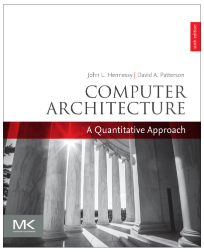
Computer Architecture

A Quantitative Approach, Sixth Edition



Chapter 6

Warehouse-Scale Computers to Exploit Request-Level and Data-Level Parallelism

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Introduction

Introduction

- Warehouse-scale computer (WSC)
  - Provides Internet services
    - Search, social networking, online maps, video sharing, online shopping, email, cloud computing, etc.
  - Differences with HPC “clusters”:
    - Clusters have higher performance processors and network
    - Clusters emphasize thread-level parallelism, WSCs emphasize request-level parallelism
  - Differences with datacenters:
    - Datacenters consolidate different machines and software into one location
    - Datacenters emphasize virtual machines and hardware heterogeneity in order to serve varied customers

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Introduction

- Important design factors for WSC:
  - Cost-performance
    - Small savings add up
  - Energy efficiency
    - Affects power distribution and cooling
    - Work per joule
  - Dependability via redundancy
  - Network I/O
  - Interactive and batch processing workloads

Introduction

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Introduction

- Ample computational parallelism is not important
  - Most jobs are totally independent
  - "Request-level parallelism"
- Operational costs count
  - Power consumption is a primary, not secondary, constraint when designing system
- Scale and its opportunities and problems
  - Can afford to build customized systems since WSC require volume purchase
- Location counts
  - Real estate, power cost; Internet, end-user, and workforce availability
- Computing efficiently at low utilization
- Scale and the opportunities/problems associated with scale
  - Unique challenges: custom hardware, failures
  - Unique opportunities: bulk discounts

Introduction

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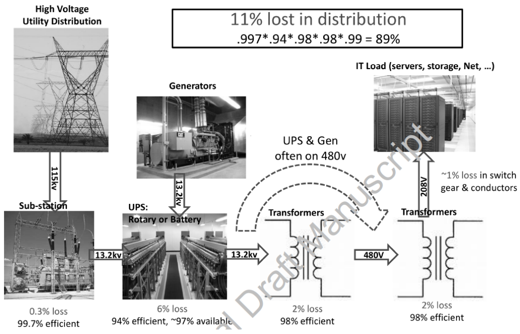
Efficiency and Cost of WSC

- **Location of WSC**
  - **Proximity to Internet backbones, electricity cost, property tax rates, low risk from earthquakes, floods, and hurricanes**
- **Power distribution**



Efficiency and Cost of WSC

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Prgrm'g Models and Workloads

- 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

Programming Models and Workloads for WSCs

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Prgrm'g Models and Workloads

Programming Models and Workloads for WSCs

- Example:
  - 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
  - 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));

Prgrm'g Models and Workloads

Programming Models and Workloads for WSCs

- Availability:
  - Use replicas of data across different servers
  - Use relaxed consistency:
    - No need for all replicas to always agree
- File systems: GFS and Colossus
- Databases: Dynamo and BigTable

Prgrm'g Models and Workloads

- MapReduce runtime environment schedules map and reduce task to WSC nodes
  - Workload demands often vary considerably
  - Scheduler assigns tasks based on completion of prior tasks
  - Tail latency/execution time variability: single slow task can hold up large MapReduce job
  - Runtime libraries replicate tasks near end of job

Programming Models and Workloads for WSCs

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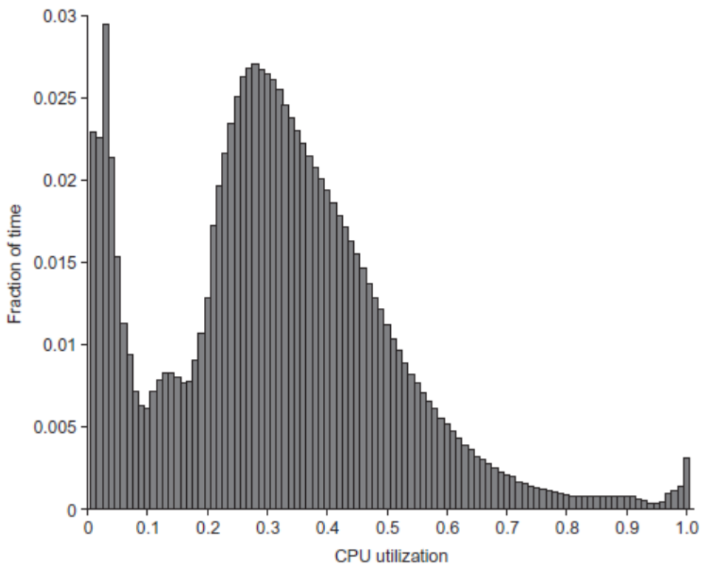
Prgrm'g Models and Workloads



Programming Models and Workloads for WSCs

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Computer Architecture of 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 switch higher in hierarchy
  - Uplink has 6-24X times lower bandwidthGoal is to maximize locality of communication relative to the rack

Computer Ar4chitecture of WSC

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Storage

- Storage options:
  - Use disks inside the servers, or
  - Network attached storage through Infiniband

  - WSCs generally rely on local disks
  - Google File System (GFS) uses local disks and maintains at least three relicas

Computer Ar4chitecture of WSC

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Array Switch

- 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
  - Often utilize content addressible memory chips and FPGAs

Computer Ar4chitecture of WSC

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WSC Memory Hierarchy

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

	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

Computer Ar4chitecture of WSC

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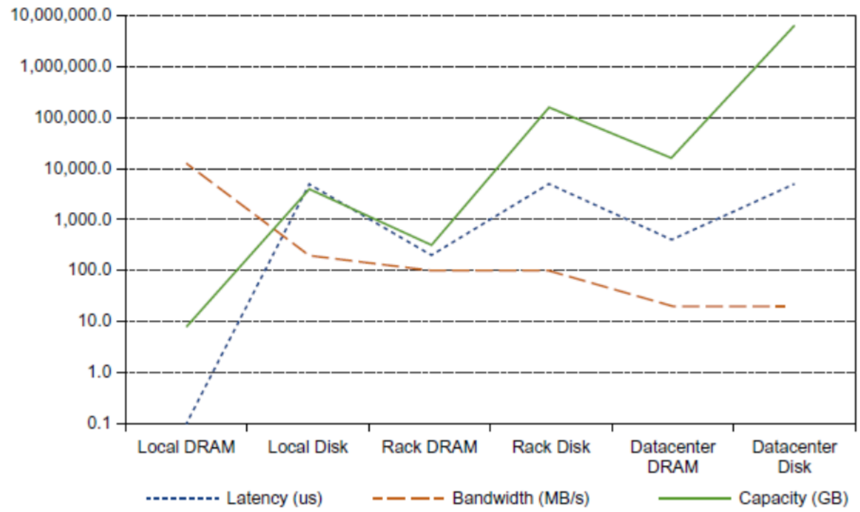
WSC Memory Hierarchy

Computer Ar4chitecture of WSC



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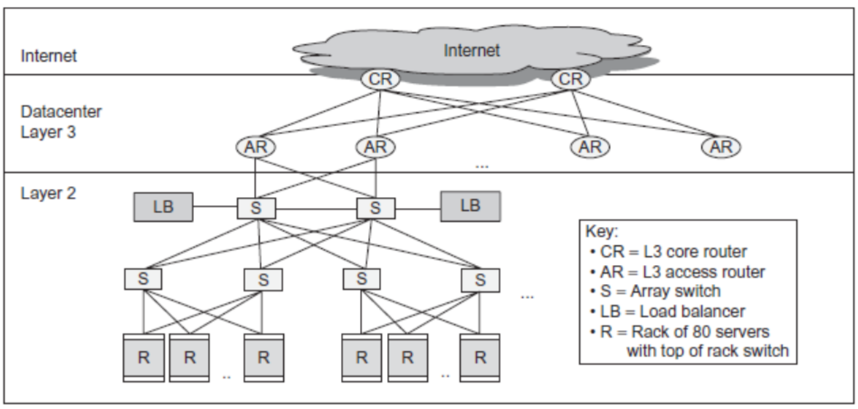
WSC Memory Hierarchy

Computer Ar4chitecture of WSC



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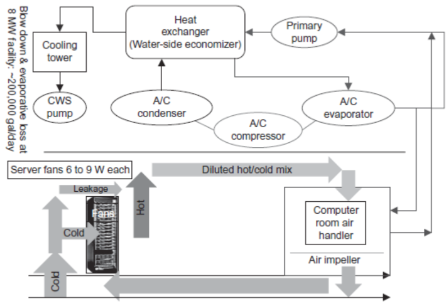
Infrastructure and Costs of WSC

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



Physcical Infrastrcuture and Costs of WSC

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Infrastructure and Costs of WSC

- 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:
  - Chillers: 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

Physcical Infrastrcuture and Costs of WSC

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Infrastructure and 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%

Physcical Infrastrcuture and Costs of WSC

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Measuring Efficiency of a WSC

- Power Utilization Effectiveness (PEU)
  - = Total facility power / IT equipment power
  - Median PUE on 2006 study was 1.69
- Performance
  - Latency is 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 be below 100 ms

Physcical Infrastrcuture and Costs of WSC

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Measuring Efficiency of a WSC

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%

Physcical Infrastrcuture and Costs of WSC

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Cost of a WSC

- Capital expenditures (CAPEX)
  - Cost to build a WSC
  - $9 to 13/watt
- Operational expenditures (OPEX)
  - Cost to operate a WSC

Physcical Infrastrcuture and Costs of WSC

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Cloud Computing

- **Amazon Web Services**
  - **Virtual Machines: Linux/Xen**
  - **Low cost**
  - **Open source software**
  - **Initially no guarantee of service**
  - **No contract**

Cloud Computing

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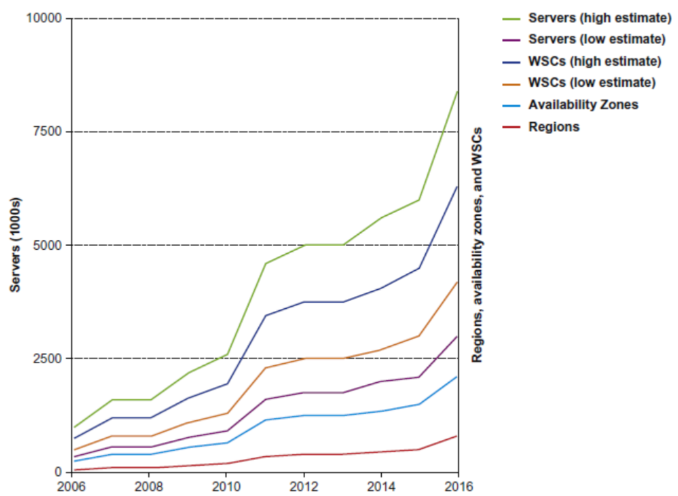
Cloud Computing

- **Cloud Computing Growth**



Cloud Computing

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Fallacies and Pitfalls

- Cloud computing providers are losing money
  - AWS has a margin of 25%, Amazon retail 3%
- Focusing on average performance instead of 99th percentile performance
- Using too wimpy a processor when trying to improve WSC cost-performance
- Inconsistent Measure of PUE by different companies
- Capital costs of the WSC facility are higher than for the servers that it houses

Fallcies and Pitfalls

Fallacies and Pitfalls

- Trying to save power with inactive low power modes versus active low power modes
- Given improvements in DRAM dependability and the fault tolerance of WSC systems software, there is no need to spend extra for ECC memory in a WSC
- Coping effectively with microsecond (e.g. Flash and 100 GbE) delays as opposed to nansecond or millisecond delays
- Turning off hardware during periods of low activity improves the cost-performance of a WSC

Fallcies and Pitfalls