Warehouse-scale Computing

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Credits

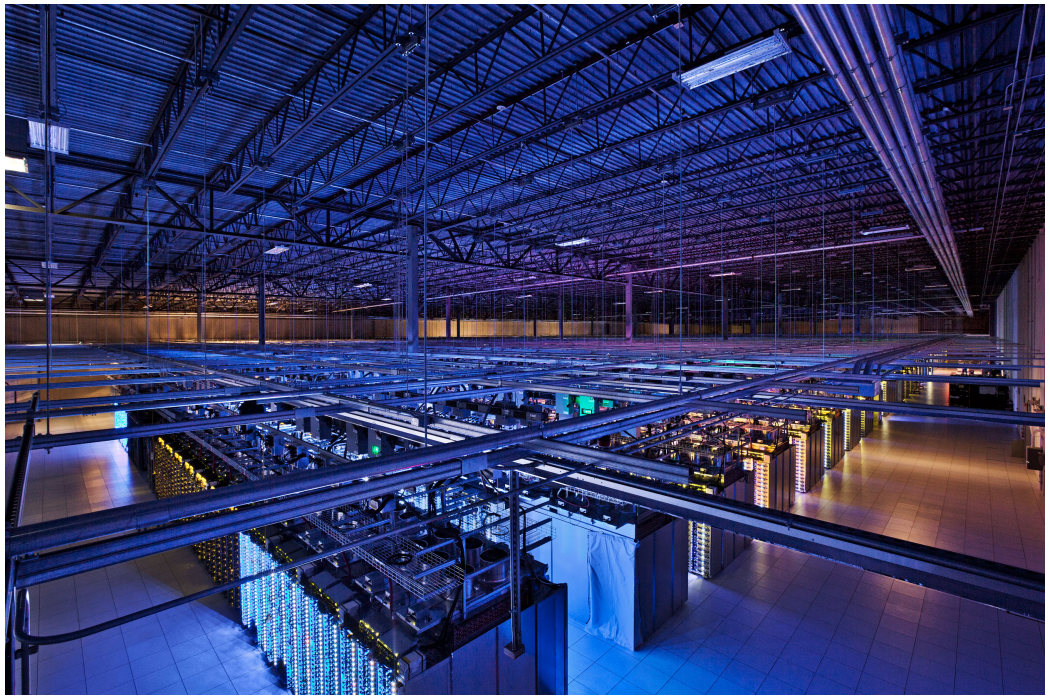
- Luis Barosso, Warehouse Scale Computing, SIGMOD Keynote, 2010.
- Luiz André Barroso, Jimmy Clidaras, and Urs Hölzle. The Datacenter as a Computer: An Introduction to the Design of Warehouse-Scale Machines, Second edition. Synthesis Lectures on Computer Architecture 2013 8:3, 1-154. Morgan Claypool. http://bit.ly/wsc-2ed
- Luiz André Barroso and Urs Hölzle. The Case for Energy-Proportional Computing. IEEE Computer, December 2007
- Mohammad Al-Fares, Alexander Loukissas, and Amin Vahdat. 2008. A scalable, commodity data center network architecture. *Proceedings of ACM SIGCOMM 2008*. ACM, New York, NY, USA, 63-74. http://doi.acm.org/10.1145/1402958.1402967

The Shift to Server Side Computing

Computing is shifting to very small and very big devices

User-interface centric device

Large data centers



Server-side applications provide services formerly in clients

—e.g., email, office applications, backups …

Factors Driving the Shift to Internet Services

- Improved user experience
  - —e.g., ease of management and ubiquity of access
- Advantages for vendors
  - —simpler to make software changes and improvements
    - – deploy all improvements and fixes <u>inside data centers</u>
    - – restrict hardware deployment to a few well-tested configurations
- Compute-intensive workloads better-suited for servers
  - —search services (web, images, etc.)
  - —language translation services
    - – leverage massive-scale language models

Warehouse-scale Computer (WSC)

Google's $1.2B data center, The Dalles, Oregon

Google data center locations

Americas
- The Dalles, Oregon
- Berkeley County, South Carolina
- Council Bluffs, Iowa
- Douglas County, Georgia
- Quilicura, Chile
- Mayes County, Oklahoma
- Lenoir, North Carolina

Asia
- Changhua County, Taiwan
- Singapore

Europe
- Hamina, Finland
- St Ghislain, Belgium
- Dublin, Ireland
- Eemshaven, Netherlands

WSC: More than a Data Center

Data Center

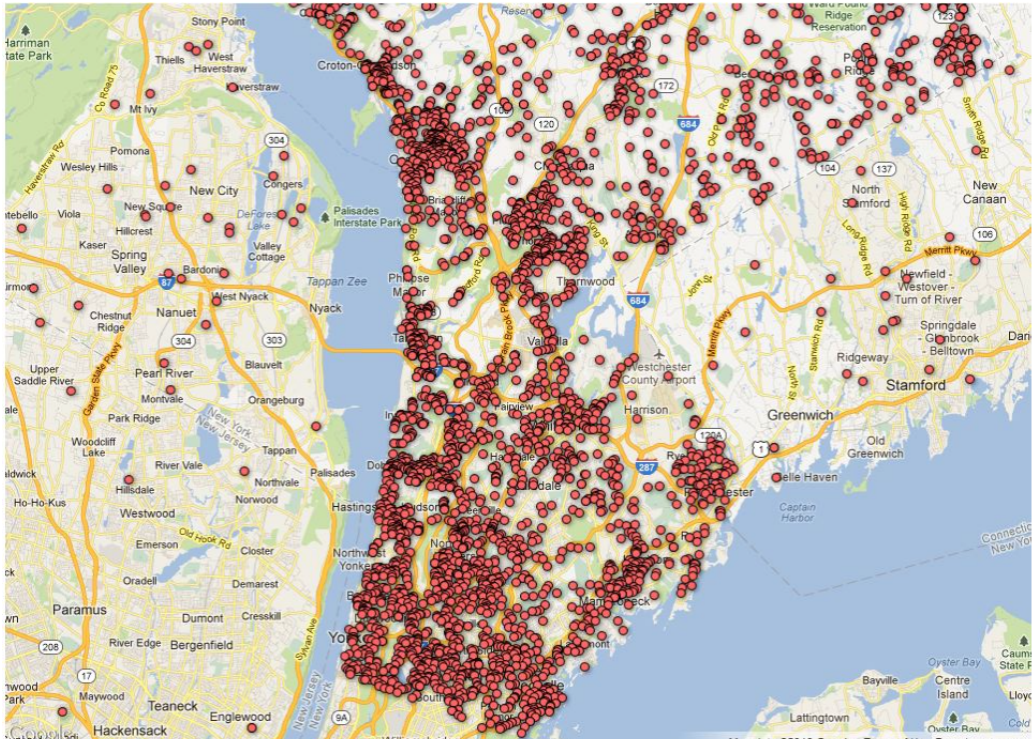
- —co-located machines that share power, security, environment, and network connectivity needs
- —applications: a few binaries, each running on a dedicated, isolated HW infrastructure
- —heterogeneous hardware and system software
- —partitioned resources, managed and scheduled separately
- —facility and computing equipment designed separately

Warehouse-scale Computer

- —computing system designed to run massive internet services
  - — e.g., Facebook, Amazon …
- —applications: tens of binaries running on hundreds to thousands of machines
- —homogeneous hardware and system software
- —common pool of resources that are managed centrally
- —integrated design of facility and computing machinery

Applications: Data Centers vs. WSC

- **Data center: program = executable on a single machine**
- **WSC: program = an internet service**
  - **—tens or more executables interact to provide complex services**
    - **e.g., search, maps, photo and video services, …**
  - **—executables for a service might be implemented and maintained by different teams of engineers**
    - **across organizational, geographic, and company boundaries**



Mashup: This map shows pistol permits registered with the County Clerk's Office in Westchester, NY

WSC Software Stack

- **Platform-level software**
  - —firmware, kernel, operating system distribution, and libraries present in all individual servers to provide basic services
- **Cluster-level infrastructure**
  - —collection of distributed systems software that manages resources and provides services at the cluster level
    - – distributed file systems, schedulers, and RPC libraries
    - – programming models for manipulating datacenter-scale resources

      MapReduce, Hadoop

      BigTable, Chubby, Dynamo, Dremel, Sawzall, Spanner
  - —provides an operating system for a warehouse scale computer
- **Application-level software: implements a specific service**
  - —online services: e.g. Google search, Gmail, and Google Maps
  - —offline computations: large-scale data analysis that generates data for online services
    - – e.g., indexing the Web; processing satellite images into map tiles

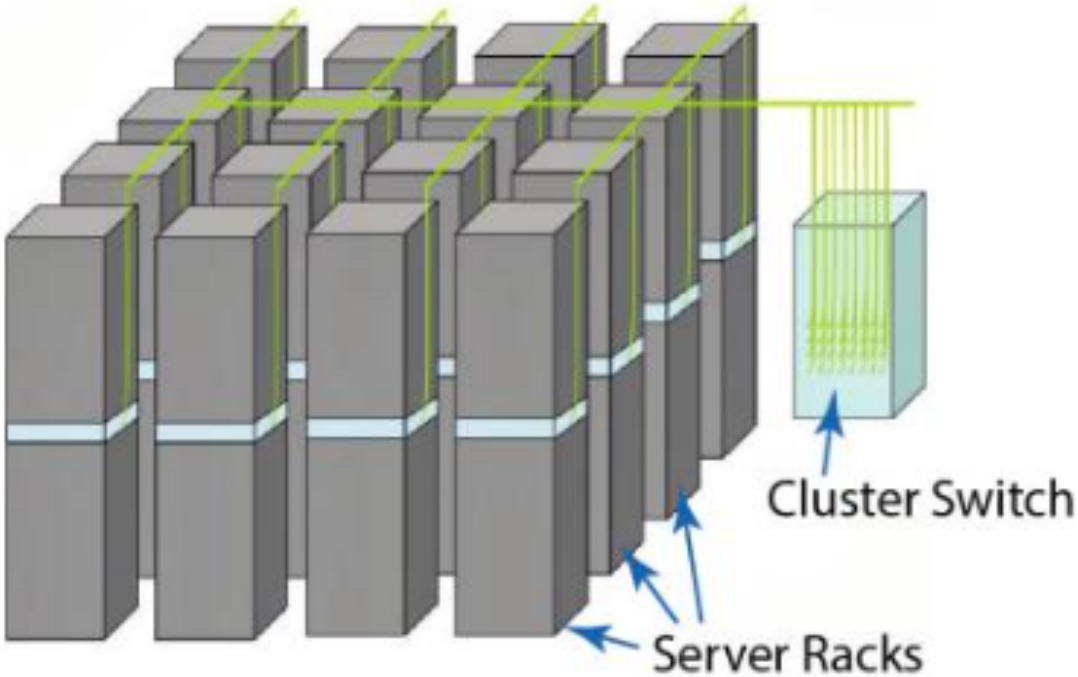
Outline

- Introduction to warehouse-scale machines
- Challenges at large scale
  - —complexity of the storage hierarchy
  - —exposure to performance variability
  - —coping with faults
- Storage availability
- Energy efficiency

The Hardware

Servers
- **CPU**
- **DRAM**
- **Disks**

Racks
- **40-80 servers**
- **Ethernet switch**



Warehouse-scale computer

increasing scale, programming complexity

Figure credit: Barroso et al. The Datacenter as a Computer: An Introduction to the Design of Warehouse-Scale Machines, Second edition. 2013. Morgan Claypool.

Hypothetical Warehouse-scale System

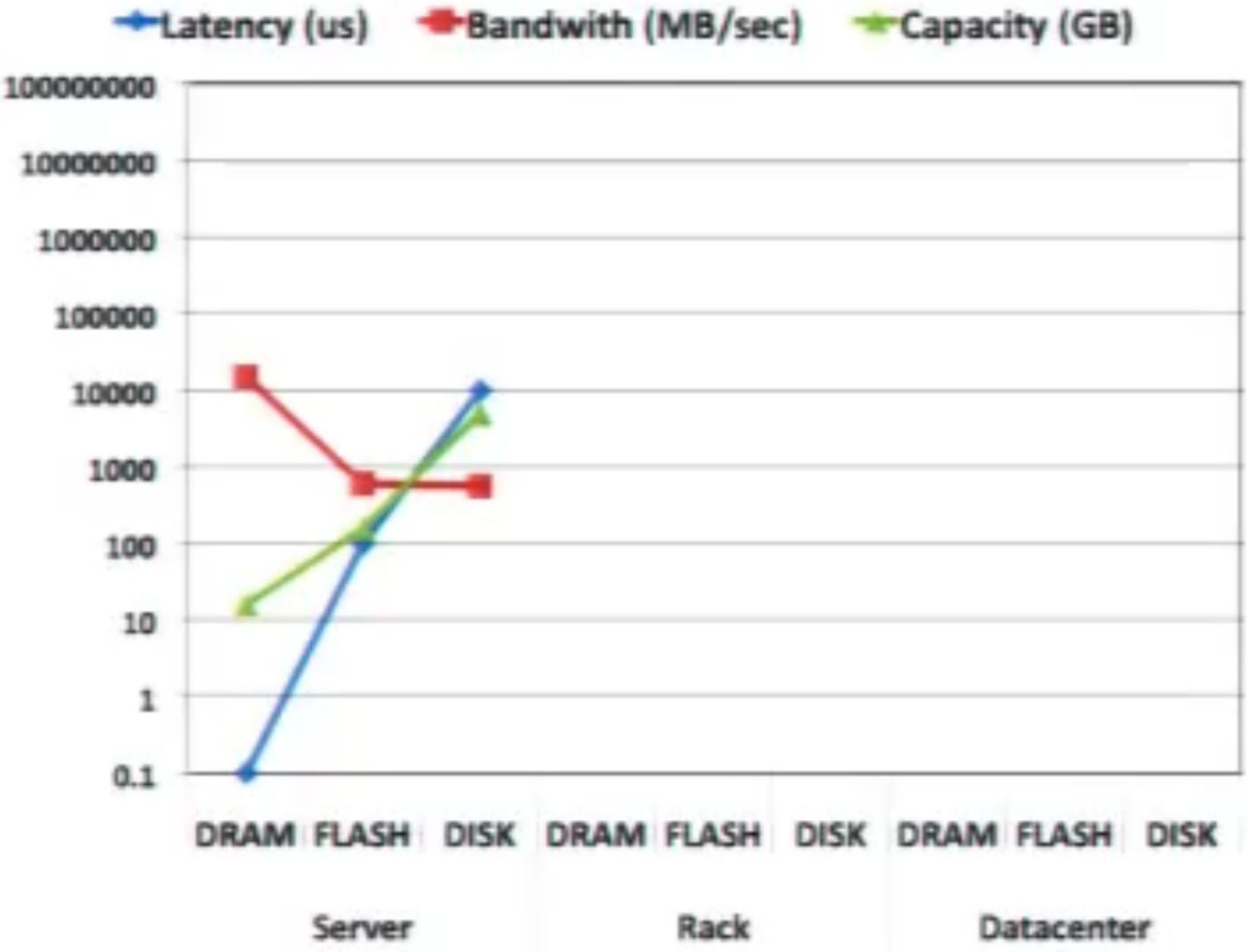
- **Servers**
  - —dual-socket x86 platform
  - —16GB DRAM
  - —5 x 1 TB disks, 1 160GB SSD (FLASH)

- **Racks**
  - —40 servers
  - —1 x 48-port Gigabit Ethernet switch
    - – 8 ports up, 40 down - 5 x 1 oversubscription

- **Warehouse-scale computer**
  - —10,000 servers (250 racks)
  - —2k-port Gigabit Ethernet Switch

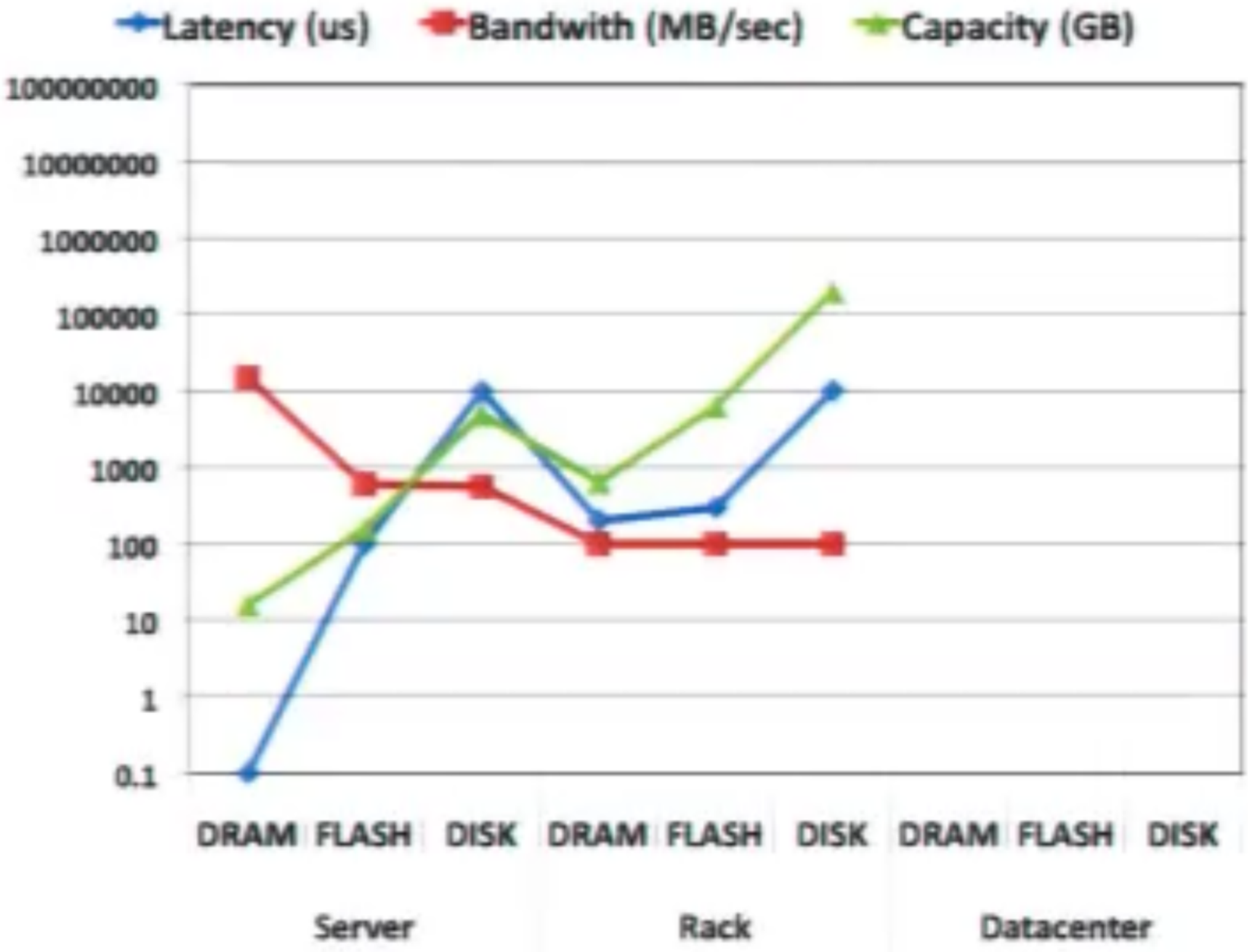
Luis Barosso, Warehouse-scale Computing, SIGMOD Keynote, 2010.

Storage Hierarchy - Single Server



Luis Barosso, Warehouse-scale Computing, SIGMOD Keynote, 2010.

Storage Hierarchy - One Rack



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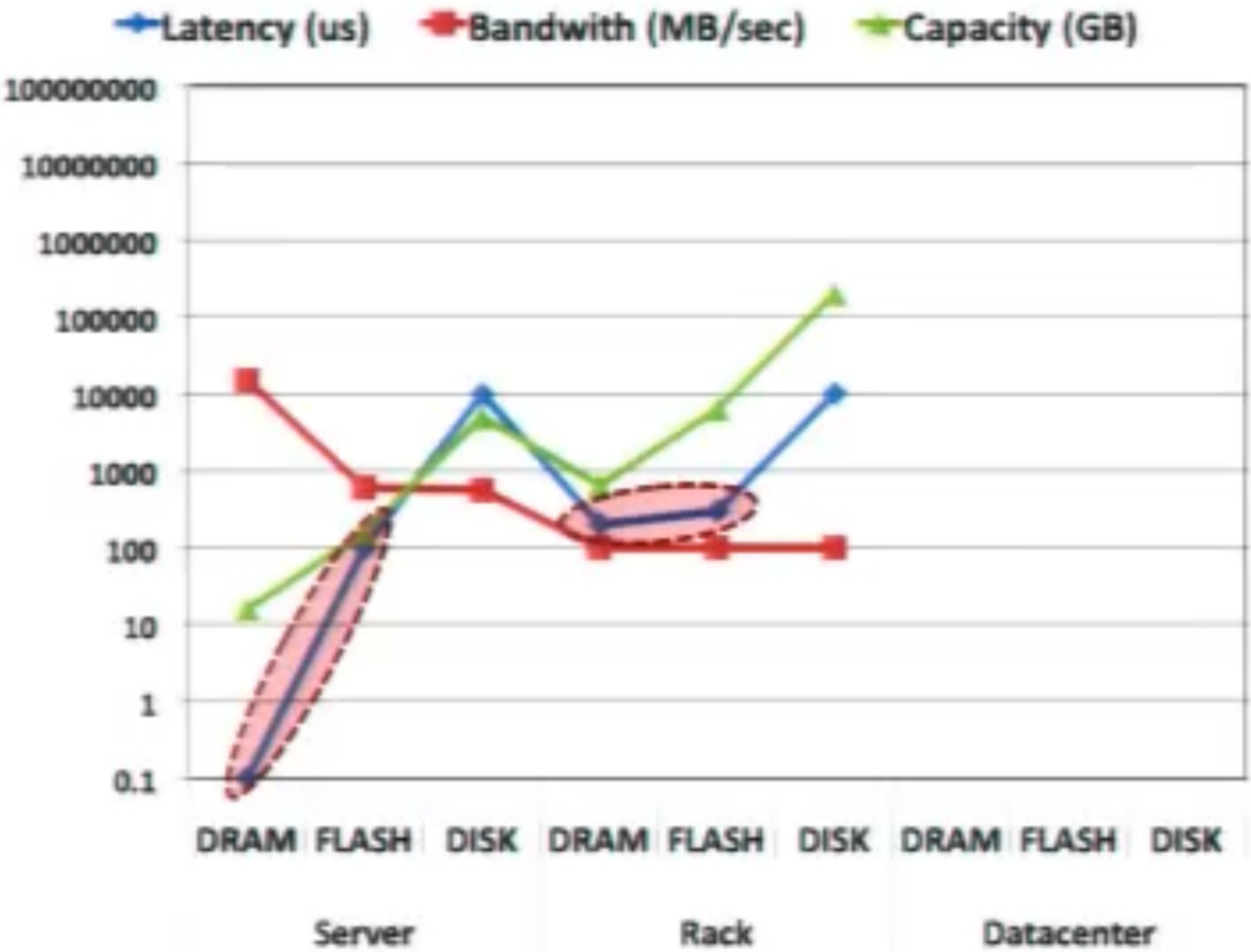
Storage Hierarchy - One Rack



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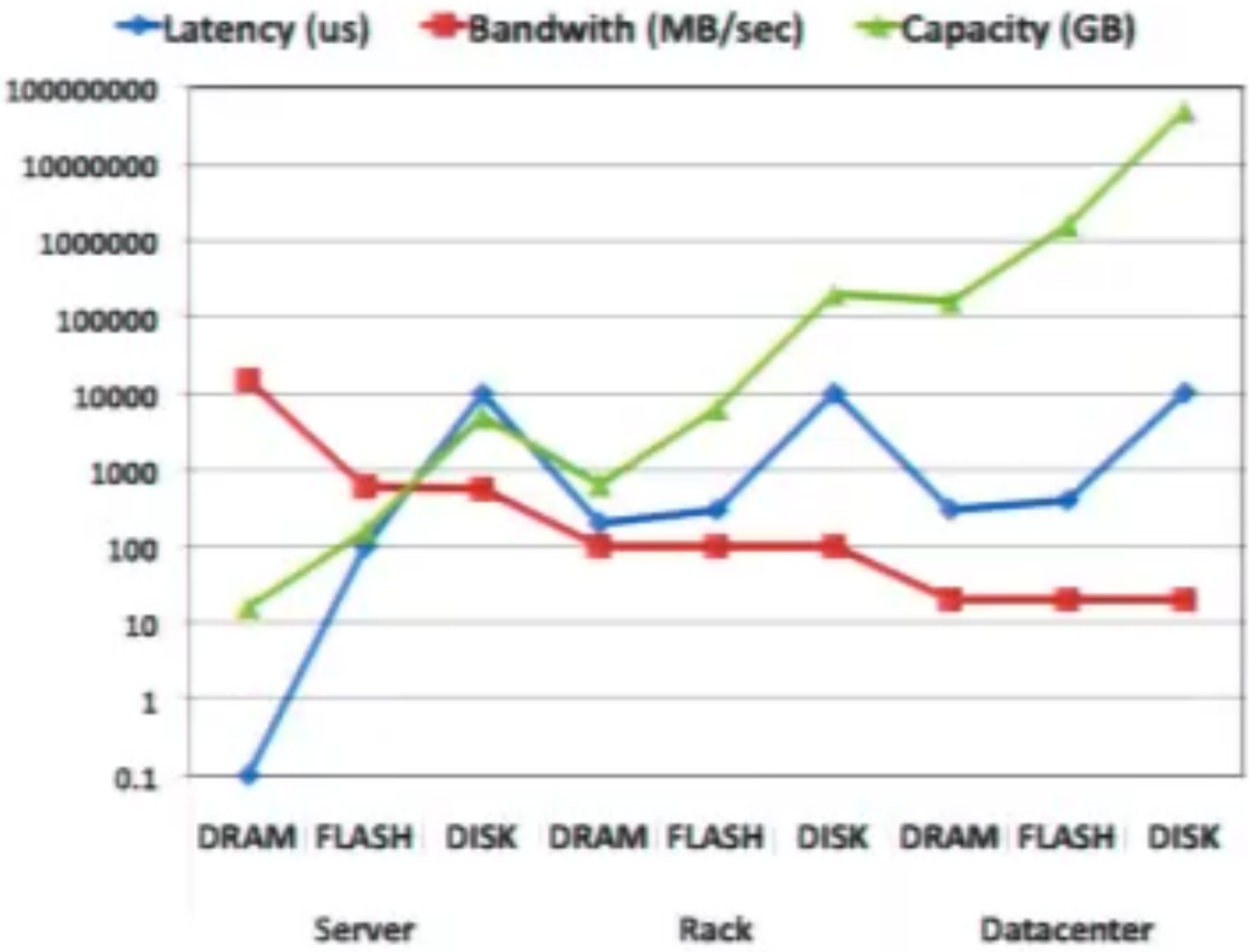
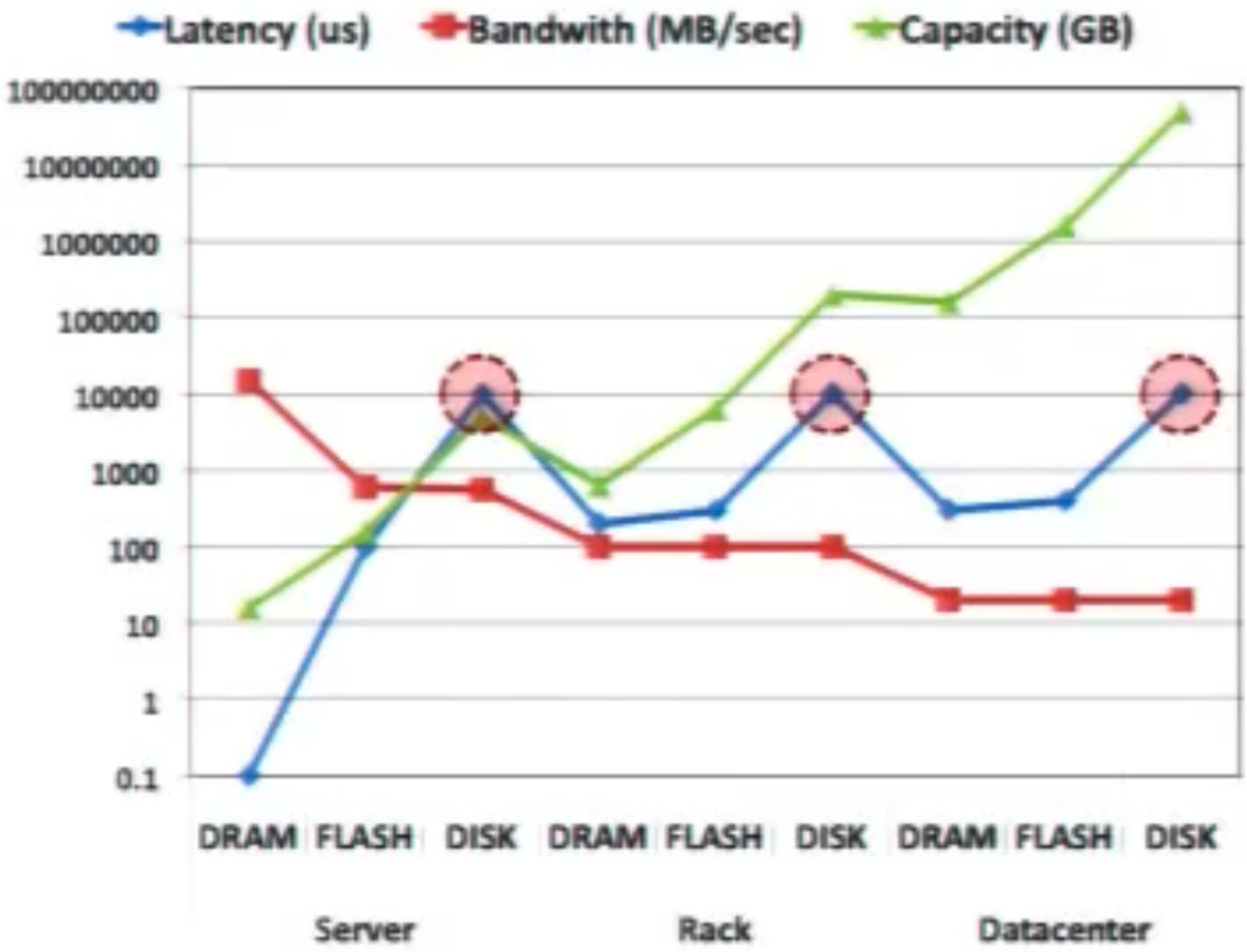
Storage Hierarchy - Warehouse Scale



Luis Barosso, Warehouse-scale Computing, SIGMOD Keynote, 2010.

Storage Hierarchy - Warehouse Scale



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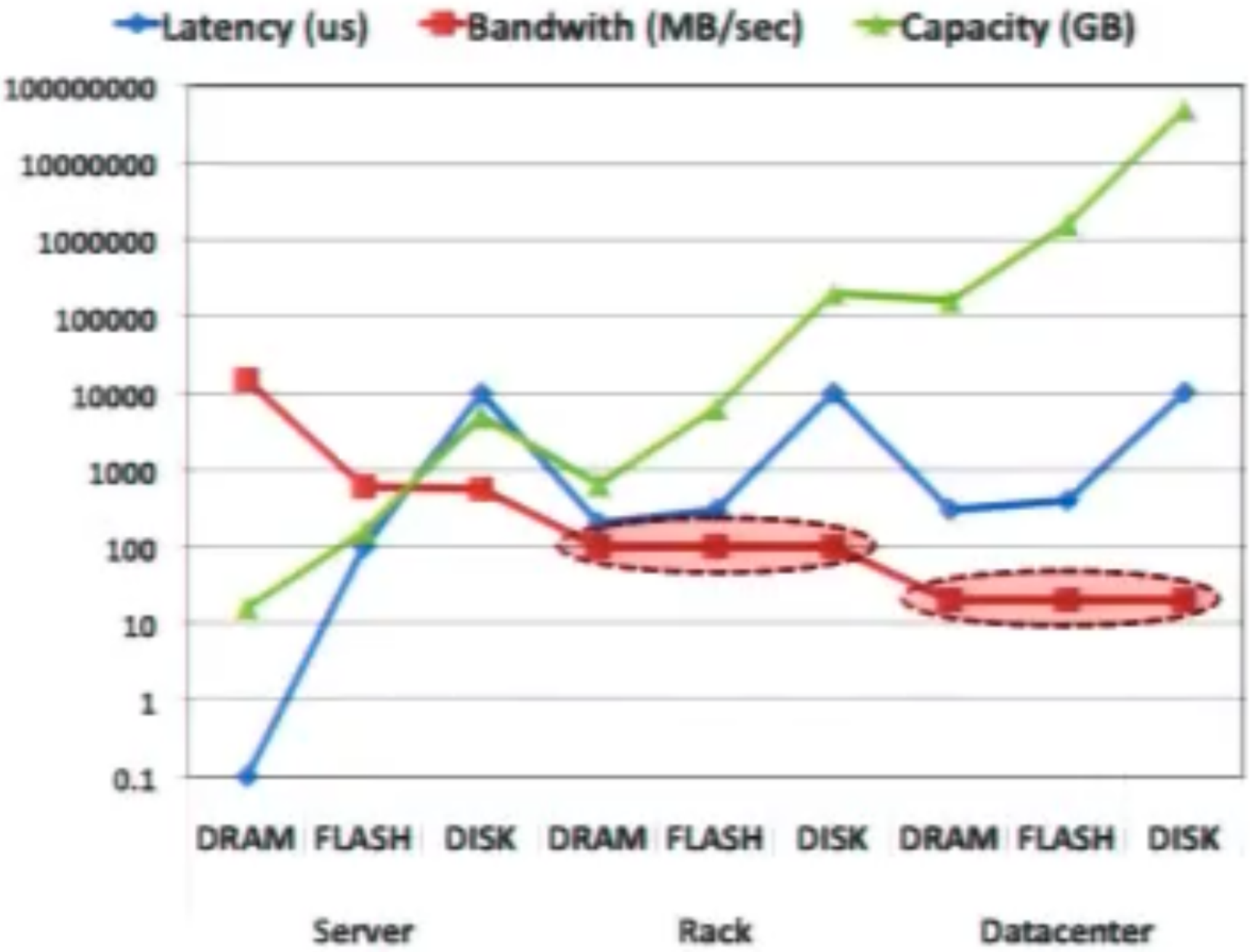
Storage Hierarchy - Warehouse Scale

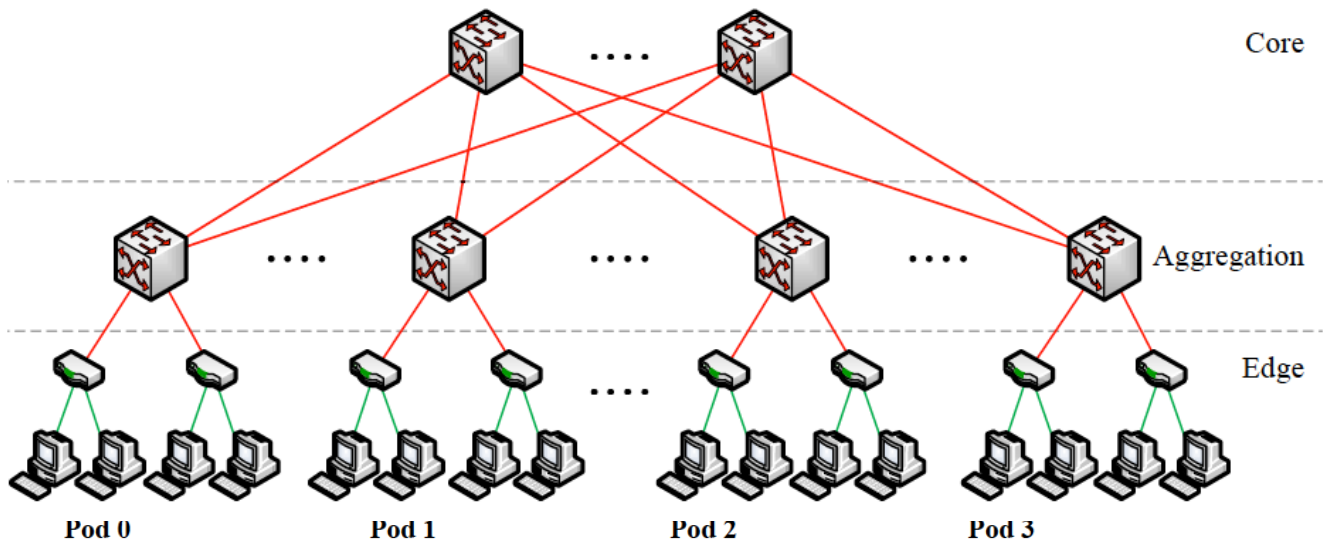


Luis Barosso, Warehouse-scale Computing, SIGMOD Keynote, 2010.

Addressing Networking Bottlenecks

- **Bandwidth: cost per gigabit port**
  - —48-port (rack) switch: $16
  - —10,000-port (data center) switch: … priceless
- **Promising approach for lower cost large-scale networking**
  - —large switch built from a collection of small commodity switches

Figure credit: Al-Fares et al. A Scalable, Commodity Data Center Network Architecture. SIGCOMM 2008.



- **User messaging latency is embarrassingly high (~100 us)**
  - —sub 10us latencies were demonstrated 25 years ago
  - —should be possible to approach it with commodity systems
  - —mostly a software problem

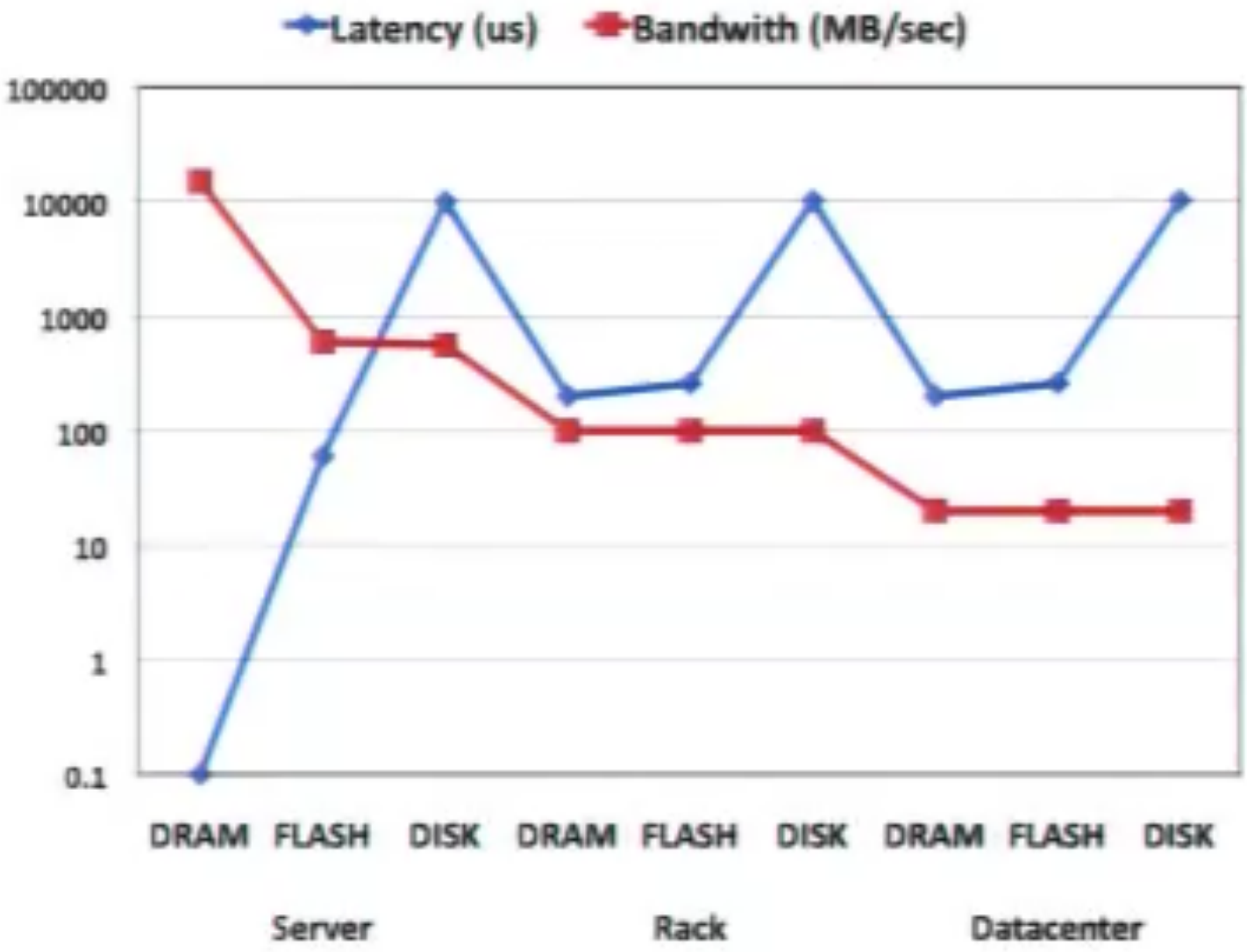
FLASH (SSDs) in Warehouse-scale Machines

- **Promising technology, yet somewhat slow adoption**
  - —endurance and retention are not yet proven in the field
  - —not a DRAM replacement (too slow)
- **Intriguing proposition as a hard drive replacement**
  - —SSDs are 17-32x more expensive per GB
  - —SSDs are 50-100x less expensive per random read op/sec
- **More useful metric is what you get for the same cost**
  - —1/16 of the capacity; 40x of the read operations (for 4K blocks)

FLASH Value Proposition

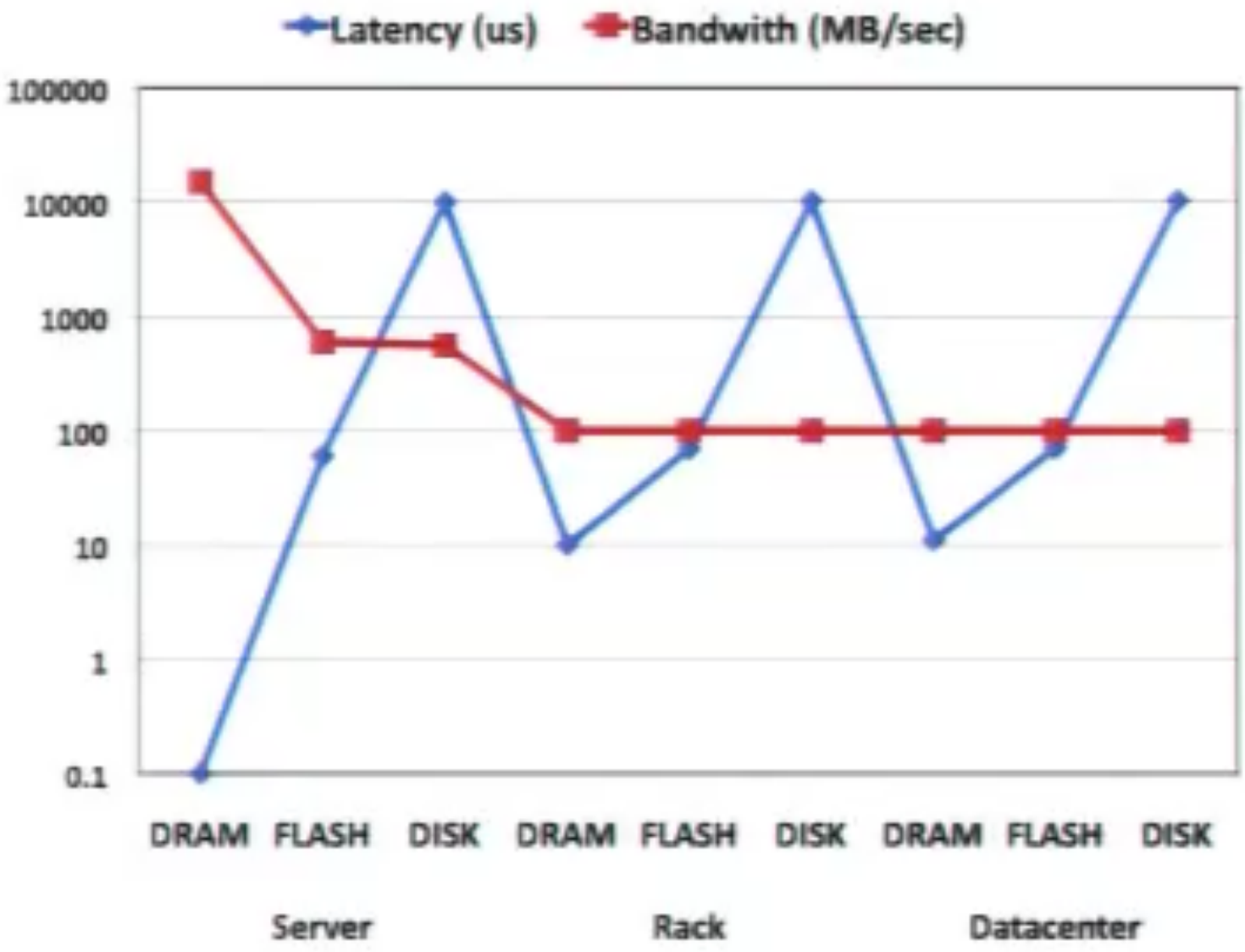
- **Bottom line**
  - —too good to ignore: fills an important latency gap
  - —too expensive to replace hard drives
- **Using FLASH for data-center computing is a difficult software challenge**
  - —want
    - – 90% of the data on disk, especially cold data
    - – want 99% of your high BW accesses to come from FLASH
  - —will require sophisticated software systems to make this happen
- **Cluster level architecture may need to be revisited**
  - —replacing one HD in a 6-disk storage node with an SSD
    - – increases random read block capacity by 100x
  - —will need faster networking at the warehouse-scale to substantially benefit from these devices

Original Bumpy Storage Hierarchy

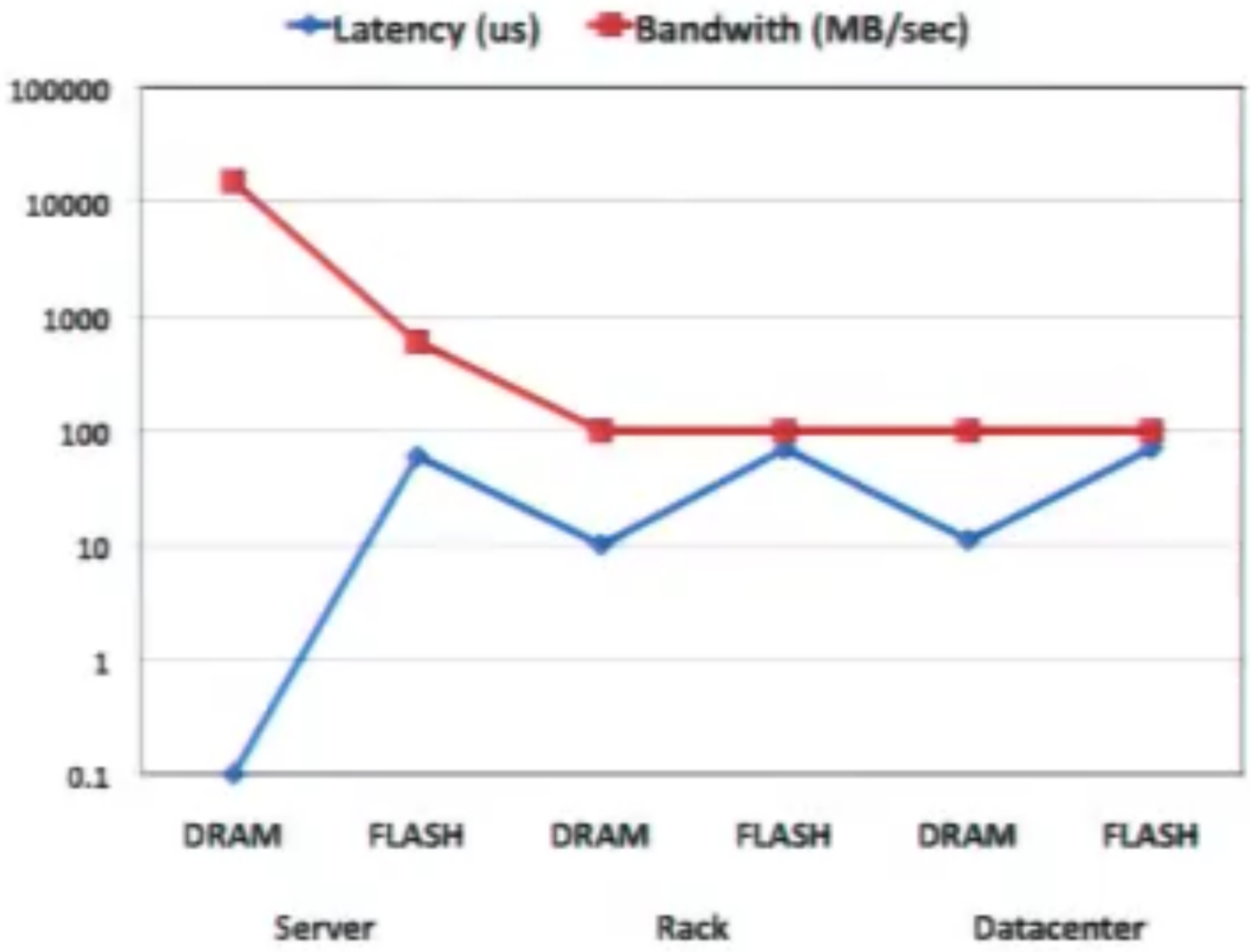


(capacity curve removed)

Zero Oversubscription and Fast Messaging



> 99% of Accesses from FLASH



Luis Barosso, Warehouse-scale Computing, SIGMOD Keynote, 2010.

Performance Variability and Faults

Large Scale: Exposure to Performance Variability

- **Rare slowdown events can hurt**
  - —average server response is 100ms, but every 10K queries, it takes 1s (random performance hiccup)
  - —a service that uses one machine: 0.1% of slow queries
  - —a service that uses 5K machines: 50% slow queries
- **Minimizing performance idiosyncrasies is key**
- **Need software systems that can work around such slowdowns**

Large Scale Brings Exposure to Faults

- **Some fault and availability statistics to keep in mind**

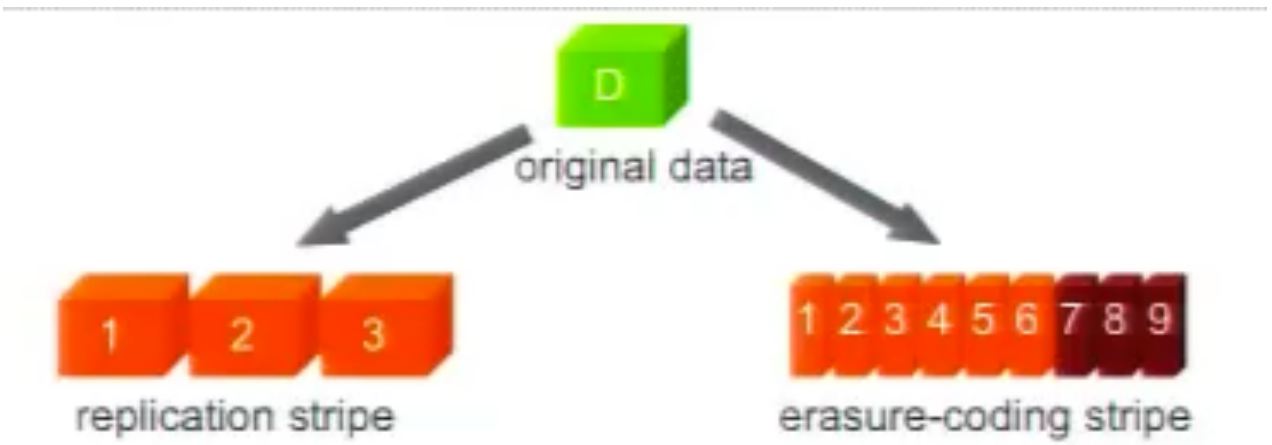
99-99.9%	internet availability
> 1%	rate of uncorrectable DRAM errors/server/year
2-10%	disk drive annualized failure rate
~2	crashes per server per year
> 1	power utility events / year

- **Service running on 2000 servers**
  —over 10 machines crash per day!

Service Level Outages

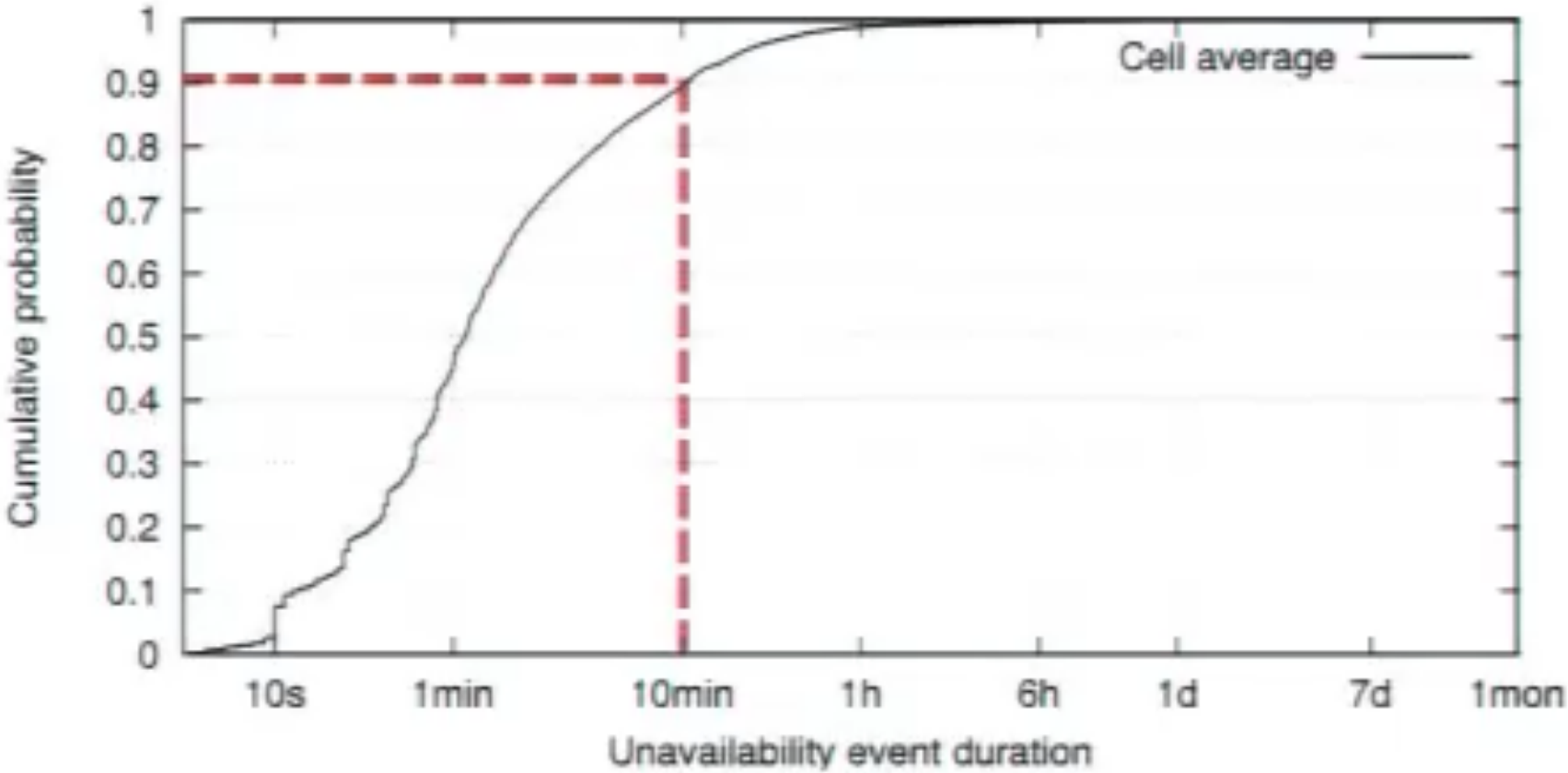
- Top three causes
  - —networking issues
  - —power issues
  - —oops issues
    - all other automated or manmade mistakes
- Rare but actual cases of long-haul networking problems
  - —dead horses
  - —wild dogs
  - —sharks
  - —thieves
  - —drunken hunters
  - —…

Storage Availability



- **Place data blocks of each stripe in different fault domains**
  - **—different disks, servers, racks**
  - **—distribute data blocks across the whole cluster**
    - **read operations are easily load balanced**
    - **recovery is highly efficient**
- **What affects data availability as seen by a client of a cluster file system?**

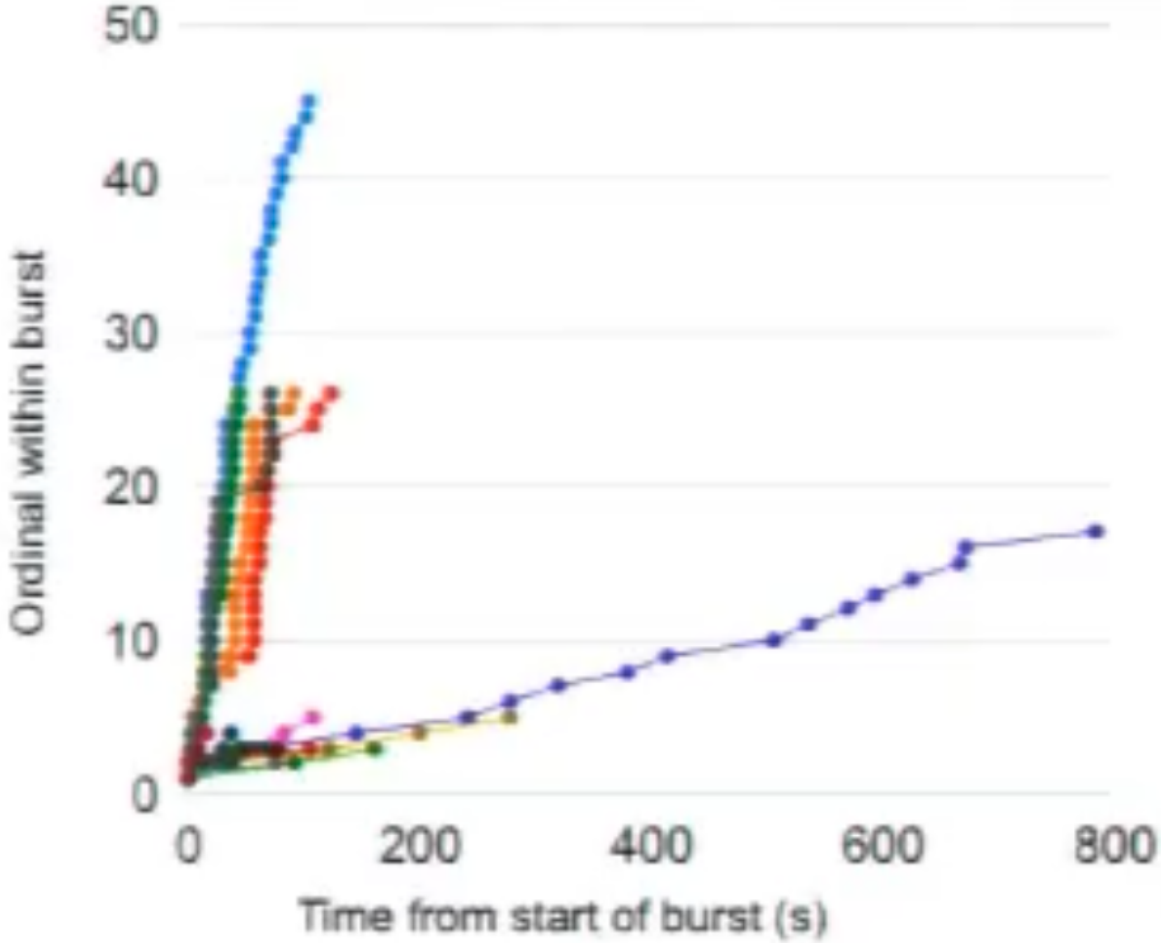
Observed Unavailability Events in the Field



- **Most errors are transient and short (no data loss)**
- **Usually, better to wait before initiating recovery operations**

Luis Barosso, Warehouse-scale Computing, SIGMOD Keynote, 2010.

Understanding Fault Correlations Matters



- **Approximately 10% of faults are part of a correlated burst**
- **Most small bursts have no rack correlation**
- **Most large bursts are highly rack correlated**

Luis Barosso, Warehouse-scale Computing, SIGMOD Keynote, 2010.

Some Lessons From Field Data Analysis

- **Software-induced faults dominate**
  - —impact of hardware faults on availability is very small
- **Correlated faults have a dramatic impact on cluster file systems**
  - —failure to account for fault-correlation overestimates data availability by over two orders of magnitude
  - —MTTF of R=2x2 is 3x that of R=4
- **Correlated failures drastically reduce the benefits of additional replication**
  - —uncorrelated: moving from R=2 to R=3 MTTF increases by 3500x
  - —correlated: moving from R=2 to R=3 MTTF increases by 11x

Energy Efficiency Challenges

NY Times: Power, Pollution and the Internet

By JAMES GLANZ SEPT. 22, 2012

… **tens of thousands of data centers now exist** to support the overall explosion of digital information …

A yearlong examination by The New York Times has revealed that this foundation of the information industry is sharply at odds with its image of sleek efficiency and environmental friendliness.

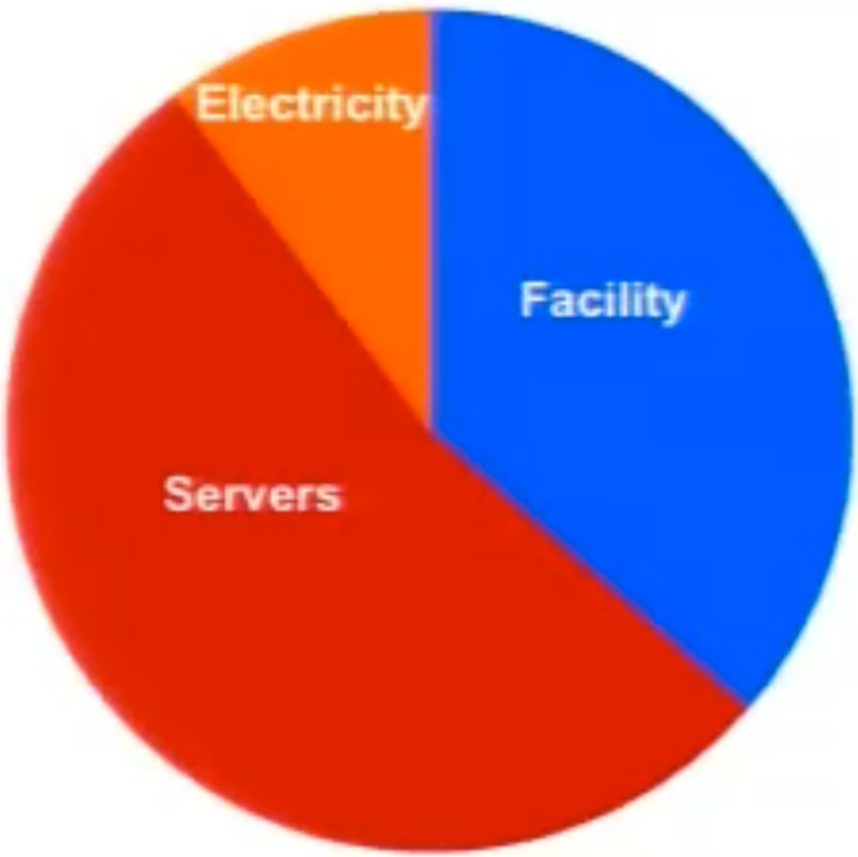
Most data centers, by design, consume vast amounts of energy in an incongruously wasteful manner, interviews and documents show. Online companies typically run their facilities at maximum capacity around the clock, whatever the demand. As a result, **data centers can waste 90 percent or more of the electricity they pull off the grid**, The Times found.

…

Worldwide, the **digital warehouses use about 30 billion watts of electricity, roughly equivalent to the output of 30 nuclear power plants, according to estimates industry experts compiled for The Times**. Data centers in the United States account for one-quarter to one-third of that load, the estimates show.

…

Cost Breakdown of a Large Data Center



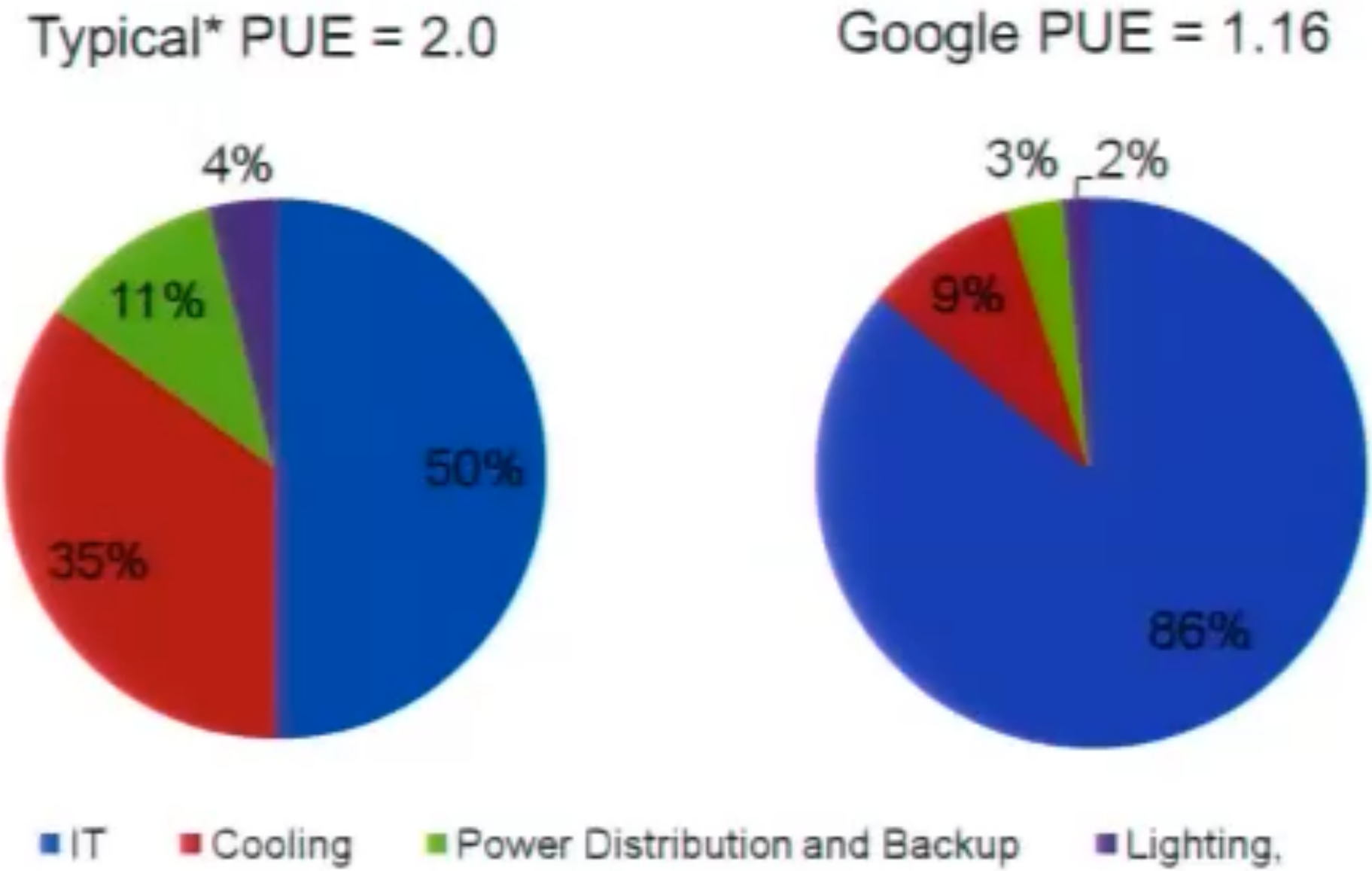
Parameters
Low-end server ($3000 - 300W) 3 year depreciation
Data center costs: $15/Watt 12 year depreciation
Cost of electricity: $0.062 kWh
PUE = 2
Cost of capital included

- **Electricity costs not yet dominant**
- **However, facility costs related to cooling capacity**
- **Energy related costs approaching server costs**

PUE = Power Usage Effectiveness

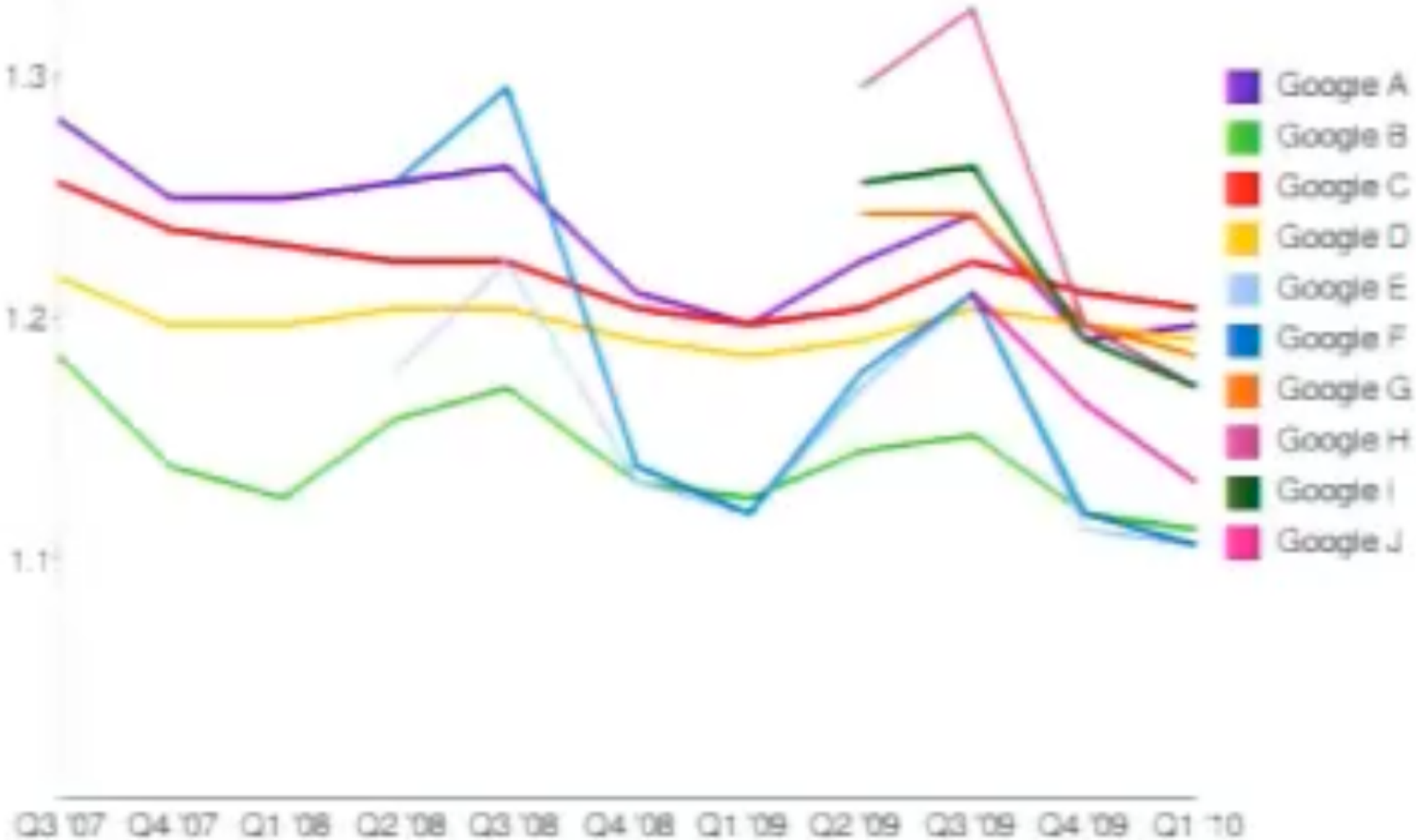
$$\text{PUE} = \frac{\text{Total Facility Energy}}{\text{IT Equipment Energy}}$$

Dramatic Reduction of Overheads



Google Data Center Efficiencies

PUE



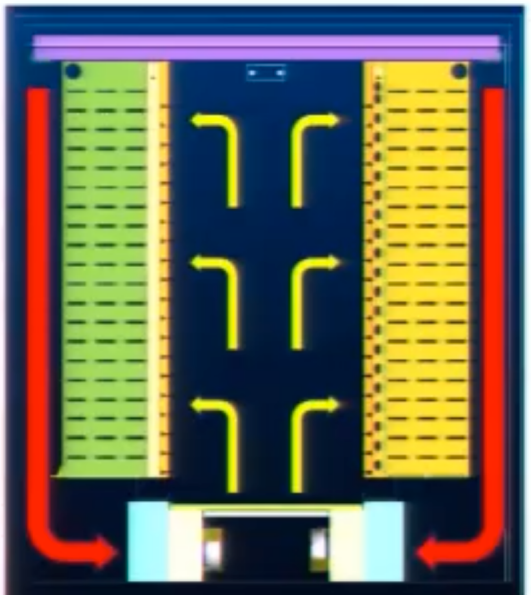
Overall

Trailing 12-month avg energy-weighted PUE=1.18

Google Container-based Data Centers

Google's first container-based data center (2005)
Slots for 45K servers in 45 containers
10MW load, PUE = 1.25

https://www.youtube.com/watch?v=zRwPSFpLX8I



Cooling innovations

- **Manage airflow: eliminate hot/cold mixing**
- **Raise cold aisle temperature**
- **Evaporative cooling suffices**

What's Next?

- **Mechanical and power engineers have done their job**
- **Most of the energy is now going to computing equipment**
- **Time for the computer scientists to do their part**
  - **—hardware is still generally very inefficient**
  - **—software has an important role as well**

Differences between Handheld and WSC

- **Handheld, e.g., smartphone**
  - —lots of idle time
  - —idle mode efficiency suffices
- **WSC**
  - —never idle
  - —rarely at peak
  - —need to be efficient across the usage spectrum
    - – what happens if you are using 10-40% of capacity?

Average CPU Utilization in a Data Center

> 5K servers over a 6 month period

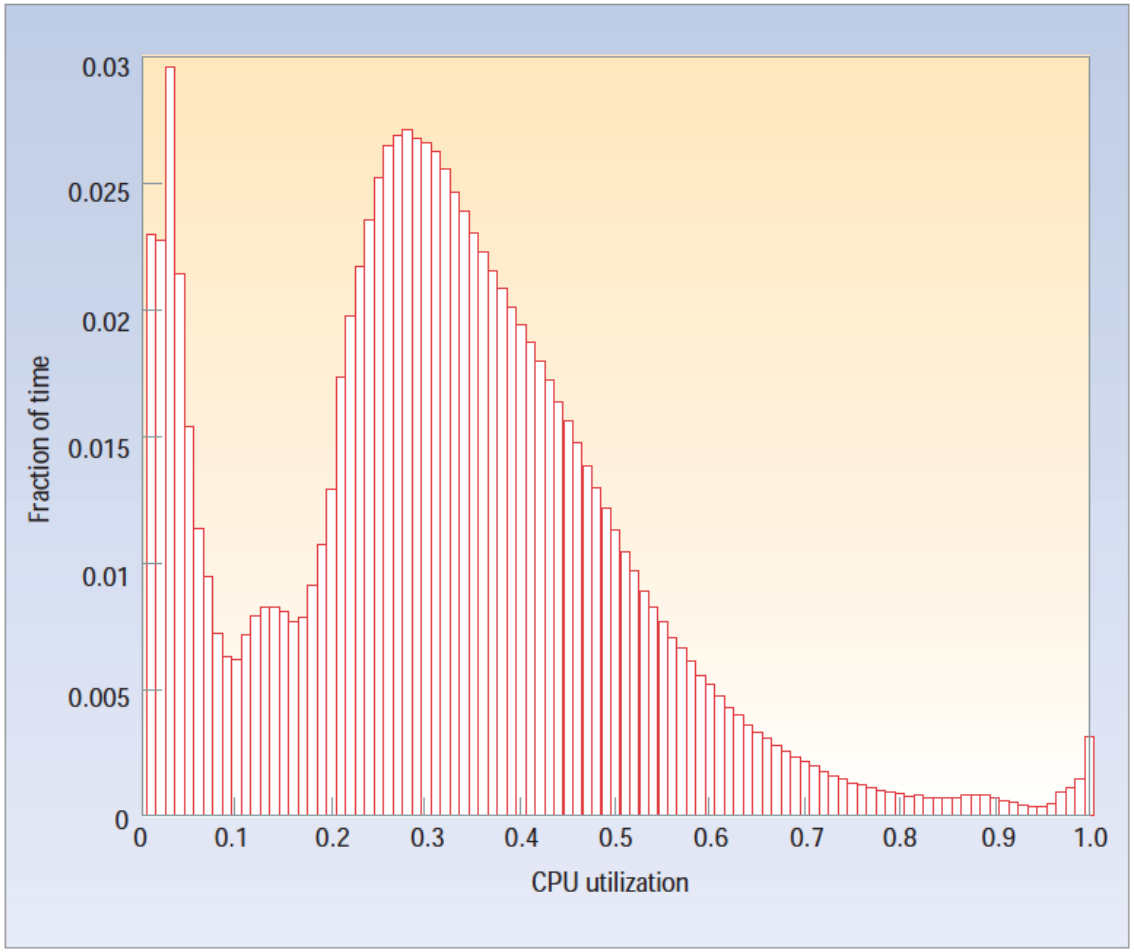


Figure 1. Average CPU utilization of more than 5,000 servers during a six-month period. Servers are rarely completely idle and seldom operate near their maximum utilization, instead operating most of the time at between 10 and 50 percent of their maximum utilization levels.

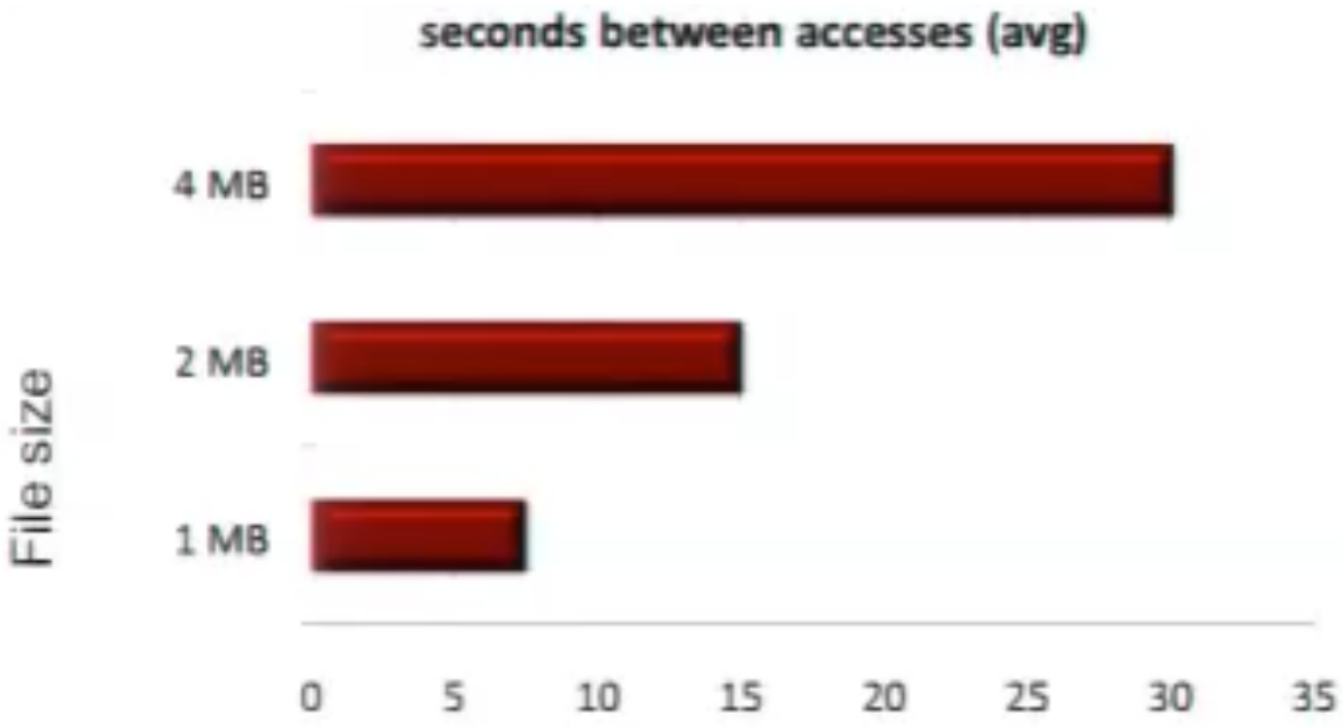
Figure credit: Luiz André Barroso and Urs Hölzle. The Case for Energy-Proportional Computing. IEEE Computer, Dec 2007

Idleness Doesn't Occur in the Wild

- **Idleness is fragile**
  - —takes everyone to build and anyone to destroy
- **Well designed distributed systems software will**
  - —parallelize over lots of machines
  - —load balance effectively
  - —distribute data widely
  - —exploit locality
  - —avoid bursts
- **All of the above work against idleness!**

Can You Spin Down a Server Disk?

- **Consider a 2TB drive filled only with cold files**
  - **—files accessed (randomly) only twice per year**



- **Average idleness interval is smaller than the latency to spin up a drive (approx 1 minute)**

Goal: Energy-proportional Computing

- **No work → no power consumed**
- **Some work → some power consumed**
- **Lots of work → lots of power consumed**

How Energy-proportional is Today's HW?

- **Measure energy usage at 10% utilization**
- **Energy proportional system should use 10% of peak energy**

CPUs	33%
Memory	60%
Disks	80%
Network Switches	90%+
Servers	65%

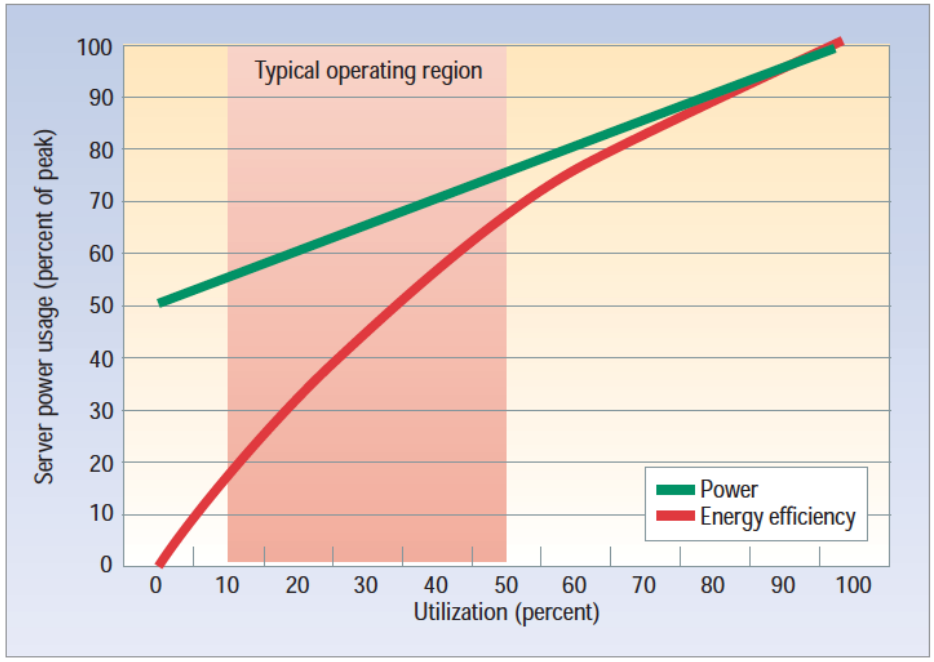


Figure 2. Server power usage and energy efficiency at varying utilization levels, from idle to peak performance. Even an energy-efficient server still consumes about half its full power when doing virtually no work.

Figure credit: Luiz André Barroso and Urs Hölzle. The Case for Energy-Proportional Computing. IEEE Computer, Dec 2007

Improving Computing Efficiency with SW

- **Write good software**
  - **—few performance optimizations hurt energy efficiency**
- **Build elastic software**
  - **—manufacture idleness by migrating computation and data**
  - **—turn components/machines off**
  - **—adds significant complexity!**

Conclusions

- **Massive scale of WSC brings new challenges**
  - —unprecedented depth and complexity of the storage hierarchy
    - FLASH and faster networking (together) show promise for simplifying life of programmers
  - —build robust internet services that survive
    - continuing failure/recovery of components
    - large exposure to rare performance glitches
- **Fault correlation has a dramatic impact on distributed storage availability**
  - —hard to handle: main concern for large-scale robust services
- **Energy efficiency**
  - —time for computer scientists to do their part
  - —factor of 2-10 potentially available from CS techniques