Performance of an Infrastructure for Worldwide Parallel Computing

Thomas T. Kwan and Daniel A. Reed
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Thomas T. Kwan*          Daniel A. Reed†
Department of Computer Science
University of Illinois
Urbana, Illinois 61801
kwan@cs.uiuc.edu, reed@cs.uiuc.edu

Abstract

The millions of Java-capable computers on the Internet provide the hardware needed for a national and international computing infrastructure, a virtual parallel computer that can be tapped for many uses. To date, however, little is known about the cost and feasibility of building and maintaining such global, large scale structures. In this work, we evaluate the performance of a Java/WWW-based infrastructure to gain insights into the feasibility and projected cost of initializing and maintaining wide-area hierarchies that contain up to one million nodes.

1. Introduction

With advances in high-speed networking, exploding interest in the World Wide Web (WWW), and widespread availability of Java, millions of Java-capable computers are now connected to the Internet. These heterogeneous laptops, personal computers, and workstations are emerging as a pool of distributed, platform-independent, Java virtual machines. The large scale deployment of these systems provides the substrate for a possible national and international computing infrastructure — a virtual parallel computer that can be tapped for many uses.

Although such an infrastructure could catalyze new software for distributed information mining and wide area computing, developing the middleware needed to support such wide area computing poses a host of thorny problems. Wide fluctuations in achievable work bandwidth, changing system availability, and significant differences in system capabilities (i.e., ranging from high-performance servers to inexpensive laptops) all make exploiting the large number of computing cycles available in Java-capable, WWW clients and servers extraordinarily difficult. One can effectively exploit these distributed computing cycles only when an infrastructure exists that can adapt to these variations, while providing reasonable performance and acceptable reliability. Simply put, the unreliable nature of wide area networks suggests the need to evaluate the reliability and feasibility of a globally distributed, parallel computing infrastructure.

The remainder of this paper is organized as follows. In §2, we discuss related work, and in §3, we describe the design of a large scale computing infrastructure. We evaluate the reliability and performance of the infrastructure in §4 and §5, respectively. In §6 we analyze the feasibility of wide area hierarchy formation, and in §7, we evaluate the feasibility of world view maintenance and task scheduling. We explore the impact of technology on the feasible hierarchy size in §8. Finally, we conclude with a brief summary in §9.

2. Related Work

Among the many distributed computing systems described in the literature, our work shares with AppLeS [2], Legion [6], Globus [4], Condor [10], Prospero [12], and ATLAS [1] the goal of harnessing distributed resources for large-scale computing. However, our work differs from these projects in leveraging Java-capable, desktop, WWW clients to explore scalability and related performance issues. Whereas WebOS [13] aims to provide general operating system services, we leverage extant WWW browsers as the basic software substrate.

Jini [14], DOGMA [7], Javelin [3], and WebVM [5] typify recent Java/WWW-based distributed computing systems. Our work differs in emphasizing wide-area scalability and evaluation of the cost and feasibility of

*This work was supported in part by a National Semiconductor Graduate Fellowship and a NASA Graduate Student Research Program (GSRP) Fellowship.
†Supported in part by the Defense Advanced Research Projects Agency under DARPA contracts DABT63-94-C0019 (SIO Initiative), F30002-96-C-0161 and DABT63-96-C-0027, by the National Science Foundation under grants NSF CDA 94-01124 and ASC 97-20202, and by the Department of Energy under contracts DOE B-3194, W-7405-ENG-48 and 1-B-333164.
building large, wide-area structures.

3. Design Decisions

To evaluate the feasibility of large scale computing, we designed and prototyped a Java/WWW-based infrastructure that uses WWW browsers as computation workers and WWW servers as hierarchy managers. To connect a large number of distributed machines, we first exploit locality and link the machines in a tree, where the leaves are WWW browsers, the internal nodes are WWW servers, and the edges are logical network links. The servers cooperatively manage the hierarchy of browsers executing the computation.\(^1\)

Figure 1 shows an example of a hierarchy. In this example, the manager branching factor, \(b_m\), is two, and the client branching factor, \(b_c\), is four. That is, the maximum number of children of each non-first level manager is two and the maximum number of children of each first level manager is four. As we will see in §4-§5, these branching factors are important design parameters that directly affect the reliability of the hierarchy.

In our design, we use a greedy algorithm to insert clients, attempting to cluster machines that are close in time to each other into the same subtree. (Servers join the hierarchy via a node splitting algorithm similar to that of B-trees.) To join the hierarchy, a new client connects to the root via servers specified in a configuration file. The new client then contacts each of the child servers of the root, determines the child server with the lowest latency, and establishes connection with this lowest-latency child server. The new client then continues to descend the tree by successively following the lowest-latency child server at each level until the new client reaches a first level manager and attaches to it.

To discover the arrival of new resources and the departure of current resources, we must periodically acquire information about resource availability in the infrastructure. In our design, the root maintains a global view of resource availability by periodically issuing requests for updated system state data. Information acquisition consists of a down sweep where the request is propagated from the root to the leaves, and an up sweep where information (e.g., network and machine loads) is gathered, summarized (to reduce data transmission cost), and percolated to the root. To support loosely coupled applications, we use a master-worker programming model — the master distributes tasks to the workers, and the workers perform the computation.

To determine the feasibility and cost of operating millions of nodes for global computing, we must understand the cost of the operations described in this section — that is, hierarchy formation, world view maintenance, and wide-area task scheduling. To evaluate these costs, we prototyped our infrastructure design, measured the cost of the above operations in small to modest configurations, and projected the cost of these operations in large configurations to gain insights into the possibility of operating a million node hierarchy.

4. Hierarchy Reliability

Because workers in our loosely coupled, distributed computing infrastructure join and leave the hierarchy at unpredictable times and because network connections to remote sites can fail, quantifying the reliability of a geographically distributed computing hierarchy is critical. To understand infrastructure reliability, we developed and validated a probability model that projects the reliability of large structures and estimates the machine availability under different configurations.

4.1. Probability Model

To gauge the reliability and performance of large hierarchies, we use the expected number of available

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\(^1\)We use the terms clients, browsers, and workers as synonyms. Similarly, we use the terms servers and managers interchangeably.
4.2. Reachability Measurement

To assess the machine and network failure rate, we measured the reachability of seventeen international World Wide Web (WWW) sites using the Unix ping utility. We selected these sites to cover all continents and all U.S. regions. Once every fifteen minutes for a three month period (from April 1, 1997 to June 30, 1997), we recorded each site’s response to the ping message. We classified the site as unreachable if the ping timed out before receiving a response.

Based on the measurements, we used (2) to compute failure probabilities, concluding that across seventeen WWW sites, the average probability of failure is 0.022. On average, there is a 2.2 percent chance that a particular machine or network link is unavailable.

To verify the accuracy of the computed probability of failure, we compared our results to those obtained by Kalyanakrishnan et al in their HTTP performance study [8]. During the same month (April 1997) we conducted our ping study, Kalyanakrishnan et al independently measured the availability of WWW hosts by fetching HTML pages from the one hundred most popular WWW servers in the United States. Their measured average probability of failure is 0.007, lower than that from our ping measurements. Because the majority of the HTTP requests were to the most popular sites in the United States, these hosts tend to have good network connectivity and low machine failure rates. Therefore, we believe that our measurement
is a reasonable, conservative estimate of the current reliability of nodes on a wide area network, whereas the estimate from the HTTP study represents an improvement over the average reliability.

4.3. Reliability Projection

Based on (4), Figure 2 shows reliability projections when the probability of failure is 0.022 (as measured), 0.011 (a 2X improvement), and 0.044 (a 2X degradation). In these projections, we used a client branching factor of fifty. However, results are qualitatively similar for other large branching factors.

As shown in Figure 2, a small increase in the manager branching factor greatly enhances the reliability of the infrastructure when the branching factor is small. The rapid decrease in tree height significantly reduces the number of nodes between the clients and the root, concomitantly increasing the reliability.

Figure 2 also shows that the percentage of available clients in a one million client configuration lies between 65 and 90 percent for measured link/node probability of failure. However, even a two-fold decrease in \( p_f \) (e.g., as might occur in a highly congested or bandwidth constrained environment) substantially reduces client availability, suggesting the need for redundancy techniques (e.g., scheduling redundant tasks). Below, we discuss the balance between server redundancy and computation performance.

5. Performability

Given fixed resources, one can allocate servers to maximize reliability or performance, but not both. Hence, one must balance the need for reliability against the desire for high performance, judiciously allocating resources to maximize performability [11].

Figure 3 illustrates a hierarchy with three redundant servers per node at the top two levels of the hierarchy. To accommodate redundancy, one can modify server insertion algorithms to insert new servers at key points. When a server later fails, one of the redundant servers can assume the function of the failed one. To quantify the performability of the hybrid infrastructure, we derive the number of available clients as a function of redundant servers per node and levels with redundancy.

5.1. Performability Metrics

To derive the number of available clients, let \( r \) be the number of redundant servers per node, and let \( l_r \) be the number of layers of managers (numbering from the root) with redundant servers. Hence, on the path from a client to the root, there are \( l_r \) nodes with redundant servers. The probability that all these nodes are available is given by

\[
(1 - p_f)\left(1 + r\right)^{l_r}
\]

where \( p_f \) is the probability of node or link failure.

For the remaining nodes on the path that have no redundancy, the probability that they are available is given by

\[
(1 - p_f)^{H_r + 1 - l_r}
\]

where \( H_r \) is the height of the hierarchy. Hence, the expected number of available clients \( E_{mc} \) is obtained
by multiplying the number of clients by the product of (5) and (6):

\[ M_1(l_r, r)b_c \left[ (1 - p_f)^{H_r - l_r} \left( 1 - p_f^{(1+r)} \right)^{l_r} \right] \]  (7)

where \( M_1(l_r, r) \) is the number of first level managers, and \( b_c \) is the client branching factor. Because the number of first level managers now depends on the number of managers removed from the original hierarchy for redundancy, \( M_1 \) is a function of the level of redundancy and the number of redundant servers.

To compute \( M_1 \), we remove nodes from the lower levels of the tree until we have secured enough nodes for redundancy use; \( M_1 \) is the number of first level managers remaining. During the removal, however, we seek to preserve as many first level managers as possible by removing internal managers that have no descendants so the first level managers can continue to anchor clients, the computing engines of the hierarchy.

In sum, (7) gives the performability metric of the infrastructure, allowing us to explore performability as a function of the level of redundancy \( l_r \), the number of redundant servers per node \( r \), the probability of link or node failure \( p_f \), and the hierarchy structure \((b_c, n_c, \text{ and } H_r)\). Below, we evaluate performability by systematically varying these parameters.

5.2. Hierarchy Structure Implications

Using a link/node failure rate of 0.022 as analyzed in §4.2, Figure 4 shows the performability of a one million client hierarchy as a function of the level of redundancy and the number of redundant server per node. The figure shows that the percentage of available clients increases with redundancy up to level four. Beyond that point, the percentage of available clients decreases because the redundant structure requires the removal of too many managers from the lower levels, significantly reducing the number of first level managers that can anchor clients for computation. Figure 4 also shows that the number of redundant servers per manager has little effect on the availability of the clients — one redundant server per manager is sufficient to increase the performability of the infrastructure.

In brief, our detailed analysis [9] shows that varying the number of clients, the client branching factor, and the tree height yield results qualitatively similar to those in Figure 4. Hence, one can achieve reasonable performability by providing one redundant server per node for the first few levels of the hierarchy.

5.3. Performability Projection

To evaluate effects of technology evolution and network congestion on the availability of the infrastructure with redundant servers, Figure 5 shows the result of computing the percentage of available clients as a function of the link or node failure rate.

With perfect link/node reliability (i.e., \( p_f=0 \)), redundancy actually reduces client availability because WWW servers are reserved as backups rather than being deployed for production use. However, as the link/node failure rate increases, hierarchies with redundant servers outperform those without redundant structures. The larger the link/node failure rate, the larger the gap between the performance of hierarchies with and without redundancy. With increasing Internet popularity, the surge in networking traffic is likely to result in more network congestion, making redun-
dant structures critical for large scale computing.

6. Hierarchy Formation Costs

To determine whether it is feasible and practical to form large scale computing structures on the Internet given current wide-area latencies, we must quantify the cost of hierarchy construction. Below, we investigate the maximum feasible hierarchy size (i.e., without redundant structures) given current Internet performance and reliability attributes.

6.1. Node Insertion Time Complexity

To estimate the largest scale hierarchy currently feasible, we began by enumerating the number of component operations required to build the hierarchy as a function of the manager branching factor; see [9] for the detailed derivation. Our derivation shows that the time complexity of hierarchy formation is roughly

$$O\left( \frac{b_m}{b_m - 1} \right) + O\left( \frac{b_m}{\log b_m \log (n_c/b_c)} \right).$$

The first term in (8) represents the cost of inserting internal nodes; the second term is associated with the cost of client tree descent during client insertion. Based on (8), Figure 6 summarizes the insights we gained from complexity analysis of hierarchy formation.

The figure shows that as one increases the manager branching factor, the cost of inserting internal nodes decreases rapidly due to the exponential decrease in the number of internal managers. However, as one increases the manager branching factor beyond the inflection point, the cost of client tree descent increases due to the increasing cost of measuring latencies to more servers at each level. That is, despite the decrease in tree height with increasing manager branching factor, the large fanout at each level of the tree increases the cost of client tree descent. The increase in the cost of client tree descent increases the total cost of hierarchy formation, making it infeasible to use large manager branching factors for added reliability.

6.2. Node Insertion Time Scale

To quantify the total cost of wide area hierarchy formation, we measured the component costs of hierarchy formation by constructing wide area hierarchies using machines from Brazil, Chile, Italy, and the United States. We initialized hierarchies with different tree heights and branching factors, and measured the cost of each component operation on an international scale. Table 3 shows the average cost of various component operations and the width of half of the 95 percent confidence interval (i.e., $\Delta t$).

Using the data in Table 3 and the results from enumerating the execution frequency of each component operation during hierarchy formation, one can project the time scale for inserting servers and clients in a
wide area hierarchy. The server insertion cost is about two minutes for hierarchies with over 100,000 clients, suggesting that one should use a manager branching factor between five to ten to lower server insertion cost.

Similarly, Figure 7 shows the effect of client branching factor on client insertion time. One can reduce client insertion time by using large client branching factors. This decreases the number of managers required at the first level, reducing the total cost of insertion. As Figure 7 shows, the added savings from a client branching factor beyond twenty is not significant, suggesting that a reasonably large client branching factor is adequate for reducing the cost of hierarchy formation.

In short, based on the cost and time complexity analysis of hierarchy formation and measurements of current technologies (e.g., network speed), one should build hierarchies using a modest manager branching factor and a large client branching factor to maximize reliability and minimize hierarchy formation time.

6.3. Large-Scale Hierarchy Formation

To project the total cost of forming large hierarchies and to determine the largest, feasible hierarchy size given current technologies (e.g., network latency and processor speed), we combined the cost of server and client insertions to compute the projected total cost.

In this analysis, we made three assumptions. First, we assumed a manager branching factor of ten; second, we used a client branching factor of fifty; and third, we assumed that servers are inserted serially, and clients are inserted in parallel. We allowed up to fifty concurrent client insertions because we believe geographically distributed users will likely insert their clients at different branches of a wide area hierarchy.

Table 4 shows the configurations and costs of building wide area hierarchies that our analysis suggests are feasible given current hardware speeds and a 24 hour hierarchy initialization time.3 As shown in Table 4, given today's wide area network latencies, the largest hierarchy one can assemble within 24 hours would have approximately 25,000 clients and 600 servers.

7. Scheduling Costs

Because maintaining a global view of the resources available in a hierarchy is essential for efficient job scheduling, and assessing the scheduling overhead is critical for determining task granularity, we also performed cost and feasibility analysis of world view maintenance and task scheduling. The analysis is similar to that described in §6.1. That is, we enumerated the execution frequency of the component operations for world view maintenance and task scheduling, measured their component costs in a wide area context, and used the measurements to project their costs in a large scale, wide area environment.

Our results show that, for a one million client hierarchy, the time scales of world view maintenance and wide-area task scheduling are both near ten minutes [9]. Thus, unlike hierarchy formation, the short time scales for view maintenance and scheduling make it feasible to maintain a global view of the system and to perform large scale computation.

8 Network Evolution

To place the results in a larger context, we used our models to project the possible hierarchy sizes as a function of changes in network latencies. In this projection, we assumed that the average latencies for international, national, vBNS, and local area networks are, respectively, 300, 150, 60, and 5 milliseconds.

Figure 8 suggests that one can potentially scale to over one million nodes if wide-area network latencies approach those of local area networks, subject of course to time of flight signal delays. At this scale, the number of clients will be two orders of magnitude larger than that of hierarchies feasible with current technologies. As a result, we can view the massive computing power available in the hierarchy as a utility that can be tapped for worldwide dynamic load sharing and distributed information processing.

Given the possible hierarchy sizes shown in Figure 8, we illustrate what applications these hierarchies can enable by estimating the execution time to decrypt a 56-bit RSA Data Encryption Standard (DES) code under these configurations. In this computation, we assume that, with the use of redundant servers, 92 percent of the clients will be available. Furthermore, we assume that all the clients have roughly the computing power of an Intel Pentium 166 MHz processor.

Based on statistics from distributed.net's DES-II-1 project (see www.distributed.net for details), we

<table>
<thead>
<tr>
<th>Number of Clients</th>
<th>Number of Managers</th>
<th>Total Cost (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000</td>
<td>501</td>
<td>16.72</td>
</tr>
<tr>
<td>25,000</td>
<td>625</td>
<td>21.51</td>
</tr>
<tr>
<td>30,000</td>
<td>750</td>
<td>26.38</td>
</tr>
</tbody>
</table>

Table 4. Feasible Hierarchy Construction Cost
Figure 8. Reduced Latency Hierarchy Size

assume that each system can test $1.2 \times 10^{11}$ keys per day ($5.5 \times 10^8$ key blocks tested per day multiplied by $1.1 \times 10^9$ keys per key block, and divided by the equivalent of 50,000 Pentium processors used in the project).

Finally, we assume one must test all 72 quadrillion ($72 \times 10^{15}$) keys to break the code.

Using these assumptions, decryption time decreases dramatically from thirty days to under a day with the increase in hierarchy size. Thus, as network and computing technologies evolve, they will enable new kinds of applications that require massive computation power (e.g., knowledge discovery and data mining in distributed databases), solving problems in a small fraction of today’s execution time.

9. Conclusions

Until recently, worldwide computing lacks a universal, standard platform for cooperatively harnessing geographically distributed machines for large scale computing. The recent emergence of Java and the World Wide Web (WWW), however, created a common denominator for global computing, enabling us to tap into any machine that has a WWW browser.

Our analysis of a Java/WWW-based infrastructure showed that, given current technologies, it is feasible to build wide area hierarchies with about 25,000 clients and 600 servers. In addition, the analysis suggests using a modest manager branching factor to increase reliability, and a large client branching factor to reduce the cost of hierarchy formation.

We also found it feasible to maintain a global view and perform task scheduling atop an infrastructure that contains up to one million node. As network and computing technologies evolve, large hierarchies will enable new applications to leverage a globally distributed, parallel computer to solve large problems.

Acknowledgments. We thank Doug West for discussing the probability model, and Celso Mendes, Mario Medina, and Giuseppe Serazzi and Rosella Favino, respectively, for access to computers in Brazil, Chile, and Italy.

References