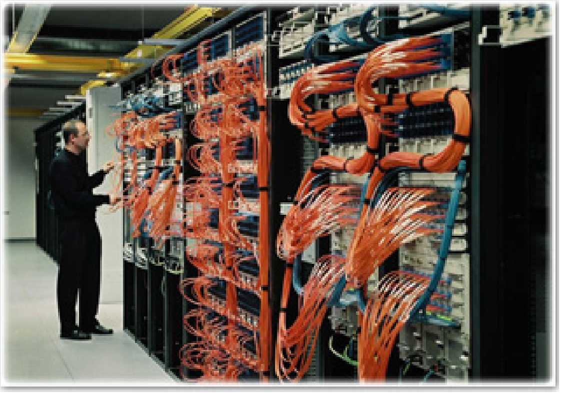
Data Center Network Topologies



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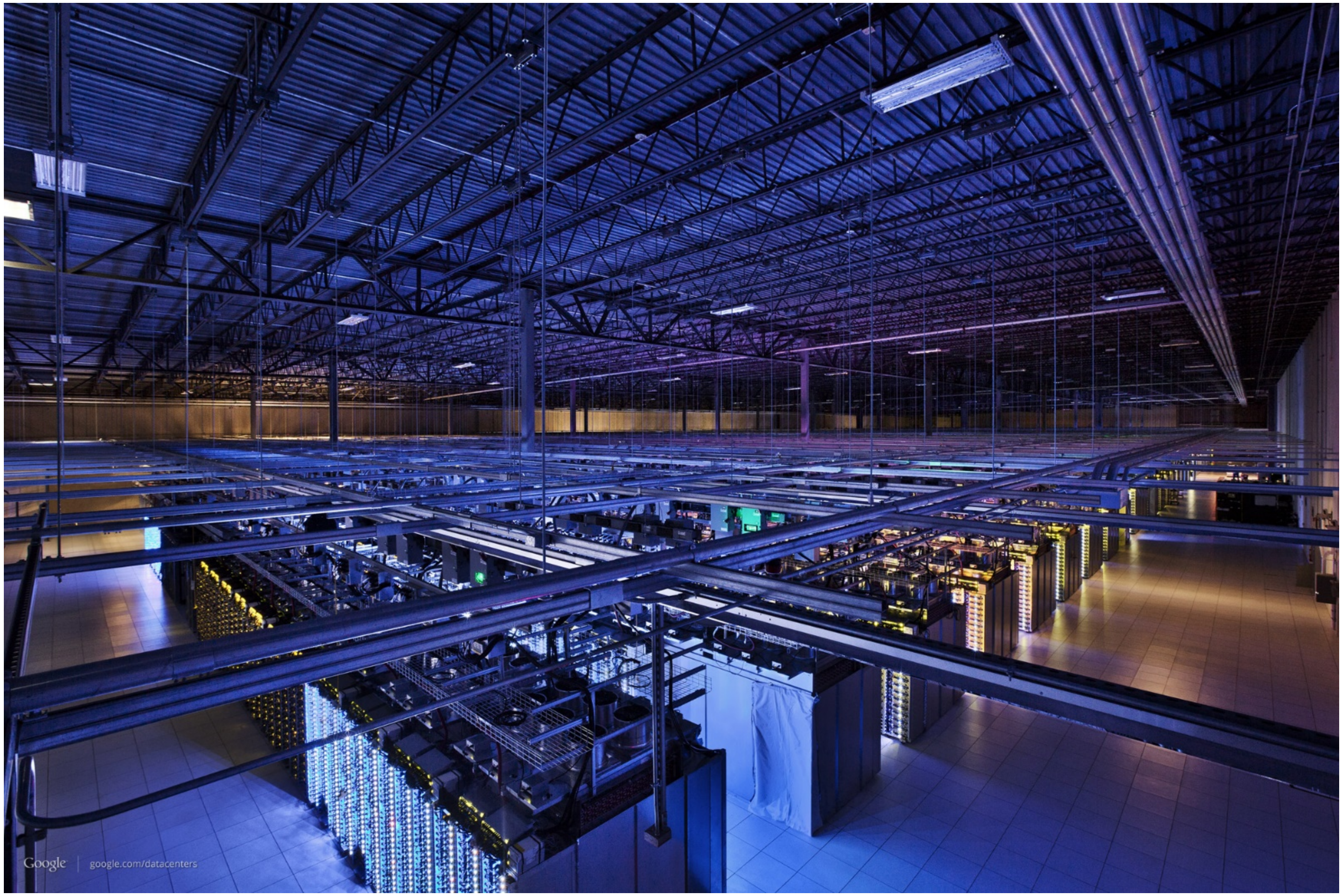
These slides and audio/video recordings of this class lecture are at:

http://www.cse.wustl.edu/~jain/cse570-19/

Overview

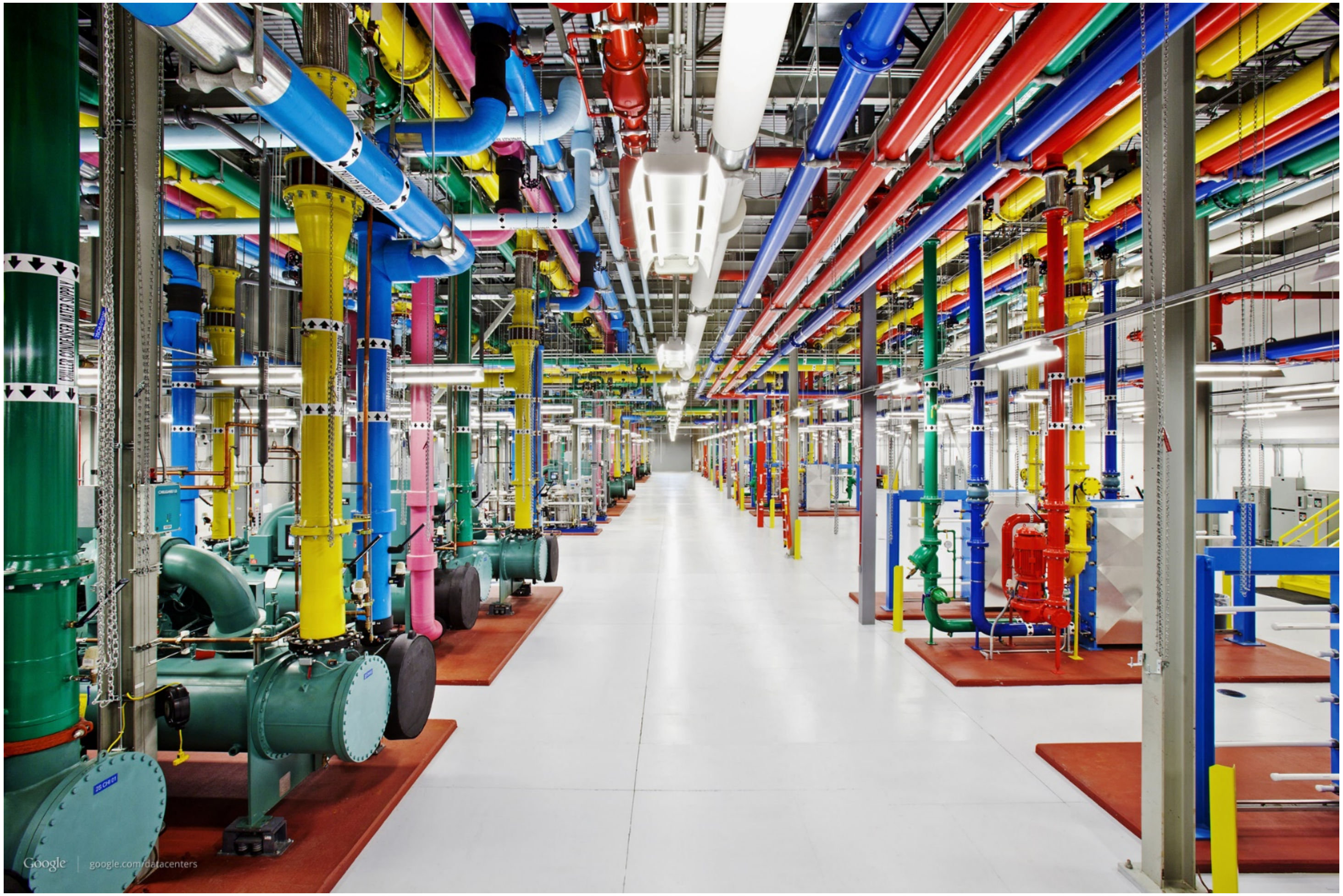
1. Data Center Physical Layout
2. Data Center Network Cabling
3. ToR vs. EoR
4. Clos and Fat-Tree topologies

Google's Data Center



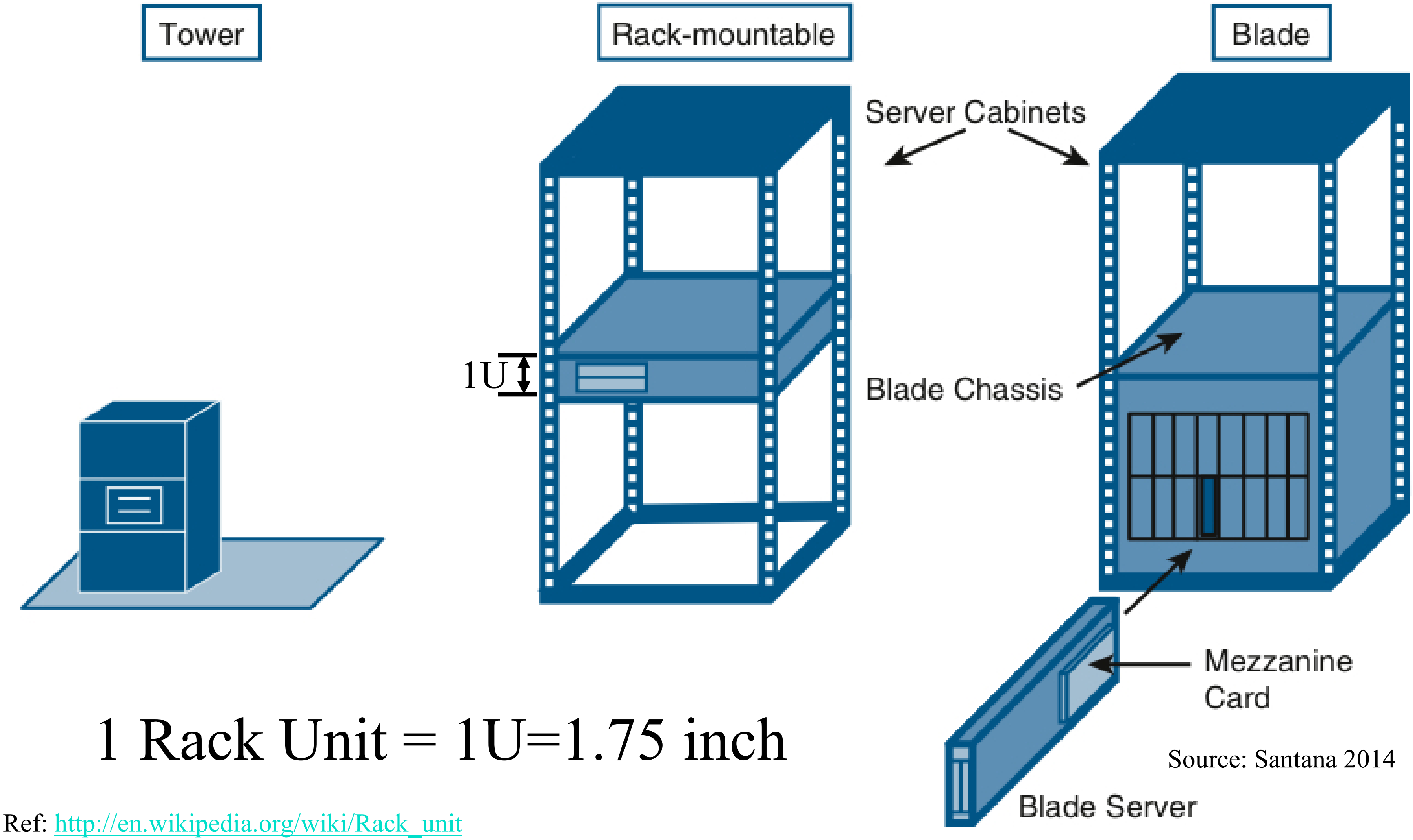
Source: http://webodysseum.com/technologyscience/visit-the-googles-data-centers/

Cooling Plant



Source: http://webodysseum.com/technologyscience/visit-the-googles-data-centers/

Servers



1 Rack Unit = 1U=1.75 inch

Source: Santana 2014

Ref: http://en.wikipedia.org/wiki/Rack_unit

Ref: G. Santana, "Data Center Virtualization Fundamentals," Cisco Press, 2014, ISBN:1587143240

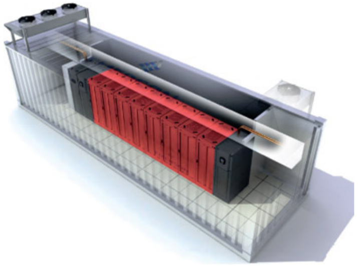
Modular Data Centers

- Small: < 1 MW, 4 racks per unit
- Medium: 1-4 MW, 10 racks per unit
- Large: > 4 MW, 20 racks per unit
- Built-in cooling, high PUE (power usage effectiveness) ≈1.02
  PUE = Power In/Power Used
- Rapid deployment

Ref: http://www.sgi.com/products/data_center/ice_cube_air/

Containerized Data Center

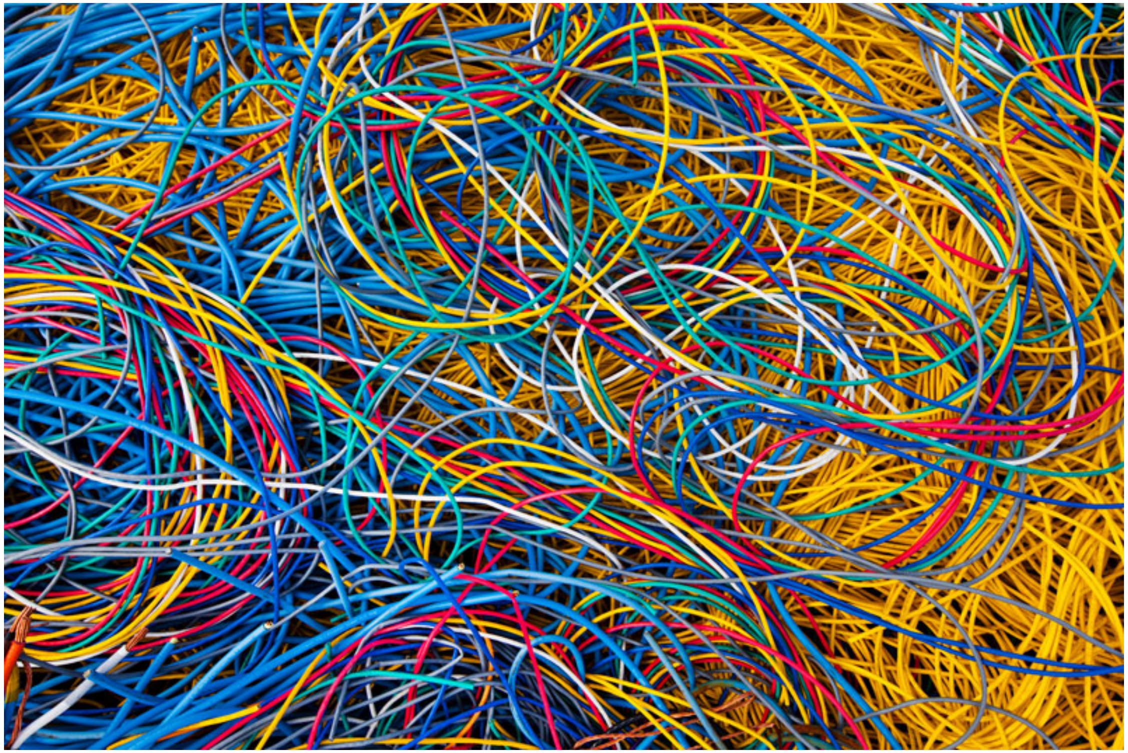
EMERSON
Datacenter Infrastructure



- Ready to Use. Connect to water and power supply and go.
- Built in cooling. Easy to scale.
  ⇒ Data Center trailer parks.
- Suitable for disaster recovery, e.g., flood, earthquake
- Offered by Cisco, IBM, SGI, Sun/ORACLE,…

Ref: http://www.datacenterknowledge.com/archives/2010/05/31/iij-will-offer-commercial-container-facility/

Unstructured Cabling

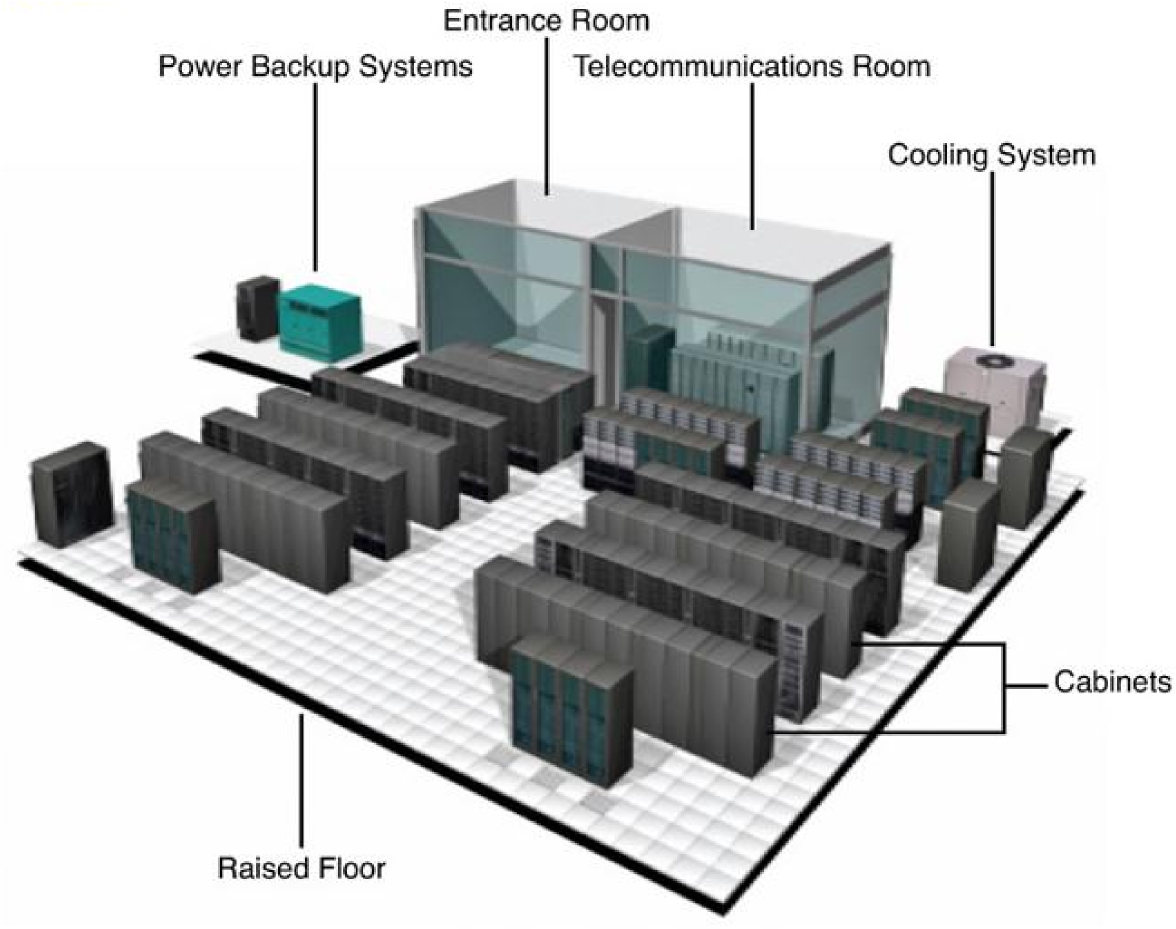


Source: http://webodysseum.com/technologyscience/visit-the-googles-data-centers/

Structured Cabling

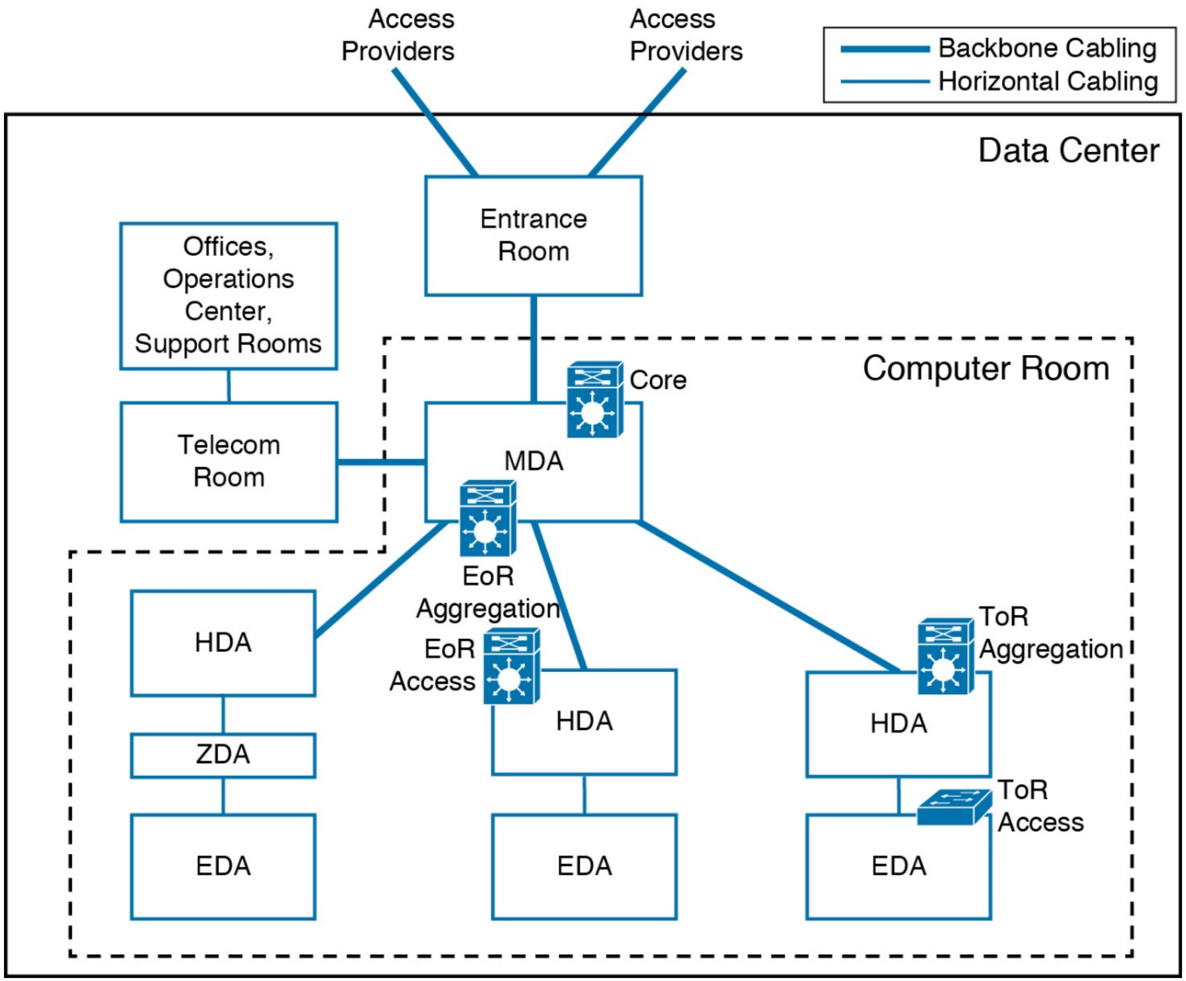
Source: http://webodysseum.com/technologyscience/visit-the-googles-data-centers/

Data Center Physical Layout



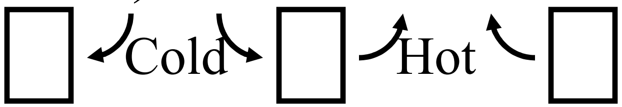
ANSI/TIA-942-2005 Standard

- ❑ Main Distribution Area (MDA)
- ❑ Horizontal Distribution Area (HDA)
- ❑ Equipment Distribution Area (EDA)
- ❑ Zone Distribution Area (ZDA)



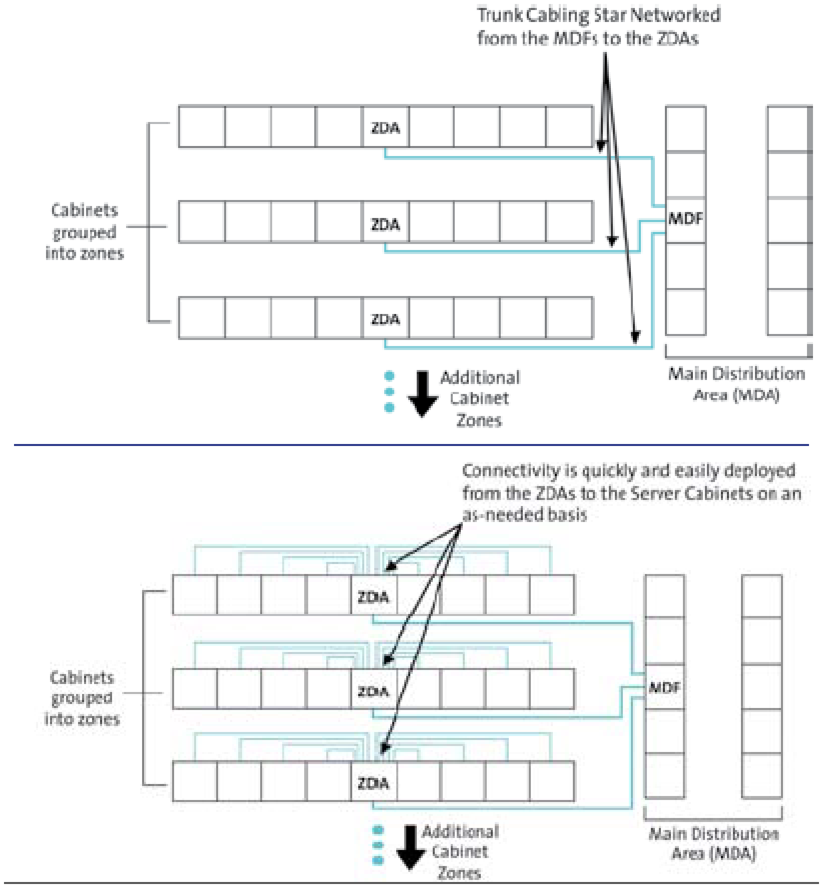
Source: Santana 2014

ANSI/TIA-942-2005 Standard

- Computer Room: Main servers
- Entrance Room: Data Center to external cabling
- Cross-Connect: Enables termination of cables
- Main Distribution Area (MDA): Main cross connect. Central Point of Structured Cabling. Core network devices
- Horizontal Distribution Area (HDA): Connections to active equipment.
- Equipment Distribution Area (EDA): Active Servers+Switches. Alternate hot and cold aisle. 

- Zone Distribution Area (ZDA): Optionally between HDA and EDA.
- Backbone Cabling: Connections between MDA, HDA, and Entrance room

Zone Distribution Area

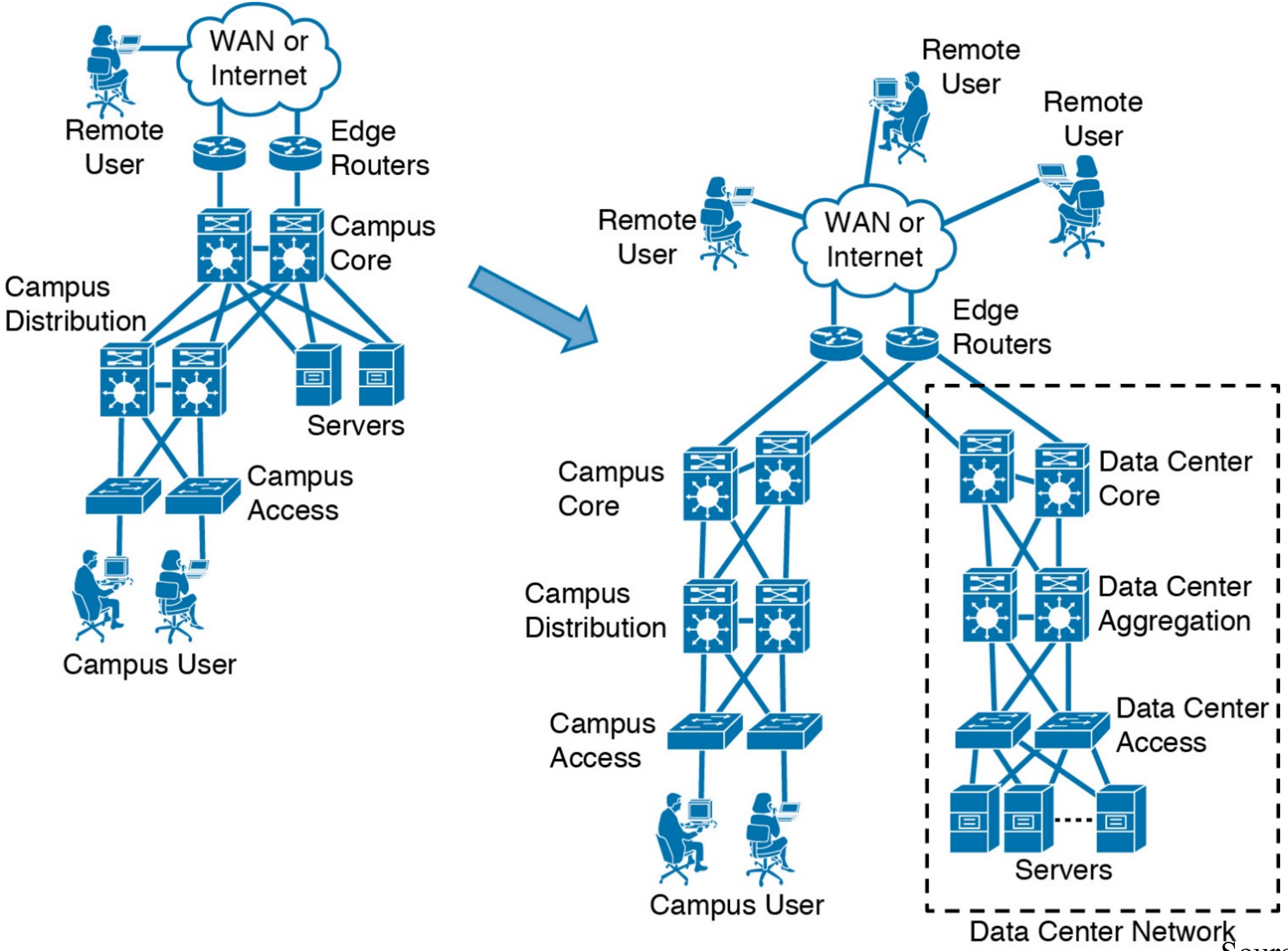

Trunk Cabling Star Networked from the MDFs to the ZDAs
ZDA
ZDA
ZDA
MDF
Cabinets grouped into zones
Additional Cabinet Zones
Main Distribution Area (MDA)
Connectivity is quickly and easily deployed from the ZDAs to the Server Cabinets on an as-needed basis
ZDA
ZDA
ZDA
MDF
Cabinets grouped into zones
Additional Cabinet Zones
Main Distribution Area (MDA)

- High-fiber count cables connect ZDA to MDA or HDA. Low-fiber count cables connect ZDA to EDA as needed.

Ref: Jennifer Cline, "Zone Distribution in the data center," http://www.graybar.com/documents/zone-distribution-in-the-data-center.pdf

Data Center Network Topologies: 3-Tier

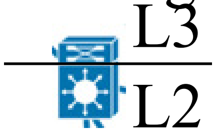
- Core, Aggregation, Access



Source: Santana 2014

3-Tier Data Center Networks

- ❑ 20-40 servers per rack. Limited by power/cooling
- ❑ Each server connected to 2 access switches with 1 Gbps (10 Gbps becoming common)
- ❑ Access switches connect to 2 aggregation
- ❑ All switches below each pair of aggregation switches form a single layer-2 domain
- ❑ All traffic **north** of aggregation switches forwarded by L3 routing (South = Servers, North = Internet)
  ⇒ Aggregation switches are L3 switches ⇒ implement routing
- ❑ Aggregation switches connect to 2 core L3 switches
- ❑ Core L3 switches connect to edge routers
- ❑ Core layer forwards data center ingress and egress traffic

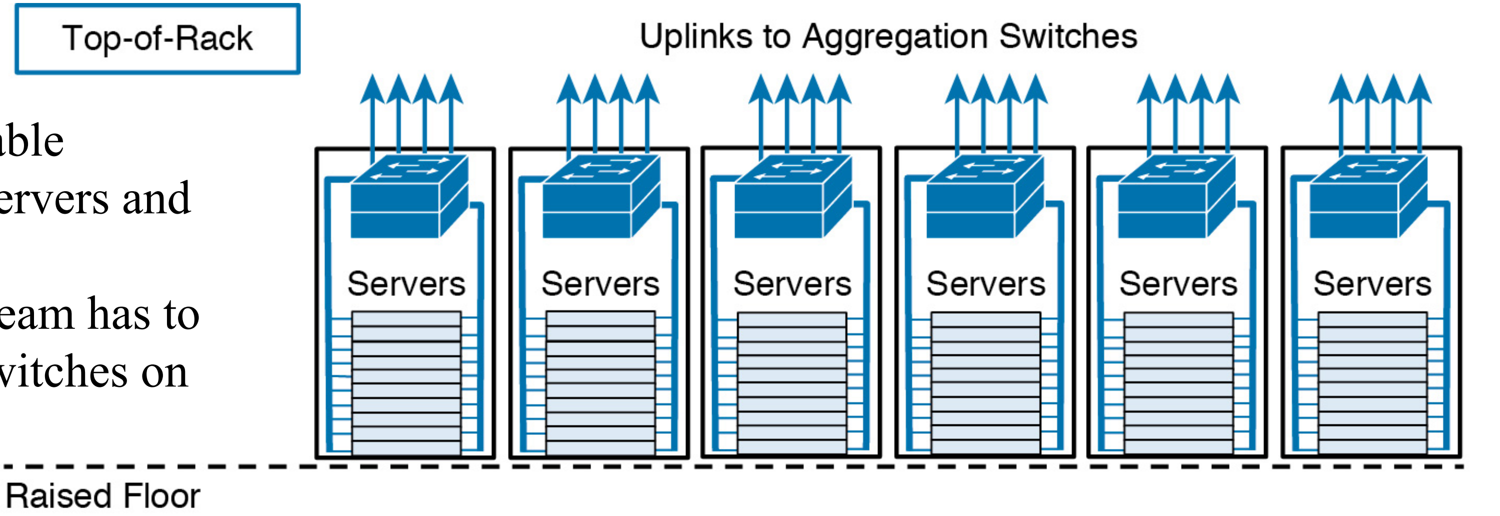


Ref: A. Greenberg, "VL2: A Scalable and Flexible Data Center Network," CACM, Vol. 54, NO. 3, March 2011, pp. 95-104, *http://research.microsoft.com/pubs/80693/vl2-sigcomm09-final.pdf*.

3-Tier Data Center Networks (Cont)

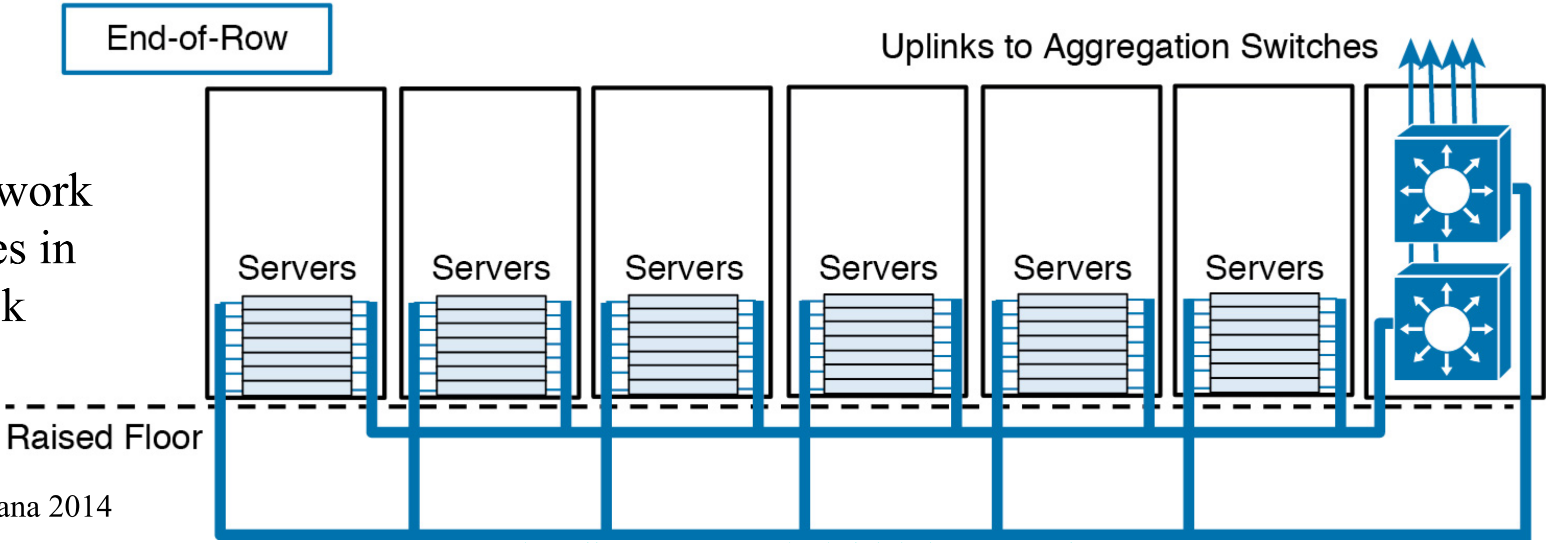
- ❑ Aggregation layer is also a place to put middleboxes, such as, firewalls, load balancers
- ❑ Access Layer provide high number of ports for connectivity.
- ❑ Low Latency: In high-frequency trading market, a few microseconds make a big difference.
  ⇒ Cut-through switching and low-latency specifications.
- ❑ Each Layer 2 domain typically limited to a few hundred servers to limit broadcast
- ❑ Most traffic is internal to the data center.
- ❑ Most of the flows are small.
  Mode = 100 MB. DFS uses 100 MB chunks.
- ❑ Aggregation layer forwards server-to-server traffic in the data center => Not ideal for East-West Traffic
- ❑ Network is the bottleneck.
  Uplinks utilization of 80% is common.

Switch Locations



Smaller cable between servers and switches

Network team has to manage switches on all racks



All network switches in one rack

Source: Santana 2014

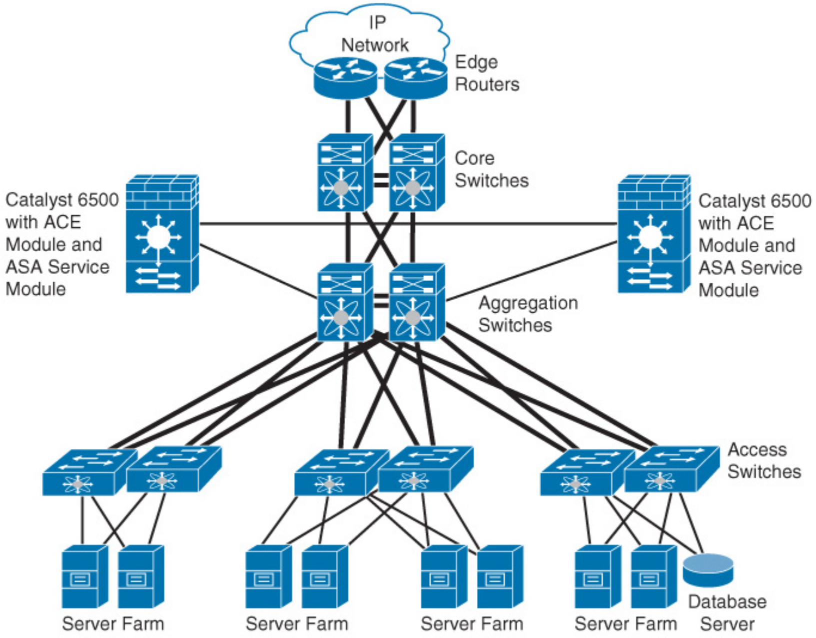
ToR vs EoR

- ToR:
  - + Easier cabling
  - - If rack is not fully populated ⇒ unused ToR ports
  - - If rack traffic demand is high, difficult to add more ports
  - - Upgrading (1G to 10G) requires complete Rack upgrade

- EoR:
  - - Longer cables
  - + Severs can be placed in any rack
  - + Ports can easily added, upgraded

3-Tier Hierarchical Network Design

- All servers require application delivery services for security (VPN, Intrusion detection, firewall), performance (load balancer), networking (DNS, DHCP, NTP, FTP, RADIUS), Database services (SQL)
- ADCs are located between the aggregation and core routers and are shared by all servers



Source: Santana 2014

- Stateful devices (firewalls) on Aggregation layer
- Stateful = State of TCP connection
- Stateless, e.g., DNS

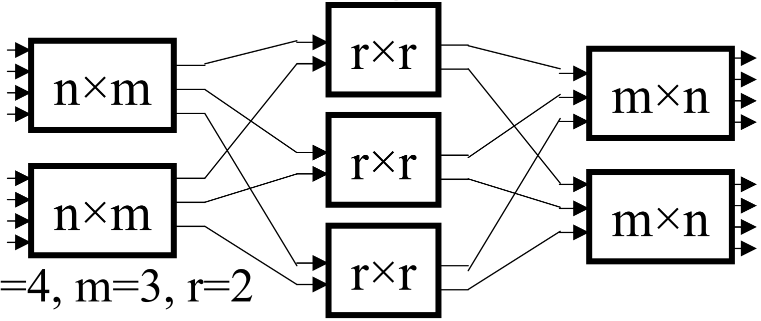
Problem with 3-Tier Topology

- Failure of a single link can reduce the available bandwidth by half
- With more than two aggregation switches, spanning tree becomes unpredictable in case of certain failures.
- Two aggregation switch => They are the bottleneck
- It is not possible for VLANs to span across multiple pairs of aggregation switches since the pairs are connected by L3
- VLAN provisioning becomes laborious

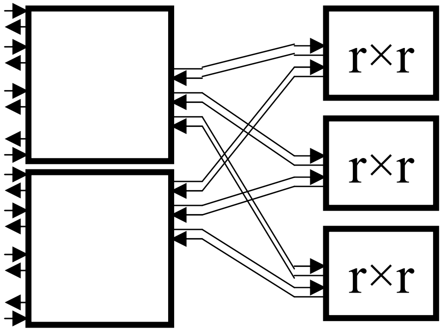
Ref: Dinesh G. Dutt, "Cloud-Native Data Center Networking," O'Reilly Media, Inc., December 2019, ISBN: 9781492045595, Safari Book.

Clos Networks

- Multi-stage circuit switching network proposed by Charles Clos in 1953 for telephone switching systems
- Allows forming a large switch from smaller switches
  The number of cross-points is reduced ⇒ Lower cost (then)
- 3-Stage Clos(n, m, r): ingress (rn×m), middle (mr×r), egress (rm×n)
- *Strict-sense non-blocking* if $m \geq 2n-1$. Existing calls unaffected.
- *Rearrangeably non-blocking* if $m \geq n$
- Can have any odd number of stages, e.g., 5
- **Folded**: Merge input and output in to one switch



n=4, m=3, r=2



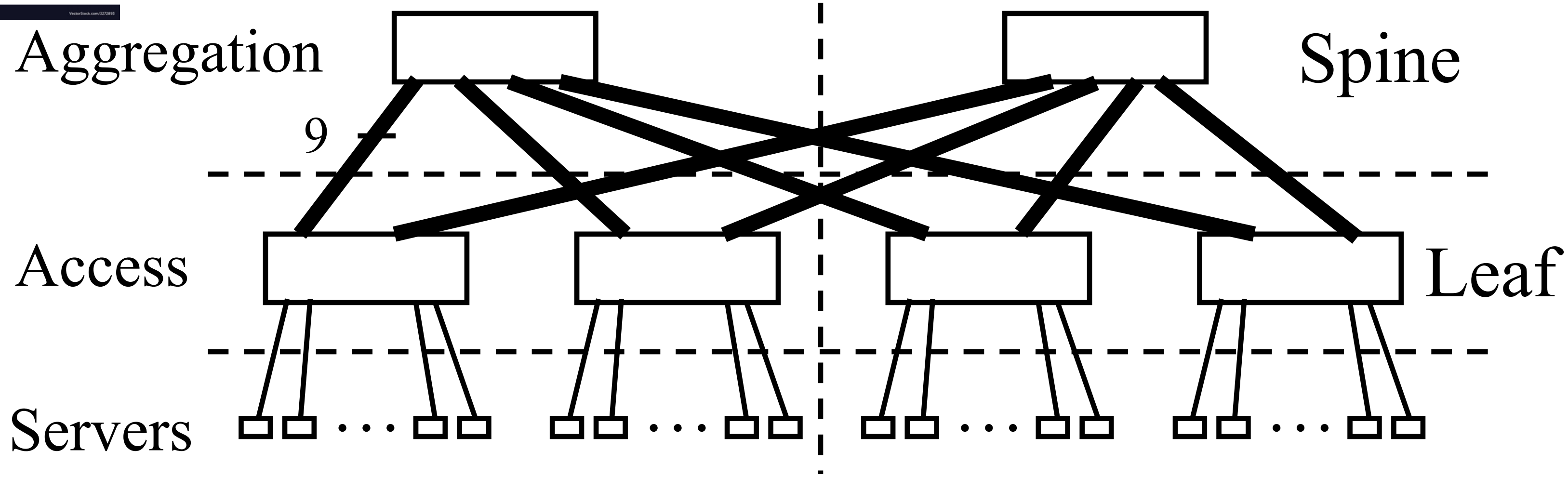
n+m port switches r-port switches

Ref: http://en.wikipedia.org/wiki/Clos_network

Homework 3A

- Draw a 3-stage clos(4, 5, 3) topology and its folded version. $n = 4$, $m = 5$, $r = 3$

Fat-Tree DCN Example

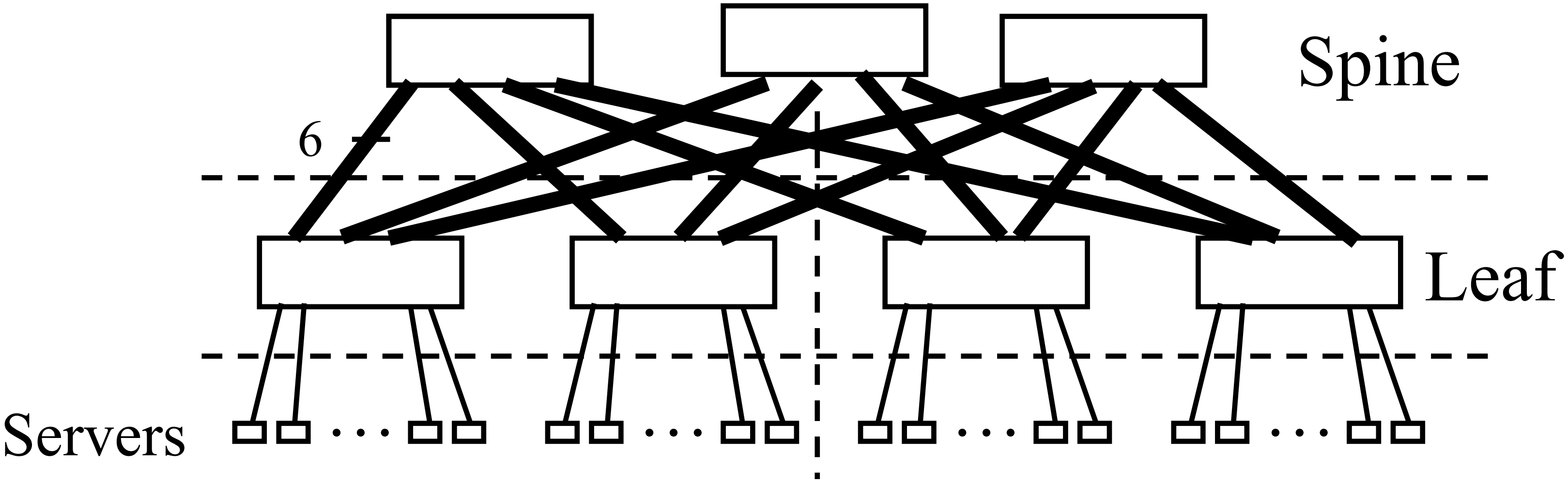


- 6 identical 36-port switches. All ports 1 Gbps. 72 Servers.
- Each access switch connects to 18 servers.
  9 Uplinks to first aggregation switch.
  Other 9 links to 2nd aggregation switch.
- Throughput between any two servers = 1 Gbps using ECMP
  Identical bandwidth (36 Gbps) at any bisection.
- Negative: Cabling complexity

Ref: Teach yourself Fat-Tree Design in 60 minutes, http://clusterdesign.org/fat-trees/

Fat-Tree Topology (Cont)

- Half of leaf switch ports are towards servers and the other half towards spine
- With 36 port switches ⇒ 18 ports to spine ⇒ 2, 3, 6, 9, 18 spine switches
- Maximum # of spine switches = ½ # of ports on leaf switches



- Largest configuration with n-port switches: $n^2/2$ servers can be connected using $n+n/2$ switches.

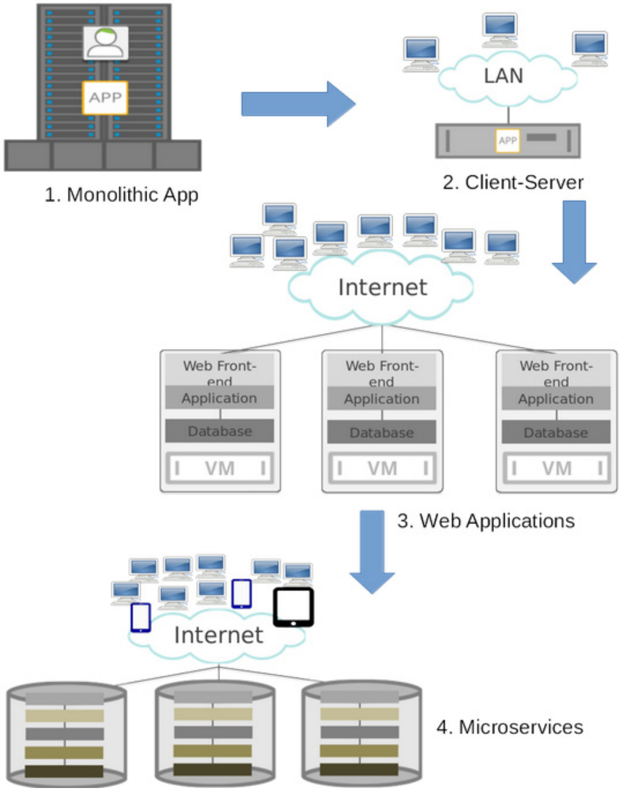
Homework 3B

1. Draw the largest Fat-tree topology using 4-port switches. Assume each server is connected to a single leaf switch while the leaf switches are multi-homed to spine switches. There is no core tier.
2. How many servers can be connected in the above configuration?
3. How many switches in all are required in the above configuration?
4. How many servers can be connected using 64-port switches.
5. How many switches are required to form the spine and the leaves using 64-port switches.

Evolution of Applications

Pre-1985

1985-1995



1995-2015

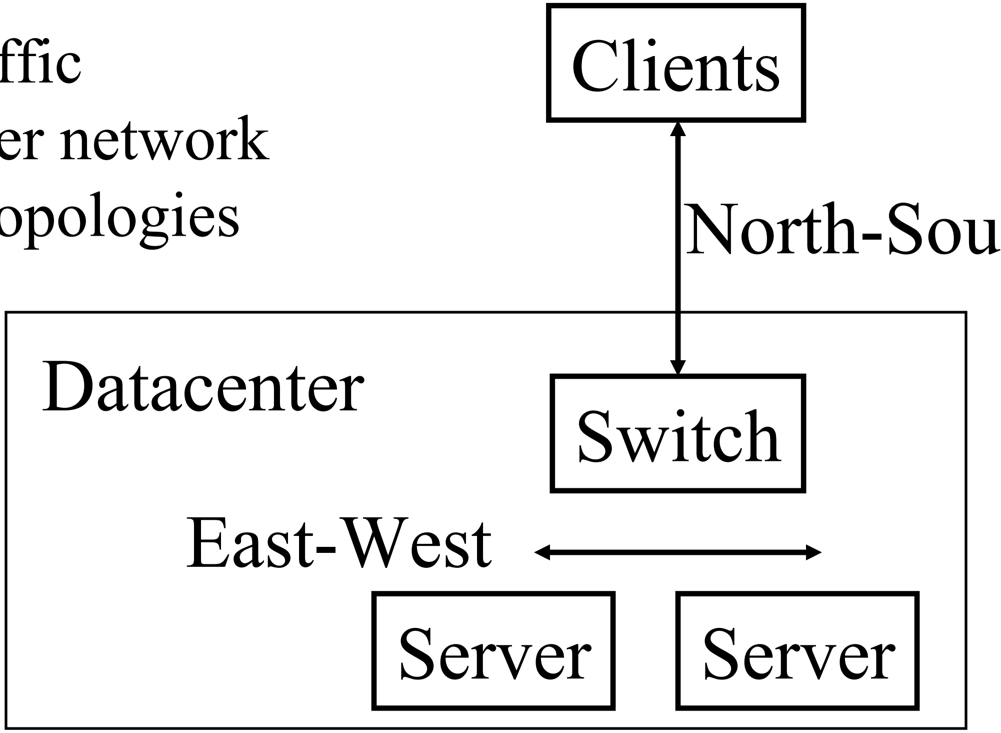
2015+

- ❑ Larger Servers to Micro-Services ⇒ Increasing network demand

Ref: Dinesh G. Dutt, "Cloud-Native Data Center Networking," O'Reilly Media, Inc., December 2019, ISBN: 9781492045595, Safari Book.

North-South vs. East-West Traffic

- Previously, most of the traffic was north-south
  ⇒ Between servers in the data center and clients out-side
- Now the trend is towards traffic between servers for big data analysis
  ⇒ East-West traffic
  ⇒ Requires flatter network
  ⇒ Fat-tree like topologies



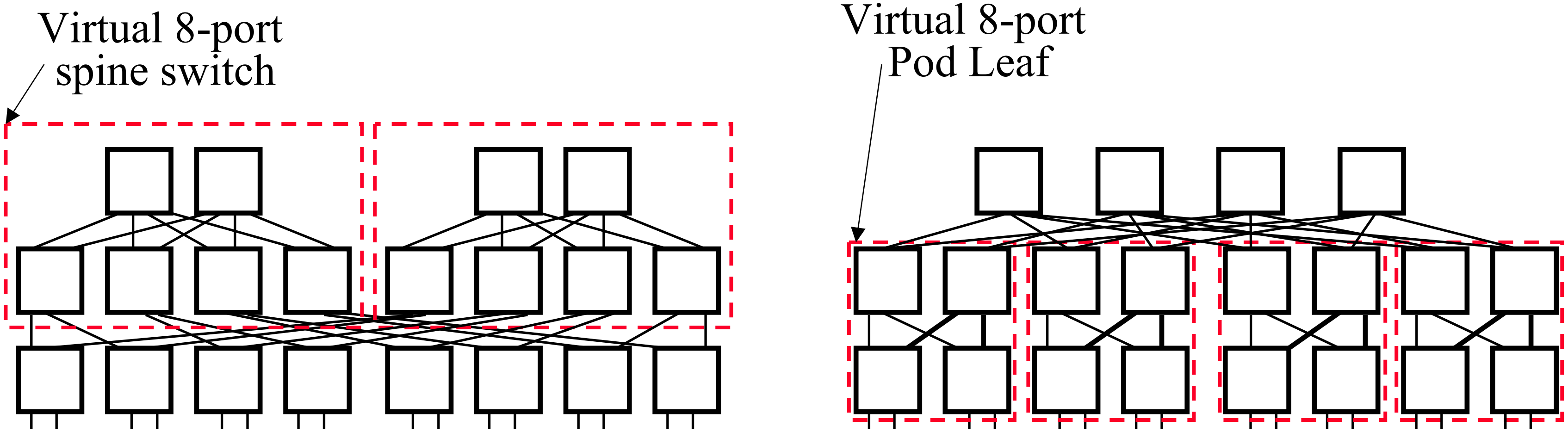
Advantages of 2-Tier Architecture

- Homogeneous Equipment: Spine and leaf switches both have the same number of ports with the same speed.
  ⇒ Maintenance and replacements is easier
- L2 forwarding is used only in each rack.
  ⇒ a new protocol (VXLAN) is used for routing between racks
- A leaf can reach any other leaf via any spine at the same cost
  ⇒ Equal cost multi-path (ECMP) simplifies routing
- All packets of a flow are sent using the same path to avoid out-of-order arrivals.
  - Flow = {Source IP, Dest IP, L4 Protocol, Source Port, Dest Port)
  - Flow hashing is used to select a spine switch

Ref: Dinesh G. Dutt, "Cloud-Native Data Center Networking," O'Reilly Media, Inc., December 2019, ISBN: 9781492045595, Safari Book.

Variations

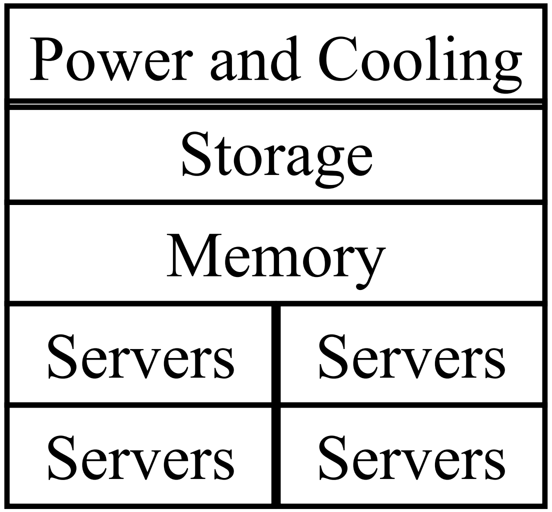
- Higher-speed Inter-Switch Links (ISLs) may be used:
  - 1 Gbps server/10 Gbps ISL, 10 Gbps Server/40 Gbps ISL
  - Reduces number of spine switches required (Smaller number of ECMP may result in some congestion. Also, loss of a spine may have a more severe impact)
- Two leaves per rack. Hosts are dual-ported.
- Three-tier Clos: $n^3/4$ servers using $n+n^2$ switches



Ref: Dinesh G. Dutt, "Cloud-Native Data Center Networking," O'Reilly Media, Inc., December 2019, ISBN: 9781492045595, Safari Book.

Rack-Scale Architecture

- ❑ Traditionally each server has its own cooling, storage, memory, and networking ⇒ Inefficient use of dedicated resources
- ❑ Shared resources ⇒ Rack-Scale Architecture (RSA)
- ❑ Memory, Storage, Cooling is shared by all servers on the rack
  Server "sleds" plug in to networking board on the back
- ❑ Buy complete racks rather than individual servers
- ❑ Being standardized by Open Compute Project (OCP)



Power and Cooling

Storage

Memory

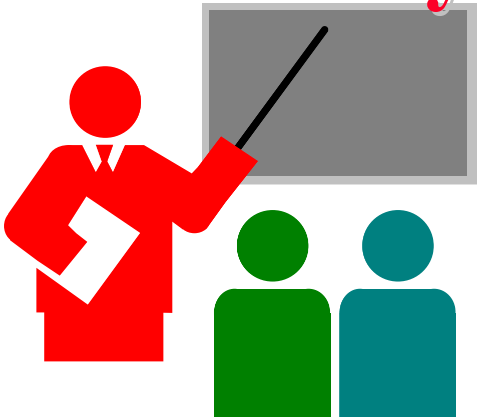
Servers Servers

Servers Servers

Micro-Servers

- Microserver = a small system on a chip (SOC) containing CPU, memory and multiple NICs
- Many microservers on a board (look like memory DIMMs)
- Microserver sleds can replace server sleds in rack scale architecture

Summary



1. Modular data centers can be used for easy assembly and scaling
2. Three tiers:
   1. Access, Aggregation, Core
   2. Application delivery controllers between Aggregation and core.
   3. Need large L2 domains => Past
3. Clos-Based Fat-tree topology is being used to improve performance and reliability

Acronyms

ADC	Application Delivery Controller
ANSI	American National Standards Institute
BPE	Business Process Engineering
CSW	Core Switch
DCBX	Data Center Bridging eXtension
DCN	Data Center Network
DFS	Distributed File System
DHCP	Dynamic Host Control Protocol
DIMM	Dual Inline Memory Module
DNS	Domain Name System
ECMP	Equal Cost Multipath
EDA	Equipment Distribution Area
EoR	End of Row

Acronyms (Cont)

ETS	Enhanced Transmission Selection
EVB	Edge Virtual Bridge
FC	Fibre Channel
FSW	Fabric switch
FTP	File Transfer Protocol
HDA	Horizontal Distribution Area
LACP	Link Aggregation Control Protocol
LAG	Link Aggregation
LLDP	Link Layer Discovery Protocol
MAC	Media Access Control
MDA	Main Distribution Area
MW	Mega-Watt
NIC	Network Interface Card
NTP	Network Time Protocol
NVGRE	Network Virtualization using Generic Routing Encapsulation
OCP	Open Compute Project

Acronyms (Cont)

PFC	Priority Flow Control
PUE	Power Usage Effectiveness
RADIUS	Remote Authentication Dial-In User Service
RPC	Remote Procedure Call
RSA	Rack Scale Architecture
RSW	Rack switch
SOC	System on Chip
SQL	Structured Query Language
SSW	Spine Switches
STP	Spanning Tree Protocol
TIA	Telecommunications Industry Association
ToR	Top of Rack
TRILL	Transparent Interconnection of Lots of Link
VLAN	Virtual Local Area Network
VM	Virtual Machine
VPN	Virtual Private Network

Acronyms (Cont)

VRF	Virtual Routing and Forwarding
VXLAN	Virtual Extensible Local Area Network
ZDA	Zone Distribution Area

Reading List

- Dinesh G. Dutt, "Cloud-Native Data Center Networking," O'Reilly Media, Inc., ecember 2019, ISBN: 9781492045595, Safari Book (Chapters 2 and 3)
- G. Santana, “Data Center Virtualization Fundamentals,” Cisco Press, 2014, ISBN:1587143240 (Safari book) (Chapters 1 and 2)

References

- A. Greenberg, "VL2: A Scalable and Flexible Data Center Network," CACM, Vol. 54, NO. 3, March 2011, pp. 95-104, *http://research.microsoft.com/pubs/80693/**vl2**-sigcomm09-final.pdf*
- http://en.wikipedia.org/wiki/Clos_network
- Teach yourself Fat-Tree Design in 60 minutes, http://clusterdesign.org/fat-trees/
- http://webodysseum.com/technologyscience/visit-the-googles-data-centers/
- http://www.sgi.com/products/data_center/ice_cube_air/
- Datacenter Infrastructure - mobile Data Center from Emerson Network Power, http://www.datacenterknowledge.com/archives/2010/05/31/iij-will-offer-commercial-container-facility/
- Jennifer Cline, “Zone Distribution in the data center,” *http://www.graybar.com/documents/**zone-distribution**-in-the-data-center.pdf*

Wikipedia Links

- http://en.wikipedia.org/wiki/Modular_data_center
- http://en.wikipedia.org/wiki/Data_center
- http://en.wikipedia.org/wiki/Structured_cabling
- http://en.wikipedia.org/wiki/Cable_management
- http://en.wikipedia.org/wiki/Raised_floor
- http://en.wikipedia.org/wiki/Data_center#environmental_control
- https://en.wikipedia.org/wiki/Hierarchical_internetworking_model
- http://en.wikipedia.org/wiki/Fat_tree
- http://en.wikipedia.org/wiki/Clos_network

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https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Wireless and Mobile Networking (Spring 2016),
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https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw