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# SERVER DESIGNS FOR WAREHOUSE-COMPUTING ENVIRONMENTS

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THE ENORMOUS SCALE OF WAREHOUSE-COMPUTING ENVIRONMENTS LEADS TO UNIQUE REQUIREMENTS IN WHICH COST AND POWER FIGURE PROMINENTLY. MODELS AND METRICS QUANTIFYING THESE REQUIREMENTS, ALONG WITH A BENCHMARK SUITE TO CAPTURE WORKLOAD BEHAVIOR, HELP IDENTIFY BOTTLENECKS AND EVALUATE SOLUTIONS. A HOLISTIC APPROACH LEADS TO A NEW SYSTEM ARCHITECTURE INCORPORATING VOLUME NON-SERVER-CLASS COMPONENTS IN NOVEL PACKAGING SOLUTIONS, WITH MEMORY SHARING AND FLASH-BASED DISK CACHING.

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..... In recent years, one of the biggest trends in the server market has been the emergence of the large-scale data center, driven by Internet-sector growth. Indeed, recent market research identifies the Internet sector as the fastest-growing segment of the overall server market, growing by 40 to 65 percent every year, and accounting for more than 65 percent of low-end-server revenue growth in 2006. Furthermore, several recent news articles and keynote speeches have highlighted this area's importance.<sup>1,2</sup>

One of the most interesting aspects of this growth is the unique set of challenges it presents for server design. Internet-sector infrastructures have millions of users running on hundreds of thousands of servers, making the ability to scale-out server configurations a key design requirement. Experts have compared these environments to a large warehouse-style computer, with distributed applications such as mail, search, and so on.<sup>1</sup> For companies in this market, data-center infrastructure—including power and cooling—can be the largest capital and operating expense, motivating

companies to focus on the sweet spot of commodity pricing and energy efficiency. Furthermore, the high volume of this market and the dominance of a few key players—for example, Google, Microsoft, Amazon—allow for exploring novel approaches such as custom-designed servers in greenfield data centers, newly built from the ground up.

Our work addresses these challenges and opportunities by developing workloads and metrics targeted toward large-scale data centers, and using these tools to build and analyze new system architectures optimized for the Internet sector. We created an evaluation infrastructure including a benchmark suite for warehouse-computing workloads, and detailed performance, cost, and power models and metrics. These tools let us see the contributions of all layers within large-scale data centers, and lead us to the identification of the CPU, cooling, memory, and disk as the key performance-per-cost bottlenecks. Using our understanding of the importance of these components, we created a system architecture that holistically addresses each

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**Table 1. Details of our benchmark suite representing Internet-sector workloads.**

<b>Workload</b>	<b>Emphasis</b>	<b>Description</b>	<b>Performance metric</b>
Web search	Role of unstructured data	Nutch running on Apache Tomcat with a 1.3-Gbyte index (1.3 million documents) and 25 percent of index terms cached in memory, with a 2-Gbyte Java heap size. Quality of service (QoS) requires more than 95 percent of queries to take under 0.5 seconds.	Request per second (RPS) with QoS
Web mail	Interactive Internet services	Front end: Squirrelmail with Apache and PHP4. Back end: Courier-Internet Message Access Protocol and Exim. One-thousand virtual users with 7 Gbytes of emails. Email and attachment sizes and use patterns modeled after MS Exchange 2003 LoadSim for heavy users. QoS requires more than 95 percent requests to take under 0.8 second.	RPS with QoS
Video hosting	Use of rich media	Modified SPECweb2005 Support workload with YouTube traffic characteristics. Apache Tomcat with Rock httpd server.	RPS with QoS
MapReduce	Web as a platform	Apache Hadoop with four threads per CPU and 1.5-Gbyte Java heap size. Two workloads: distributed file write (mapred-wr) and word count (mapred-wc).	Execution time

layer through novel features, including the use of low-cost, low-power components from the high-volume, embedded market; new packaging solutions; memory sharing; and flash-based disk caching. Our results are promising, providing an average twofold improvement in performance per dollar for our benchmarks. More importantly, our work highlights the potential of cost-efficient, ensemble-level design, and suggests the usefulness of further research in this area.

### Evaluation environment

Due to the novelty of warehouse-computing environments and the lack of public information available, we developed a new workload suite, as well as cost, power, and performance models tailored to this domain. In addition, we propose a performance-per-cost metric for large-scale data centers, and using this metric along with our tools, we perform an analysis to identify the key cost bottlenecks that need to be addressed using new system architectures.

### Workloads

One key contribution of our work is the development of a benchmark suite that

models warehouse-computing workloads. Applications in this area are different from traditional benchmarks due to their scale and level of user involvement. This difference is reflected by our benchmark suite's focus on large data sets, user interactivity, and cluster-level processing. We based our suite on open source software and publicly available real-world traces in the hope that the suite will be useful to other researchers.

The benchmark suite comprises four workloads representative of different services in Internet-sector data centers. Our workloads include Web search, Web mail, video hosting, and MapReduce,<sup>3</sup> which emphasize unstructured data, user involvement, rich media types, and the Web as a platform, respectively. Table 1 lists these benchmarks in greater detail, including the software used for each benchmark. To emulate the large data sets typically found in these workloads, we have used a wide array of sources, including data gathered from public sites (Wikipedia search index), internally collected statistics (e-mail statistics from within the University of Michigan), and previously published data (recorded YouTube traffic at an edge network<sup>4</sup>). To make simulation

feasible, we use scaled-down versions of these data sets. One issue adding to the complexity of our workloads is the importance of throughput and latency—in the Internet sector, both the number of requests per second processed and the network response time are key performance measures. Thus, to drive our workloads, we have developed software clients that change their request rates dynamically to achieve the highest possible throughput while maintaining quality-of-service guarantees for response time. Note that this does not apply to Map-Reduce, which is a cluster-processing job. We believe this benchmark suite is a good representative of Internet-sector workloads for our study, and provides a sound basis for future expansion.

### Metrics and models

In addition to using these benchmarks to compare the performance of different server designs, we defined several key metrics and models that give a detailed overview of Internet-sector environments. Our primary metric was the sustainable performance divided by total cost of ownership (TCO). For TCO, we assumed a three-year depreciation cycle and consider costs associated with base hardware, burdened power and cooling, and real estate.

Our cost model consists of two main components: base hardware and burdened power and cooling costs. For the base hardware costs, we aggregate the costs of the individual components—that is, CPU, memory, disk, board, and power and cooling components—at a per-server level. We combine these costs at the rack level, and then consider additional switch and enclosure costs for the rack. For the power and cooling costs, we use two subcomponents. We first compute the rack-level power consumption ( $P_{\text{consumed}}$ ) by summing the power used for the CPU, memory, disk, power and cooling, and the rest of the board at the per-server level, and additional switch power at the rack level. We prorate this by an activity factor of 0.75 because the published power numbers we use are worst-case numbers, which are higher than the actual power consumption. We then use  $P_{\text{consumed}}$  to determine the burdened

**Table 2. Servers' cost models.**

<b>Details</b>	<b>Server 1 cost (dollars)</b>	<b>Server 2 cost (dollars)</b>
CPU	1,700	650
Memory	350	350
Disk	275	120
Board and management	400	250
Power and fans	500	250
Total server	3,225	1,620
Switch and rack	2,750	2,750
Servers per rack	40	40
Three-year power and cooling	2,464	1,561
Total costs	5,758	3,249

**Table 3. Servers' power models.**

<b>Details</b>	<b>Server 1 power (watts)</b>	<b>Server 2 power (watts)</b>
CPU	210	105
Memory	25	25
Disk	15	10
Board and management	50	40
Power and fans	40	35
Total server	340	215

cost of power and cooling using the methodology discussed by Patel et al.,<sup>5</sup> which factors in electricity costs for the system and the cooling, as well as the amortized infrastructure costs for power and cooling.

To evaluate performance, we used Hewlett-Packard Labs' COTSon simulator,<sup>6</sup> which is based on AMD's SimNow infrastructure.<sup>7</sup> COTSon is a validated full-system x86/x86-64 simulator, running 64-bit Debian Linux with the 2.6.15 kernel. COTSon is flexible enough to let us simulate several server configurations and multisystem models.

### Cost analysis

We use these workloads, metrics, and detailed models as tools to evaluate the contributions of all layers in a warehouse-computing environment. Tables 2 and 3 list the costs and

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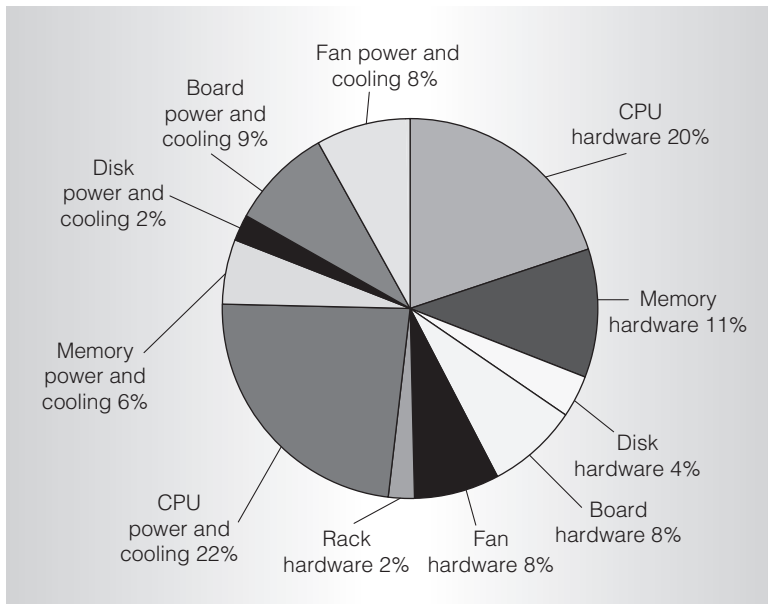


Figure 1. Cost breakdown for server 2, a low-end server-class system configuration.

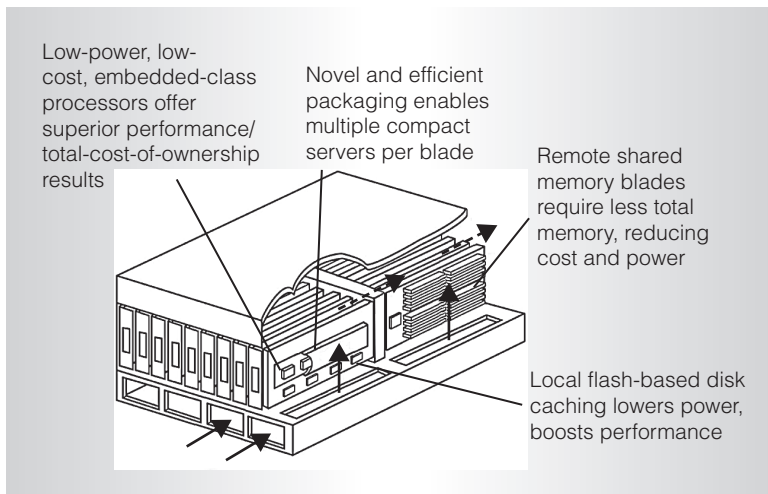


Figure 2. Our system’s architecture illustrating a holistic approach to improving component costs.

memory and disk contribute similarly. Thus, to achieve compelling performance-per-dollar advantages, we need solutions to holistically address multiple components.

**New server architecture**

Based on the insights gained from the previous cost and power-use analysis, we consider three key issues aimed at a holistic solution:

- reducing overall CPU-related costs by using lower-cost, lower-power (but also lower-performance) nonserver processors;
- reducing the burdened costs of power with novel packaging solutions; and
- improving the memory and disk subsystems using solutions geared toward low power and low aggregate costs.

Figure 2 shows our system architecture, which uses novel designs and optimizations to address each of these issues.

**Low-power CPUs**

Server designs for databases or high-performance computing have traditionally focused on obtaining the highest performance per server. However, the nature of Internet sector workloads encourages scale-out environments, which use many servers to achieve high performance. This requires instead a focus on performance per cost per server. Indeed, publications by large Internet-sector companies, such as Google,<sup>8</sup> exhibit the usefulness of building servers using commodity desktop-PC parts. The logic behind this is that volume drives cost. Compared to servers that have a limited market and higher price margins, commodity PCs have a much larger market that enables lower prices. Additionally, these systems don’t include cost premiums for high-end features that the built-in reliability support of the software stack for Internet-sector workloads makes redundant.

In this section, we evaluate the effectiveness of low-end servers and desktops for the warehouse-computing market. We take the focus on performance per cost one step further, exploring an alternative commodity market: the embedded and mobile segment. Trends in transistor scaling and embedded-processor design have brought powerful,

power use for existing midrange (server 1) and low-end (server 2) server configurations. Figure 1 shows a breakdown of the total costs for the low-end server, separated as infrastructure and burdened power and cooling. This data highlights several interesting points. We see that power and cooling costs are comparable to hardware costs. Although the CPU hardware and power and cooling are the two largest total costs, several other components including

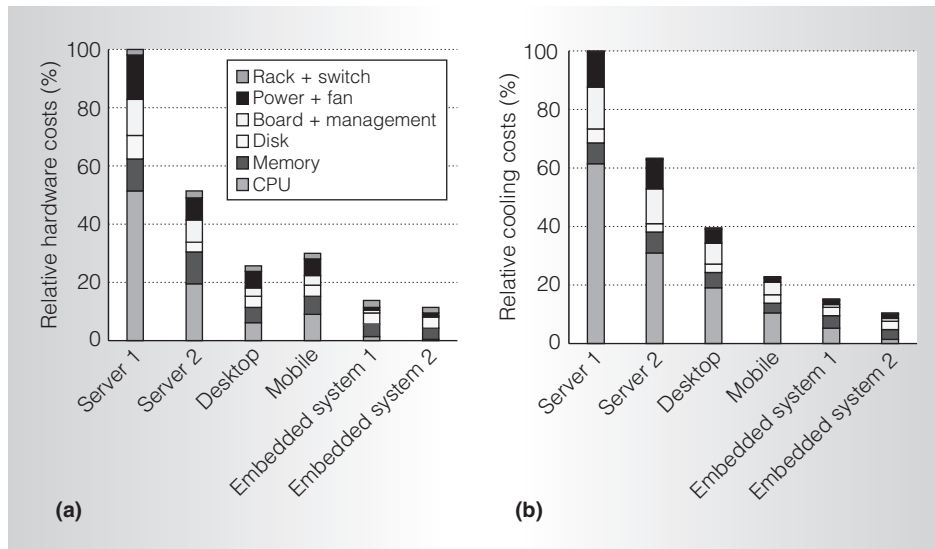


Figure 3. Summary of benefits from using low-cost, low-power CPUs from nonserver markets: infrastructure costs (a) and cooling costs (b).

general-purpose, multicore processors to the embedded arena. Devices using embedded CPUs are shipped in even higher volume than desktops, leading to greater cost savings. Additionally, embedded parts are often designed for minimal power consumption due to their use in mobile systems. Power is a large portion of total lifecycle costs, so greater power efficiency reduces costs. The key open question is whether these cost and power benefits can offset the performance degradation relative to the baseline server.

To perform this evaluation, we consider six system configurations:

- server 1 (midrange),
- server 2 (low end),
- desktop,
- mobile,
- embedded 1 (midrange), and
- embedded 2 (low end).

All the systems are dual core excluding server 1, which is a quad core, and embedded system 2, which is a single core. All have 4 Gbytes of memory. Servers 1 and 2 use fully buffered dual inline memory modules (FB-DIMMs); desktop, mobile, and embedded system 1 use double data rate (DDR) 2 memory; and embedded system 2 uses DDR1 memory. Server 1 has a 15,000-revolutions-per-minute disk

and a 10-Gbit network interface controller, while the other systems have a 7,200-RPM disk and a 1-Gbit NIC. Our goal for these experiments is to isolate the effect of the processor type, so we keep memory and disk capacity constant.

Figures 3a and 3b summarize the breakdown of infrastructure costs and the burdened power and cooling costs. Table 4 shows the variation in performance per cost for each system. In the table, the harmonic mean row shows the average performance per cost, computed as the harmonic mean of the throughput and reciprocal of execution times divided by total system costs.

As Figure 3a illustrates, at a per-system level, the hardware costs are dramatically lower for the consumer systems. The biggest reduction comes in the CPU component. The use of consumer technologies, such as DDR2 memory, leads to reductions in other components as well. The costs of the desktop system are 25 percent of the costs of the server 1 configuration, whereas the costs of embedded system 1 are only 15 percent of the costs of the server 1 configuration. In the mobile system, we see higher costs relative to the desktop because of the premium for low-power components in this market. Figure 3b shows similar trends for power and cooling costs. The desktop system has 60 percent lower power and cooling costs

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**Table 4. Normalized performance per total-cost-of-ownership efficiency.**

Workload	Server 2 (%)	Desktop (%)	Mobile (%)	Embedded	Embedded
				system 1 (%)	system 2 (%)
Web search	120	113	124	167	97
Web mail	86	59	62	80	46
Video hosting	171	291	351	600	215
MapRed-wc	128	221	200	334	147
MapRed-wr	164	246	268	359	106
Harmonic mean	127	137	144	200	94

than server 1, but the embedded system 1 system does even better, saving 85 percent of the costs.

Table 4 shows significant improvements in performance per cost for the desktop, mobile, and embedded system 1 relative to server 1; however, embedded system 2 doesn't perform well. Given the relative losses in performance to the benefits in costs, these systems often have superior performance per cost compared to server 1. On video hosting and MapReduce, embedded system 1 achieves three- to sixfold improvement in performance per total costs—due to these workloads being primarily network or disk bound. Embedded system 1 achieves an improvement of 67 percent for Web search, but has a net degradation in performance per cost for Web mail because of a significant performance decrease. Overall, our workloads show a benefit from lower-end consumer platforms optimized for power and costs, compared to server 1. A key result from our study is that embedded systems could offer more cost savings at the same performance; but the choice of embedded platform is important (for example, embedded system 1 versus embedded system 2). It must be noted that these results hold true for our workloads, but more study is needed before we can generalize these results to all variations of Internet-sector workloads.

#### Cooling and packaging

Our discussion in the “Cost analysis” section notes that after the processor, the next largest cost factor is the burdened cost of cooling. Using lower-power systems presents new opportunities for smaller form factor boards, which in turn allow for

cooling system optimizations. Here, we discuss two such optimizations—dual-entry enclosures with directed airflow and board-level aggregated heat removal—using blade servers as the exemplar for the rest of our discussions, because they're well known in the market.

#### *Dual-entry enclosures with directed airflow.*

Figure 2 shows how we can redesign a server-level enclosure to allow inserting blades from front and back to attach to a midplane within the enclosure. The idea behind this is to partition the airflow and allow directing of cold air vertically through the blades. We achieve this by increasing the enclosure's volume to create an inlet and exhaust plenum, and direct the airflow in the directions indicated by the arrows in Figure 2. This design maintains airflow through all the blades in parallel from intake plenum to exhaust plenum. Compared to conventional blade enclosures, which force air directly from front to back, this design has a shorter flow length (the distance traversed by the air), lower preheat (the temperature of the air hitting the blades), and reduced pressure drop and volume flow. Our thermomechanical analysis of the thermal-resistance, airflow improvements with this design shows an almost 50 percent improvement in cooling efficiencies. Compared to the baseline that allows forty 1U servers on each rack, our design allows forty 75-watt blades in a 5U enclosure, allowing 320 systems on each rack.

*Board-level aggregated heat removal.* Figure 4 shows an even more radical packaging design. With low-power systems, we can consider



servers with much smaller form factors that are integrated on conventional blades that fit into an enclosure. Figure 4 shows an innovative packaging scheme that aggregates the power-dissipating components at the device and package level. We intersperse the smaller form factor server modules with planar heat pipes that transfer heat to a central location with an effective conductivity three times that of copper. The design removes aggregated heat with a larger, optimized heat sink, which enables channeling airflow through a single heat sink as opposed to multiple separate conventional heat sinks. The increases in conductivity and heat-extraction area lead to more effective cooling. We can connect the smaller blades through different interfaces, such as Computer-on-Module Express or Advanced Mezzanine Card interfaces. With higher power budgets, one large blade can support four smaller modules, allowing 1,250 systems on each rack.

These cooling optimizations could improve efficiencies two- to fourfold. Although we use specialized designs, our cooling solutions should perform effectively in other enterprise environments. When combined with the significant and growing fraction of the market represented by warehouse-computing environments, these designs should have enough volume to drive commoditization.

#### Other optimizations

Our cost analysis showed that memory and disk are other key factors in server systems' overall performance per cost. We developed optimized memory and disk subsystems that lower costs and power while maintaining high performance by exploiting memory and disk behaviors and characteristics.

Our memory design leverages the observation that memory demands across workloads can vary widely. Studies have shown that per-server sizing for peak loads can lead to significant ensemble-level overprovisioning;<sup>9,10</sup> this problem is exacerbated in large-scale data centers running a variety of applications. To address memory overprovisioning, we provision memory at a coarser, per-blade-chassis granularity, sizing each larger unit to meet the expected aggregate peak demand. In our design, we connect servers within a blade enclosure to a memory blade, which provides

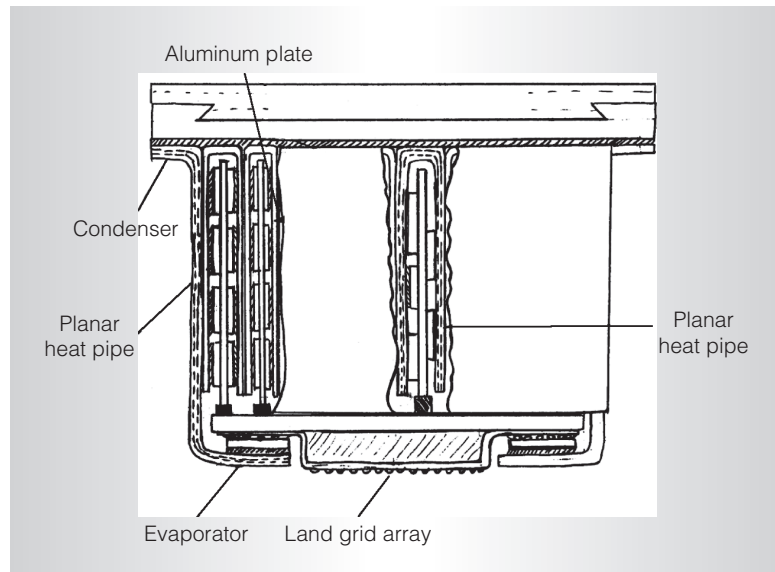


Figure 4. Aggregated heat removal design.

a remote memory pool that is dynamically partitioned among the servers. By exploiting locality while using the remote memory, the systems can have a reduced local memory and still maintain high performance. Within a single enclosure, we connect the server and memory blades via a high-speed interconnect (for example, PCIe). We provide the servers with simple hardware support and make minor changes to the operating system or hypervisor to let applications transparently use the remote memory.<sup>11</sup> This hierarchical design enables further optimizations, such as the use of power-down modes and lower-cost DRAM. By provisioning memory more accurately across servers, our design obtains notable power and cost savings.

Our disk optimizations use low-power, laptop-class disks to reduce power consumption, and have flash-based disk caching to provide higher performance. We move the laptop disks to a basic storage area network (SAN) interfaced through the Serial ATA interface. By using a SAN, we can make individual server blades smaller, allowing small module form factors. Although the disks have lower power and a smaller form factor, they come with the trade-offs of lower performance and higher price. To offset this, we use a flash-based disk-caching mechanism,<sup>12</sup> with the flash located on the server board itself. The flash holds any recently

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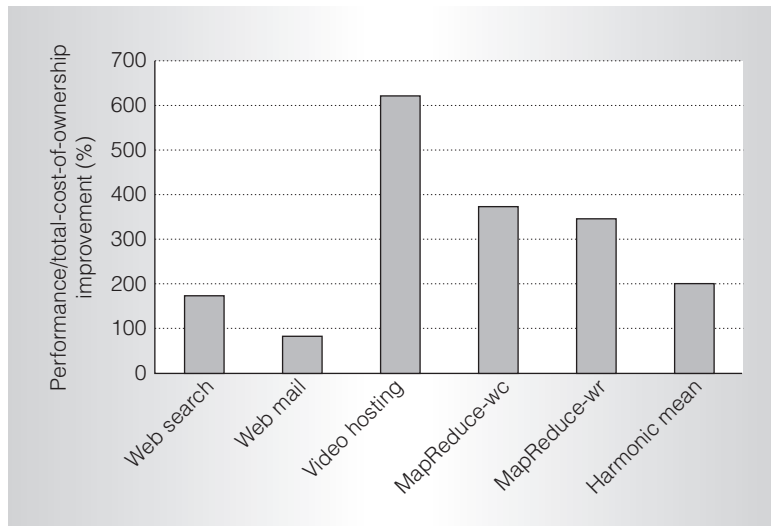


Figure 5. Performance per total-cost-of-ownership improvements from our unified design compared to a baseline midrange server.

accessed pages from the disk, and the system checks its contents any time a page is not found in the operating system's page cache. Flash-based disk caching combined with low-power laptop disks provides performance-per-cost advantages over traditional server-class disks and allows even greater compaction.

#### Unified design

Our solutions so far have targeted the top performance-per-cost factors we identified in current servers: CPU, cooling and packaging, memory, and disk. Although we've discussed their benefits in isolation, we designed all of our optimizations to work in combination, addressing our holistic design motivation.

Figure 2 shows our unified design, which uses embedded-class, dual-core processors and small form-factor blades with aggregated cooling, housed in an enclosure with directed airflow. We use a remote memory blade and remote low-power disks with flash-based disk caching to enable this level of compaction. The use of the low-power components and efficient cooling and packaging are critical to making this super-dense server feasible for large-scale data centers. Although some of the changes required for this configuration assume custom components, they'll likely become cost-effective in a few years, leveraging the volume in this market.

Figure 5 shows how our solution significantly improves cost and power efficiencies compared to the baseline, midrange server system. For the video hosting and MapReduce benchmarks, the performance and TCO improves by 3.5 to 6 times for the next-generation solution. These benefits come equally from infrastructure costs and power savings. Web search gets lower benefits—10 to 70 percent improvement—and Web mail sees degradations (20 percent for the next-generation system). Figure 5 also shows the harmonic mean across our benchmarks. Overall, our solution can improve sustained throughput per total infrastructure dollar by 2 times. That is, for the same performance as the baseline, our solution gets a 60 percent reduction in power, a 55 percent reduction in overall costs, and requires 30 percent less rack space (assuming four air-cooled embedded blades on each larger blade).

We don't intend for our proposed techniques to be the final word on warehouse-computing designs, but rather to illustrate the substantial improvements achievable when system architects take an ensemble-level view. Overall, as enterprises gravitate toward ever more cost-conscious and data-center-level solutions, holistic approaches such as the ones used in this article will likely be a key part of future system designs. MICRO

#### References

1. L. Barroso, "Warehouse-Scale Computers," *Usenix Ann. Technical Conf.*, Usenix, 2007; <http://www.usenix.org/events/usenix07/tech/>.
2. R. Bryant, "Data Intensive Super Computing: Taking Google-Style Computing Beyond Web Search," *Computing Community Consortium at the Federated Computing Research Conf.*, 2007; <http://lazowska.cs.washington.edu/fcrc/Bryant.FCRC.pdf>.
3. J. Dean and S. Ghemawat, "MapReduce: Simplified Data Processing on Large Clusters," *Proc. Symp. Operating System Design and Implementation (OSDI-6)*, Usenix, 2004, pp. 137-150.
4. P. Gill et al., "YouTube Traffic Characterization: A View from the Edge," *Proc. Internet Measurement Conf.*, ACM Press, 2007, pp. 15-28.



5. C. Patel and A. Shah, *Cost Model for Planning, Development and Operation of a Data Center*, tech. report HPL-2005-107R1, Hewlett-Packard, 2005.
6. A. Falcon, P. Faraboschi, and D. Ortega, "Combining Simulation and Virtualization through Dynamic Sampling," *Proc. IEEE Int'l Symp. Performance Analysis of Systems and Software (ISPASS)*, IEEE CS Press, 2007, pp. 72-83.
7. R. Bedichek, "SimNow: Fast Platform Simulation Purely in Software," *Proc. Hot Chips 16*, IEEE CS Press, 2004; [http://www.hotchips.org/archives/hc16/2\\_Mon/15\\_HC16\\_Sess4\\_Pres1\\_bw.pdf](http://www.hotchips.org/archives/hc16/2_Mon/15_HC16_Sess4_Pres1_bw.pdf).
8. L. Barroso, J. Dean, and U. Holzle, "Web Search for a Planet: The Google Cluster Architecture," *IEEE Micro*, vol. 23, no. 2, 2003, pp. 22-28.
9. X. Fan, W. Weber, and L. Barroso, "Power Provisioning for a Warehouse-Sized Computer," *Proc. 34th Int'l Symp. Computer Architecture (ISCA-34)*, ACM Press, 2007, pp. 13-23.
10. P. Ranganathan et al., "Ensemble-Level Power Management for Dense Blade Servers," *Proc. 33rd Int'l Symp. Computer Architecture (ISCA-33)*, ACM Press, 2006, pp. 66-77.
11. M. Ekman and P. Stenstrom, "A Cost-Effective Main Memory Organization for Future Servers," *Proc. IEEE Parallel and Distributed Processing Symp. (IPDPS)*, IEEE Press, 2005.
12. T. Kgil and T. Mudge, "Flashcache: A NAND Flash Memory File Cache for Low Power Web Servers," *Proc. Int'l Conf. Compilers, Architecture, and Synthesis for Embedded Systems (Cases)*, ACM Press, 2006, pp. 103-112.

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