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Great Ideas in Computer Architecture
(a.k.a. Machine Structures)

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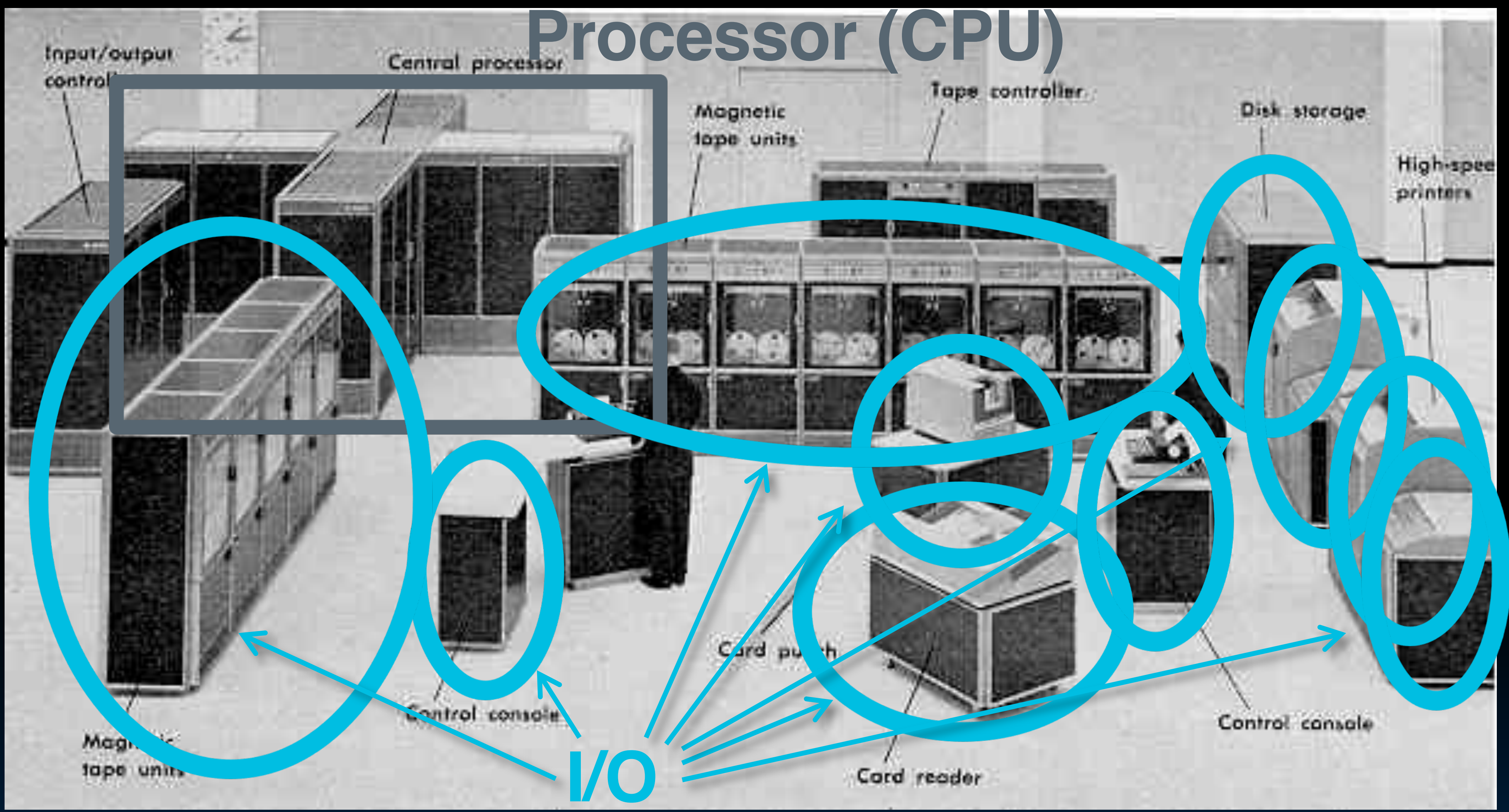
Datacenters & Cloud Computing

Eras of Computer Hardware

Review … where are we?

- **Great Ideas in Computer Architecture**
  - ✓ Layers of Representation/Interpretation
  - ✓ Moore's Law
  - ✓ Principle of Locality/Memory Hierarchy
  - Parallelism
  - Performance Measurement and Improvement
  - Dependability via Redundancy

Computer Eras: Mainframe 1950s-60s



"Big Iron": IBM, UNIVAC, … build $1M computers for businesses → COBOL, Fortran, timesharing OS

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Minicomputer Eras: 1970s

Using integrated circuits, Digital, HP… build $10k computers for labs, universities ➔ C, UNIX OS

PC Era: Mid 1980s - Mid 2000s

Using microprocessors, Apple, IBM, … build $1k computer for 1 person ➔ Basic, Java, Windows OS

PostPC Era: Late 2000s - ??

Personal Mobile Devices (PMD): Relying on wireless networking, Apple, Nokia, … build $500 smartphone and tablet computers for individuals
➔ Objective C, Swift, Java, Android OS + iOS

Cloud Computing: Using Local Area Networks, Amazon, Google, … build $200M Warehouse Scale Computers with 100,000 servers for Internet Services for PMDs
➔ MapReduce, Ruby on Rails

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Warehouse Scale Computers

Why Cloud Computing Now?

- "The Web Space Race": Build-out of extremely large datacenters (10,000's of commodity PCs)
  - Build-out driven by growth in demand (more users)
  - Infrastructure software and Operational expertise
- Discovered economy of scale: 5-7x cheaper than provisioning a medium-sized (1000 servers) facility
- More pervasive broadband Internet so can access remote computers efficiently
- Commoditization of HW & SW
  - Standardized software stacks

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November 2020 AWS Instances & Prices

Instance	Per Hour	$ Ratio to Small	EC2 Compute Unit (integer)	Virtual Cores (vCPU)	Memory (GiB)	Disk (GiB)
Standard Small (t3.small)	$0.021	1	Variable	2	2	EBS
Standard Large (t3.large)	$0.083	4	Variable	2	8	EBS
Standard 2x Extra Large (t3.2xlarge)	$0.333	16	Variable	8	32	EBS
High-Mem Large (r5.large)	$0.126	6	10	2	16	EBS
High-Mem Double Xlarge (r5.2xlarge)	$0.504	24	37	8	64	EBS
High-Mem 24x Large (r5.24xlarge)	$6.048	288	337	96	768	EBS
High-CPU Large (c5.large)	$0.085	4	10	2	4	EBS
High-CPU 18x Large (c5.18xlarge)	$3.060	146	281	72	144	EBS

- **Closest computer in WSC example is Standard 2X Extra Large**
- **At these low rates, Amazon EC2 can make money! (even utilized 50% time)**
- **EBS = Elastic Block Store (SSD=$0.10/GB-month, HDD=$0.045/GB-month)**
- **Each also comes with dedicated attached SSD if you choose & pay for that**

Warehouse Scale Computers

- **Massive scale datacenters: 10,000 to 100,000 servers + networks to connect them together**
  - Emphasize cost-efficiency
  - Attention to power: distribution and cooling
- **(relatively) homogeneous hardware/software**
- **Offer very large applications (Internet services): search, social networking, video sharing**
- **Very highly available: < 1 hour down/year**
  - Must cope with failures common at scale
- **"…WSCs are no less worthy of the expertise of computer systems architects than any other class of machines"**

  – Barroso and Hoelzle 2009

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Design Goals of a WSC

- **Unique to Warehouse-scale**
  - Ample parallelism:
    - Batch apps: large number independent data sets with independent processing.
    - Also known as Data-Level Parallelism
  - Scale and its Opportunities/Problems
    - Relatively small number of these make design cost expensive and difficult to amortize
    - But price breaks are possible from purchases of very large numbers of commodity servers
    - Must also prepare for high # of component failures
  - Operational Costs Count:
    - Cost of equipment purchases << cost of ownership

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E.g., Google's Oregon WSC

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Containers in WSCs

Inside WSC

Inside Container

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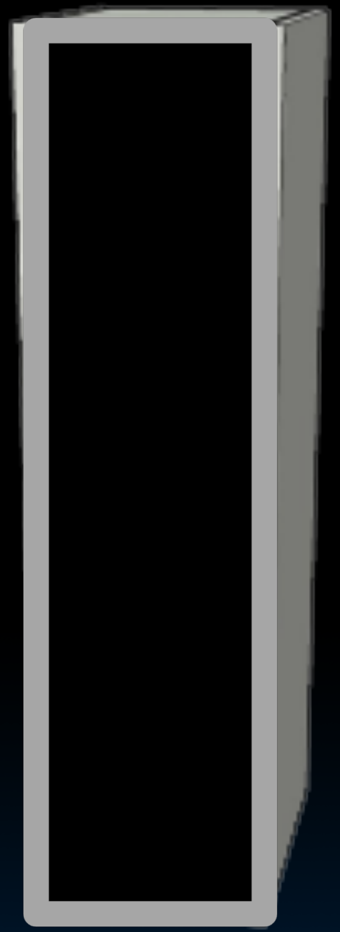
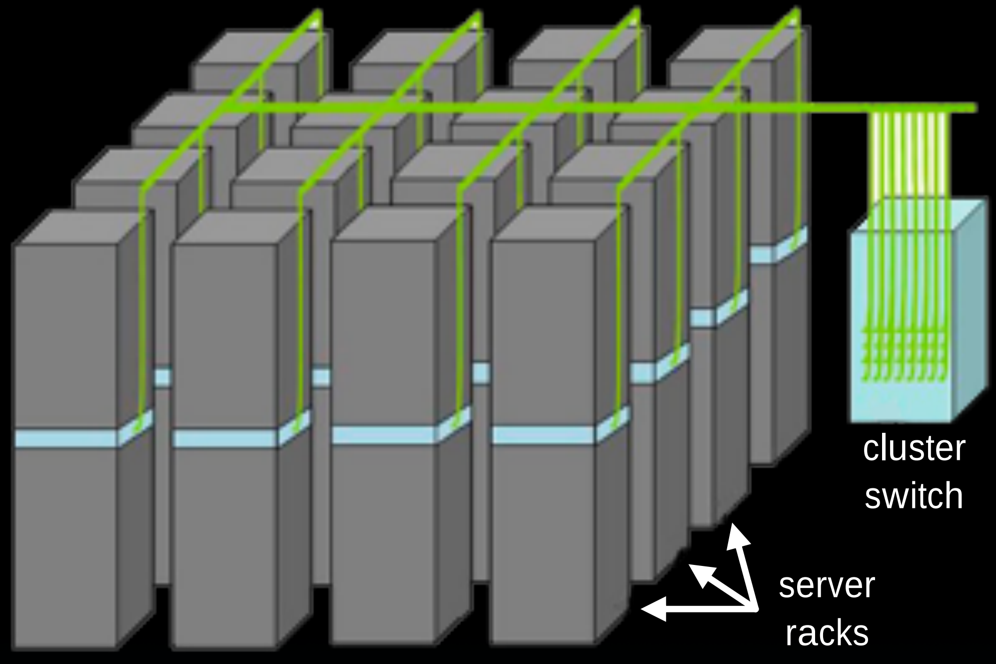
Equipment Inside a WSC

Server (in rack format):
1 ¾ inches high "1U", x 19 inches x 16-20 inches: 8 cores, 16 GB DRAM, 4x1 TB disk



7 foot Rack: 40-80 servers + Ethernet local area network (1-10 Gbps) switch in middle ("rack switch")



Array (aka cluster):
16-32 server racks + larger local area network switch ("array switch") 10X faster → cost 100X: cost f(N^2)

Server, Rack, Array

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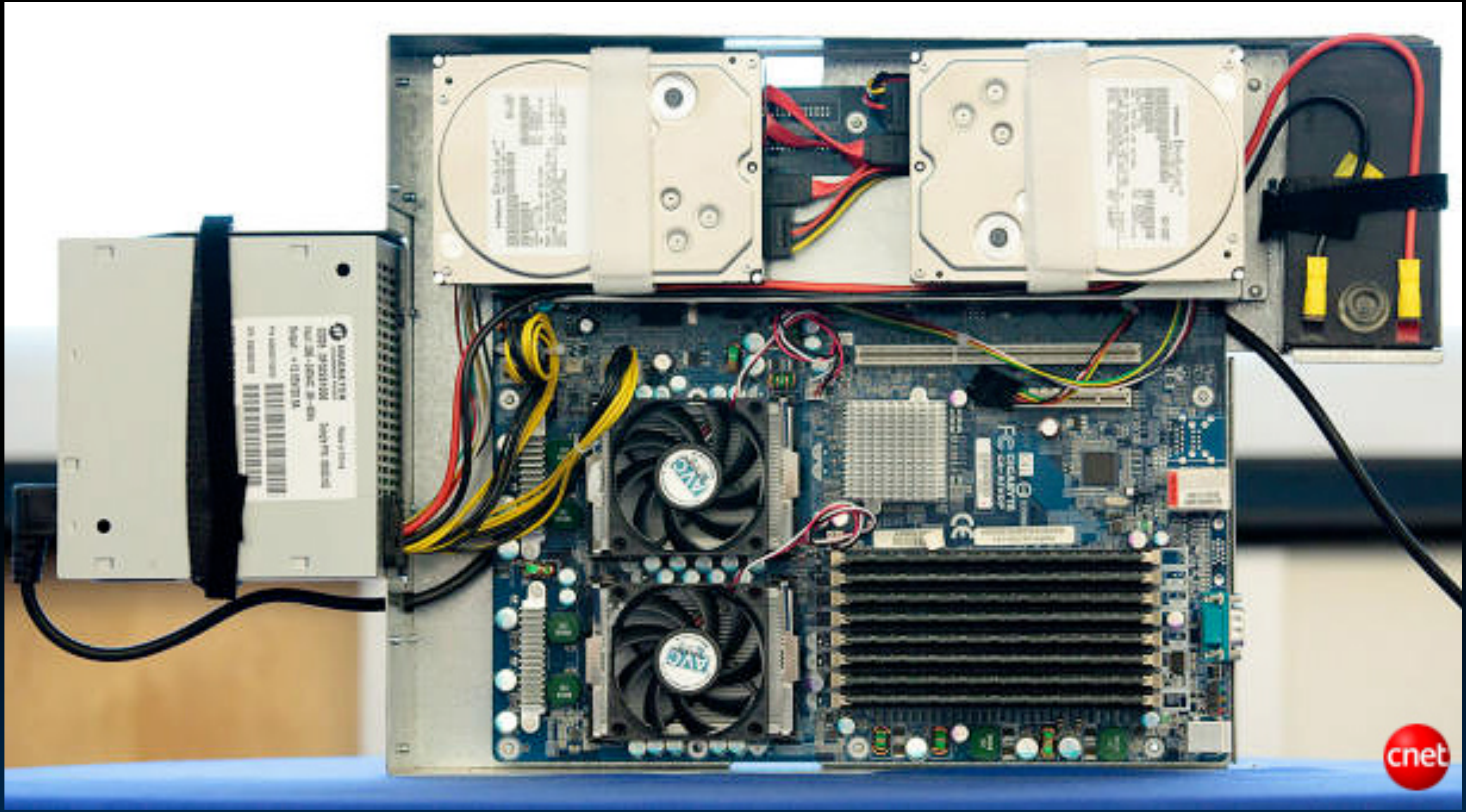
Google Server Internals



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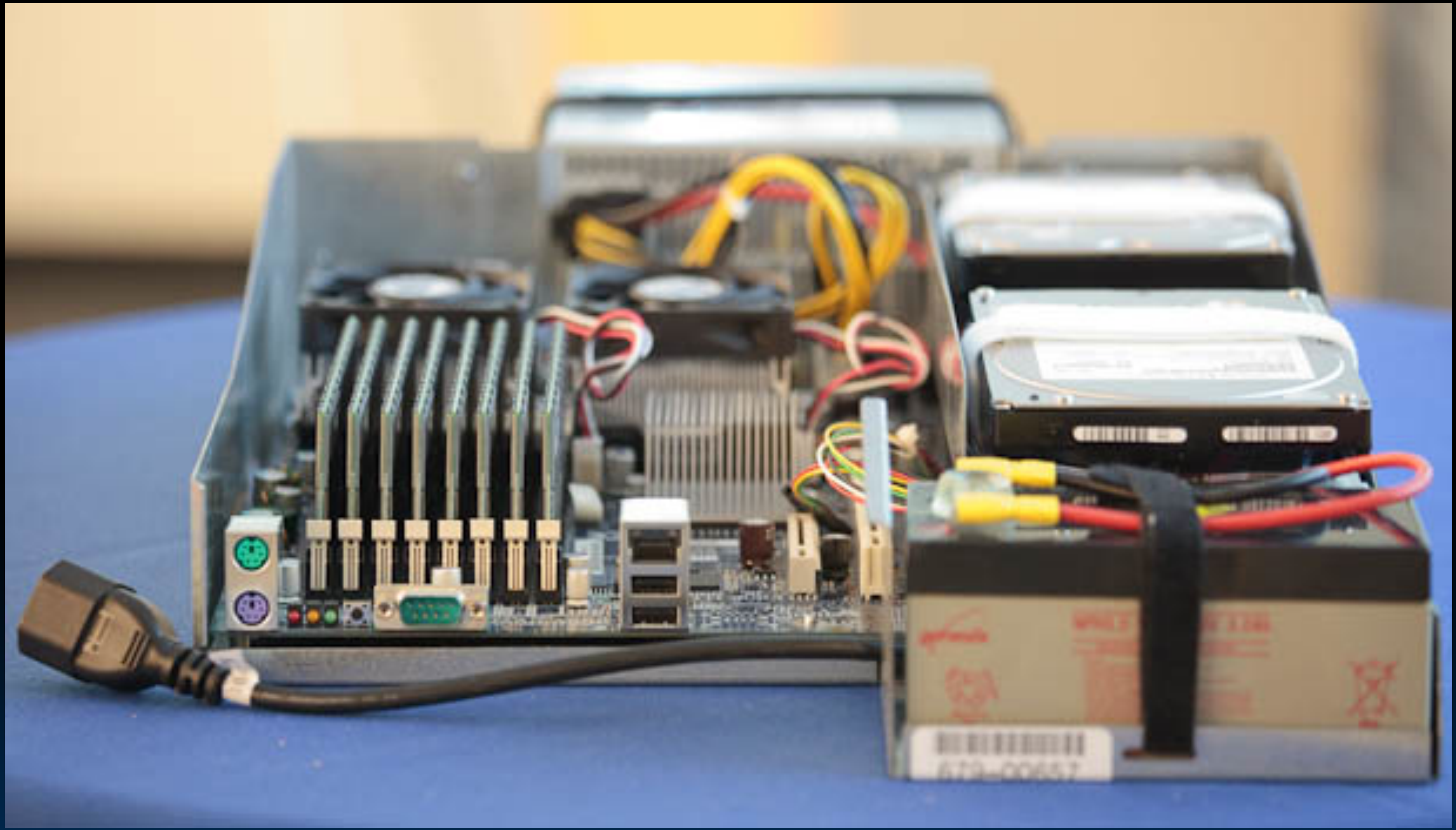
Google Server Internals



Defining Performance

- What does it mean to say X is faster than Y?

- 2009 Ferrari 599 GTB
  - 2 passengers, 11.1 secs for quarter mile (call it 10sec)
- 2009 Type D school bus
  - 54 passengers, quarter mile time? (let's guess 1 min)
- **Response Time** or **Latency**
  - time between start and completion of a task
  - E.g., time to move vehicle ¼ mile
- **Throughput** or **Bandwidth**
  - total amount of work in a given time
  - E.g., passenger-miles in 1 hour

Coping with Performance in Array

Lower latency to DRAM in another server than local disk

Higher bandwidth to local disk than to DRAM in another server

	Local	Rack	Array
Racks	--	1	30
Servers	1	80	2400
Cores (Processors)	8	640	19,200
DRAM Capacity (GB)	16	1,280	38,400
Disk Capacity (TB)	4	320	9,600
DRAM Latency (microseconds)	0.1	100	300
Disk Latency (microseconds)	10,000	11,000	12,000
DRAM Bandwidth (MB/sec)	20,000	100	10
Disk Bandwidth (MB/sec)	200	100	10

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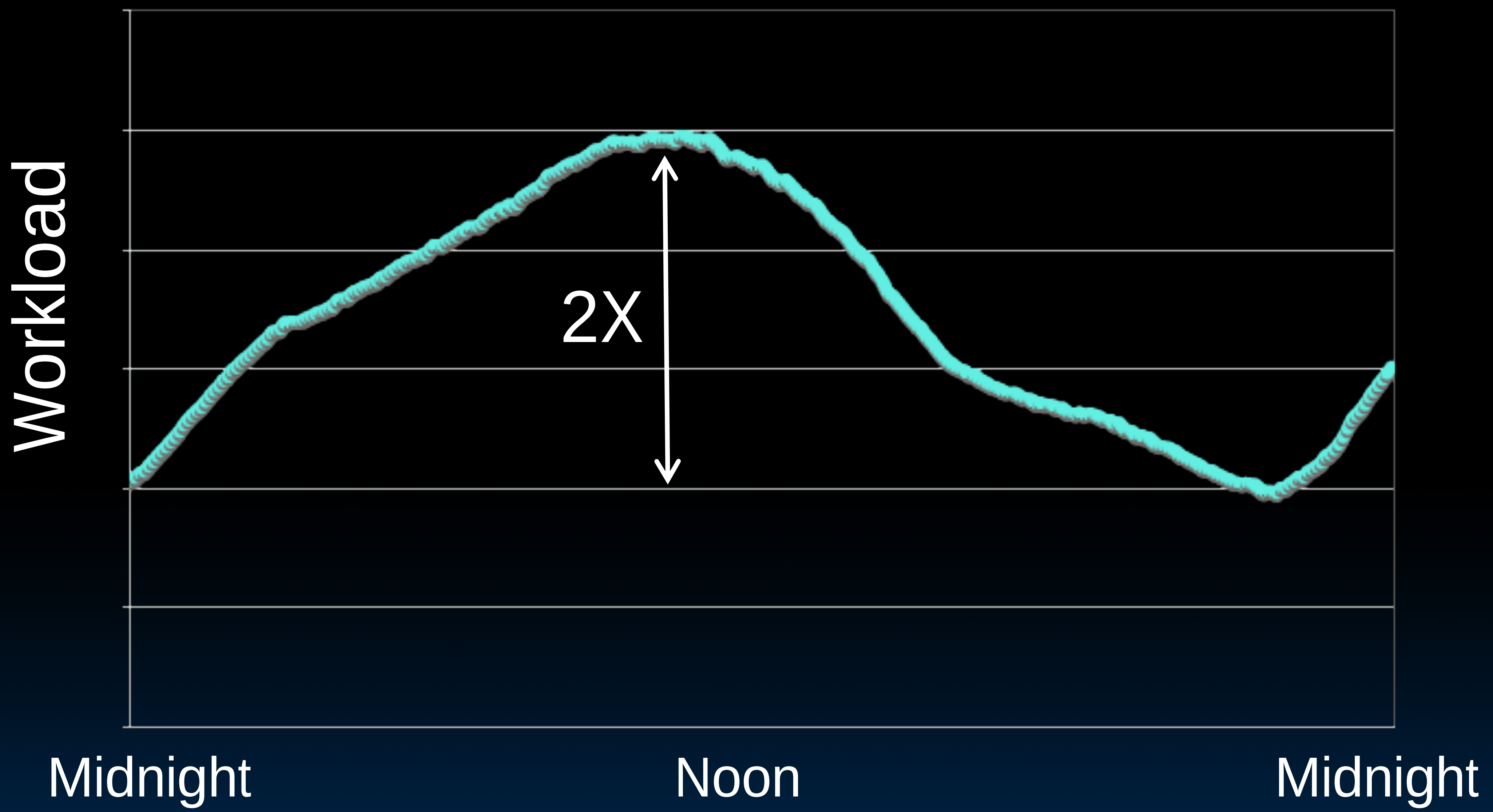
Power Usage Effectiveness (PUE)

Coping with Workload Variation

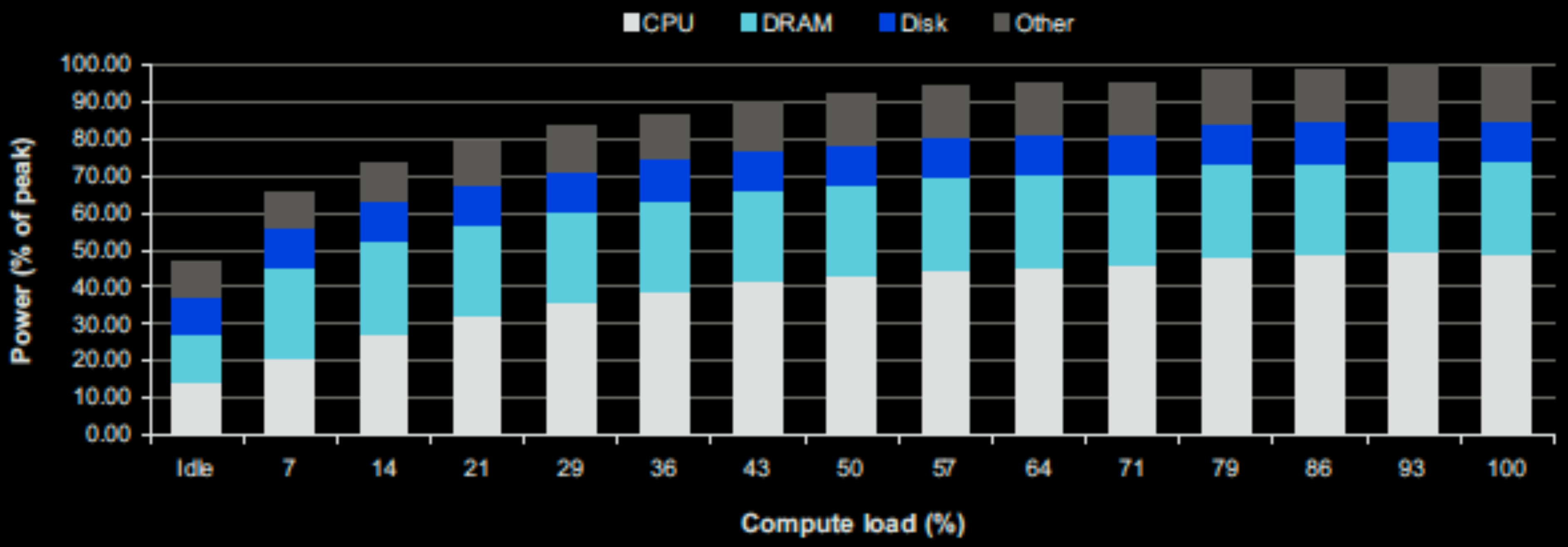


- **Online service: Peak usage 2X off-peak**

Impact of latency, bandwidth, failure, varying workload on WSC software?

- WSC Software must take care where it places data within an array to get good performance
- WSC Software must cope with failures gracefully
- WSC Software must scale up and down gracefully in response to varying demand
- More elaborate hierarchy of memories, failure tolerance, workload accommodation makes WSC software development more challenging than software for single computer

Power vs. Server Utilization



- Server power usage as load varies idle to 100%
- Uses ½ peak power when idle!
- Uses ⅔ peak power when 10% utilized! 90%@ 50%!
- Most servers in WSC utilized 10% to 50%
- Goal should be Energy-Proportionality:
  % peak load = % peak energy

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Power Usage Effectiveness

- **Overall WSC Energy Efficiency: amount of computational work performed divided by the total energy used in the process**
- **Power Usage Effectiveness (PUE):**
  Total building power / IT equipment power
  - A power efficiency measure for WSC, not including efficiency of servers, networking gear
  - 1.0 = perfection

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PUE in the Wild (2007)

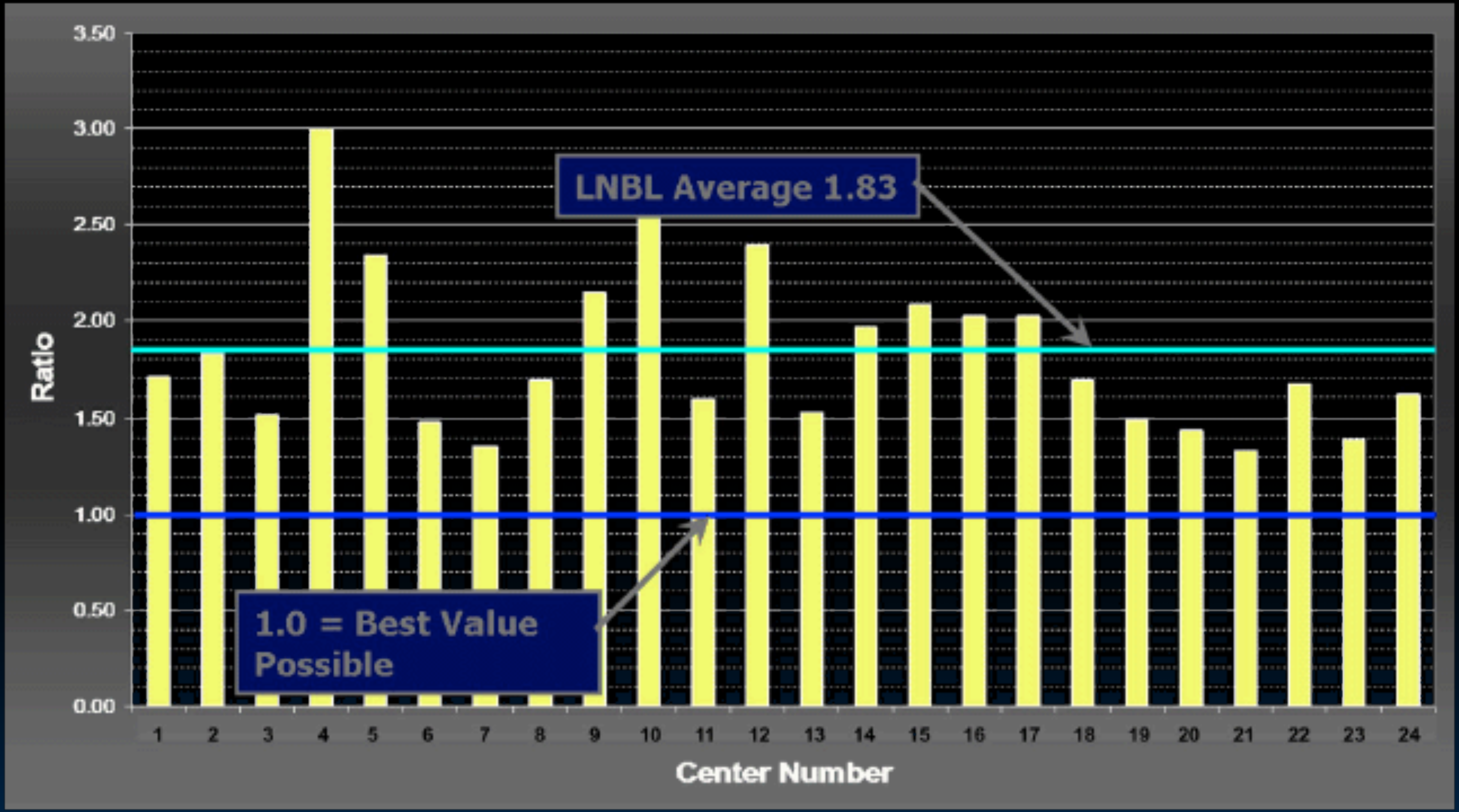
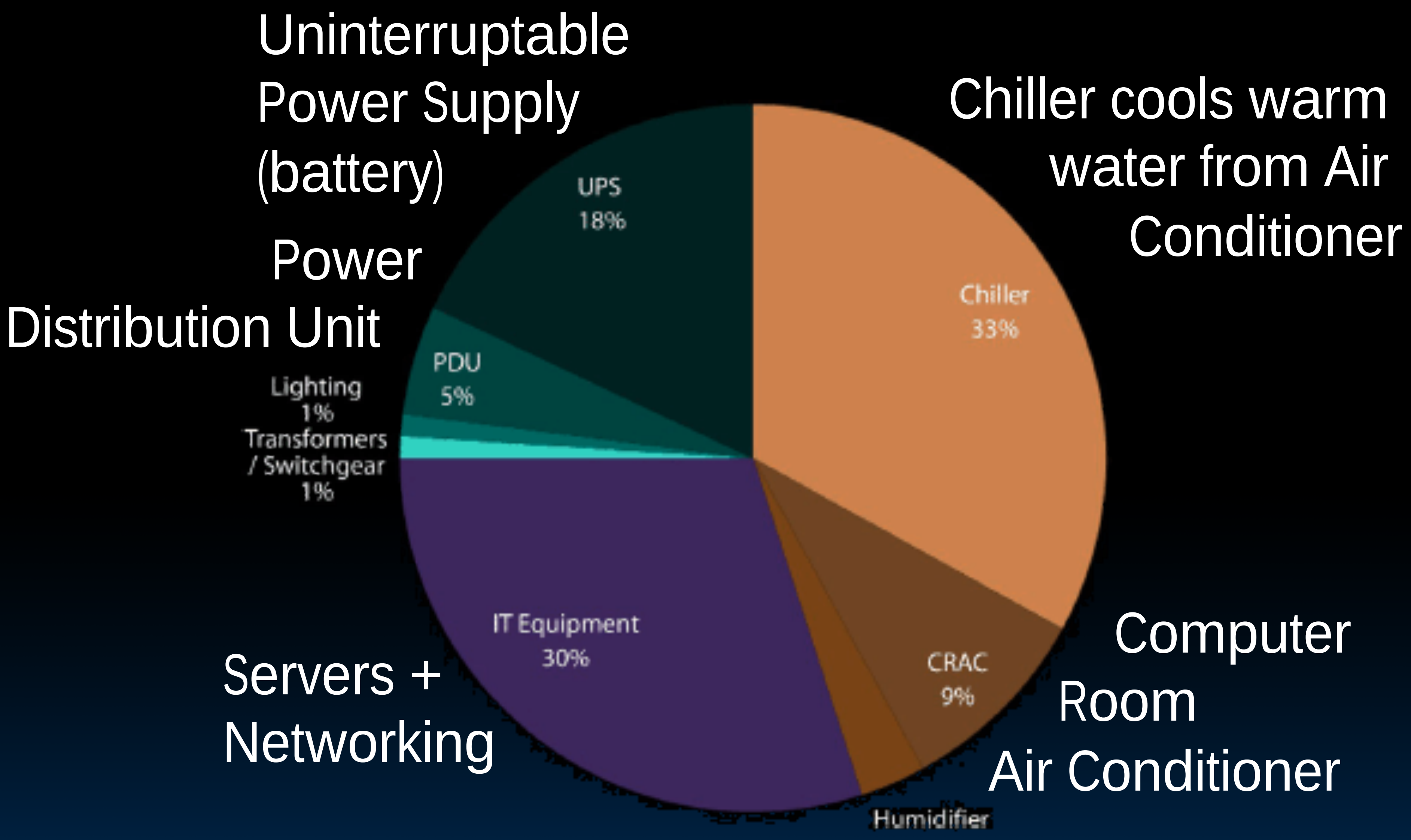


FIGURE 5.1: LBNL survey of the power usage efficiency of 24 datacenters, 2007 (Greenberg et al.)

High PUE: Where Does Power Go?



Google WSC A PUE: 1.24

- **Careful air flow handling**
  - Don't mix server hot air exhaust with cold air (separate warm aisle from cold aisle)
  - Short path to cooling so little energy spent moving cold or hot air long distances
  - Keeping servers inside containers helps control air flow
- **Elevated cold aisle temperatures**
  - 81° F instead of traditional 65° - 68° F
  - Found reliability OK if run servers hotter
- **Use of free cooling**
  - Cool warm water outside by evaporation in cooling towers
  - Locate WSC in moderate climate so not too hot or too cold
- **Per-server 12-V DC UPS**
  - Rather than WSC wide UPS, place single battery per server board
  - Increases WSC efficiency from 90% to 99%
- **Measure vs. estimate PUE, publish PUE, and improve operation**

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Computing in the News

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

- **2011** www.nytimes.com/2011/09/09/technology/google-details-and-defends-its-use-of-electricity.html
  - 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.
  - Search cost per day (per person) same as running a 60-watt bulb for 3 hours
- **2018** techcrunch.com/2018/04/04/google-matches-100-percent-of-its-power-consumption-with-renewables/
  - Google: "Over the course of 2017, across the globe, for every kilowatt-hour of electricity we consumed, we purchased a kilowatt-hour of renewable energy from a wind or solar farm that was built specifically for Google. This makes us the first public Cloud, and company of our size, to have achieved this feat"

Computing in the News

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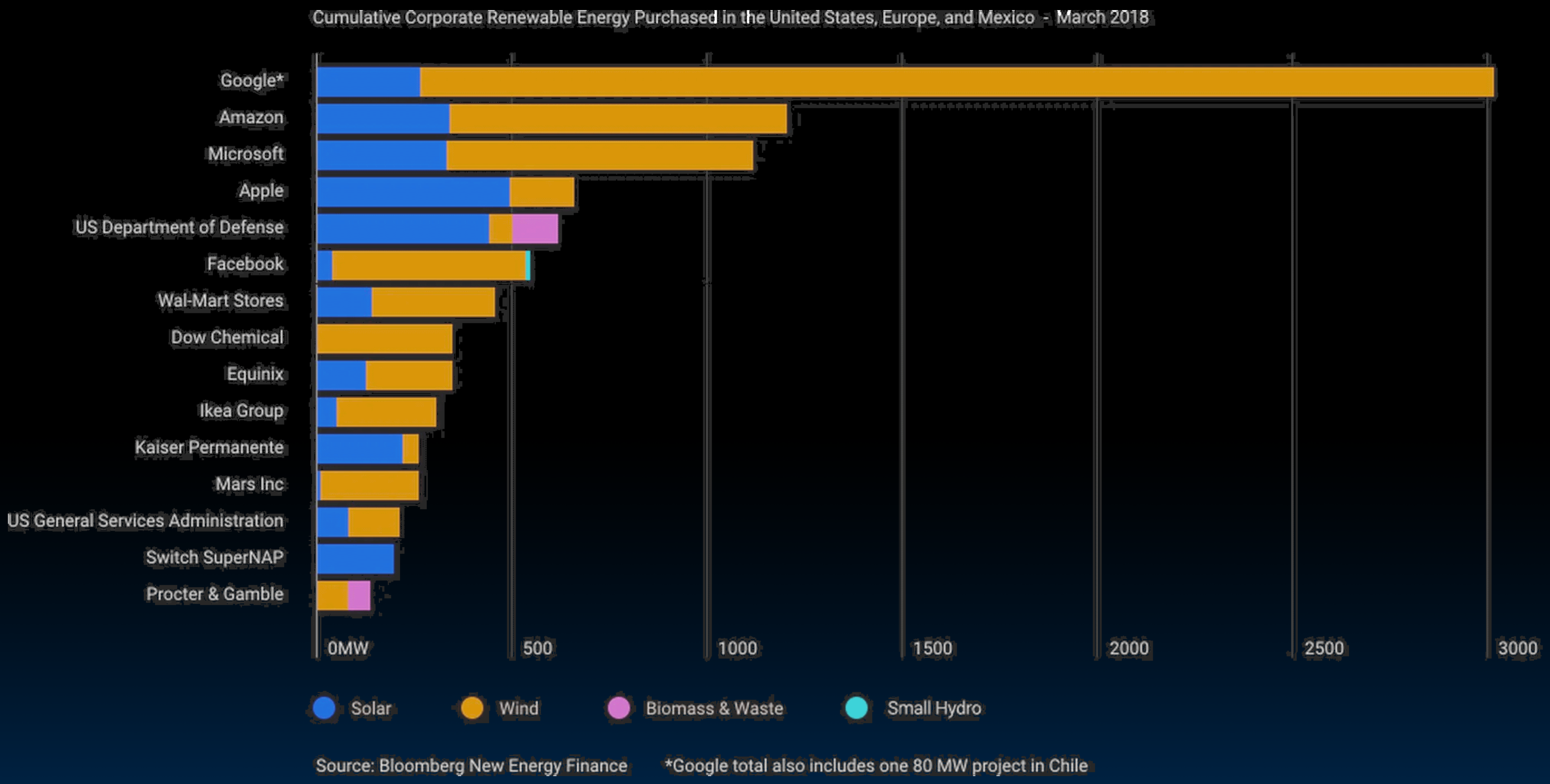

Summary

- **Parallelism is one of the Great Ideas**
  - Applies at many levels of the system – from instructions to warehouse scale computers
- **Post PC Era: Parallel processing, smart phone to WSC**
- **WSC SW must cope with failures, varying load, varying HW latency bandwidth**
- **WSC HW sensitive to cost, energy efficiency**
- **WSCs support many of the applications we have come to depend on**

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