CS 61C: Great Ideas in Computer Architecture (Machine Structures)
Warehouse-Scale Computing

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http://inst.eecs.berkeley.edu/~cs61c/

Coherency Tracked by Cache Block

- Block ping-pongs between two caches even though processors are accessing disjoint variables
- Effect called *false sharing*
- How can you prevent it?

Review: Understanding Cache Misses: The 3Cs

- Compulsory (cold start or process migration, 1st reference):
  - First access to block, impossible to avoid; small effect for long-running programs
  - Solution: increase block size (increases miss penalty; very large blocks could increase miss rate)
- Capacity (not compulsory and…)
  - Cache cannot contain all blocks accessed by the program ***even with perfect replacement policy in fully associative cache***
  - Solution: increase cache size (may increase access time)
- Conflict (not compulsory or capacity and…):
  - Multiple memory locations map to the same cache location
  - Solution 1: increase cache size
  - Solution 2: increase associativity (may increase access time)
  - Solution 3: improve replacement policy, e.g.. LRU

Fourth "C" of Cache Misses: *Coherence* Misses

- Misses caused by coherence traffic with other processor
- Also known as *communication* misses because represents data moving between processors working together on a parallel program
- For some parallel programs, coherence misses can dominate total misses
  - It gets even more complicated with multithreaded processors: You want separate threads on the same CPU to have common working set, otherwise you get what could be described as ***in***coherence misses

New-School Machine Structures (It's a bit more complicated!)

Software *Hardware*

- Parallel Requests
  Assigned to computer
  e.g., Search "cats"
- Parallel Threads
  Assigned to core
  e.g., Lookup, Ads
- Parallel Instructions
  >1 instruction @ one time
  e.g., 5 pipelined instructions
- Parallel Data
  >1 data item @ one time
  e.g., Deep Learning for image classification
- Hardware descriptions
  All gates @ one time
- Programming Languages

Harness Parallelism & Achieve High Performance

Back in 2011

- Google disclosed that it continuously uses enough electricity to power 200,000 homes, but it says that in doing so, it also makes the planet greener.
- Average energy use per typical user per month is same as running a 60-watt bulb for 3 hours (180 watt-hours).

Urs Hoelzle, Google SVP
Co-author of today's reading

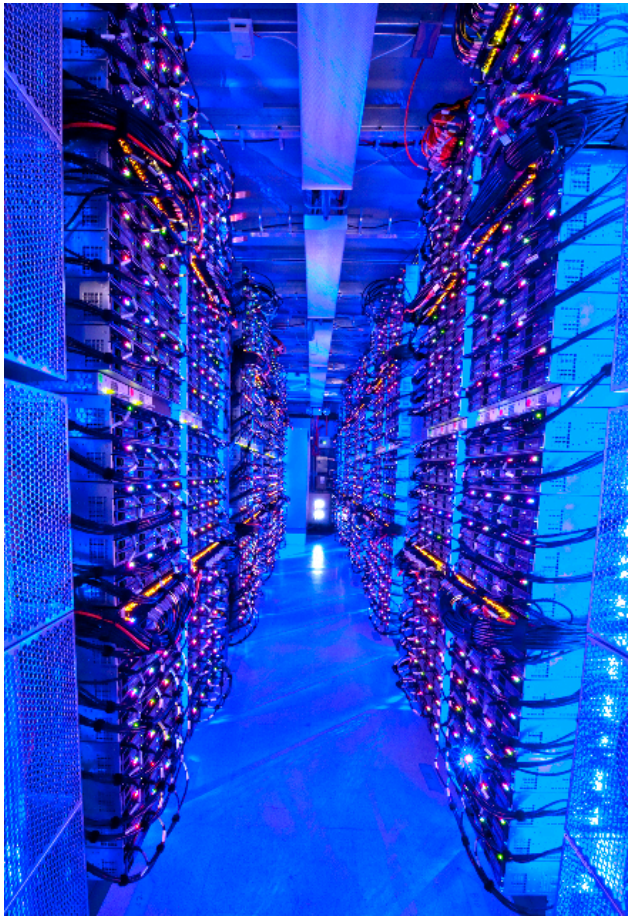
http://www.nytimes.com/2011/09/09/technology/google-details-and-defends-its-use-of-electricity.html

Google's WSCs

Containers in WSCs

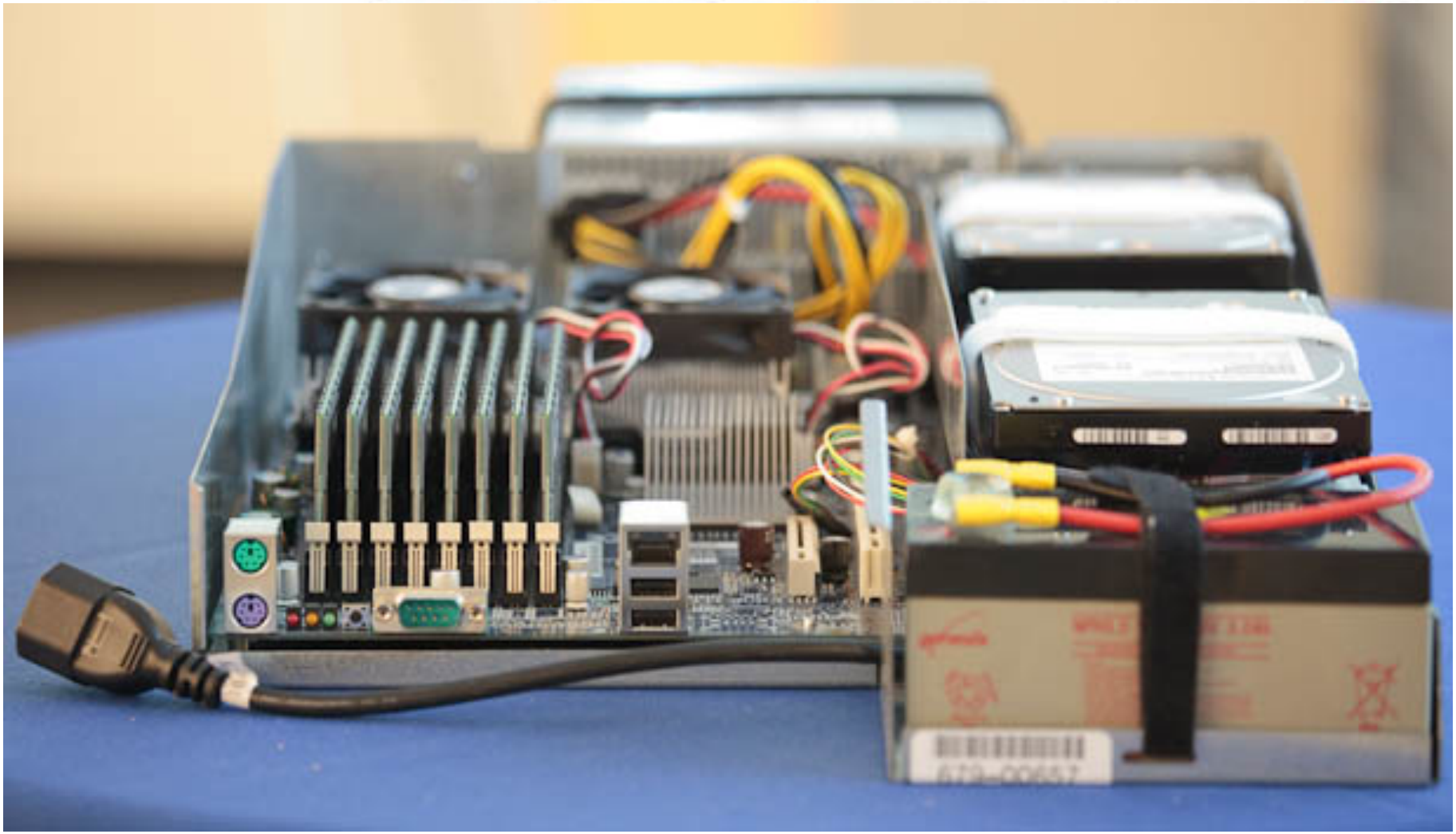
Inside WSC

Inside Container



Server, Rack, Array

Google Server Internals



Warehouse-Scale Computers

- Datacenter
  - Collection of 10,000 to 100,000 servers
  - Networks connecting them together
- ***Single gigantic*** machine
- Very large applications (Internet service): search, email, video sharing, social networking
- Very high availability
- "…WSCs are no less worthy of the expertise of computer systems architects than any other class of machines" Barroso and Hoelzle, 2009

Unique to WSCs

- Ample Parallelism
  - **Request-level Parallelism:** ex: Web search
  - **Data-level Parallelism:** ex: Image classifier training
- Scale and its Opportunities/Problems
  - **Scale of economy**: low per-unit cost
  - Cloud computing: rent computing power with low costs (ex: AWS)
- Operation Cost Count
  - Longer life time (>10 years)
  - **Cost of equipment purchases << cost of ownership**
  - Often semi-custom or custom hardware
    - But consortiums of hardware designs to save cost there
- Design for failure:
  - Transient failures
  - Hard failures
  - **High # of failures**

    ex: 4 disks/server, annual failure rate: 4%
    → WSC of 50,000 servers: 1 disk fail/hour

WSC Architecture

1U Server:

8-16 cores,

16 GB DRAM,

4x4 TB disk

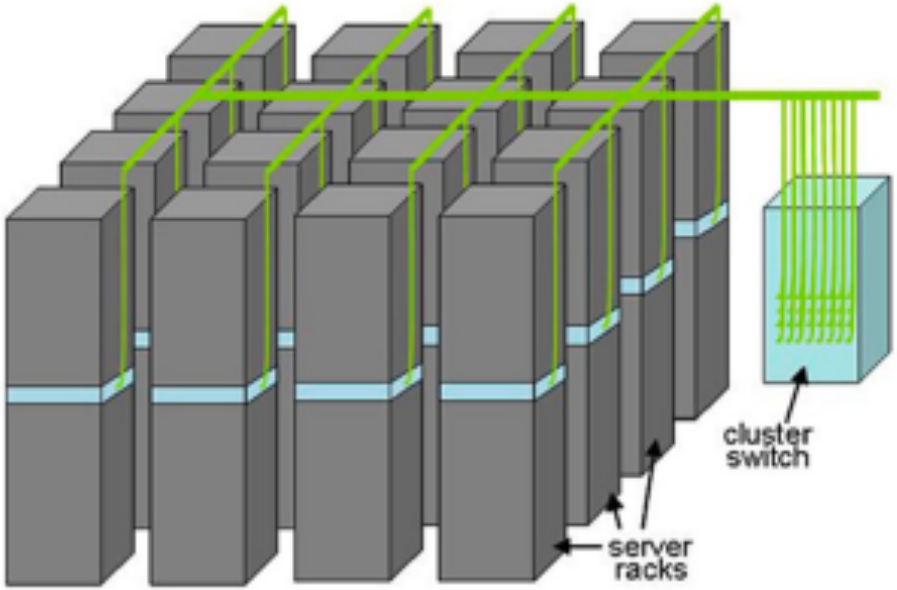
+ disk pods

Rack:

40-80 severs,

Local Ethernet (1-10Gbps) switch

(30$/1Gbps/server)



Array (aka cluster):

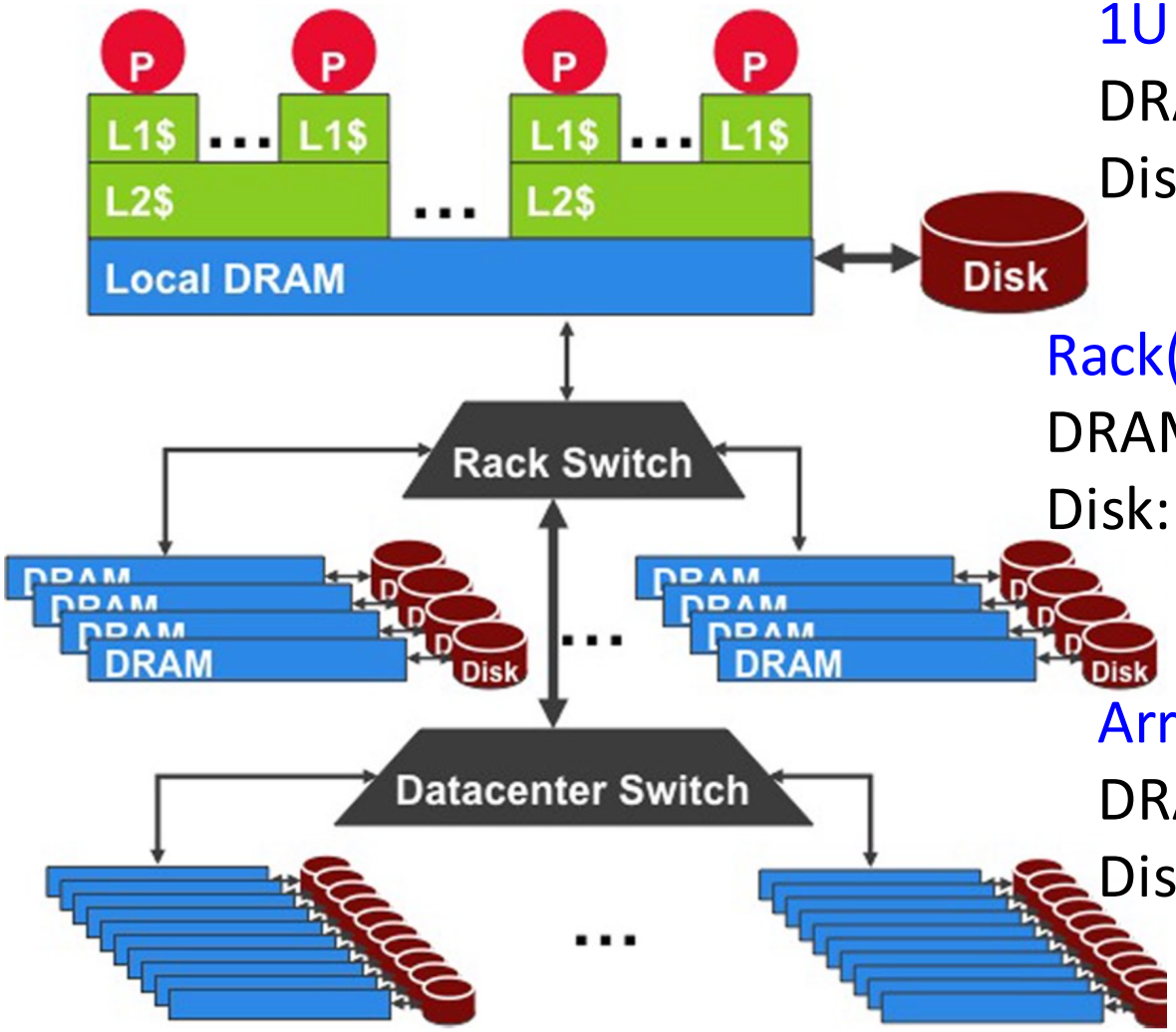
16-32 racks

Expensive switch

(10X bandwidth → 100x cost)

WSC Storage Hierarchy

Lower latency to DRAM in another server than local disk
Higher bandwidth to local disk than to DRAM in another server



1U Server:

DRAM: 16GB, 100ns, 20GB/s

Disk: 2TB, 10ms, 200MB/s

Rack(80 severs):

DRAM: 1TB, 300us, 100MB/s

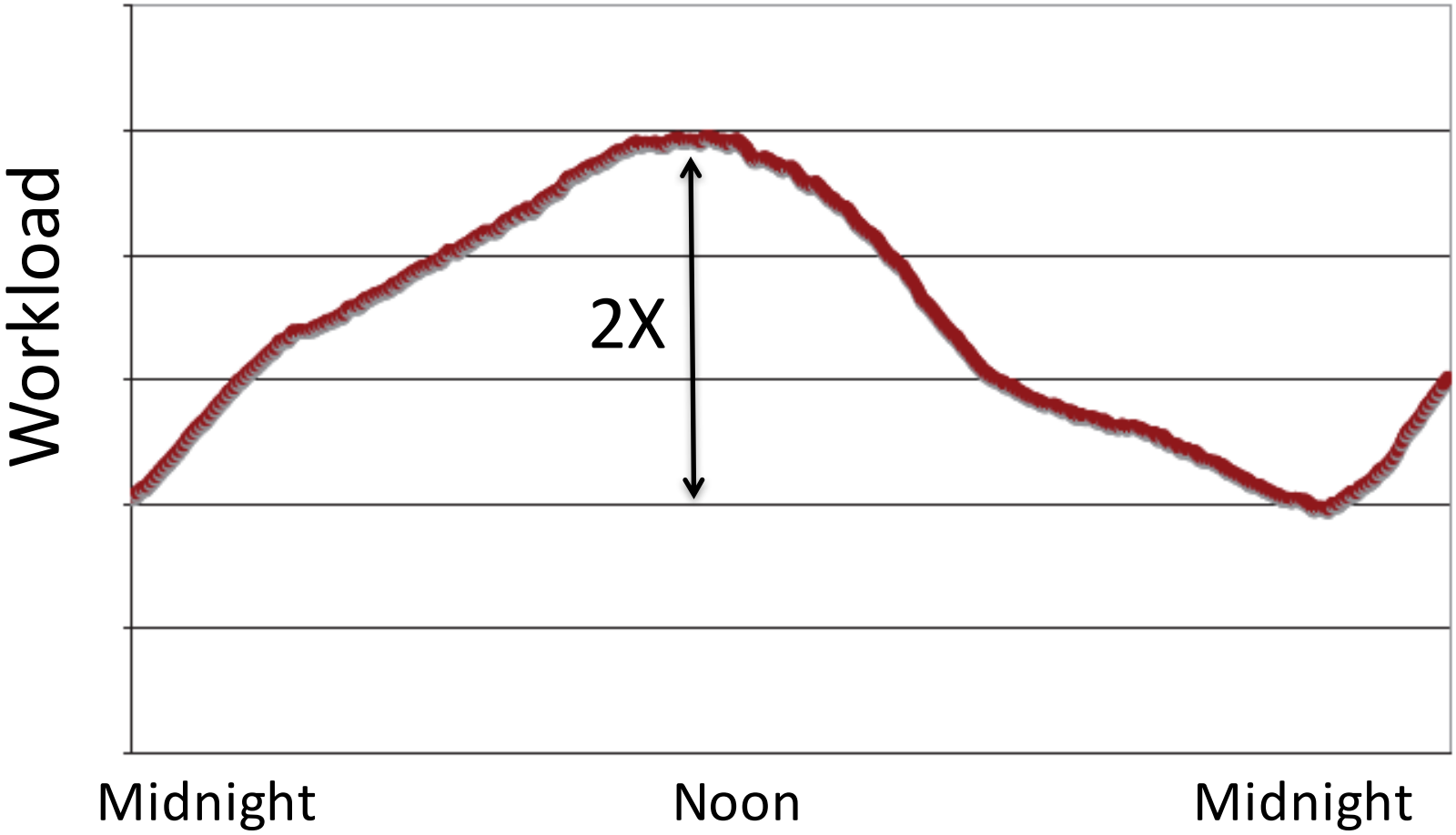
Disk: 160TB, 11ms, 100MB/s

Array(30 racks):

DRAM: 30TB, 500us, 10MB/s

Disk: 4.80PB, 12ms, 10MB/s

Workload Variation



- Online service: Peak usage 2X off-peak

Impact on WSC software

- ***Latency, bandwidth*** → Performance
  - Independent data set within an array
  - Locality of access within server or rack
- ***High failure rate*** → Reliability, Availability
  - Preventing failures is effectively ***impossible*** at this scale
  - Cope with failures gracefully by designing the system as a whole
- ***Varying workloads*** → Availability
  - Scale up and down gracefully
- More challenging than software for single computers!

Power Usage Effectiveness

- Energy efficiency
  - Primary concern in the design of WSC
  - Important component of the total cost of ownership
- Power Usage Effectiveness (PUE):

$$\frac{\textbf{Total Building Power}}{\textbf{IT equipment Power}}$$

  - A power efficiency measure for WSC
  - Not considering efficiency of servers, networking
  - Perfection = 1.0
  - Google WSC's PUE = 1.2
    - Getting pretty close to Amdahl's law limit

PUE in the Wild (2007)

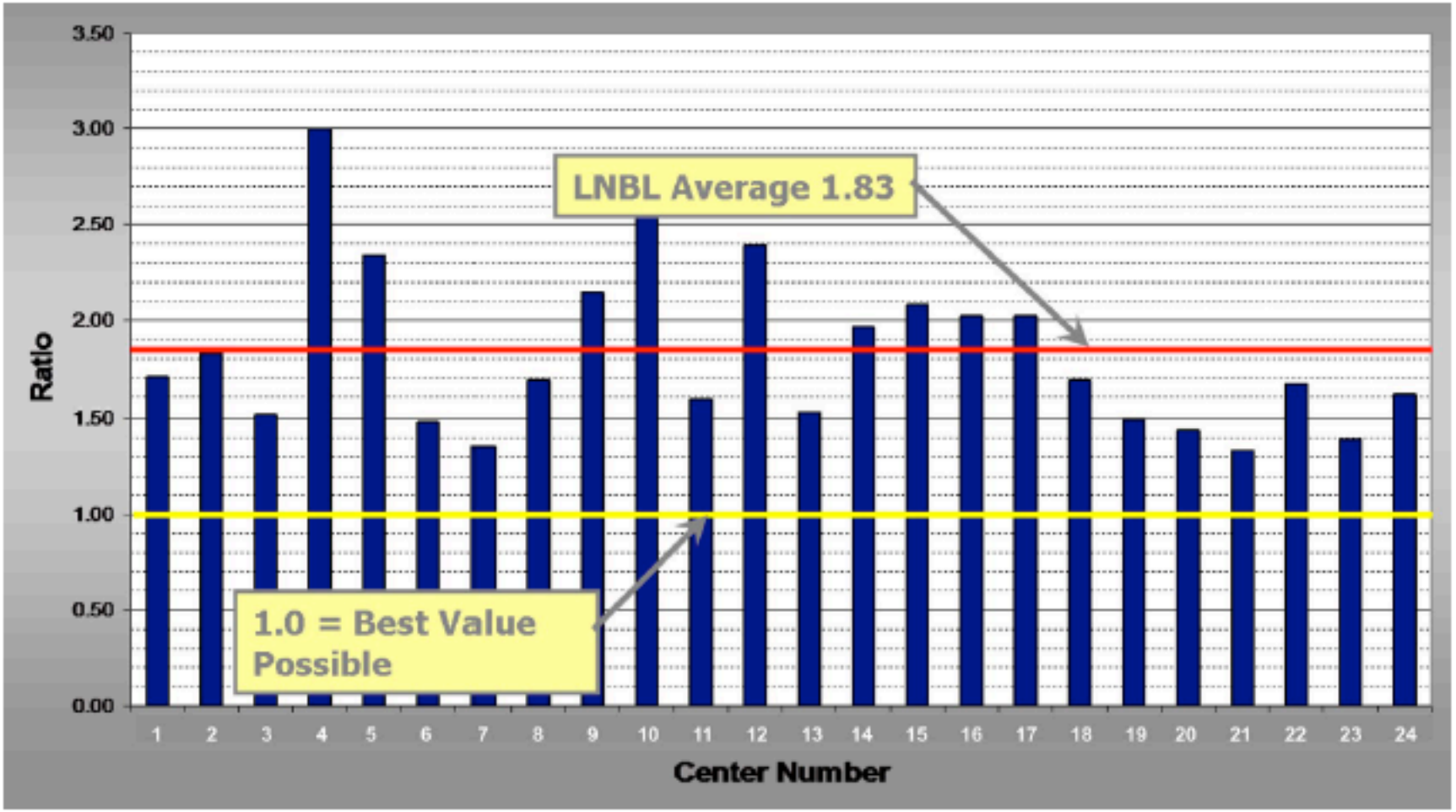
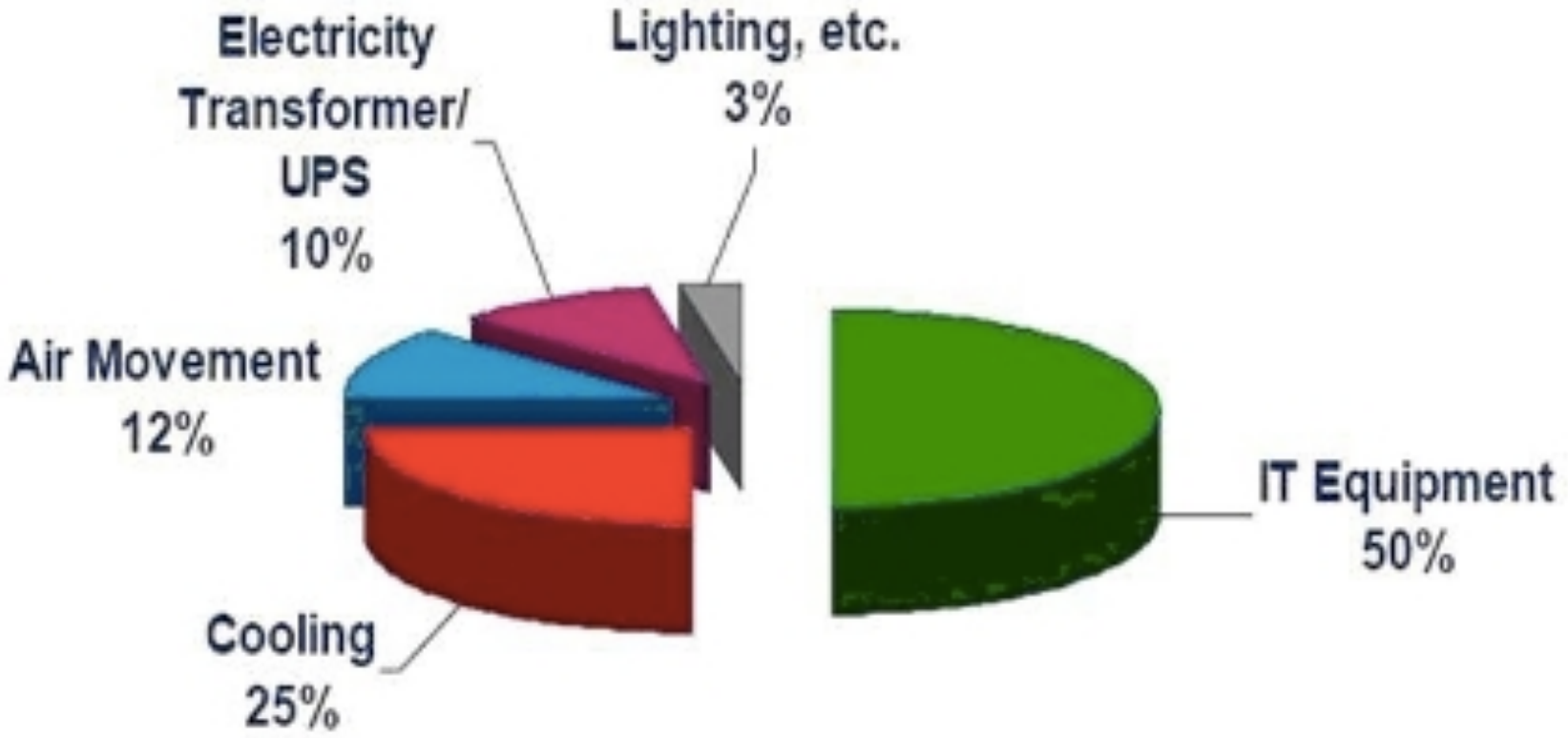
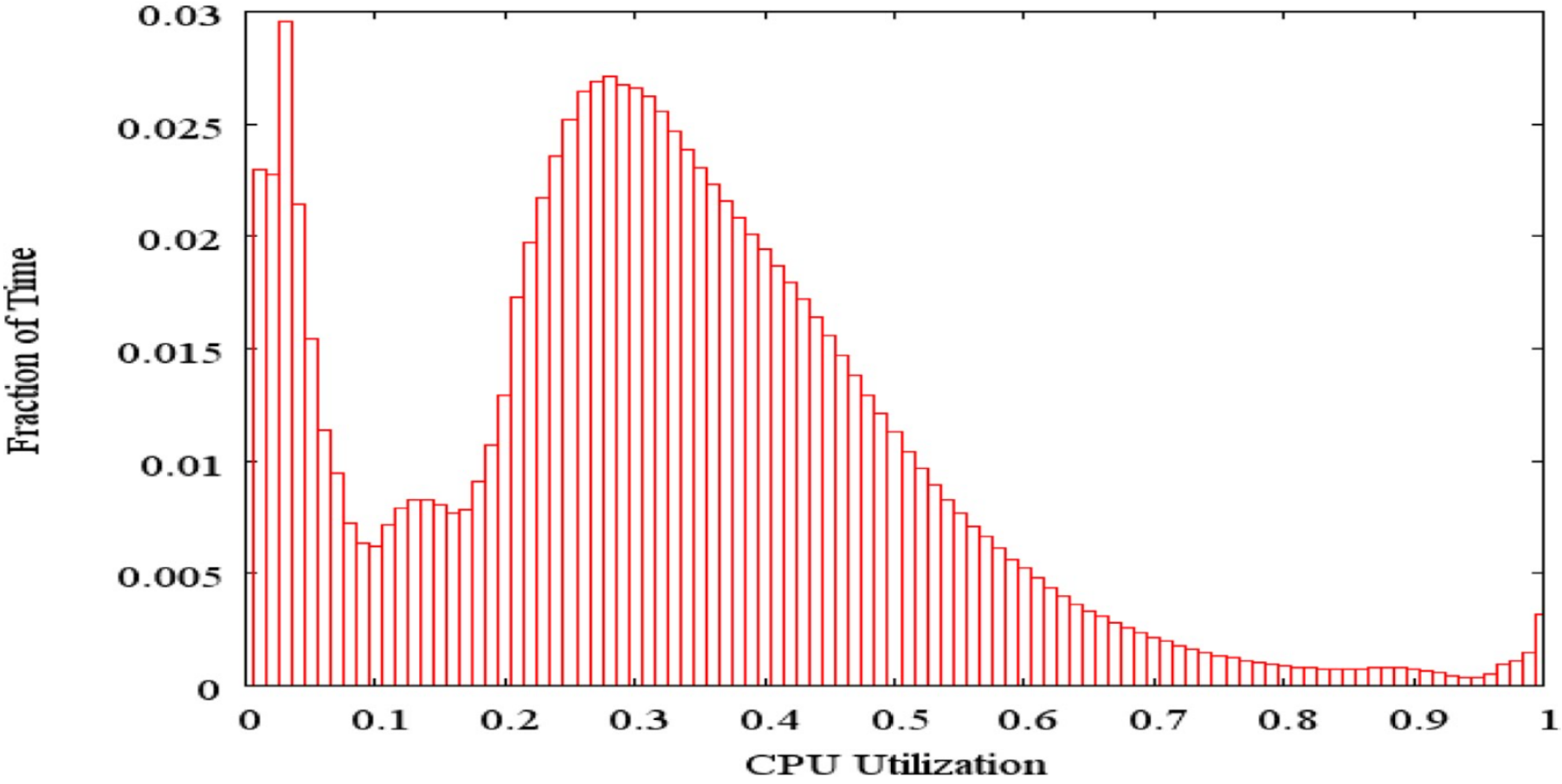


FIGURE 5.1: LBNL survey of the power usage efficiency of 24 datacenters, 2007 (Greenberg et al.)

Where Data Center Power Goes



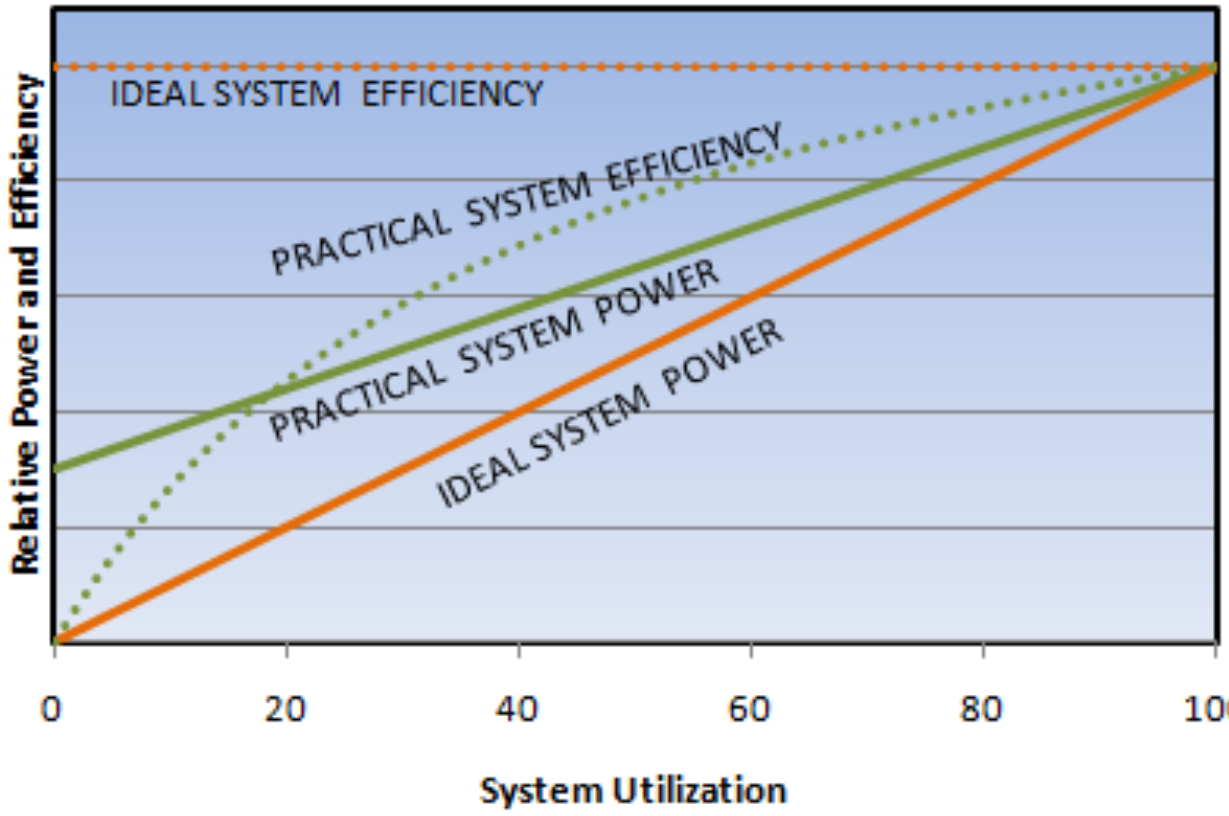
Load Profile of WSCs



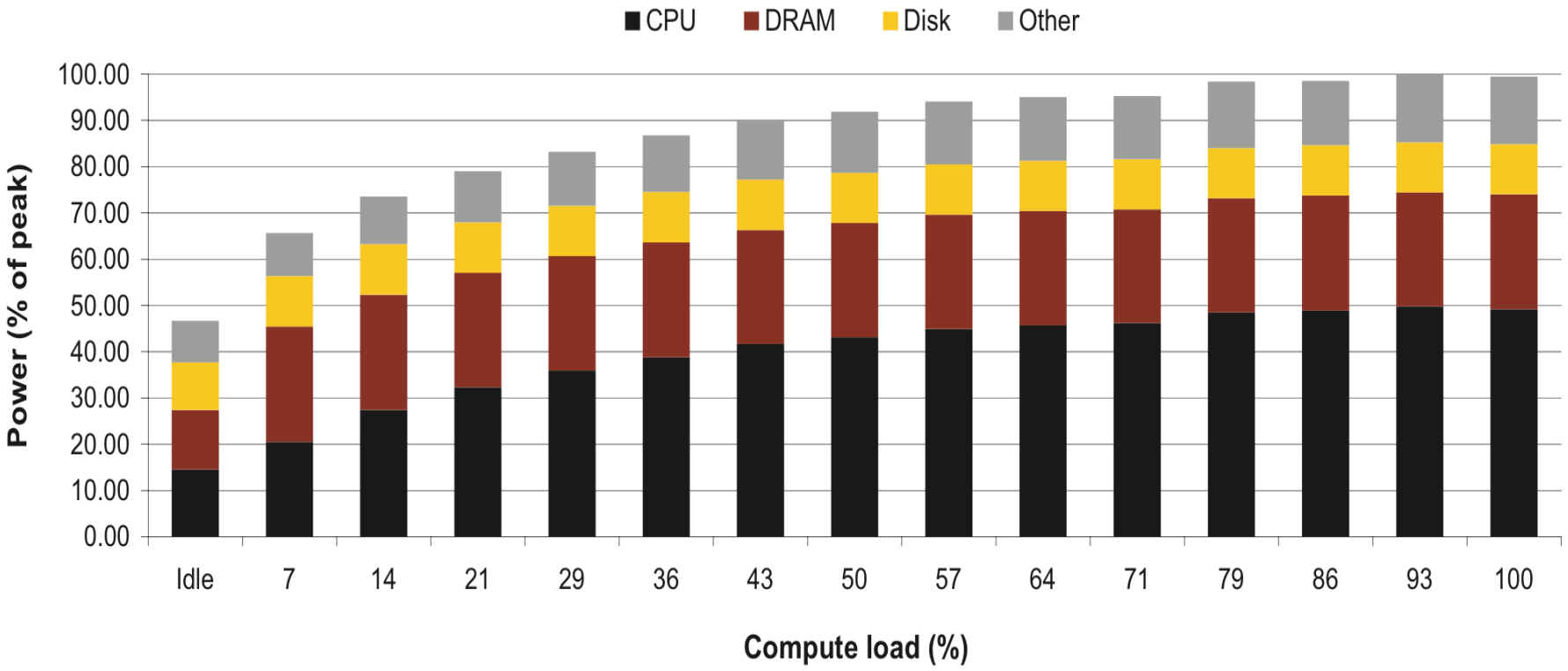
- Average CPU utilization of 5,000 Google servers, 6 month period
- Servers rarely idle or fully utilized, operating most of the time at ***10% to 50%*** of their maximum utilization

Energy-Proportional Computing: Design Goal of WSC

- Energy = Power x Time, Efficiency = Computation / Energy
- Desire:
  - Consume almost no power when idle ("Doing nothing well")
  - Gradually consume more power as the activity level increases



Cause of Poor Energy Proportionality



- CPU: 50% at peek, 30% at idle
- DRAM, disks, networking: 70% at idle!
  - Because they are never really idle unless they are powered off!
- Need to improve the energy efficiency of peripherals

Clicker/Peer Instruction: Which Statement is True

- **A: Idle servers consume almost no power.**
- **B: Disks will fail once in 20 years, so failure is not a problem of WSC.**
- **C: The search requests of the same keyword from different users are dependent.**
- **D: More than half of the power of WSCs goes into cooling.**
- **E: WSCs contain many copies of data.**

Administrivia

- Reminder that Project 4 is out…

Agenda

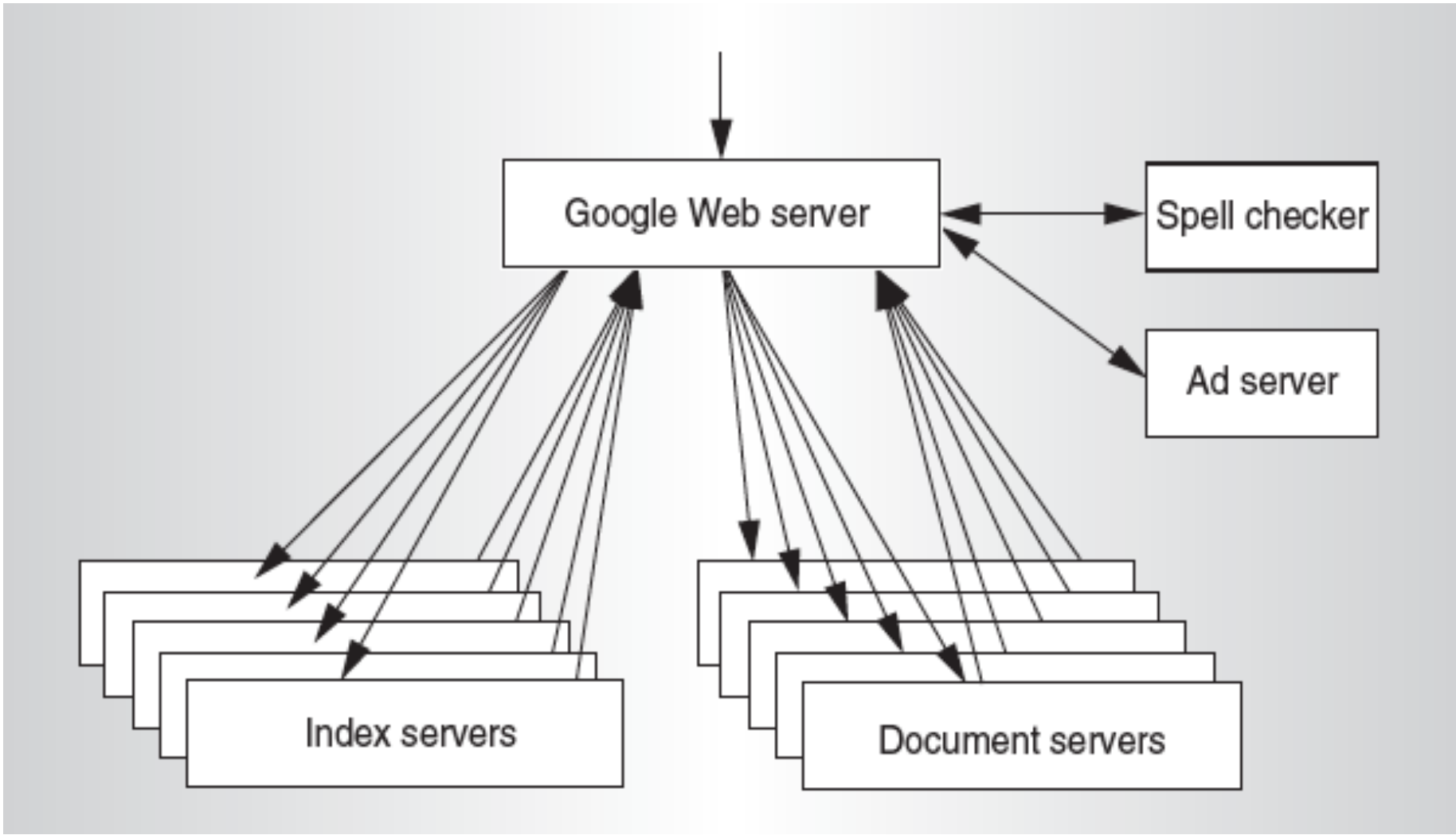
- Warehouse Scale Computing
- Administrivia & Clickers/Peer Instructions
- Request-level Parallelism

  e.g. Web search

Request-Level Parallelism (RLP)

- Hundreds of thousands of requests per sec.
  - Popular Internet services like web search, social networking, …
  - Such requests are largely independent
    - Often involve read-mostly databases
    - Rarely involve read-write sharing or synchronization across requests
- Computation easily partitioned across different requests and even within a request

Google Query-Serving Architecture



Anatomy of a Web Search

cats

Web Images Videos News Shopping More Search tools

About 650,000,000 results (0.29 seconds)

Black Cats are Good Luck - berkeleyhumane.org
Ad www.berkeleyhumane.org/adopt-a-**cat**
In October, Adopt a Black **Cat** For only $10. Save a Life Today!

Cat - Wikipedia, the free encyclopedia
https://en.wikipedia.org/wiki/**Cat** Wikipedia
The domestic **cat** (Felis catus or Felis silvestris catus) is a small, typically furry, domesticated, and carnivorous mammal. They are often called house **cats** when ...
African wildcat - Creme Puff - List of cat breeds - Human interaction with cats

Cats (musical) - Wikipedia, the free encyclopedia
https://en.wikipedia.org/wiki/**Cats**_(musical) Wikipedia
Cats is a musical composed by Andrew Lloyd Webber, based on Old Possum's Book of Practical **Cats** by T. S. Eliot, and produced by Cameron Mackintosh.

Music: Andrew Lloyd Webber
Lyrics: T. S. Eliot; Trevor Nunn (addition...
Premiere: 11 May 1981 – New London ...
Awards: 1981 Laurence Olivier Award for .

Cats - Mashable
mashable.com/**category**/**cats**/ Mashable
The domestic **cat** (Felis catus or Felis silvestris catus) is a small, usually furry, domesticated, carnivorous mammal. It is often called the housecat when kept as an ...

Cat Health Center | Cat Care and Information from WebMD
pets.webmd.com/**cats**/ WebMD
WebMD veterinary experts provide comprehensive information about **cat** health care, offer nutrition and feeding tips, and help you identify illnesses in **cats**.

In the news

Cat killer on the loose? Police think so
Detroit Free Press - 17 hours ago
Police say someone has been beating **cats** to death in Hazel Park two blocks north of Detroit ...

New Study Finds Cats Have The Surface Area Of A Ping Pong Table
Popular Science - 18 hours ago

This breed of cats makes them look just like werewolves
AOL News - 2 days ago

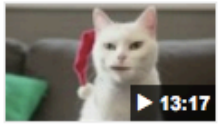
More news for cats

Cats - Reddit
https://www.reddit.com/r/**cats**/ Reddit
Your reddit account must be at least 15 days of age to post in /r/**cats**. Redditors ... The mom **cat** has a very special mark on her coat that I think you all would like.

Cats: Pictures, Videos, Breaking News - Huffington Post
www.huffingtonpost.com/news/**cats**/ The Huffington Post
Big News on **Cats**. Includes blogs, news, and community conversations about **Cats**.

Cats on About.com - All About Cats and Kittens
cats.about.com › About Home
Learn all about the care and feeding of **cats**. Free articles on **cat** behavior, **cat** health, pregnancy and birth, vet care and the human bond with **cats**.

Funny Cats Big Compilation 2015! [NEW] - YouTube



https://www.youtube.com/watch?v=eVo3LbVWjWc
Dec 2, 2014 - Uploaded by Funny Animals Channel
New Crazy compilation of 2014. ENJOY and SUBSCRIBE, Merry Christmas!

Anatomy of a Web Search (1/3)

- Google “cats”
  - Direct request to “closest” Google WSC
    - Handled by DNS
  - Front-end load balancer directs request to one of many arrays (cluster of servers) within WSC
    - One of potentially many load balancers
  - Within array, select one of many Goggle Web Servers (GWS) to handle the request and compose the response pages
  - GWS communicates with Index Servers to find documents that contains the search word, “cats”
    - Index servers keep index in RAM, not on disk
  - Return document list with associated relevance score

Anatomy of a Web Search (2/3)

- In parallel,
  - Ad system: run ad auction for bidders on search terms
    - Yes, you are being bought and sold in a realtime auction all over the web
    - Page ads are worse than search ads
- Use docids (Document IDs) to access indexed documents
- Compose the page
  - Result document extracts (with keyword in context) ordered by relevance score
  - Sponsored links (along the top) and advertisements (along the sides)

Anatomy of a Web Search (3/3)

- Implementation strategy
  - Randomly distribute the entries
  - Make many copies of data (a.k.a. “replicas”)
  - Load balance requests across replicas
- ***Redundant copies*** of indices and documents
  - Breaks up search hot spots, e.g. “Taylor Swift”
  - Increases opportunities for ***request-level parallelism***
  - Makes the system more ***tolerant of failures***

Summary

- Warehouse Scale Computers
  - New class of computers
  - Scalability, energy efficiency, high failure rate
- Request-level parallelism

  e.g. Web Search
- Data-level parallelism on a large dataset
  - A gazillion VMs for different people
  - MapReduce
  - Hadoop, Spark