Data Center Networking

Lecture 9

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http://www.cs.rutgers.edu/~sn624/553-S23

Parts of this lecture were heavily adapted from slides by Mohammad Alizadeh and Changhoon Kim

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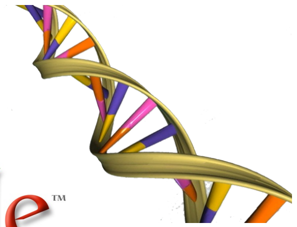
What are data centers?

- Large facilities with ~100K servers
  - Compute, storage, and networking working in concert
  - “Warehouse-Scale Computers”

Types of Data Centers



- Specialized data centers built for one or a few big apps
  - Social networking: Facebook, Insta
  - Web Search: Google, Bing
- "Cloud" data centers
  - Amazon EC2, Microsoft Azure
  - Google App Engine

Data Centers with 100,000+ Servers


Microsoft

Scale of mega-data centers (circa 2016)

Each DC hosts ~100K servers

100s of Petabytes of storage

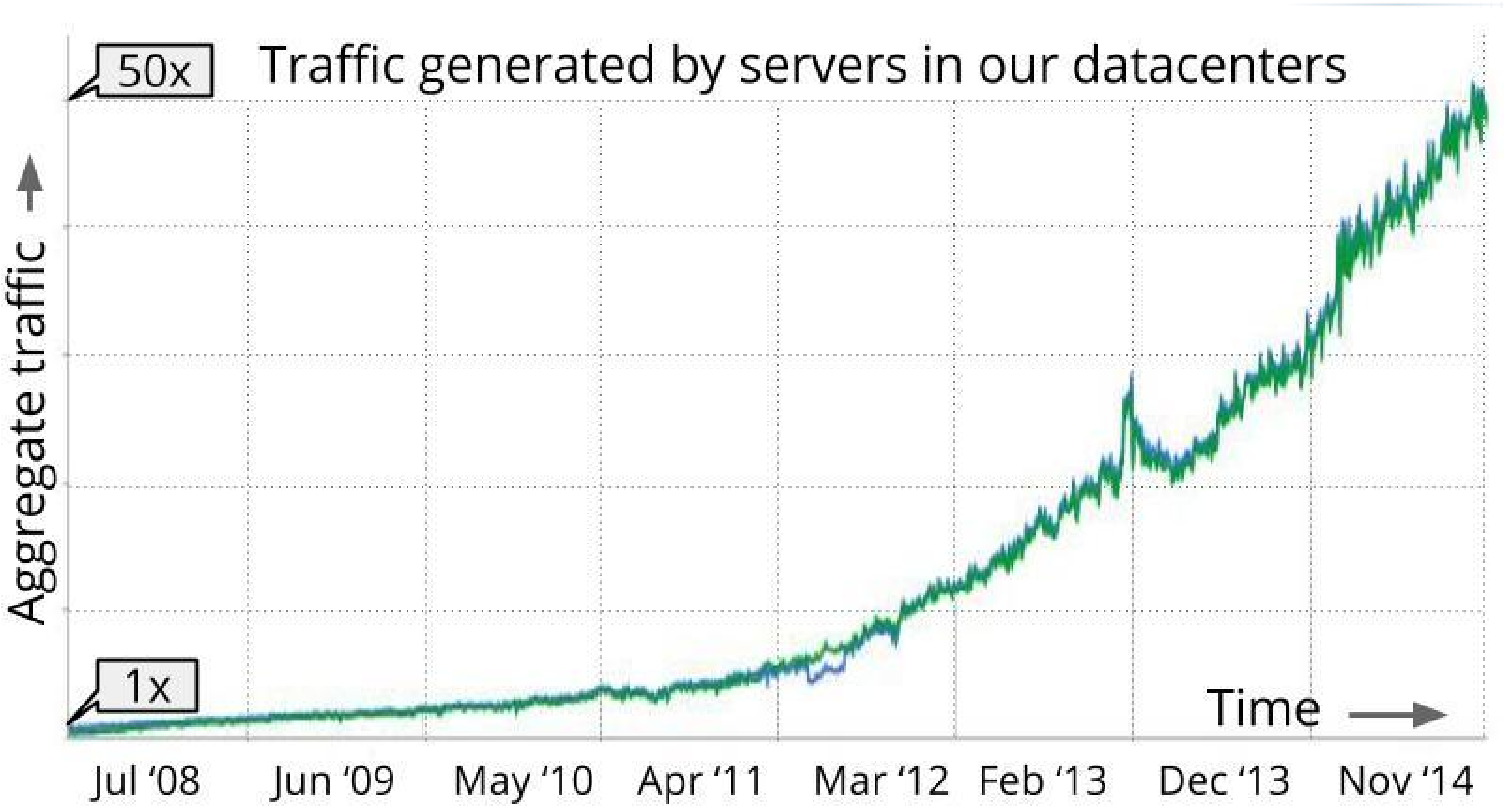
100s of Terabits/s of Bandwidth
(more than core of Internet)

10-100MW of power
(1-2% of global energy consumption)

Cost upwards of $1--4 billion per (mega) data center

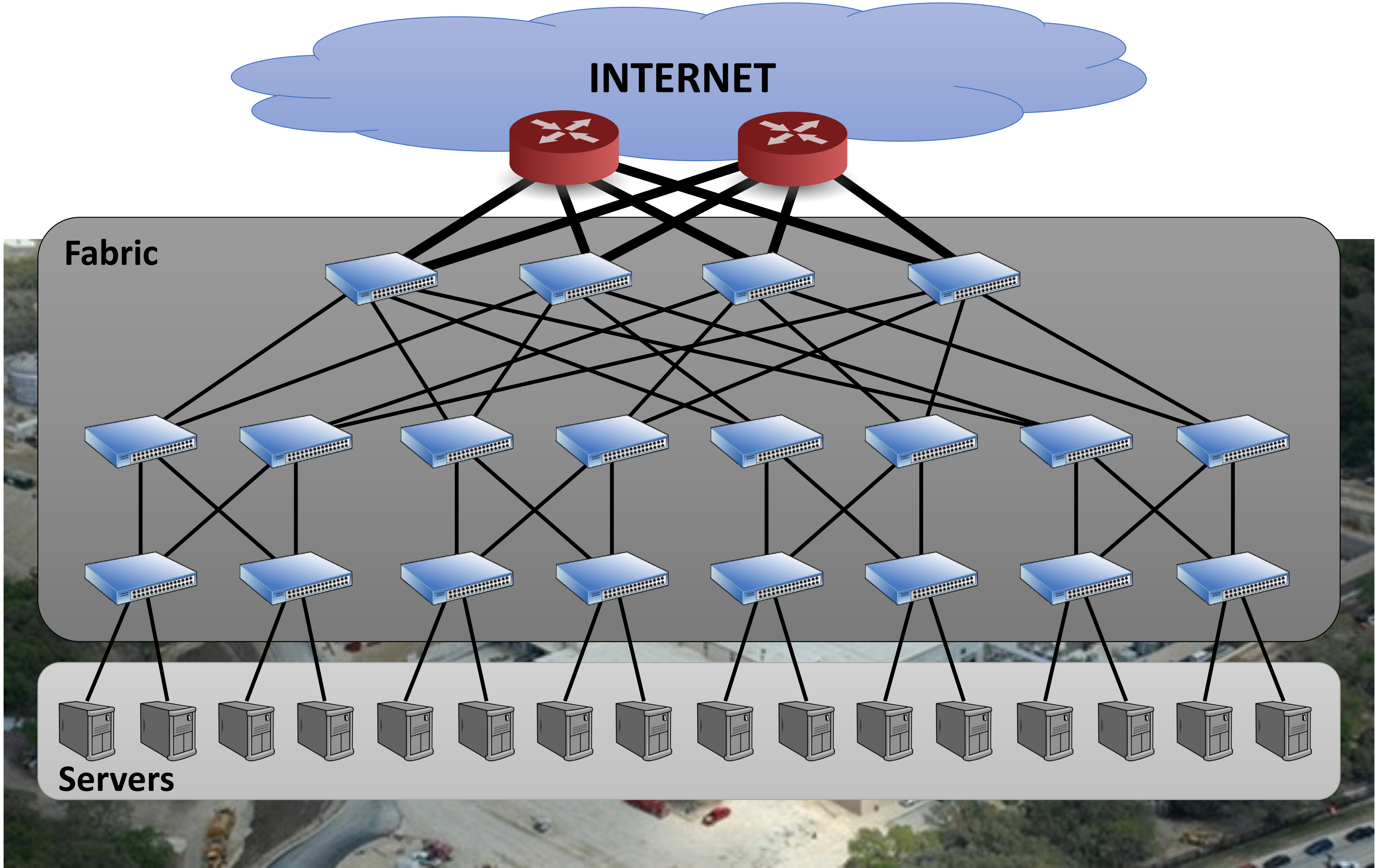
100s of millions of users per data center app

Datacenter traffic growth



Source: "Jupiter Rising: A Decade of Clos Topologies and Centralized Control in Google's Datacenter Network", SIGCOMM 2015.

How a data center looks on the inside


INTERNET
Fabric
Servers

Review: Basics of data center topology

- Servers arranged into *racks*
  - Some people call the individual server in a rack a *blade*
  - Each slot also called a pizza box or 1U (“1 unit”)

- Switch interconnecting all servers at the top of the rack
  - Forms the edge of the network
  - You’ll see the name Top-Of-Rack (ToR) switch

- ToR switches are interconnected by the rest of the network fabric

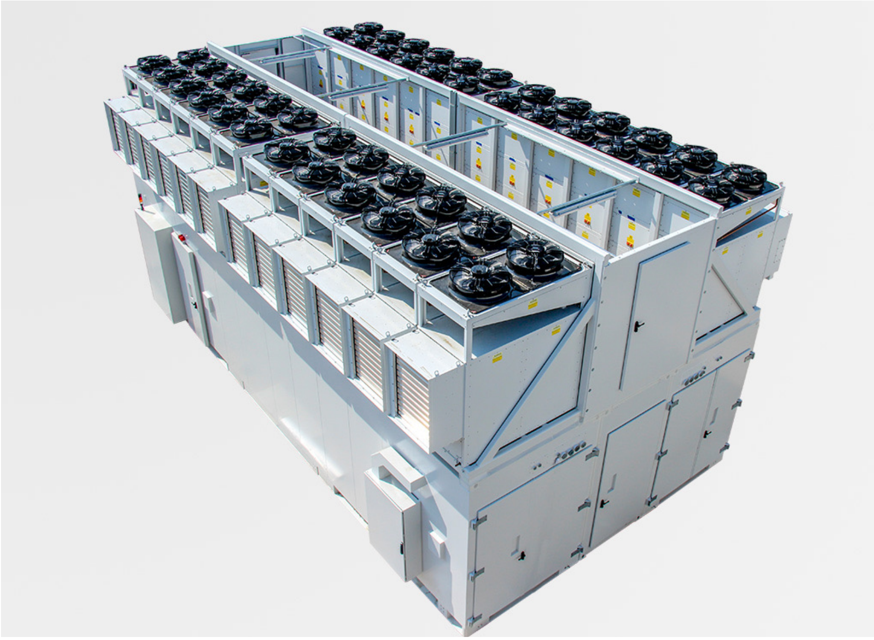
Half-filled rack

- Cabling from servers to the switch
- Power, network backplane running on top

Fully filled rack

- With this kind of density, you need effective *cooling*
- Different kinds of cooling possible.
  - “Free” cooling with external air, pumped refrigerants, etc.


Cloud
Data Center



What's different about DCNs?

- Single administrative domain
  - Change all endpoints and switches if you want
  - Limited interfaces with the outside world
- Unique network properties
  - Tiny round trip times (microseconds)
  - Massive multipath topologies
  - Shallow-buffered switches
- Latency and tail-latency critical
  - Tail latency: high %-ile (e.g., 99.9) of a latency distribution
  - Network is a backplane for large-scale parallel computation
- Together, serious implications for the application, transport, network, link layer designs one can use

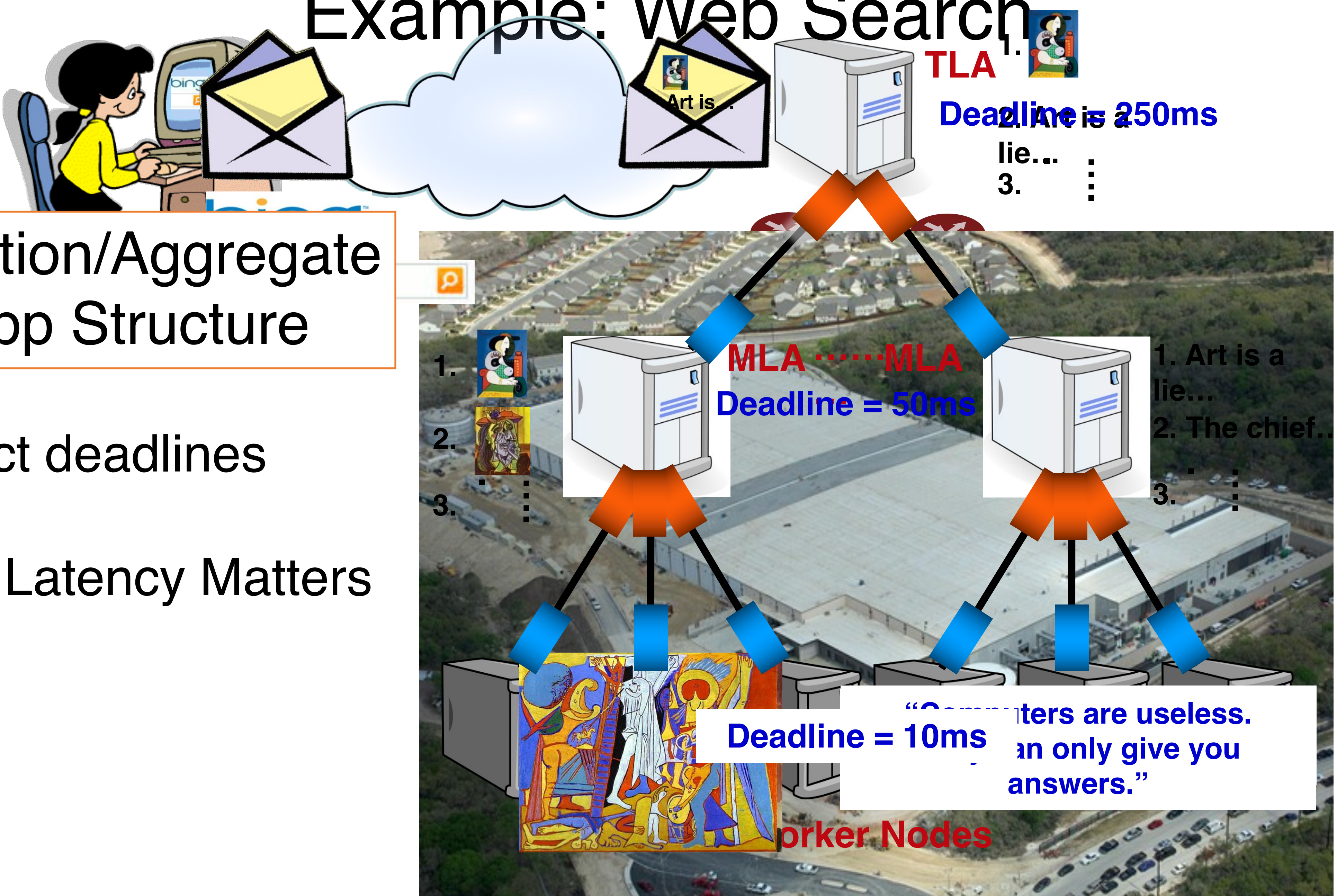
Goal: Support cloud app requirements

- On-demand
  - Use resources when you need it; pay-as-you-go
  - Elastic: Scale up & down based on demand
- Multi-tenancy
  - Multiple independent users share infrastructure
  - Security and resource isolation
  - SLOs on performance & reliability
- Dynamic Management
  - Resiliency: isolate failure of servers and storage
  - Workload movement: move work to other locations

Example: Web Search

Partition/Aggregate
App Structure

- Strict deadlines
- Tail Latency Matters



Challenges in DCNs

Data center costs

Amortized Cost*	Component	Sub-Components
~45%	Servers	CPU, memory, disk
~25%	Power infrastructure	UPS, cooling, power distribution
~15%	Power draw	Electrical utility costs
~15%	Network	Switches, links, transit

The Cost of a Cloud: Research Problems in Data Center Networks.
Sigcomm CCR 2009. Greenberg, Hamilton, Maltz, Patel.

*3 yr amortization for servers, 15 yr for infrastructure, 5% cost of money

Server costs

30% server utilization considered “good” in data centers

- Application demands uneven across the resources
  - Each server has CPU, memory, disk: most applications exhaust one resource, stranding the others
- Long provisioning timescales
  - New servers purchased quarterly at best
- Uncertainty in demand
  - Demand for a new service can spike quickly
- Risk management
  - Not having spare servers to meet demand brings failure just when success is at hand

Goal: Agility: any service, any server

- Turn the servers into a single large pool
- Dynamically expand and contract service footprint as needed
- Place workloads where server resources are available
- Easier to maintain *availability*
  - If one rack goes down, machines from another still available

- Want to view DCN as a pool of compute connected by one big high-speed fabric

Steps to achieving Agility

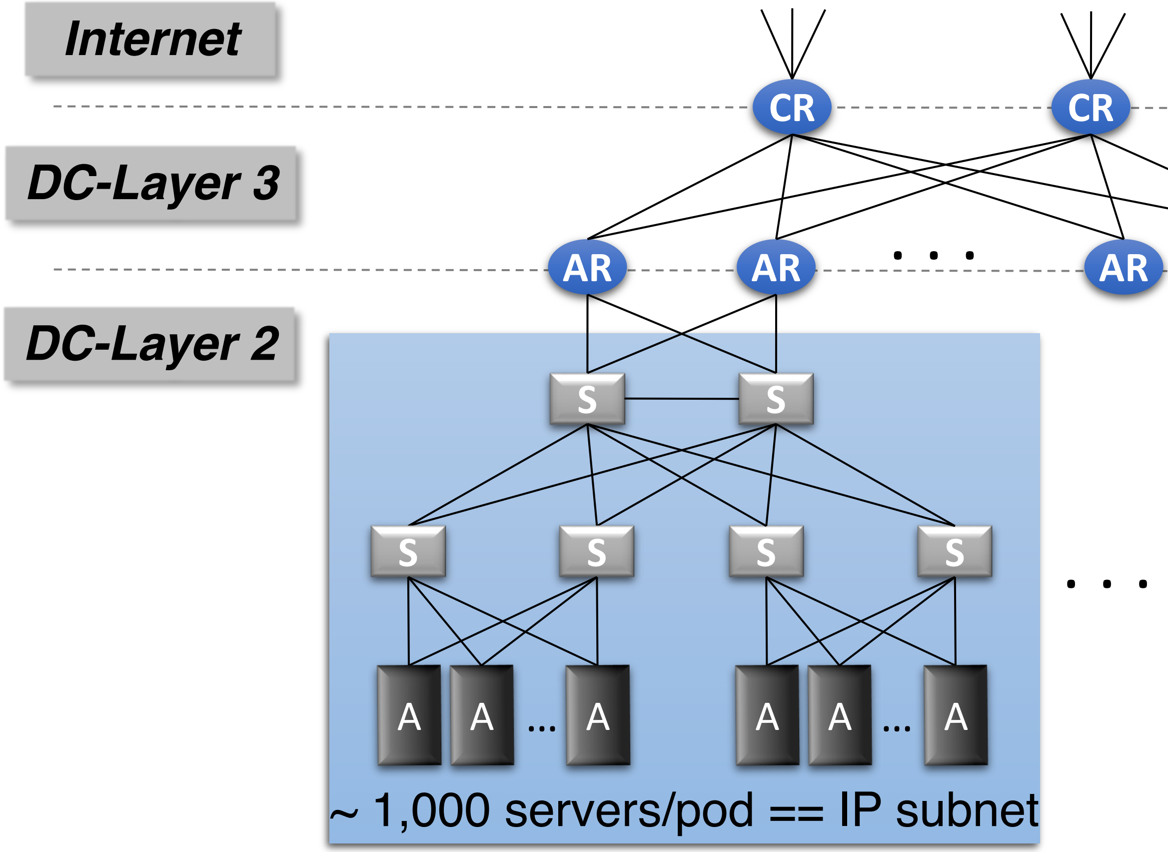
- Workload (compute) management
  - Means for rapidly installing a service's code on a server
  - *Virtual machines, disk images, containers* ✓
- Storage management
  - Means for a server to access persistent data
  - *Distributed global filesystems (e.g., HDFS, blob stores)* ✓
- Network and Routing management
  - Communicate efficiently with other servers, regardless of where they are in the data center

??

Achieving agility requires DCN to have…

- Massive bisection bandwidth
  - Bandwidth between any two "halves" of the network across a cut
  - Topologies, addressing, routing (Multiple paths ➔ Load balancing)
- Ultra-Low latency (<10 microseconds)
  - The right transport? Switch scheduling/buffer management?
  - Schedule packets or control transmission rates?
  - Centralized or distributed control?
- Effective Resource Management (across servers & switches)
  - Multi-tenant performance isolation
  - App-aware packet or flow scheduling

Conventional DC network



Key

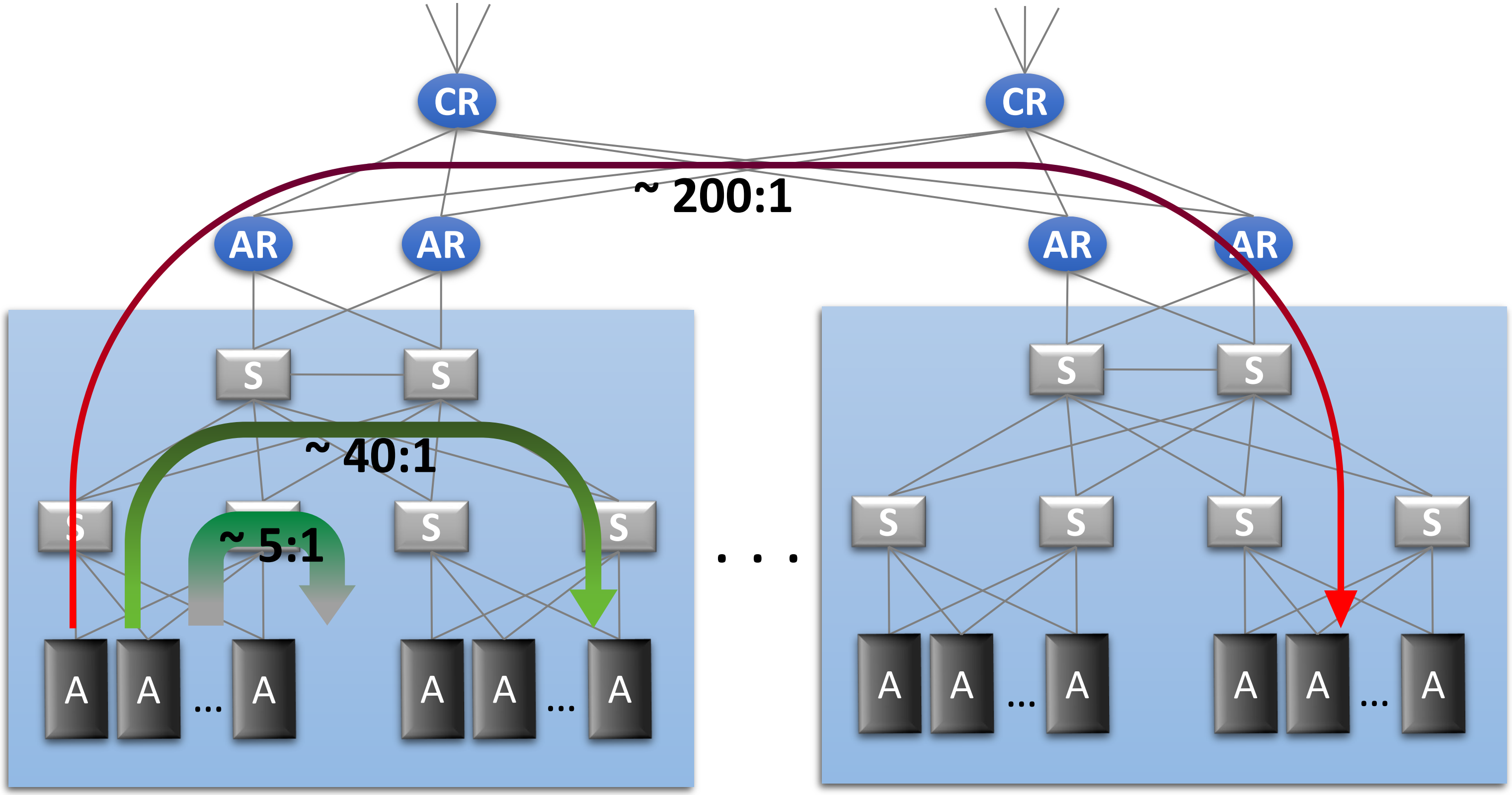
- **CR** = Core Router (L3)
- **AR** = Access Router (L3)
- **S** = Ethernet Switch (L2)
- **A** = Rack of app. servers

Source: “Data Center: Load balancing Data Center Services”, Cisco 2004

Layer 2 vs. Layer 3

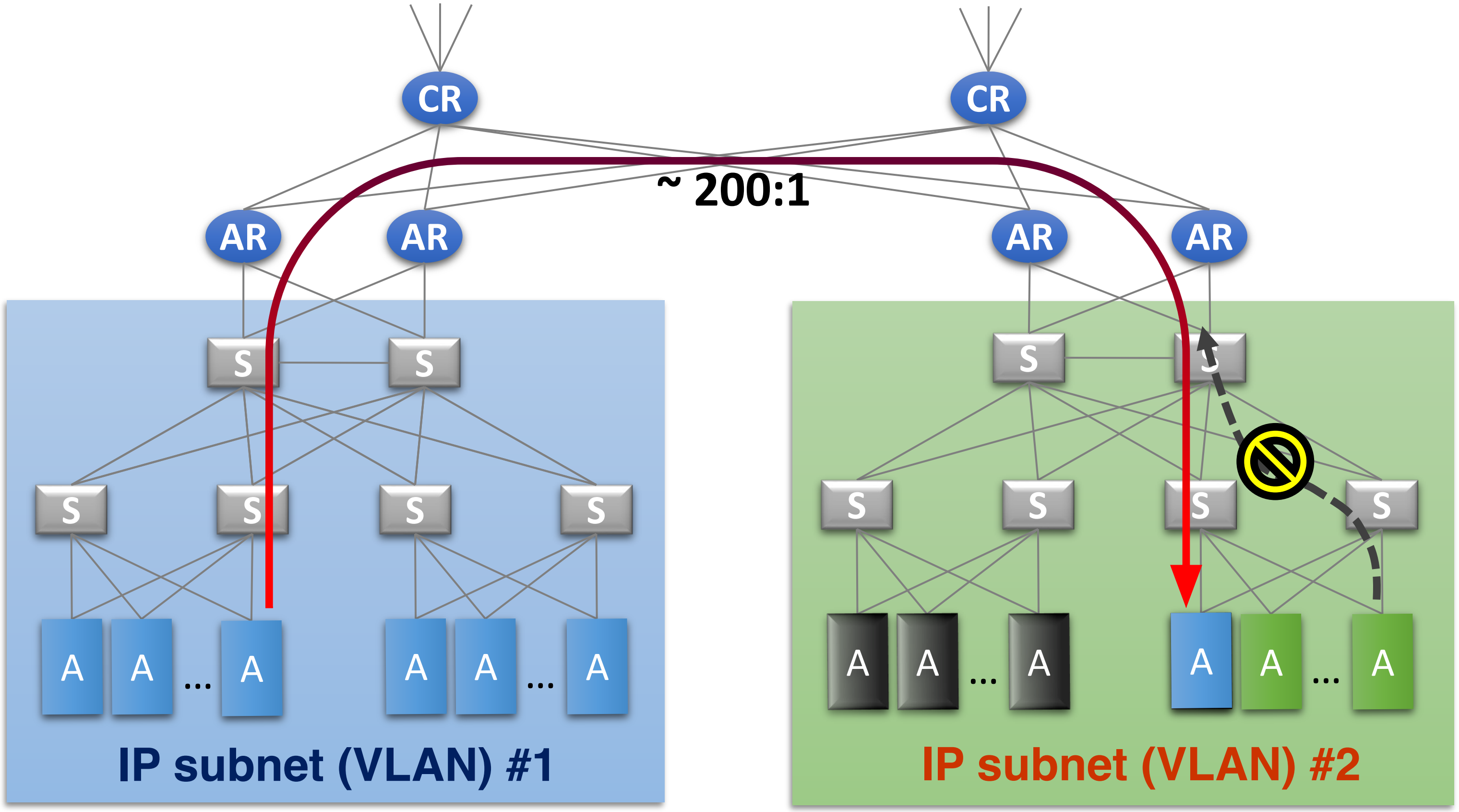
- Ethernet switching (layer 2)
  - ✓Fixed IP addresses and auto-configuration (plug & play)
  - ✓Seamless mobility, migration, and failover
  - x Broadcast limits scale (ARP)
  - x Spanning Tree Protocol: no multipath routing
- IP routing (layer 3)
  - ✓Scalability through hierarchical addressing
  - ✓Multipath routing through equal-cost multipath
  - x More complex configuration
  - x Can't migrate w/o changing IP address

Conventional DC Network Problems



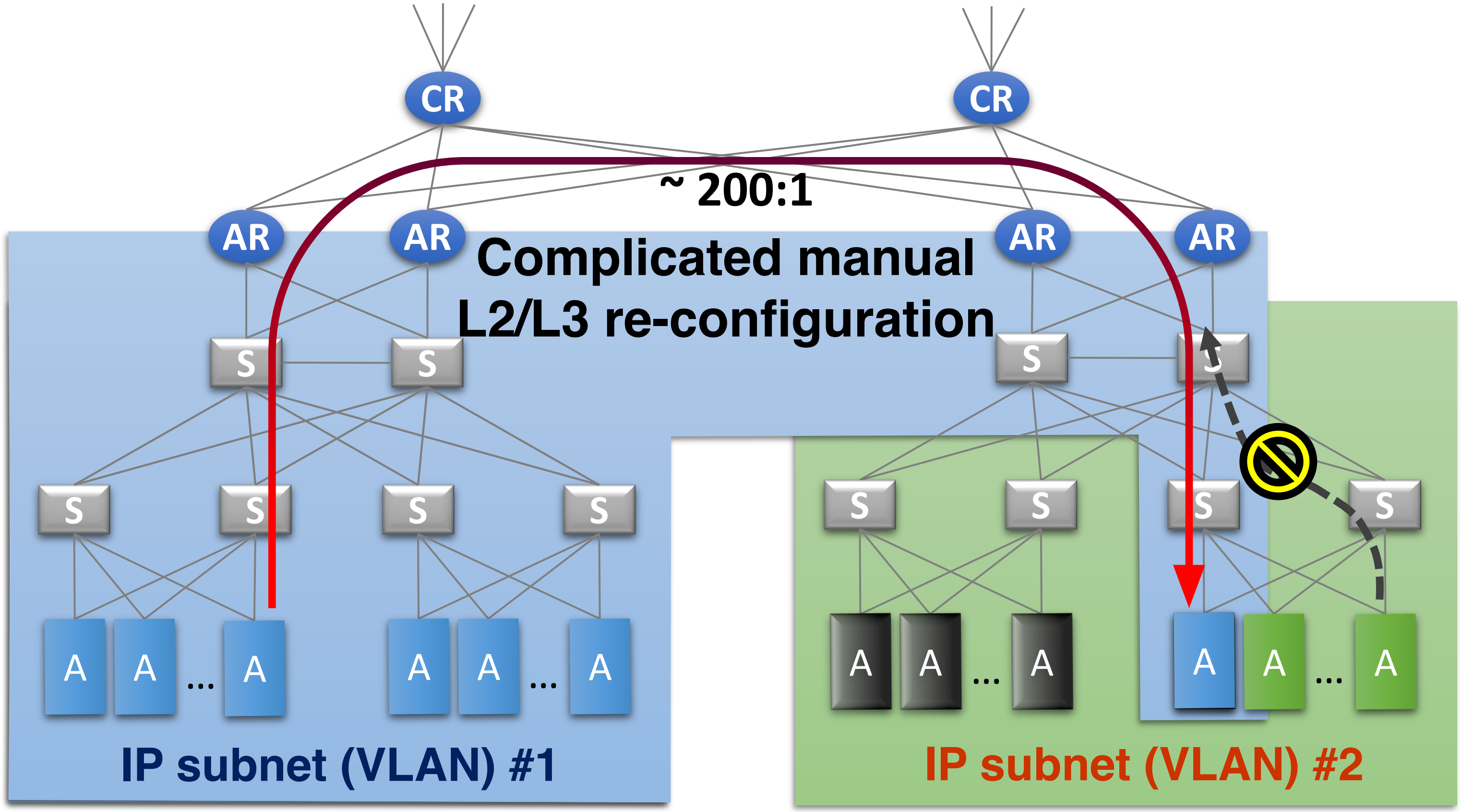
- Dependence on high-cost proprietary routers
- Extremely limited server-to-server capacity

Conventional DC Network Problems



- Resource fragmentation, significantly lowering server utilization and cost-efficiency

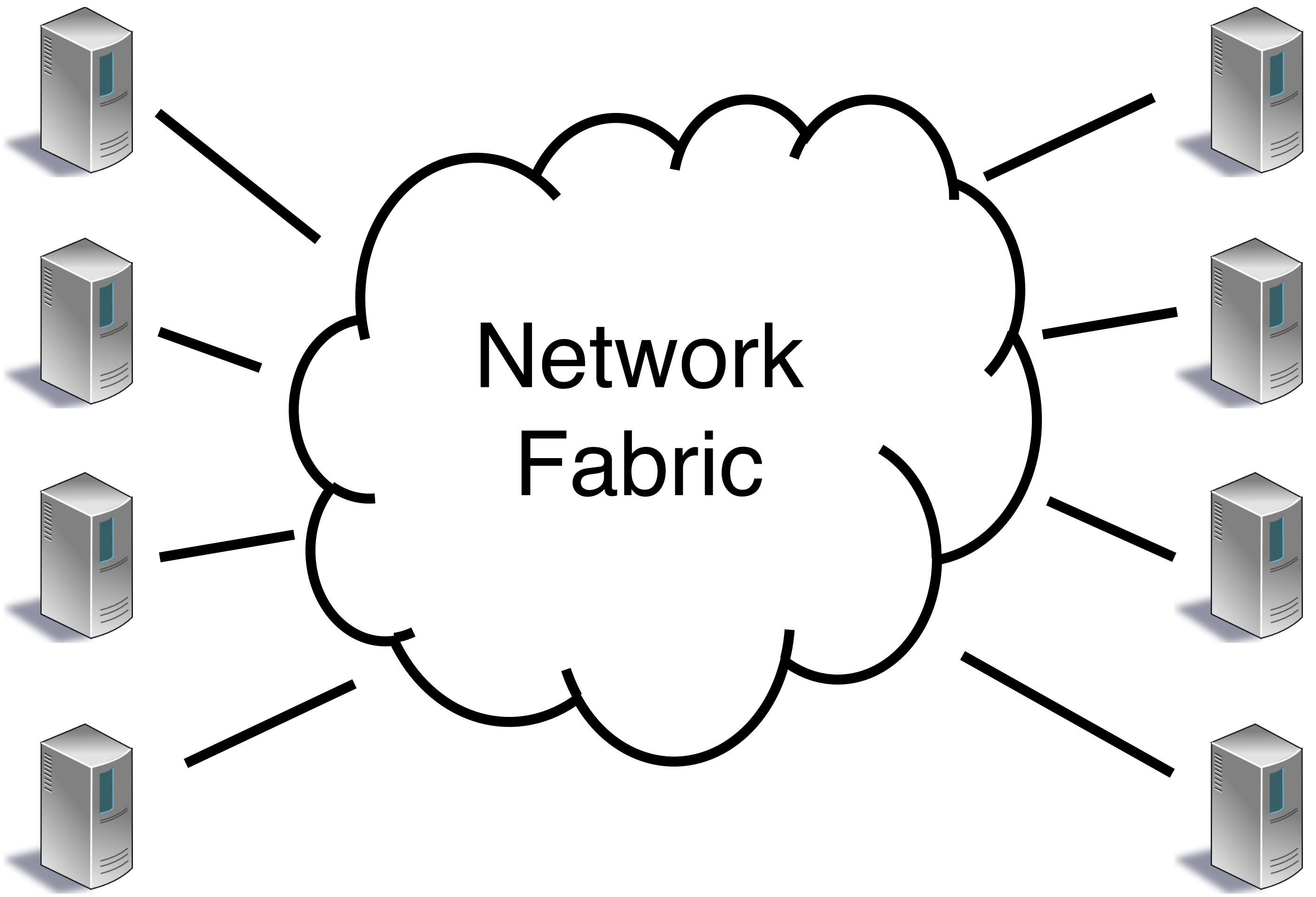
Conventional DC Network Problems



- Resource fragmentation, significantly lowering server utilization and cost-efficiency

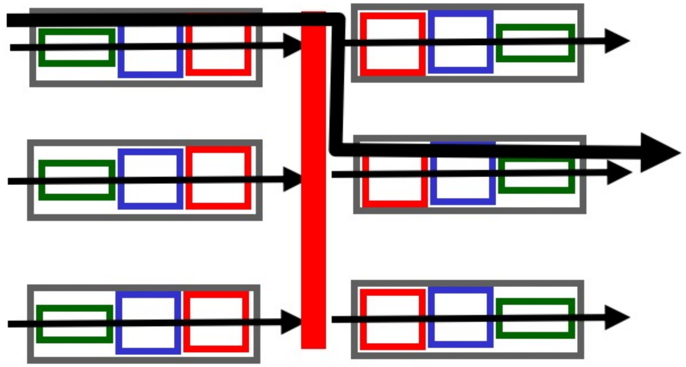
Building a high-speed switching fabric

Interconnecting fabric is key to agility

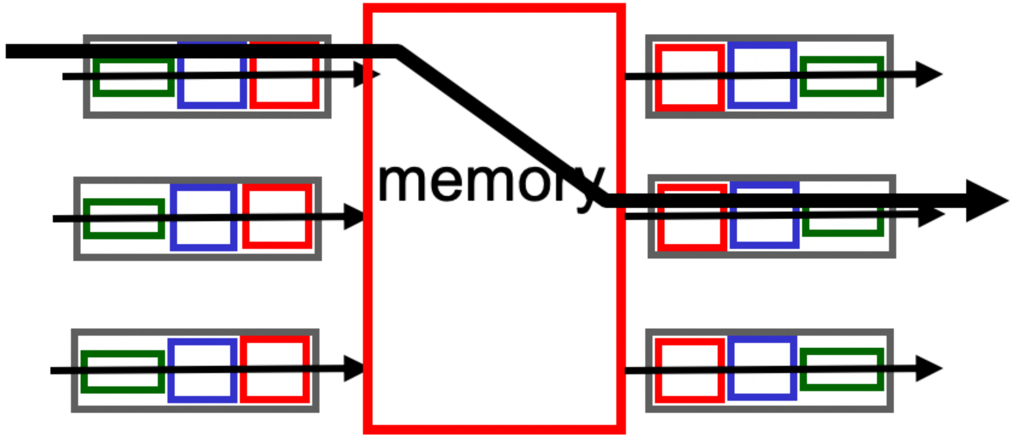


A single (n X m)-port switching fabric

- Different designs of switching fabric possible
- Assume n ingress ports and m egress ports, half duplex links



bus

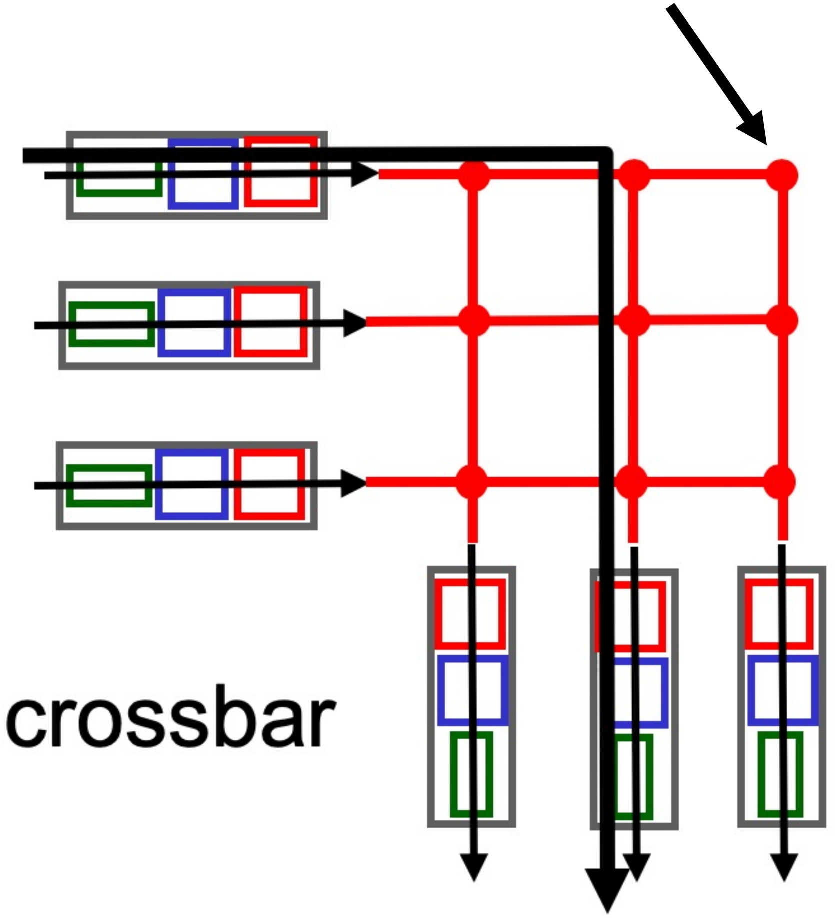


memory

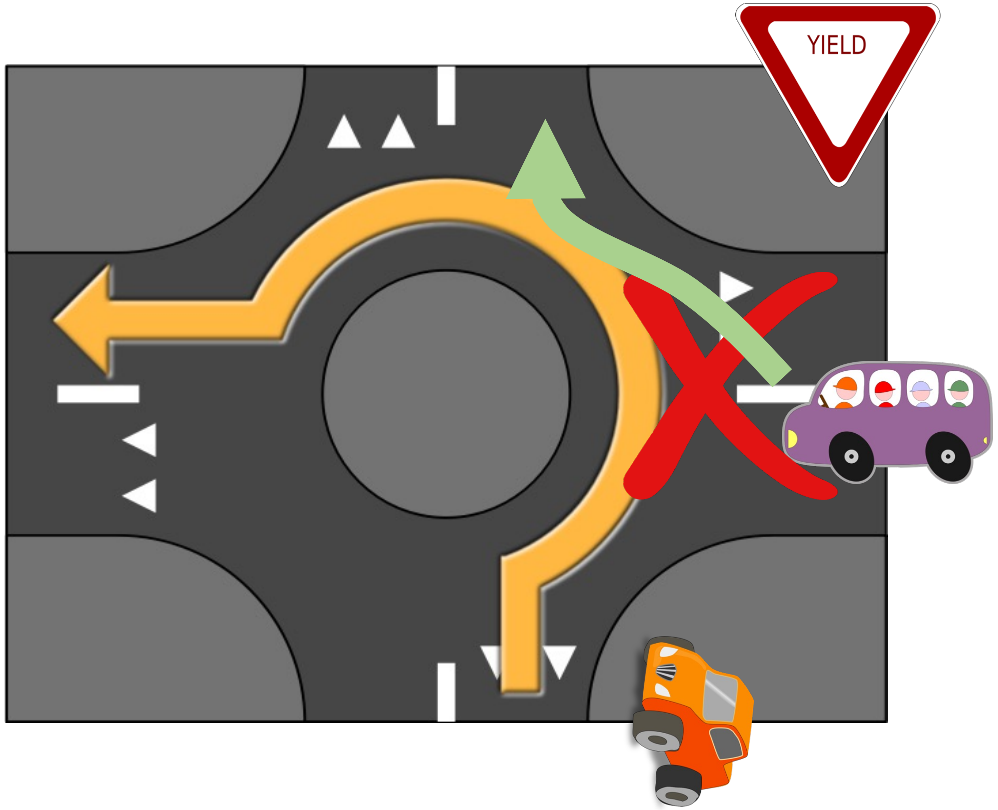
A single (n X m)-port switching fabric

- We are OK with any design such that:
- Any port can connect to any other directly if all other ports free
- Nonblocking: if input port x and output port y are both free, they should be able to connect
  - Regardless of other ports being connected.
  - If not satisfied, switch is *blocking.*

Electrical/mechanical/ electronic crossover



Nonblocking designs are nontrivial



High port density + nonblocking == hard!

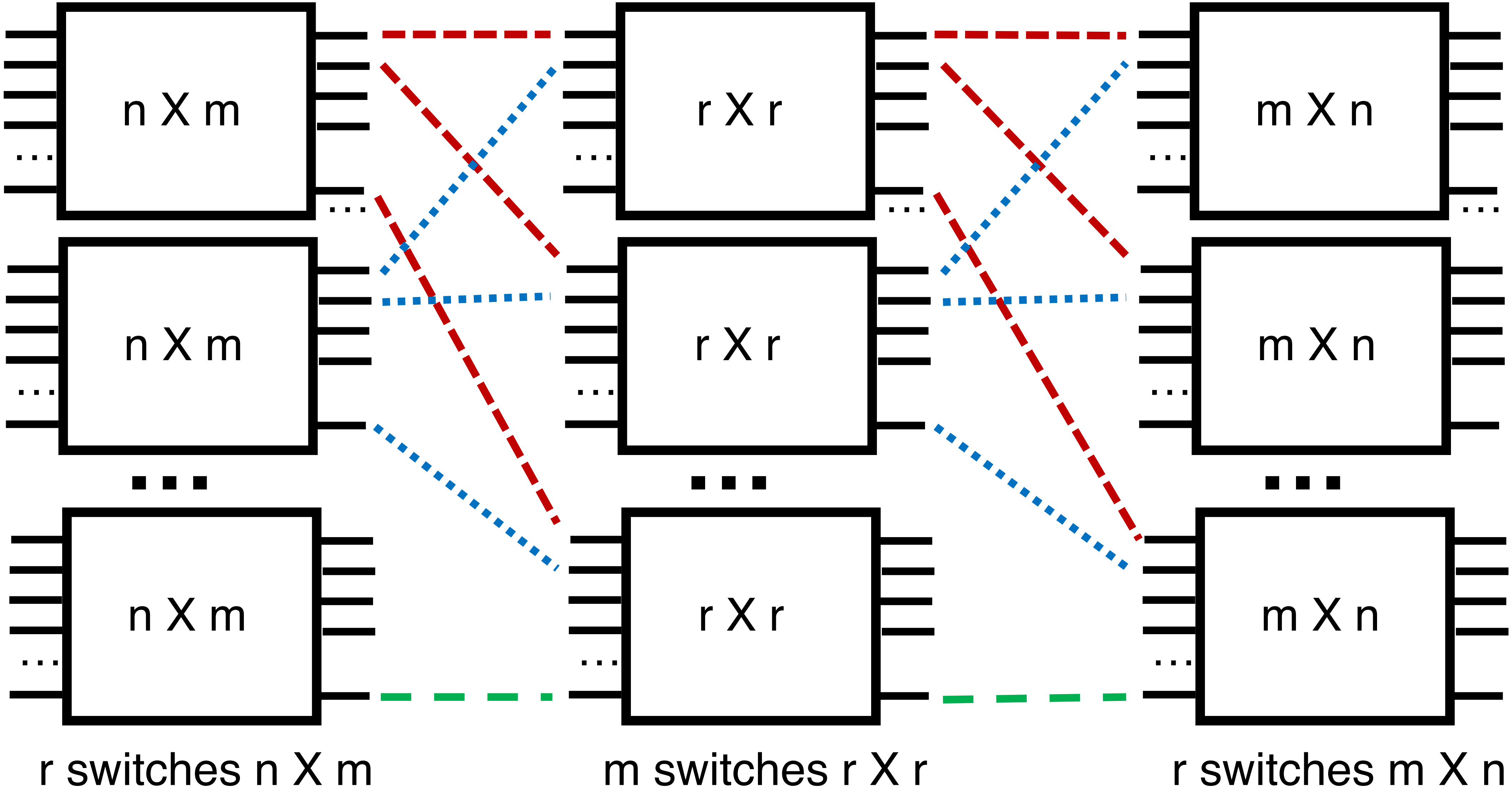
- Low-cost nonblocking crossbars are feasible for small # ports
- However, it is costly to be nonblocking with a large number of ports
- If each crossover is as fast as each input port,
  - Number of crossover points == n * m
  - Cost grows quadratically on the number of input ports
- Else, crossover must transition faster than the port
  - … so that you can keep the number of crossovers small

Nonblocking switches with many ports

- Key principle: Every fast nonblocking switch with a large number of ports is built out of many fast nonblocking switches with a small number of ports.

- How to build large nonblocking switches?
  - The subject of interconnection networks from the telephony era

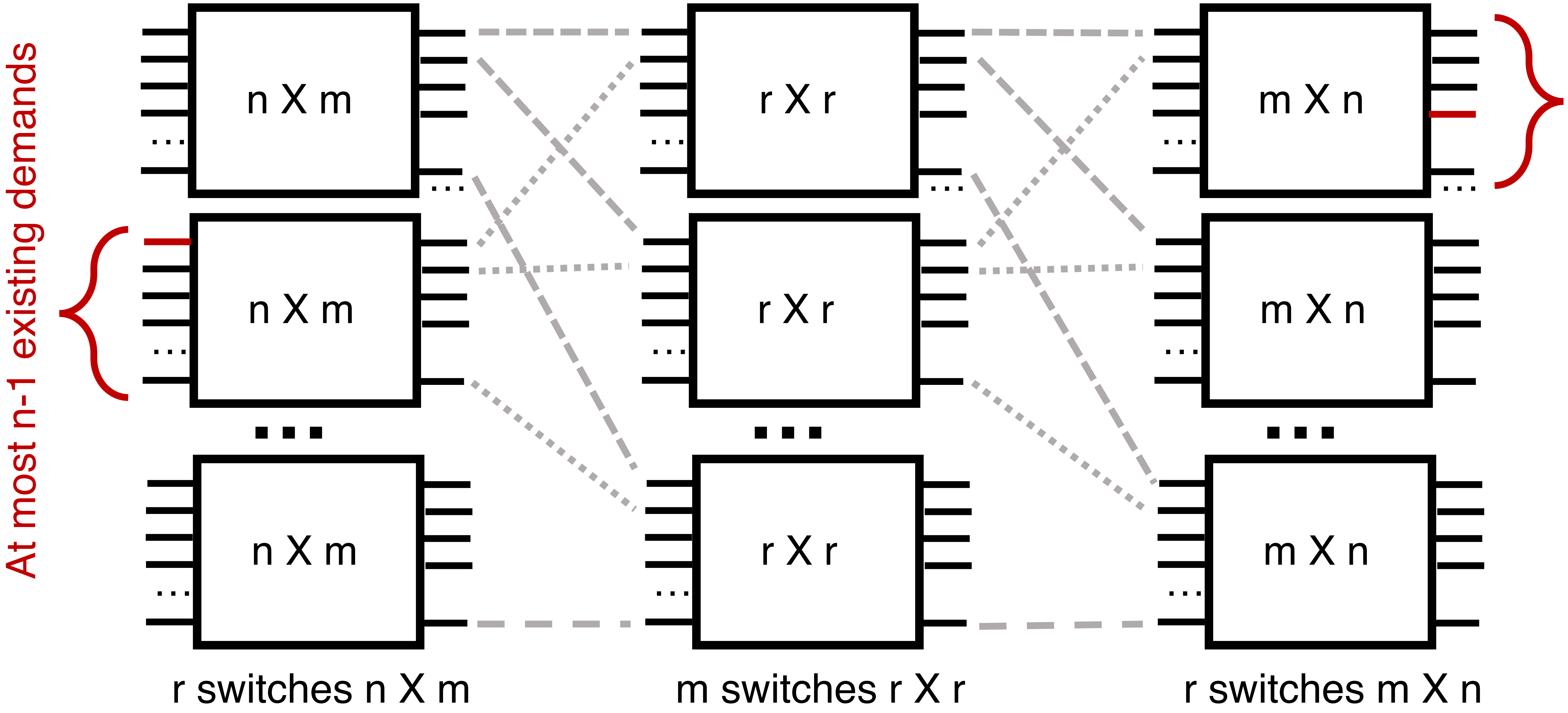
3-stage Clos network (r*n X r*n ports)



How Clos networks become nonblocking

- if $m > 2n - 2$, then the Clos network is strict-sense nonblocking.
- That is, any new demand between any pair of free (input, output) ports can be satisfied without re-routing any of the existing demands.

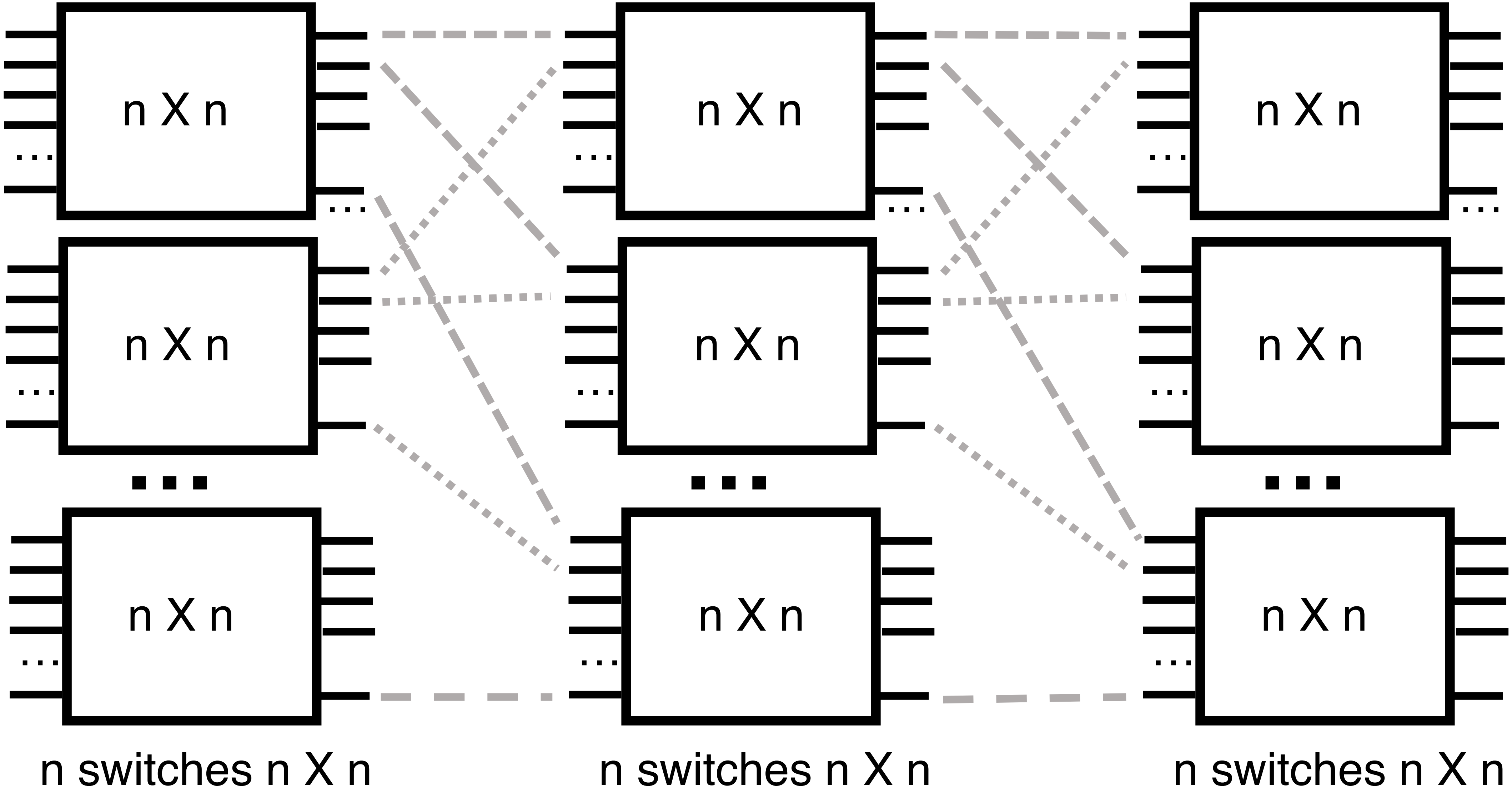
Need at most (n-1)+(n-1) middle stage



Surprising result about Clos networks

- if m >= n, then the Clos network is rearrangeably nonblocking
- That is, any new demand between any pair of free (input, output) ports can be satisfied by suitably re-routing existing demands.
- It is easy to see that m >= n is necessary
  - The surprising part is that m >= n is sufficient

Rearrangeably nonblocking Clos built with identical switches

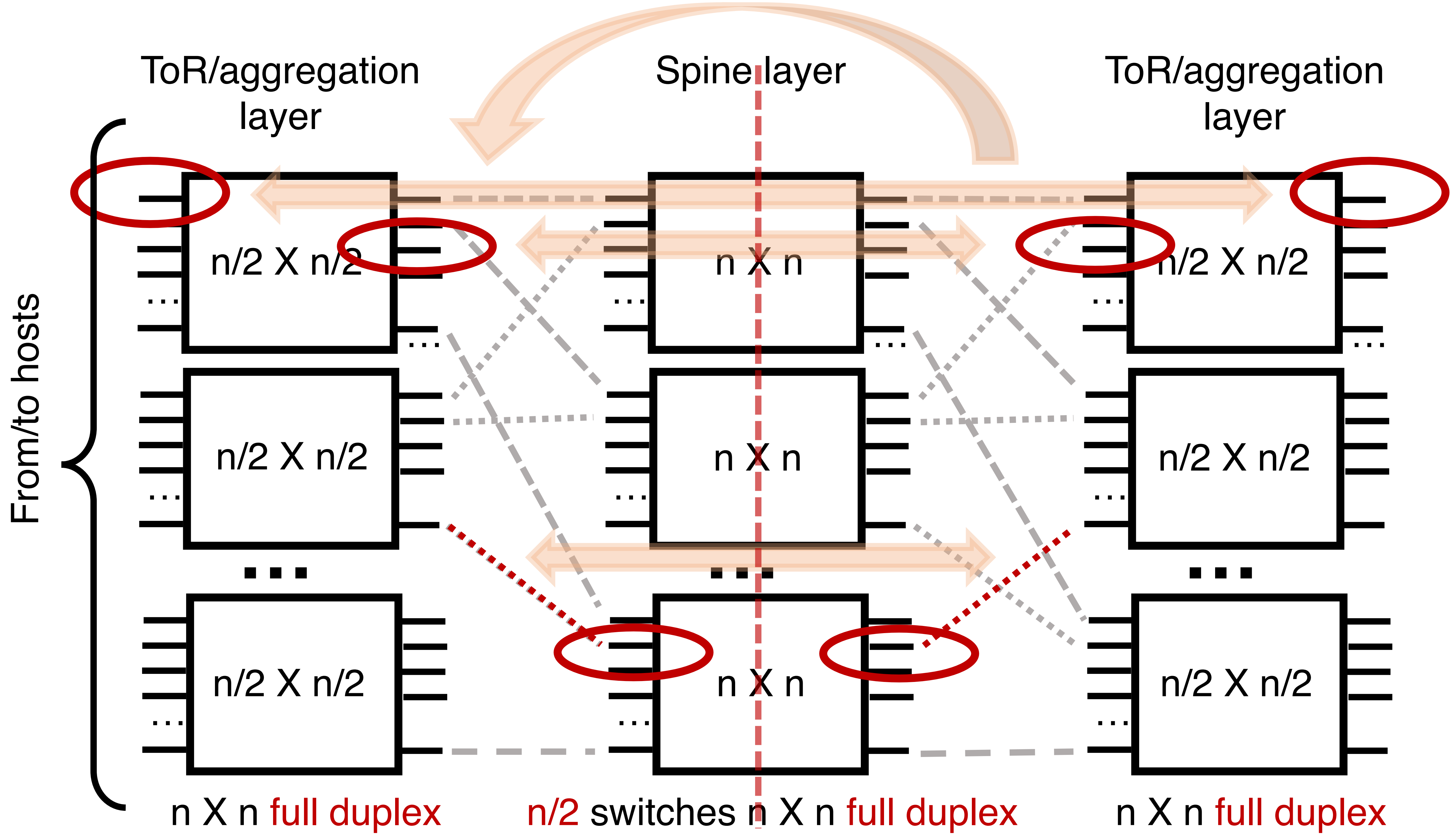


Modern data center network topologies are just folded Clos topologies.

VL2: a scalable and flexible data center network (sigcomm'09)

How does one design a Clos DCN?

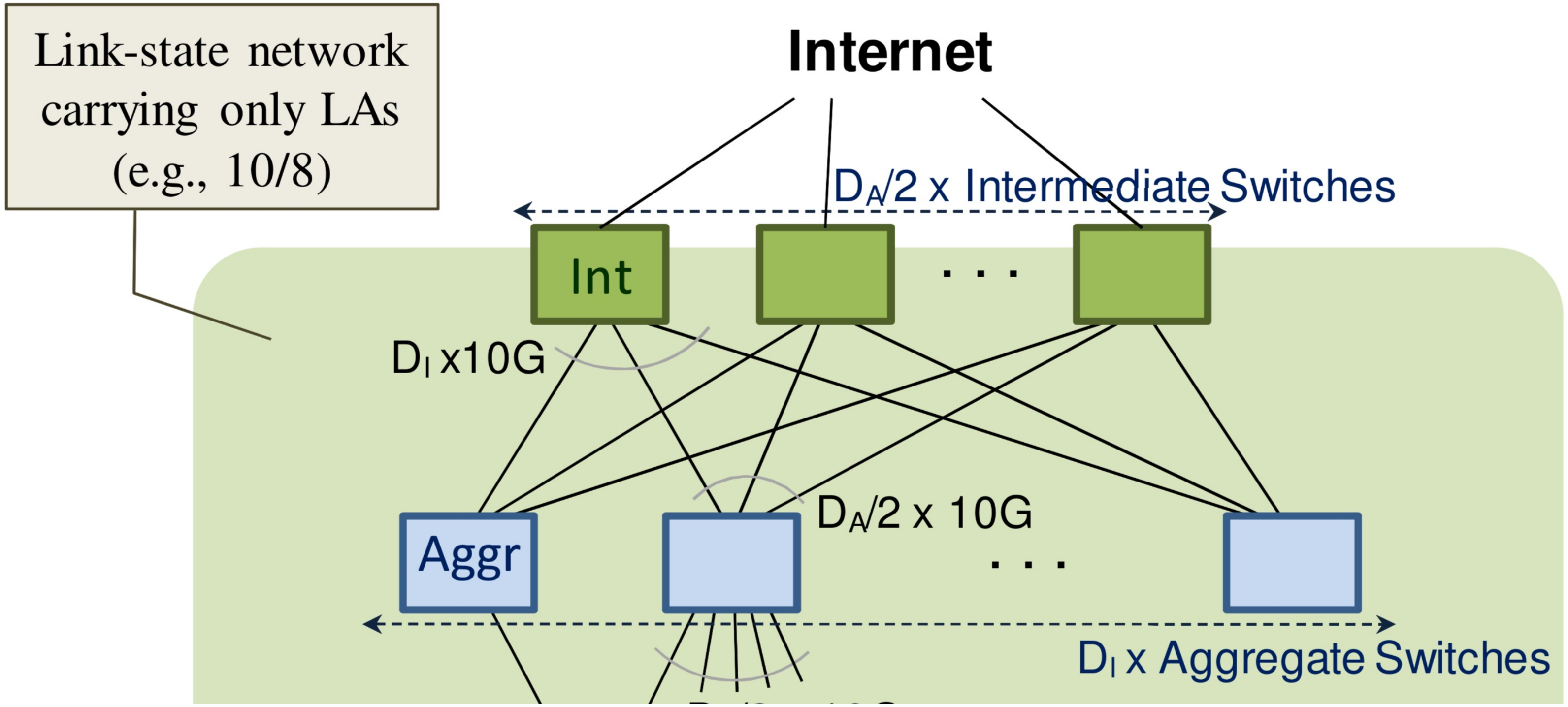
- Switches are usually n X n with full-duplex links
- Fold the 3-stage Clos into 2-stages
- Share physical resources between ingress and egress stages
- Share ports and links across the two “sides” of the middle stage



ToR/aggregation layer
Spine layer
ToR/aggregation layer
From/to hosts
n/2 X n/2
n/2 X n/2
n/2 X n/2
n X n
n X n
n X n
n/2 X n/2
n/2 X n/2
n/2 X n/2
n X n full duplex
n/2 switches n X n full duplex
n X n full duplex

Consequences of using folded Clos

- 2-stage high throughput data center topology
- All can use the same switches! (port density and link rates)



What about routing?

- We said that the Clos topology above is rearrangeably nonblocking.
- So, how to rearrange existing demands when a new packet arrives, so that it can get across as quickly as possible?
- How to do it without “interference” to (ie: rerouting) other pkts?
- VL2: We don’t need to rearrange anything.

Valiant Load Balancing (VLB)

- Designed to move data quickly for shuffling in parallel computing
- Setting: Connectivity is sparse ("hypercube" topology): log n links per node in a network with n nodes
- Key idea: pick a random node to redirect a message to from the source, then follow the shortest path to the destination from there
- Guarantee: With high probability, the message reaches its destination very quickly (log n steps)
  - Practically, this means there is very less queueing in the network

VLB in data center networks

- VLB is more general than data center networks or Clos
  - It is a form of oblivious routing
  - e.g., no need to measure traffic patterns before choosing routes
  - Extremely simple to implement: no global state
- VLB is handy in folded Clos topologies due to the numerous options to pick the first-hop from ToR switch
  - Balance load across many paths
- Very beneficial in practice
  - Performance isolation: other flows don't matter
  - High capacity ("bisection bandwidth") between two ToR ports

VLB requirements: Hose model

- The guarantees of VLB + Clos only hold under the hose model:
  - Demands for any one ToR port (send or receive) must not exceed its bandwidth.

- Very hard to enforce especially on the receiver side without sender-side rate limits.

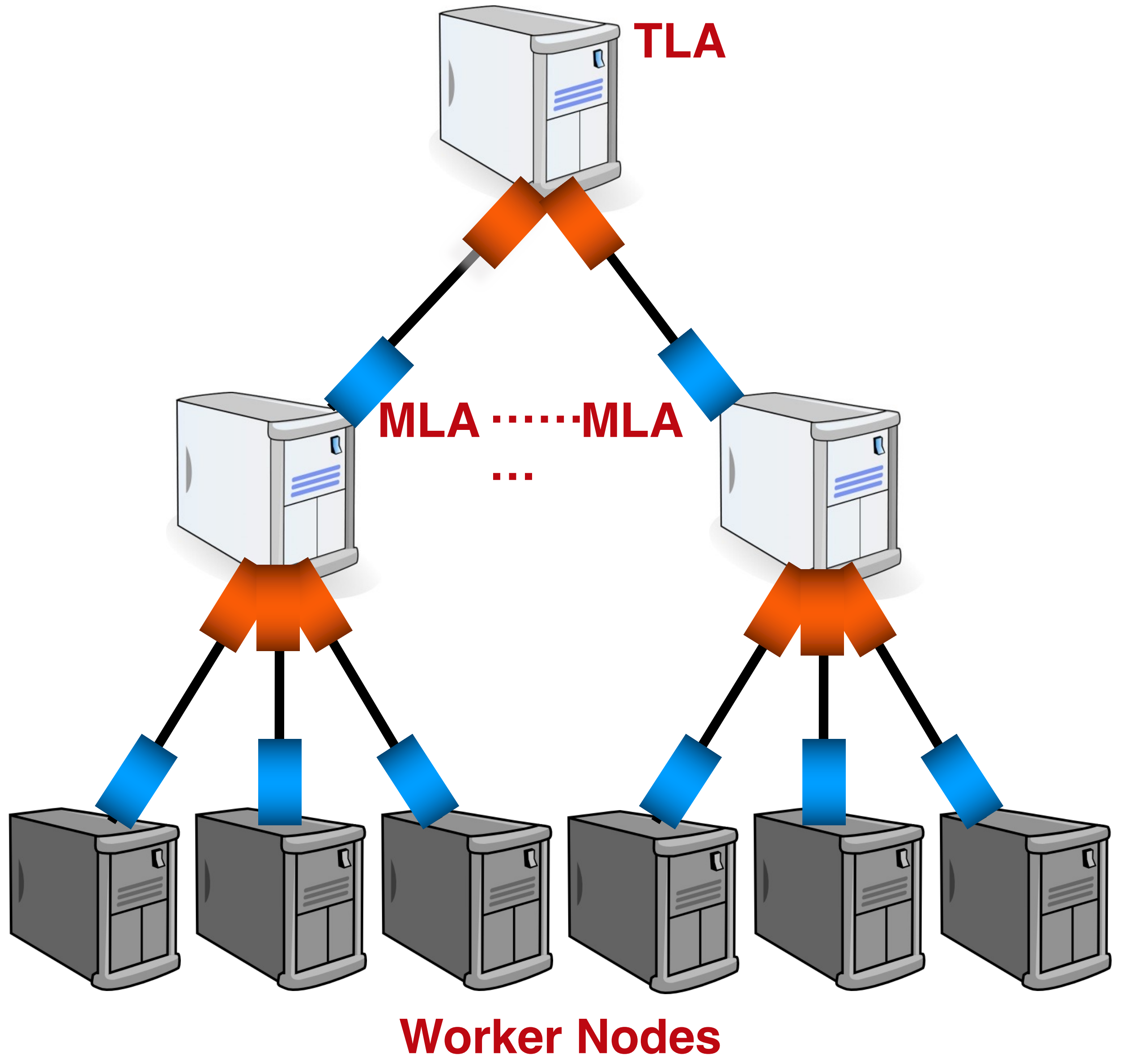
- VL2 uses TCP convergence as a way of ensuring that aggregate ToR port demand is within its bandwidth

Requirements for VLB to work well

- VLB + Clos provides high capacity if no ToR port demands more than its bandwidth (hose model)

A bunch of results arrive at MLAs and TLAs in a short period.

Demand may exceed ToR port bandwidth!



Enforcing the hose model

- Hose model is hard to enforce especially on the receiver side without sender-side rate limits

- VL2 uses TCP's convergence to bottleneck link rate as a loose method to enforce that the demand for port bandwidth is met by the available capacity.