Data Center Networks

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May 10, 2018

Network/Cluster Computing Has Been Around for a While

- Grid computing, cluster computing (Beowulf cluster)


1961, Information Processing Center at the National Bank of Arizona

- All of a sudden, data centers are extremely hot
  - **Why?**


The Scale!

- Everyone wants to operate at Internet scale
  - Millions of users
  - Zetabytes of data to analyze
    - Web server logs, Ads reviews/clicks, social networks, blogs, Twitter, video…
- But not everyone has the expertise to build a cluster
  - **Let someone else do it for you!**

Cloud Computing

- Everything is a service
  - Infrastructure
  - Platform
  - Software
  - Storage

- What actually powers the cloud?

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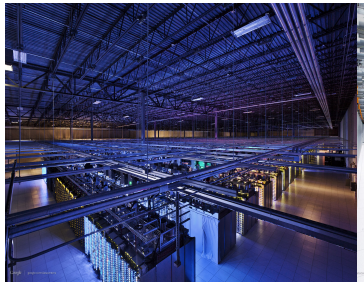
Today's Data Centers

- Warehouse of servers



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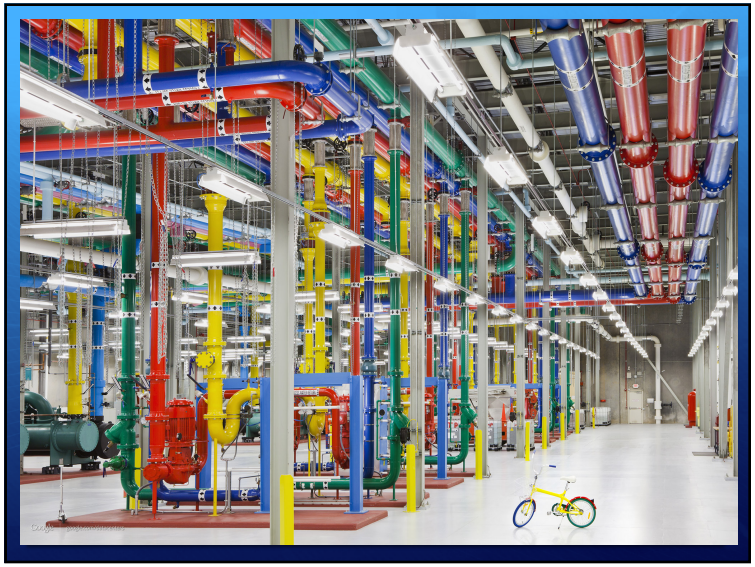

What Goes into a Data Center?

- Servers organized in racks
- Each rack has a "Top of Rack" switch
- An aggregation fabric interconnects ToR switches

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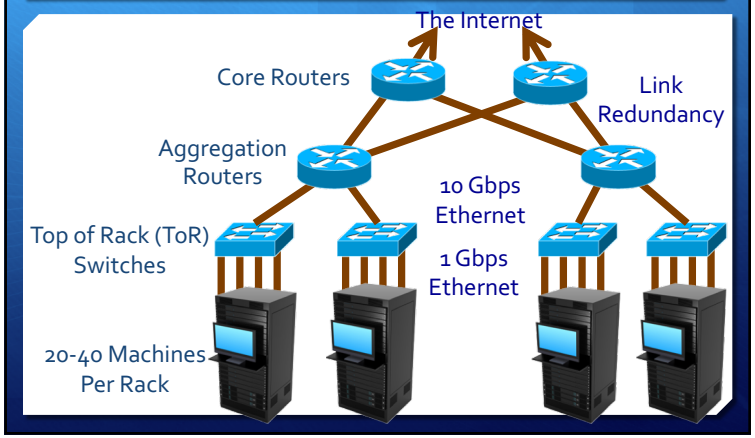
Typical Data Center Topology



What's Different about Data Center Networks?

- Huge scale
  - 1M servers (Microsoft), > $1B to build one site (Facebook)
- Speed, speed, speed…
  - High bandwidth 10/40/100Gbps
  - RTT: **10s of microseconds**
- Single administrative domain
  - Can invent your own design, control the traffic placement
- Regular/planned topologies

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Lots of Open Problems

- Diverse applications
  - Heterogeneous, unpredictable traffic patterns
  - Competition over resources
  - Isolation
  - Reliability issues
  - Privacy
- Management, diagnosis and debugging at scale
- Heat and power

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Today's Topic: Network Problems

- Data centers are data-intensive
- Hardware can handle it
  - CPUs scale with Moore's Law, RAM is almost as fast as CPU, RAID and SSDs are pretty fast
- Current network cannot handle it
  - Slow, not keeping pace over time
  - Wiring is a nightmare
  - Expensive
  - Hard to manage
  - Non-optimal protocols

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Outline

- Introduction
- Network topology
  - Fat tree
  - Wireless in data centers
  - Optical in data centers
- Transport protocols

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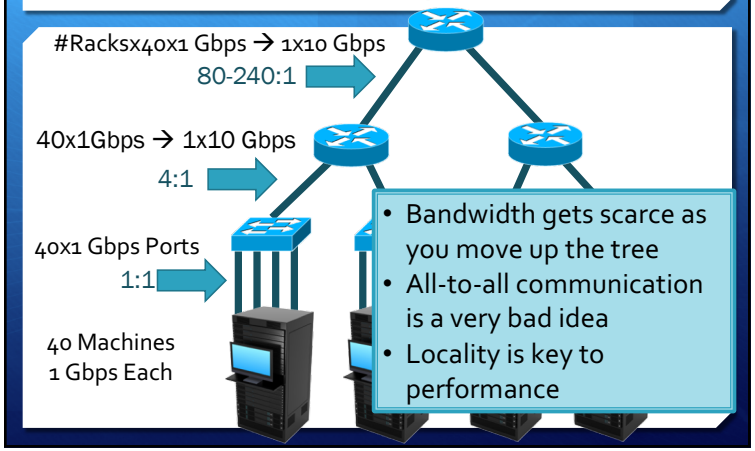
Problem: Oversubscription



Oversubscription can be Harmful

- Ruin your network
  - Limits application scalability
- Problem is about to get worse
  - 10 GigE servers are more affordable
  - 128 port 10 GigE routers are not
- An issue of the core routers
- Get rid of the core routers by using cheap switches?
  - Maintain 1:1 subscription ratio

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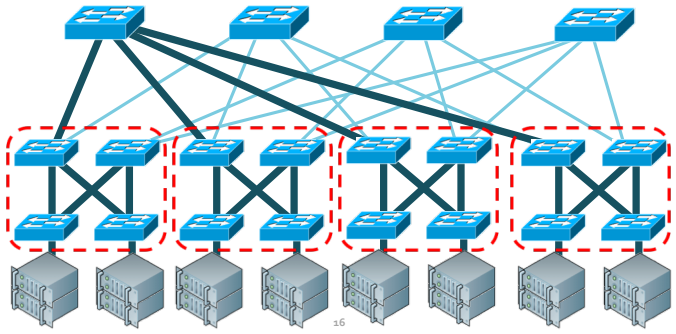
Fat-tree

To build a K-ary fat tree
- K-port switches
- K pods, each with K switches
- $K^3/4$ hosts
- $(K/2)^2$ core switches

In this example K=4
- 4-port switches
- 4 pods, each with 4 switches
- $K^3/4 = 16$ hosts
- $(K/2)^2 = 4$ core switches



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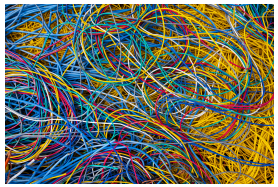
Fat-tree

- The good
  - Full bisection bandwidth
  - Low-cost, commodity hardware
  - Redundancy for failover
- The bad
  - Custom routing (NetFPGA)
  - Wiring is a nightmare
    # of wires: → $3K^3/4$
    - 48 port switches = 82944



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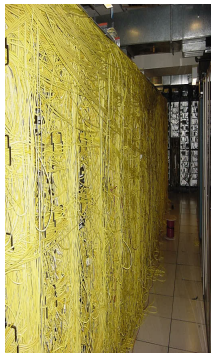
Limitations of Wired Interconnects

- Wiring is complex and costly
  - Planning, deploying, testing 10K+ fibers
  - Takes several weeks or even months
- Difficult to change wiring
  - High labor cost
  - Significant interruptions to operations
- Overprovisioning is difficult
  - Traffic demands unpredictable
  - Limited by hardware costs



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Dealing with Traffic Hotspots

- Measurements show sporadic congestion losses caused by traffic hotspots
  - Traffic hotspots are unpredictable, can appear anywhere
  - Can double failure rate for some jobs

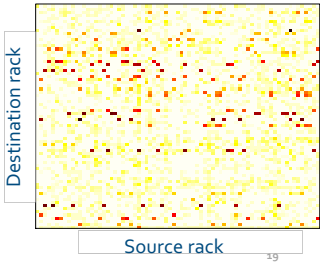

Figure source: Halperin, D., et al. Augmenting data center networks with multi-gigabit wireless links. In *Proc. of SIGCOMM* (2011)

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Dealing with Traffic Hotspots

- Measurements show sporadic congestion losses caused by traffic hotspots
  - Traffic hotspots are unpredictable, can appear anywhere
  - Can double failure rate for some jobs
- Hard to add bandwidth using wires
  - Do not know where and when to add capacity
  - Rewiring is complex, high labor cost, interrupts current operation

Need alternative solutions!

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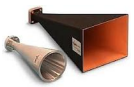
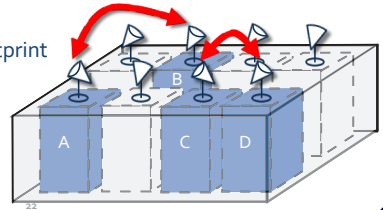
Augmenting via Wireless Links

- Key benefit: on-demand links
  - Create links on-the-fly at congestion hotspots
  - Adapt to traffic dynamics
- New wireless technology: 60 GHz beamforming
  - Multi-Gbps data rate
  - Small interference footprint





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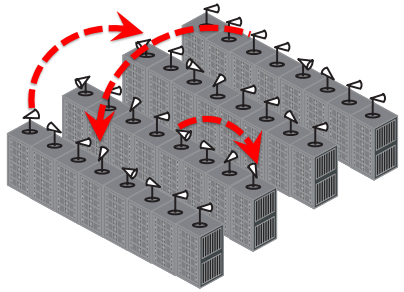
Flexible Wireless Links in Data Centers

- Connect any rack pair wirelessly to address dynamic traffic hotspots



Hard to do so using 60GHz transmissions

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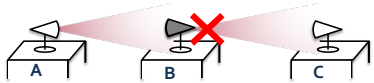
Key Challenges

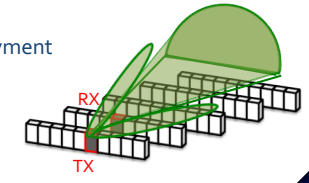
- **Link blockage**: small obstacles block the link



→ Must use multi-hop forwarding

- **Radio interference**: beam interferes with racks in its direction
  - Exacerbated by dense rack deployment
  - Signal leakage makes it worse

→ Links interfere with each other



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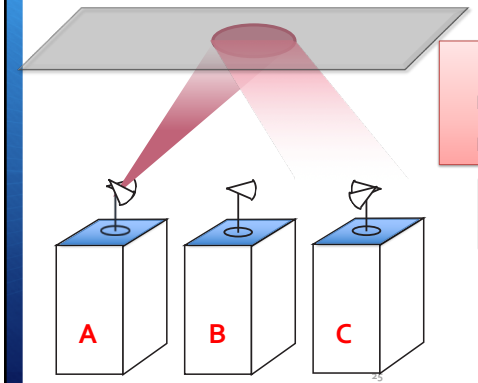
Wireless 3D Beamforming

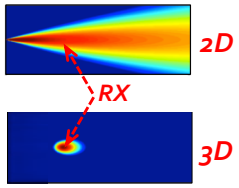
Connect racks by reflecting signals off the ceiling!



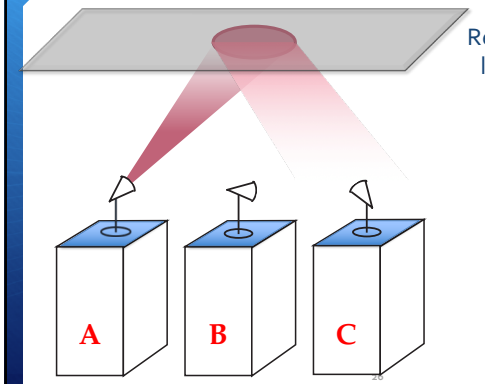
Key Benefits

No more link blockage

Much smaller interference



Easy Setup



Reuse existing hardware, low maintenance cost!

Reflector

Absorber

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3D Beamforming Summary

- New wireless primitive added into data center toolbox
  - Overcomes key challenges of using wireless in data centers
  - Opens up more opportunities of using wireless in data centers
- Practical issues
  - Traffic scheduling
  - Reflector placement, impact on data center cooling

http://www.cs.dartmouth.edu/~xia/papers/sigcomm12_beam3d.pdf

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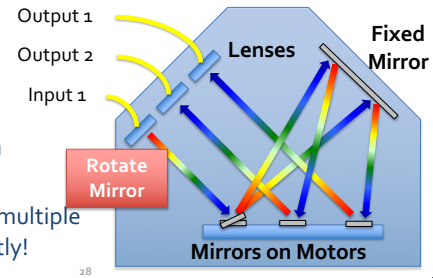
Augmenting via Optical Links

- Optical circuit switch
  - Uses mirrors to bounce light from port to port
  - No decoding
  - Mechanically adjust mirrors in milliseconds
- Wavelength division multiplexing
  - Single port carries multiple streams concurrently!



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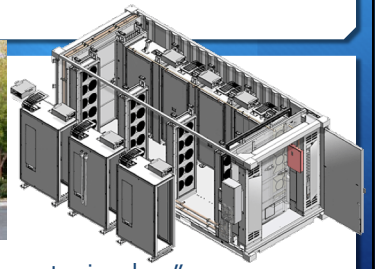
Example: Connecting Modular Datacenters



- Shipping container: "datacenter in a box"
  - 250-1K servers per container
- How do you connect the containers?
  - Copper cable constraint: physical distance matters (10GigE -> 10 meters)

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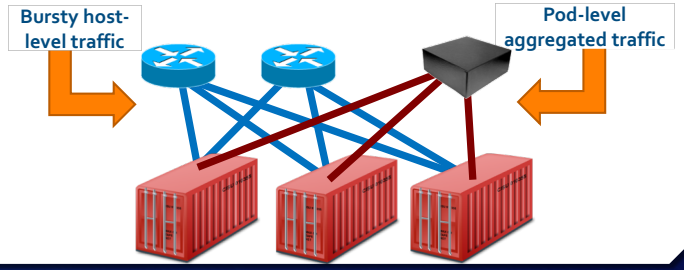
Helios: Datacenters at Light Speed

Packet switch network
- Electrical packet switches
- Connect all containers

Optical circuit network
- Optical circuit switches
- Direct container-to-container links on demand



Outline

- Introduction
- Network topology
- Transport protocols
  - Google and Facebook
  - DCTCP
  - D3

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Transport in Data Center Networks

- TCP optimized for wide area networks
  - Slow-start, AIMD convergence
  - Zero knowledge congestion control
    - Self-induces congestion, loss equals congestion
- But, data center is not the Internet
  - Latency is tiny (250µs in absence of queuing)

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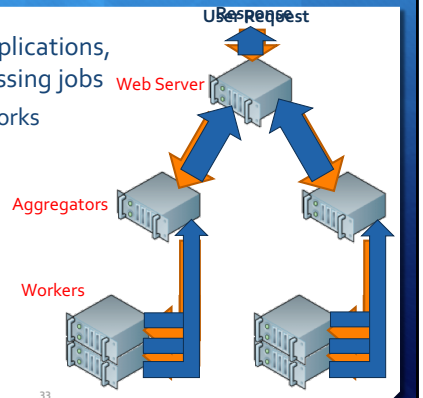
Partition/Aggregate Pattern

- Common for web applications, and even data processing jobs
  - Search, social networks
  - Dryad, MapReduce
- Responses under deadline
  - 230~300ms



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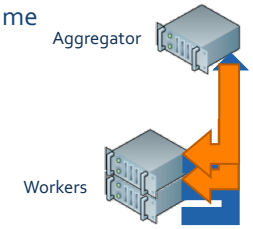
Problem: Incast

- Aggregator sends out queries to a rack of workers
  - 1 aggregator, 39 workers
- Each query takes the same time to complete
- All workers answer at the same time
  - 39 flows → 1 port
  - Limited switch memory
  - Limited buffer at aggregator
- Result: packet losses ☹



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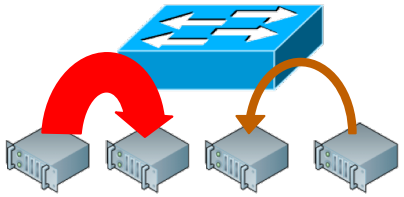
Problem: Buffer Pressure

- In theory, each port on a switch should have its own buffer
- Cheap switches share buffer memory across ports
  - Fat flows can congest the thin flow!



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Problem: Queue Buildup

- Long TCP flows congest the network
  - Ramp up, past slow start
  - Don't stop until they induce queuing + loss
  - Oscillate around max utilization
- Short flows can't compete
  - Never get out of slow start
  - Deadline sensitive!

Industry Hacks

Google

- Use heavy compression to maximize data efficiency

facebook

- Custom engineer to use UDP
- Connection pooling: share buffer pool per thread

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Dirty Slate Approach: DCTCP*

- Goals
  - Alter TCP to achieve low latency
  - Work with shallow buffered switches
  - Do not modify apps, switches, or routers
- Idea
  - Scale window in proportion to congestion
  - Use existing ECN functionality
  - Turn single-bit congestion info to multi-bit

*Data Center TCP (DCTCP). SIGCOMM'10.
http://www.sigcomm.org/sites/default/files/ccr/papers/2010/October/1851275-1851192.pdf

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ECN and ECN++

- Original ECN
  - Switches mark EC bit of packet if there is congestion
  - Receivers echo the EC bit in ACK
  - EC in ACK stays set until sender clears with CWR
- Problem: feedback is binary
- DCTCP:
  - Receiver echoes the actual EC bits
  - Sender estimate congestion ($0 \le \alpha \le 1$) each RTT based on the fraction of marked packets
  - cwnd = cwnd * $(1 - \alpha/2)$

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Shortcomings of DCTCP

- No scheduling, cannot solve incast
- Queries may still miss deadlines
  - Flows do not help if they miss the deadline
- Network throughput is not the right metric
  - Application goodput is
- TCP/DCTCP is oblivious to deadline

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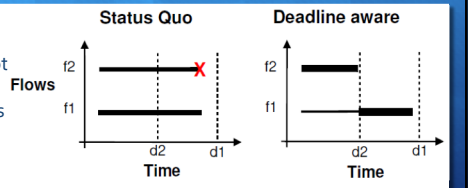
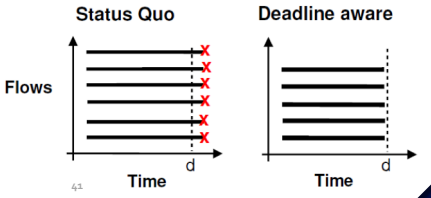
The Need of Deadline-Awareness

- Case #1
  - Fair share causes bot to fail
  - Unfair share enables both to succeed



- Case #2
  - Allowing all makes all fail
  - Quenching one leads to better goodput



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Clean Slate Approach: D3*

- **Key insight**: ask for the bandwidth required to meet the deadline
  - Hosts use flow size and deadline to request bandwidth
  - Routers measure utilization and make soft-reservations
- Challenges ahead
  - Not for incremental deployment, may not play nice with TCP
  - Complexity in the switch
  - Application level changes

*Better Never than Late: Meeting Deadlines in Datacenter Networks. SIGCOMM'11. *http://conferences.sigcomm.org/sigcomm/2011/papers/sigcomm/p50.pdf*

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Conclusion

- Data center is a super hot topic right now
  - Topology, routing
  - Network stack
  - Heat, power
  - Management
  - Applications: Hadoop, Dynamo, Cassandra, NoSQL
- Tough for academic research
  - No real data centers to test around

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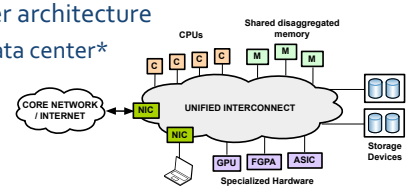
Open Problems

- Data center measurement data
  - Real traces are really hard to get
  - Hard to quantify research results
- Rethink data center architecture
  - Disaggregated data center*



*Network Support for Resource Disaggregation in Next-Generation Datacenters. HotNets'13. *http://conferences.sigcomm.org/hotnets/2013/papers/hotnets-final40.pdf*

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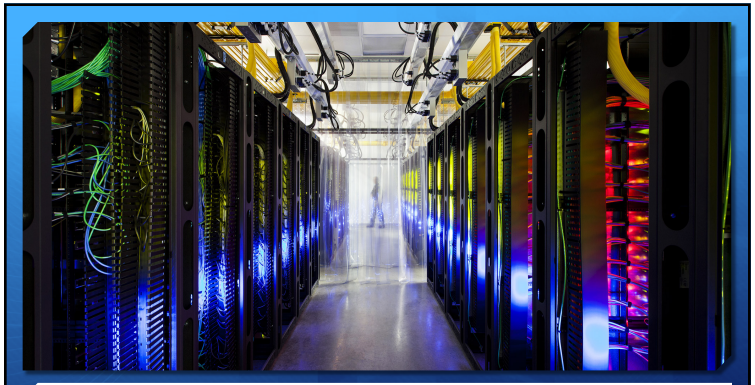

We are done!

Good luck to the last assignment!

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