Warehouse-Scale Computers

Computer Architecture:

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Introduction

- **Warehouse-scale computer (WSC)**
  - 50,000~100,000 servers
    - Network equipment connecting these servers
  - Hundreds of million dollars for building
  - Provides Internet services
    - Search
    - Social networking
    - Online maps
    - Video sharing
    - Online shopping
    - Email
    - Cloud computing, etc.

G Suite

facebook

iCloud

Major IT companies provides their services by using WSC!

WSC and Conventional Systems

- **WSC: Act as one giant machine**
  - Many orders of magnitude more users use a WSC at once
  - Users do not need to consider each machine in a system
- **HPC "clusters":**
  - Clusters have higher performance processors and network
    - Cf. They are not requisite for WSCs
  - Clusters emphasize thread-level parallelism
    - Cf. WSCs emphasize request-level parallelism
- **Datacenters:**
  - Datacenters consolidate different machines and software into one location
    - Cf. A WSC focuses on the same software
  - Datacenters emphasize virtual machines and hardware heterogeneity in order to serve varied customers

Important Design Factors for WSC

- **Cost-performance**
  - Reducing the costs of a collection of WSCs by few percent could save millions of dollars
- **Energy efficiency**
  - The majority of costs goes toward power and cooling
    - Environmental stewardship
- **Dependability via redundancy**
  - The internet nature requires 99.99% availability (1 hour/year)
- **Network I/O**
  - Interface with the external world
  - Consistency between multiple WSCs
- **Interactive and batch processing workloads**
  - Ex. of Interactive: answering search query from users
  - Ex. of batch: calculating metadata (indices) for search

Other Characteristics

- **Ample computational parallelism is not important**
  - Most jobs are totally independent because of “Request-level parallelism”
- **Operational costs count**
  - Power consumption is a primary, not secondary, constraint when designing system
- **Location counts**
  - Real estate, power cost; Internet, end-user, and workforce availability
- **Computing efficiently at low utilization**
  - Not optimized for the peak performance of the system
- **Scale and the opportunities/problems associated with scale**
  - Opportunity: Bulk discounts for custom hardware
    - Can afford to build customized systems since WSC require volume purchase
  - Problems: Failures
    - Can be covered by software redundancy

Failures: List of Outages of 2400 Servers

➢ Frequency and the reason why a WSC stops

Approx. number events in 1st year	Cause	Consequence
1 or 2	Power utility failures	Lose power to whole WSC; doesn't bring down WSC if UPS and generators work (generators work about 99% of time).
4	Cluster upgrades	Planned outage to upgrade infrastructure, many times for evolving networking needs such as recabling, to switch firmware upgrades, and so on. There are about nine planned cluster outages for every unplanned outage.
1000s	Hard-drive failures	2%–10% annual disk failure rate (Pinheiro et al., 2007)
	Slow disks	Still operate, but run 10 $\times$ to 20 $\times$ more slowly
	Bad memories	One uncorrectable DRAM error per year (Schroeder et al., 2009)
	Misconfigured machines	Configuration led to $\sim$30% of service disruptions (Barroso and HÖlzle, 2009)
	Flaky machines	1% of servers reboot more than once a week (Barroso and HÖlzle, 2009)
5000	Individual server crashes	Machine reboot; typically takes about 5 min (caused by problems in software or hardware).

Example: Calculate Availability

- Software issue → 5 min
- Hardware issue → 1 hour
- UPSs work well for power utility failure
- Slow disks are not availability issues
  - (Performance issue)

(Hours outage)

= (4 + 250 + 250 + 250) x 1 h

+ (250 + 5000) x 5

m

= 1192 h

(Availability) = (8760 – 1192)/8760 = 86%

Far from 99.99%
and need the software redundancy

Approx. number events in 1st year		Cause	
1 or 2		Power utility failures	Ignored
4		Cluster upgrades	1 hour
1000s	250	Hard-drive failures	1 hour
		Slow disks	Ignored
	250	Bad memories	1 hour
	250	Misconfigured machines	1 hour
	250	Flaky machines	5 min
5000		Individual server crashes	5 min

Programming Models and Workloads

Programming Models and Workloads

- **WSCs run both…**
  - Public-facing internet services
  - Batch applications
    - Converting video format, creating search indexes
- **Batch processing framework: MapReduce**
  - **Map:**
    - Applies a programmer-supplied function to each logical input record
    - Runs on thousands of computers
    - Provides new set of key-value pairs as intermediate values
  - **Reduce:**
    - Collapses values using another programmer-supplied function

Popularity of MapReduce

Monthly MapReduce usage at Google from 2004 to 2016

Month	Number of MapReduce Jobs	Average completion time (s)	Average no. servers per job	Avg. no. cores per server	CPU core years	Input data (PB)	Intermediate data (PB)	Output data (PB)
Sep-16	95,775,891	331	130	2.4	311,691	11,553	4095	6982
Sep-15	115,375,750	231	120	2.7	272,322	8307	3980	5801
Sep-14	55,913,646	412	142	1.9	200,778	5989	2530	3951
Sep-13	28,328,775	469	137	1.4	81,992	2579	1193	1684
Sep-12	15,662,118	480	142	1.8	60,987	2171	818	874
Sep-11	7,961,481	499	147	2.2	40,993	1162	276	333
Sep-10	5,207,069	714	164	1.6	30,262	573	139	37
Sep-09	4,114,919	515	156	3.2	33,582	548	118	99
Sep-07	2,217,000	395	394	1.0	11,081	394	34	14
Mar-06	171,000	874	268	1.6	2002	51	7	3
Aug-04	29,000	634	157	1.9	217	3.2	0.7	0.2

Time

3300x

MapReduce becomes important framework for WSCs

MapReduce Example: Word Count

```
map (String key, String value):
      // key:  document name
      // value:  document contents
      for each word w in value
            EmitIntermediate(w,”1”);
                  //Produce list of all words with value 1
reduce (String key, Iterator values):
      // key:  a word
      // value:  a list of counts
      int result = 0;
      for each v in values:
            result += ParseInt(v);
                  // get integer from key-value pair
      Emit(AsString(result));
```

Document:

red green blue red black green

Map

”red” : 1,
“green” : 1,
“blue” : 1,
“red” : 1,
“black” : 1,
“green” : 1

Reduce

”red” : 2,
“green” : 2,
“blue” : 1,
“black” : 1,

- **MapReduce can be thought of as a generalization of SIMD**
  - “Map” is for parallel execution
  - “Reduce” is for collecting the results of map functions
    - Intel AVX also includes SIMD instructions for the reduction
- **Easy to use**
  - A novice programmer can run a MapReduce task on thousand computers within 30 min

Executing MapReduce Tasks

- **MapReduce runtime environment schedules map and reduce tasks to WSC nodes**
  - The scheduler assigns tasks based on how quickly nodes complete prior tasks
    - <u>Tail latency/execution time variability</u>: A single slow task can hold up a large MapReduce job
- **Runtime libraries replicate tasks near the end of the job to other nodes**
  - Performance heterogeneity is inherent in WSC
    - Some nodes are high performance, but the others are low performance
  - Take the result from whichever finishes first!
    - No need for all replicas to always agree

Increase resource usage a few percentage points but some large tasks completed faster

Dependability in MapReduce

- **Detect and recover from errors**
  - Each node in a MapReduce job reports back to the master periodically
    - With status and the list of completed tasks
  - The master node can reassign tasks if the node does not report and seems to be dead

- **All WSCs use automated monitoring software**
  - One operator can be responsible for more than 1000 servers

System software must cope with the reality of availability in WSCs to deliver 99.99% availability

Internal Software Services

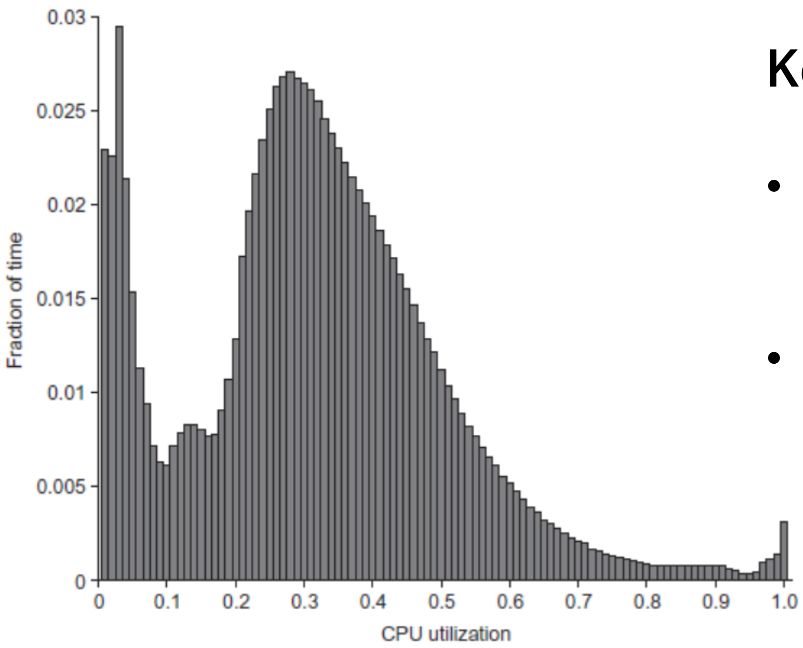
- **Internal software services for WSCs**
  - Use replicas of data across different servers
  - Use relaxed consistency:
    - No need for all replicas to always agree

- **Distributed file systems:**
  - Google File System (GFS)
  - Colossus
- **Databases:**
  - Dynamo: Amazon’s key-value storage system
  - BigTable: Google record storage systems
    - These databases relies on the file systems above
- **Even in a single server:**
  - RAID

Workload Demands for WSCs

- **Workload demands often vary considerably**

Average CPU utilization of more than 5000 servers during a 6-month period at Google



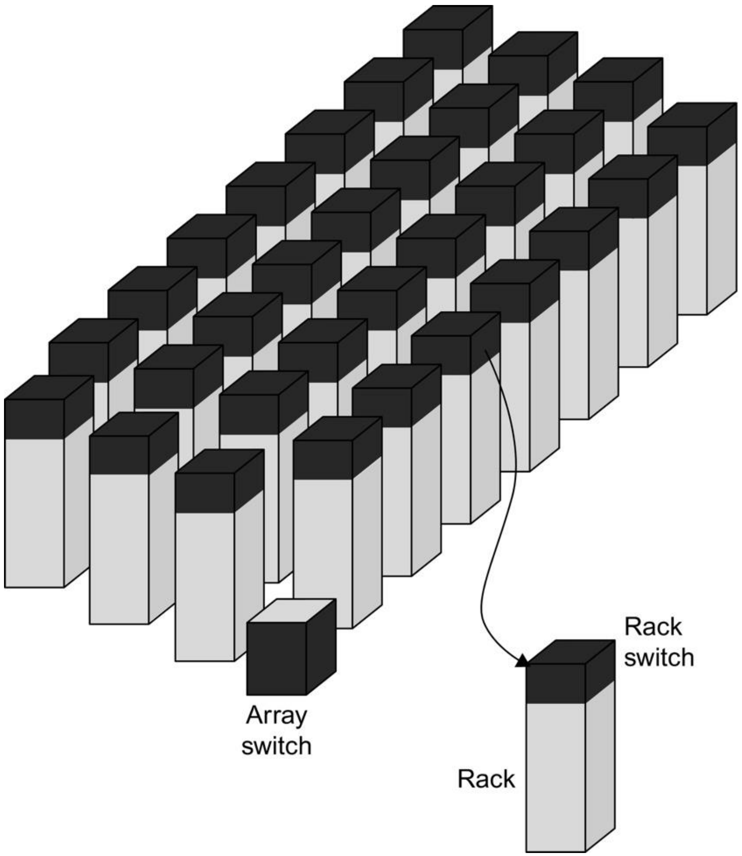
Key observations

- Servers are rarely completely idle or fully utilized
- Operating most of the time at between 10% and 50% of their maximum utilization

WSC hardware and software must cope with variability in load based on user demand

Computer Architecture of WSC

Computer Architecture of WSC



Overview of a WSC

- **WSC often use a hierarchy of networks for interconnection**
- **Each 19" rack holds 48 1U servers connected to a rack switch**
- **Rack switches are uplinked to an array switch (switch higher in hierarchy)**
  - Uplink has 6-24X times lower bandwidth: oversubscription
    - Programmers must maximize locality of communication relative to the rack
- **Array switch: More expensive switch that connects an array of racks**
  - Array switch should have 10 X the bisection bandwidth of rack switch
  - Cost of *n*-port switch grows as n^2

Storage

- **Where is the storage to be integrated? → two options**
  - Local disks inside servers in a rack
  - Disks in remote servers outside of the rack and access through Ethernet connections
- **Other options:**
  - Network-attached storage through Infiniband
    - More expensive
- **WSCs generally rely on local disks**
  - Google File System (GFS) uses local disks and maintains at least <u>three</u> replicas
    - Local disk failures, rack-level failures, whole array failures

WSC Memory Hierarchy

- Servers can access DRAM and disks on other servers using a NUMA-style interface

Latency, bandwidth, and capacity of memory hierarchy of a WSC

	Local	Rack	Array
DRAM latency (μs)	0.1	300	500
Flash latency (μs)	100	400	600
Disk latency (μs)	10,000	11,000	12,000
DRAM bandwidth (MB/s)	20,000	100	10
Flash bandwidth (MB/s)	1000	100	10
Disk bandwidth (MB/s)	200	100	10
DRAM capacity (GB)	16	1024	31,200
Flash capacity (GB)	128	20,000	600,000
Disk capacity (GB)	2000	160,000	4,800,000

Latency

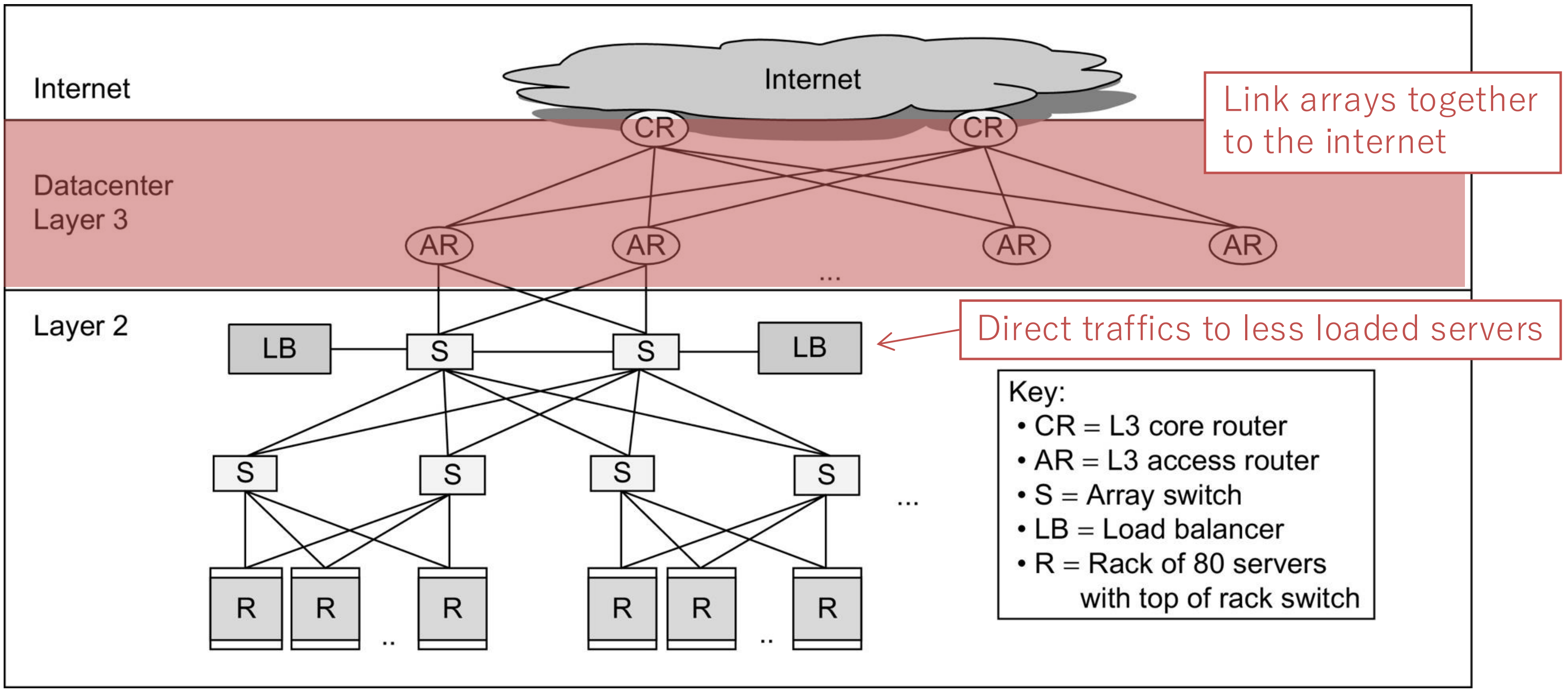
Bandiwdth

Capacity

Better latency through network, Better bandwidth in a local server

More and more servers…

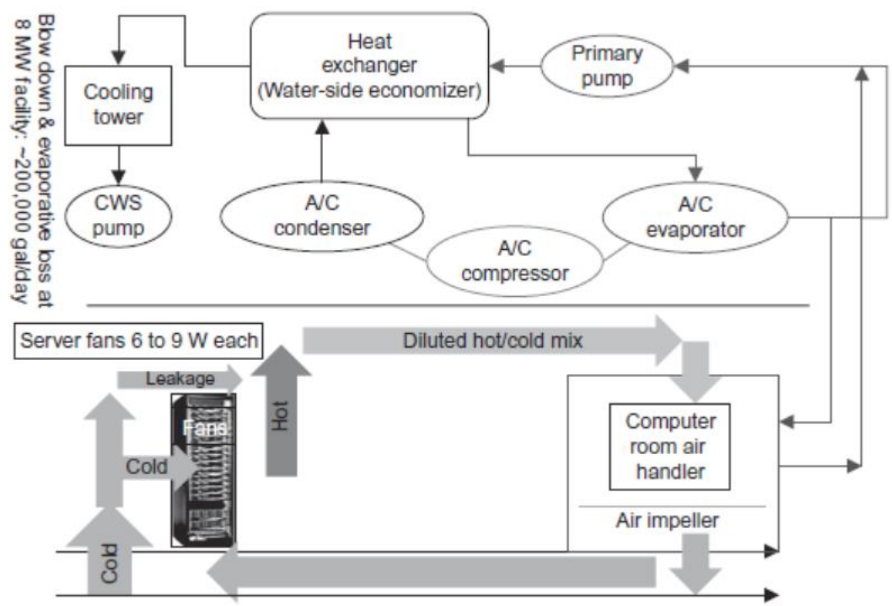
- **The WSC needs 40 arrays to reach 100,000 servers**
  - One more level in the networking hierarchy



The Efficiency and Cost of WSC

Infrastructure: Cooling System

- Cooling
  - Air conditioning used to cool server room
  - 64 F – 71 F (17 – 21 C)
    - Keep temperature higher (closer to 71 F)
  - Cooling towers can also be used
    - Minimum temperature is "wet bulb temperature"



Cost of Cooling Systems

- **Cooling system also uses water (evaporation and spills)**
  - E.g. 70,000 to 200,000 gallons per day for an 8 MW facility

- **Power cost breakdown:**
  - Bad news: only 30-50% of the power used by the IT equipment
  - Air conditioning: 10-20% of the IT power, mostly due to fans

- **How man servers can a WSC support?**
  - Each server:
    - "Nameplate power rating" gives maximum power consumption
    - To get actual, measure power under actual workloads
  - Oversubscribe cumulative server power by 40%, but monitor power closely

Costs of WSC

- **Determining the maximum server capacity**
  - Nameplate power rating: maximum power that a server can draw
  - Better approach: measure under various workloads
  - Oversubscribe by 40%

- **Typical power usage by component:**
  - Processors: 42%
  - DRAM: 12%
  - Disks: 14%
  - Networking: 5%
  - Cooling: 15%
  - Power overhead: 8%
  - Miscellaneous: 4%

Measuring Efficiency of a WSC

- **Power Utilization Effectiveness (PEU)**
  - = Total facility power / IT equipment power
  - The median PUE i n the 2006 study was 1.69

- **Performance**
  - Latency is an important metric because it is seen by users
  - Bing study: users will use search less as response time increases
  - Service Level Objectives (SLOs)/Service Level Agreements (SLAs)
    - E.g. 99% of requests are below 100 ms

Performance of a WSC and its Impact

Negative impact of delay (latency) at the Bing search server on user behavior

Server delay (ms)	Increased time to next click (ms)	Queries/ user	Any clicks/ user	User satisfaction	Revenue/ user
50	–	–	–	–	–
200	500	–	–0.3%	–0.4%	–
500	1200	–	–1.0%	–0.9%	–1.2%
1000	1900	–0.7%	–1.9%	–1.6%	–2.8%
2000	3100	–1.8%	–4.4%	–3.8%	–4.3%

- **Time to next click is roughly doubled by server delay**
  - Revenue/user dropped linearly with increasing delay
    - Given the amount of money made in search, even such small changes are disconcerting
- **Another studies shows that these effects lingered long**
  - Five week later of the experiments, 0.1% and 0.2% fewer searchers per day for users who experienced 200ms and 400ms delay, respectively

Putting It All Together

Putting it All Together: Google WSC

Power substation

Power transformer, switch, generator

Servers

Row of servers with 400V power distribution

Hot isles: Space separation for cooling

Figure 6.34 An example server from a Google WSC. The Haswell CPUs (2 sockets × 18 cores × 2 threads = 72 "virtual cores" per machine) have 2.5 MiB last level cache per core or 45 MiB using DDR3-1600. They use the Wellsburg Platform Controller Hub and have a TFP of 150 W.

Cooling Systems

The cool air blows into the server room

The cooling towers that transfer heat
to the air from the water

Where are WSCs of Google

Chiba data center in Japan
from April 2023

Figure 6.19 In 2017 Google had 15 sites. In the Americas: Berkeley County, South Carolina; Council Bluffs, Iowa; Douglas County, Georgia; Jackson County, Alabama; Lenoir, North Carolina; Mayes County, Oklahoma; Montgomery County, Tennessee; Quilicura, Chile; and The Dalles, Oregon. In Asia: Changhua County, Taiwan; Singapore. In Europe: Dublin, Ireland; Eemshaven, Netherlands; Hamina, Finland; St. Ghislain, Belgium. https://www.google.com/about/datacenters/inside/locations/.

Conclusions

Summary

- **Warehouse-scale computer (WSC)**
  - 50,000~100,000 servers
    - Network equipment connecting these servers
  - Provide services and act as one giant machine
- **Organization**
  - A hierarchy of networks for interconnection
  - Server racks connected by networks
- **Important factor of WSC**
  - Cost-performance
  - Energy efficiency
  - Dependability
  - Latency