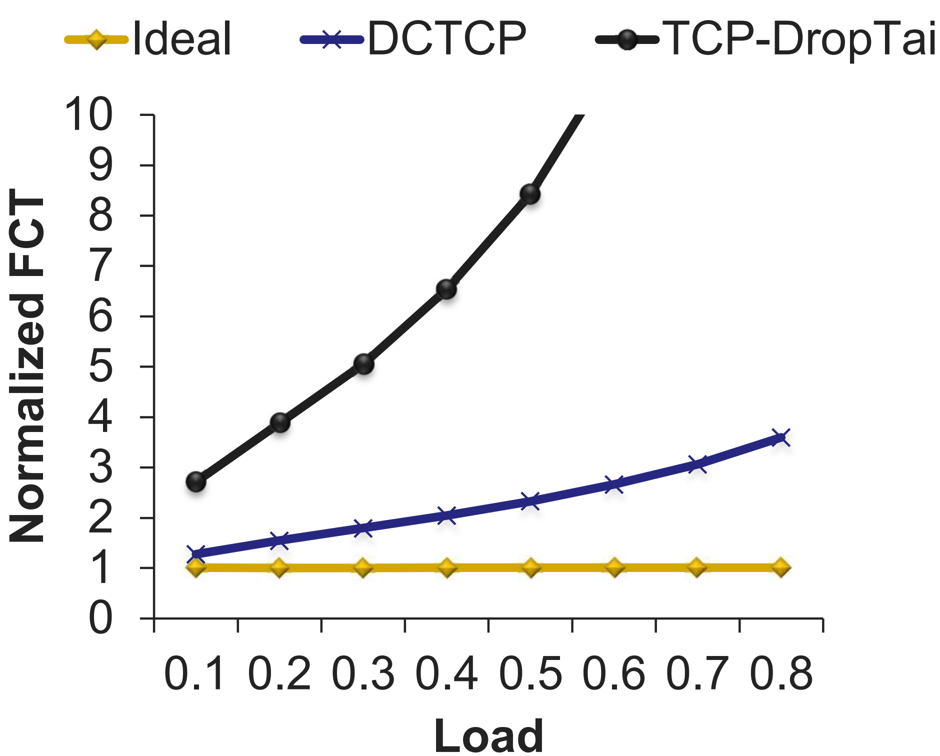
DCTCP: Why it works

- React early and quickly: use ECN
  - Avoid large buildup in queues → lower latency
- React in proportion to the extent of congestion, not its presence
  - Maintain high throughput by not over-reacting to congestion
  - Reduces variance in sending rates, lowering queue buildups
- Still far from ideal

Flow Completion Time (FCT)

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

FCT with DCTCP



Queues are still shared ⇒ Head-of-line blocking

Solution: Use priorities!

- Packets carry a single priority number
  - Priority = remaining flow size
- Switches
  - Very small queues (e.g., 10 packets)
  - Send highest-priority/ drop lowest-priority packet
- Servers
  - Transmit/retransmit aggressively (at full link rate)
  - Drop transmission rate only under extreme loss (timeouts)
- Provides FCT close to the ideal

Are we there yet?

- Nope!
- Someone asked “What do datacenter applications *really* care about?”

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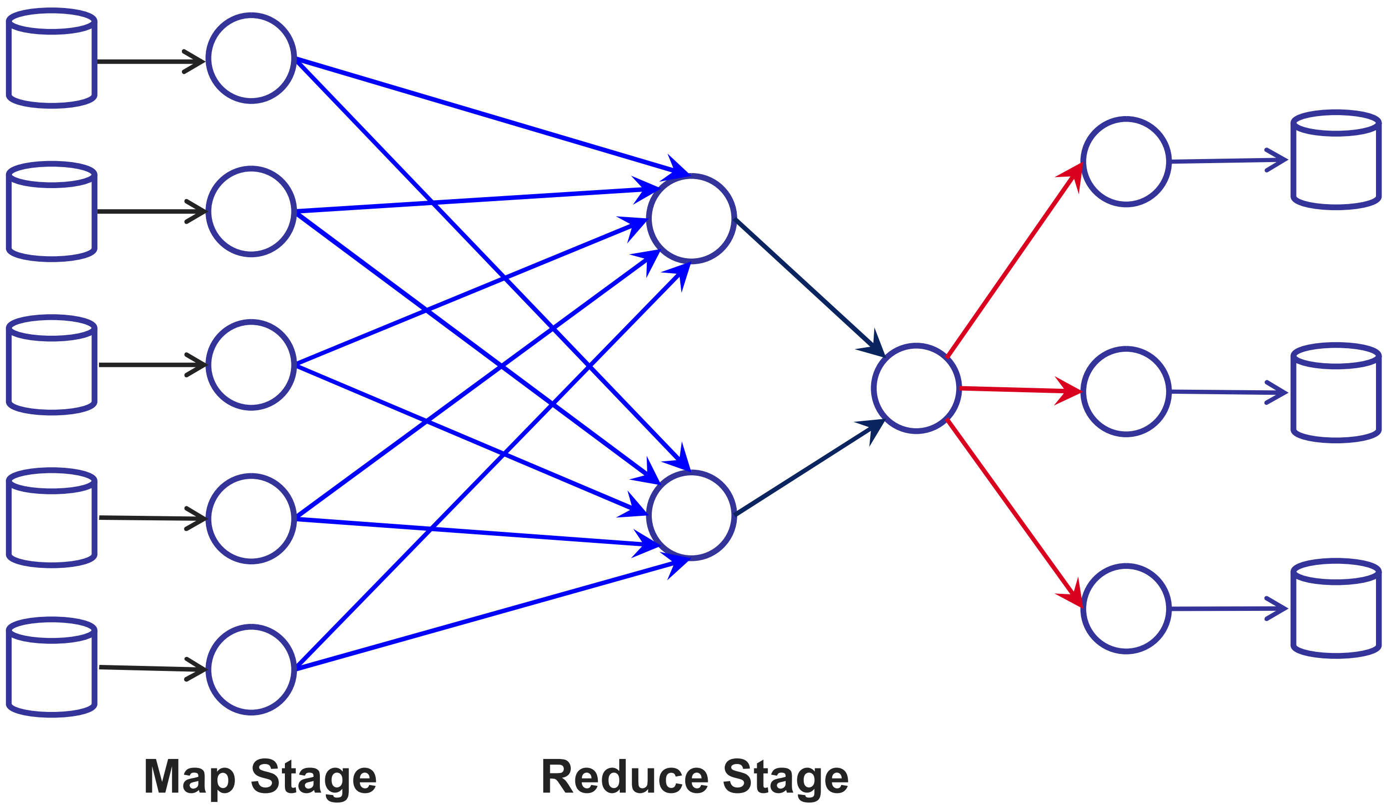
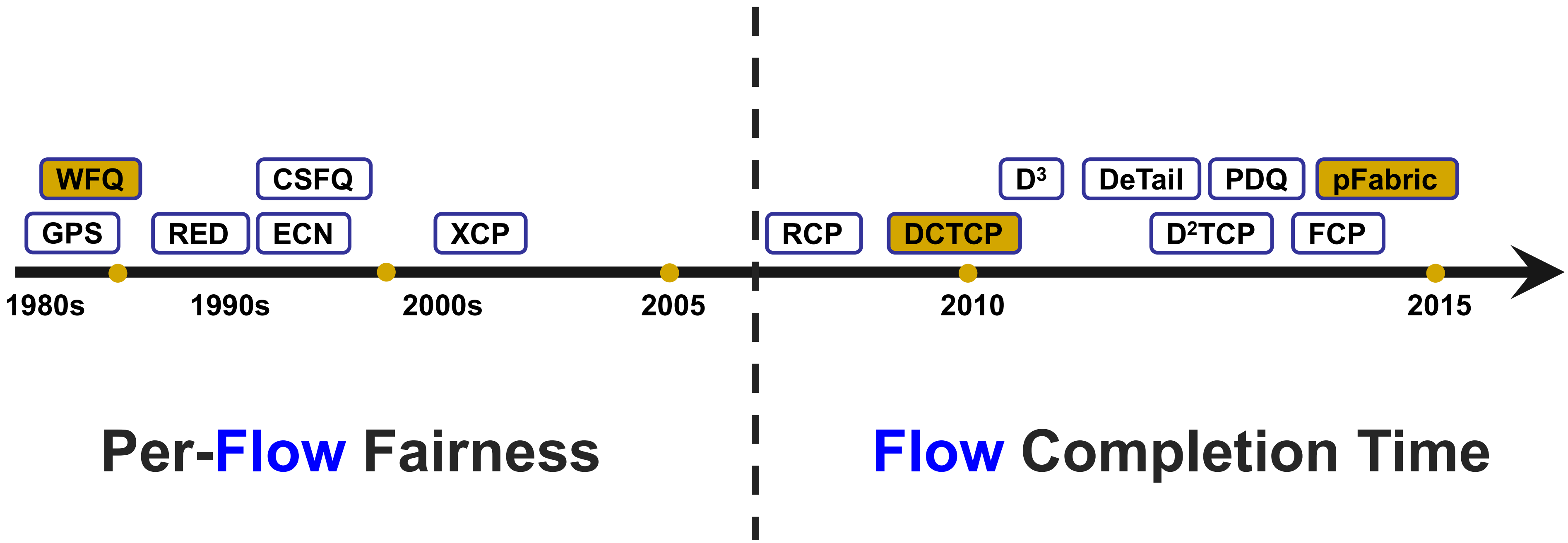
The Map-Reduce Example



Observation:
A communication stage cannot complete until all its flows have completed

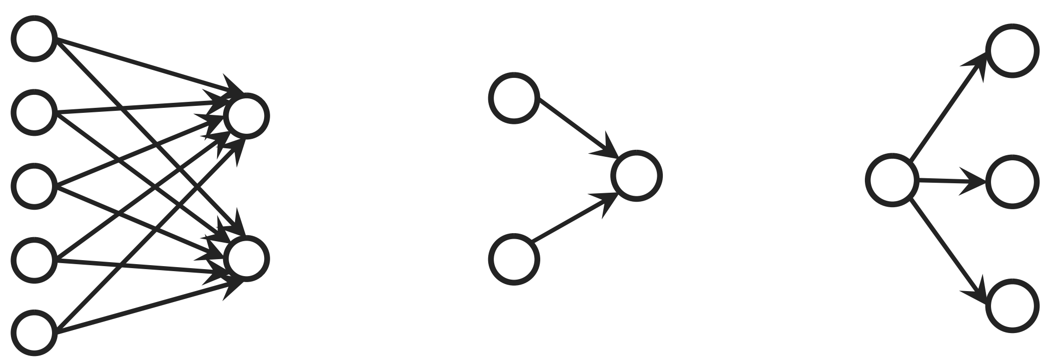
Flow-based solutions



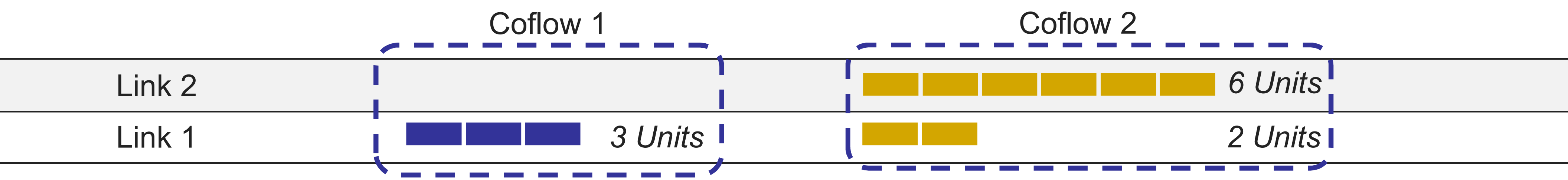
Independent flows cannot capture collective communication patterns that are common in data-parallel applications

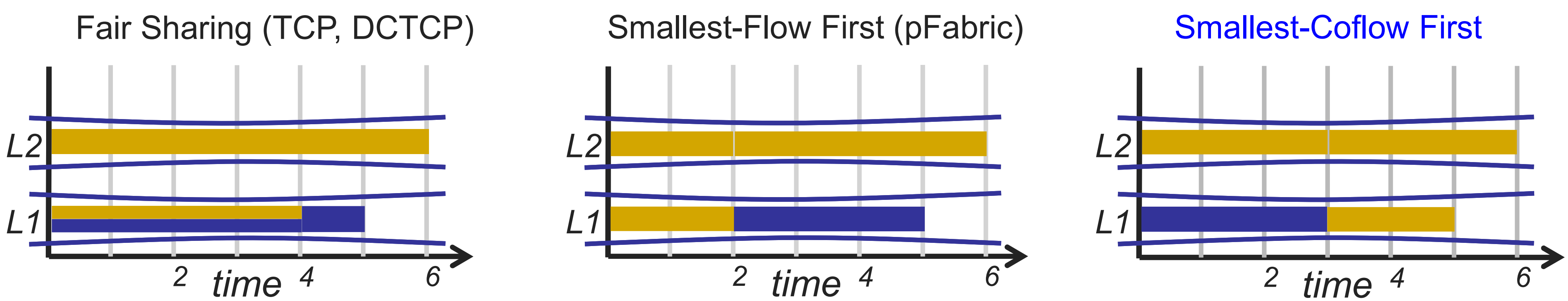
The Coflow abstraction [SIGCOMM'14]

- Coflow is a communication abstraction for data-parallel applications to express their performance goals; e.g.,
  - Minimize completion times,
  - Meet deadlines, or
  - Perform fair allocation
- Not for individual flows; for entire stages!



Benefits of inter-coflow scheduling





Fair Sharing (TCP, DCTCP)	Smallest-Flow First (pFabric)	Smallest-Coflow First
Coflow1 comp. time = 5	*Coflow1 comp. time = 5*	*Coflow1 comp. time = 3*
Coflow2 comp. time = 6	*Coflow2 comp. time = 6*	*Coflow2 comp. time = 6*
Average FCT = *5*	Average FCT = *4.33*	Average FCT = *4.67*

Coflow completion time (CCT) is a better predictor of job-level performance than FCT

Summary

- Networking in modern datacenters
  - L2/L3: Source routing and load balancing to exploit multiple paths over the Clos topology
  - L4: Find a better balance between latency and throughput requirements
  - L7: Exploit application-level information with coflows

- Last class: Final Review

TCP w/ per-packet load balancing

- Consider
  - Sender sends seq#: 1,2,3,4,5
  - Receiver receives: 5,4,3,2,1
  - Sender will enter fast retransmit, reduce CWND, retransmit #1, …
  - Repeatedly!
- Information sharing between multiple paths affects TCP
  - One RTT and timeout estimator for multiple paths
  - CWND halved when a packet is dropped on any path

Multipath TCP

- Multipath TCP (MPTCP) is an ongoing effort to extend TCP to coexist with multipath routing
  - Value beyond datacenters (e.g., spread traffic across WiFi and 4G access)

What's ideal for a 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?

How to implement coflows?

- Modify applications to annotate coflows
  - Possible to infer them as well [SIGCOMM’16]
- Managed communication
  - Applications do not communicate; instead, a central entity does the communication on their behalf
- Centralized scheduling