CLUSTER COMPUTING

A SEMINAR REPORT

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Certificate

Certified that this is a bonafide record of the seminar entitled

“ CLUSTER COMPUTING ”

presented by the following student

KUMAR KAUSHIK

of the VII semester, Computer Science and Engineering in the year 2008 in partial fulfillment of the requirements in the award of Degree of Bachelor of Technology in Computer Science and Engineering of Cochin University of Science and Technology.

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Seminar Guide	**Head of Division**

Date :

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KUMAR KAUSHIK

ABSTRACT

A computer cluster is a group of linked computers, working together closely so that in many respects they form a single computer. The components of a cluster are commonly, but not always, connected to each other through fast local area networks. Clusters are usually deployed to improve performance and/or availability over that provided by a single computer, while typically being much more cost-effective than single computers of comparable speed or availability.

The major objective in the cluster is utilizing a group of processing nodes so as to complete the assigned job in a minimum amount of time by working cooperatively. The main and important strategy to achieve such objective is by transferring the extra loads from busy nodes to idle nodes.

The seminar will contain the concepts of cluster computing and the principles involved in it.

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1.INTRODUCTION

1.1 General Introduction

Parallel computing has seen many changes since the days of the highly expensive and proprietary super computers. Changes and improvements in performance have also been seen in the area of mainframe computing for many environments. But these compute environments may not be the most cost effectiveand flexible solution for a problem. Over the past decade, cluster technologies have been developed that allow multiple low cost computers to work in a coordinated fashion to process applications. The economics, performance and flexibility of compute clusters makes cluster computing an attractive alternative to centralized computing models and the attendant to cost, inflexibility, and scalability issues inherent to these models.
Many enterprises are now looking at clusters of high-performance, low cost computers to provide increased application performance, high availability, and ease of scaling within the data center. Interest in and deployment of computer clusters has largely been driven by the increase in the performance of off-the-shelf commodity computers, high-speed, low-latency network switches and the maturity of the software components. Application performance continues to be of significant concern for various entities including governments, military, education, scientific and now enterprise organizations. This document provides a review of cluster computing, the various types of clusters and their associated applications. This document is a high-level informational document; it does not provide details aboutvarious cluster implementations and applications.

1.1.1 Cluster Computing

Cluster computing is best characterized as the integration of a number of off-the-shelf commodity computers and resources integrated through hardware, networks, and software to behave as a single computer. Initially, the terms cluster computing and high performance computing were viewed as one and the same. However, the technologies available today have redefined the term cluster computing to extend beyond parallel computing to incorporate load-balancing clusters (for example, web clusters) and high availability clusters. Clusters may also be deployed to address load balancing, parallel processing, systems management, and scalability. Today, clusters are made up of commodity computers usually restricted to a single switch or group of interconnected switches operating at Layer 2 and within a single virtual local-area network (VLAN). Each compute node (computer) may have different characteristics such as single processor or symmetric multiprocessor design, and access to various types of storage devices. The underlying network is a dedicated network made up of high-speed, low-latency switches that may be of a single switch or a hierarchy of multiple switches.

A growing range of possibilities exists for a cluster interconnection technology. Different variables will determine the network hardware for the cluster. Price-per-port, bandwidth, latency, and throughput are key variables. The choice of network technology depends on a number of factors, including price, performance, and compatibility with other cluster hardware and system software as well as communication characteristics of the applications that will use the cluster. Clusters are not commodities in themselves, although they may be based on commodity hardware. A number of decisions need to be made (for example, what type of hardware the nodes run on, which interconnect to use, and which type of switching architecture to build on) before assembling a cluster range. Each decision will affect the others, and some will probably be dictated by the intended use of the cluster. Selecting the right cluster elements involves an understanding of the application and the necessary resources that include, but are not limited to, storage, throughput, latency, and number of nodes.

When considering a cluster implementation, there are some basic questions that can help determine the cluster attributes such that technology options can be evaluated:

1. Will the application be primarily processing a single dataset?

2. Will the application be passing data around or will it generate real-time information?

3. Is the application 32- or 64-bit?

The answers to these questions will influence the type of CPU, memory architecture, storage, cluster interconnect, and cluster network design. Cluster applications are often CPU-bound so that interconnect and storage bandwidth are not limiting factors, although this is not always the case.

1.1.2 Cluster Benefits

The main benefits of clusters are scalability, availability, and performance. For scalability, a cluster uses the combined processing power of compute nodes to run cluster-enabled applications such as a parallel database server at a higher performance than a single machine can provide. Scaling the cluster's processing power is achieved by simply adding additional nodes to the cluster. Availability within the cluster is assured as nodes within the cluster provide backup to each other in the event of a failure. In high-availability clusters, if a node is taken out of service or fails, the load is transferred to another node (or nodes) within the cluster. To the user, this operation is transparent as the applications and data running are also available on the failover nodes. An additional benefit comes with the existence of a single system image and the ease of manageability of the cluster. From the users perspective the users sees an application resource as the provider of services and applications. The user does not know or care if this resource is a single server, a cluster, or even which node within the cluster is providing services. These benefits map to needs of today's enterprise business, education, military and scientific community infrastructures. In summary, clusters provide:

• Scalable capacity for compute, data, and transaction intensive applications, including support of mixed workloads
• Horizontal and vertical scalability without downtime
• Ability to handle unexpected peaks in workload
• Central system management of a single systems image
• 24 x 7 availability.

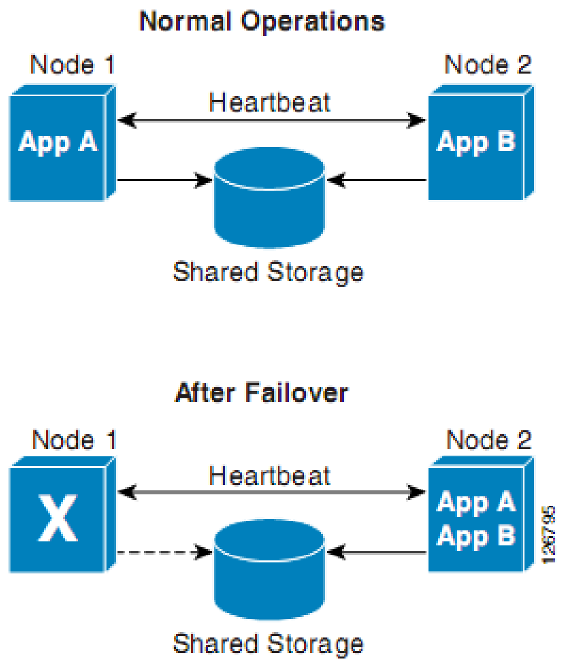
2. TYPES OF CLUSTER

There are several types of clusters, each with specific design goals and functionality. These clusters range from distributed or parallel clusters for computation intensive or data intensive applications that are used for protein, seismic, or nuclear modeling to simple load-balanced clusters.

2.1 High Availability or Failover Clusters

These clusters are designed to provide uninterrupted availability of data or services (typically web services) to the end-user community. The purpose of these clusters is to ensure that a single instance of an application is only ever running on one cluster member at a time but if and when that cluster member is no longer available, the application will failover to another cluster member. With a high-availability cluster, nodes can be taken out-of-service for maintenance or repairs. Additionally, if a node fails, the service can be restored without affecting the availability of the services provided by the cluster (see Figure 2.1). While the application will still be available, there will be a performance drop due to the missing node.
High-availability clusters implementations are best for mission-critical applications or databases, mail, file and print, web, or application servers.

Figure 1 Failover Clusters



(Failover Clusters)
(Figure- 2.1)

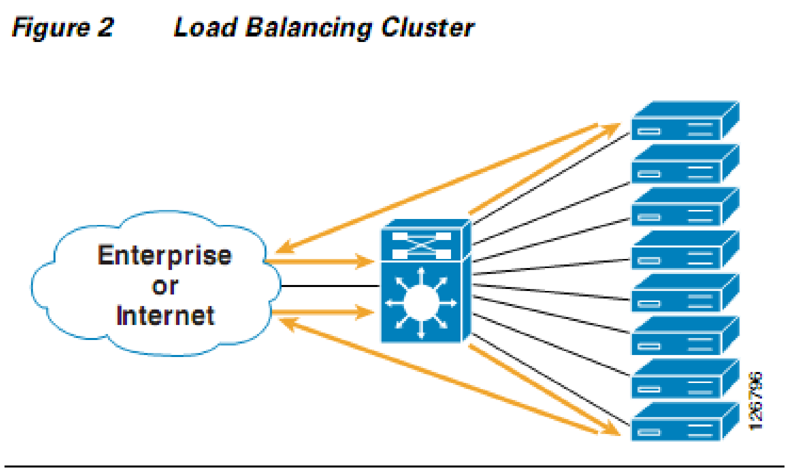
Unlike distributed or parallel processing clusters, high-availability clusters seamlessly and transparently integrate existing standalone, non-cluster aware applications together into a single virtual machine necessary to allow the network to effortlessly grow to meet increased business demands.

Cluster-Aware and Cluster-Unaware Applications

Cluster-aware applications are designed specifically for use in clustered environment. They know about the existence of other nodes and are able to communicate with them. Clustered database is one example of such application. Instances of clustered database run in different nodes and have to notify other instances if they need to lock or modify some data. Cluster-unaware applications do not know if they are running in a cluster or on a single node. The existence of a cluster is completely transparent for such applications, and some additional software is usually needed to set up a cluster. A web server is a typical cluster-unaware application. All servers in the cluster have the same content, and the client does not care from which server the server provides the requested content.

2.2 Load Balancing Cluster

This type of cluster distributes incoming requests for resources or content among multiple nodes running the same programs or having the same content (see Figure 2.2). Every node in the cluster is able to handle requests for the same content or application. If a node fails, requests are redistributed between the remaining available nodes. This type of distribution is typically seen in a web-hosting environment.



(Load Balancing Cluster)
(Figure- 2.2)

Both the high availability and load-balancing cluster technologies can be combined to increase the reliability, availability, and scalability of application and data resources that are widely deployed for web, mail, news, or FTP services.

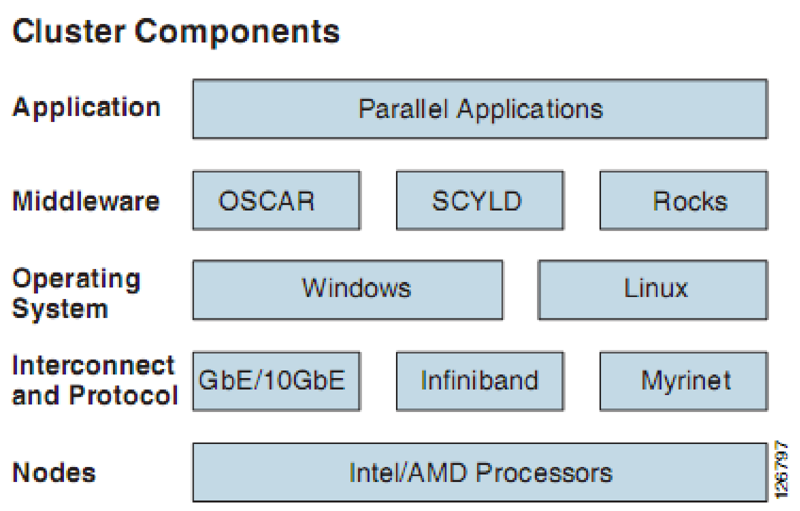
2.3 Parallel/Distributed Processing Clusters

Traditionally, parallel processing was performed by multiple processors in a specially designed parallel computer. These are systems in which multiple processors share a single memory and bus interface within a single computer. With the advent of high speed, low-latency switching technology, computers can be interconnected to form a parallel-processing cluster. These types of cluster increase availability, performance, and scalability for applications, particularly computationally or data intensive tasks. A parallel cluster is a system that uses a number of nodes to simultaneously solve a specific computational or data-mining task. Unlike the load balancing or high-availability clusters that distributes requests/tasks to nodes where a node processes the entire request, a parallel environment will divide the request into multiple sub-tasks that are distributed to multiple nodes within the cluster for processing. Parallel clusters are typically used for CPU-intensive analytical applications, such as mathematical computation, scientific analysis (weather forecasting, seismic analysis, etc.), and financial data analysis. One of the more common cluster operating systems is the Beowulf class of clusters. A Beowulf cluster can be defined as a number of systems whose collective processing capabilities are simultaneously applied to a specific technical, scientific, or business application. Each individual computer is referred to as a “node” and each node communicates with other nodes within a cluster across standard Ethernet technologies (10/100 Mbps, GbE, or 10GbE). Other high-speed interconnects such as Myrinet, Infiniband, or Quadrics may also be used.

3. CLUSTER COMPONENTS

The basic building blocks of clusters are broken down into multiple categories: the cluster nodes, cluster operating system, network switching hardware and the node/switch interconnect (see Figure 3). Significant advances have been accomplished over the past five years to improve the performance of both
the compute nodes as well as the underlying switching infrastructure.

Figure 3 Cluster Components



(Cluster Components)

(Figure- 3)

Application : It includes all the various applications that are going on for a particular group. These applications run in parallel. These includes various query running on different nodes of the cluster. This can be said as the input part of the cluster component.

Middleware: These are software packages which interacts the user with the operating system for the cluster computing. In other words we can say that these are the layers of software between applications and operating system. Middleware provides various services required by an application to function correctly. The software that are used as middleware are:

OSCAR

Features:

- Image based Installation.
- Supported by Red Hat 9.0 and Mandrake 9.0.
- Processors supported: x86, Itanium (in beta).
- Interconnects: Ethernet, Myrinet.
- Diskless support in development.
- Opteron support in development.
- High-availability support in alpha testing.

SCYLD

Features:

- Commercial distribution.
- Single system image design.
- Processors: x86 and Opteron.
- Interconnects: Ethernet and Infiniband.
- MPI and PVM.
- Diskful and diskless support.

Rocks

Features:

- Processors: x86, Opteron, Itanium.
- Interconnects: Ethernet and Myrinet.
- Compute node management via Red Hat's kickstart mechanism.
- Diskfull only.
- Cluster on CD.

Operating System: Clusters can be supported by various operating systems which includes Windows, Linux.etc.

Interconnect: Interconnection between the various nodes of the cluster system can be done using 10GbE, Myrinet etc. In case of small cluster system these and be connected with the help of simple switches.

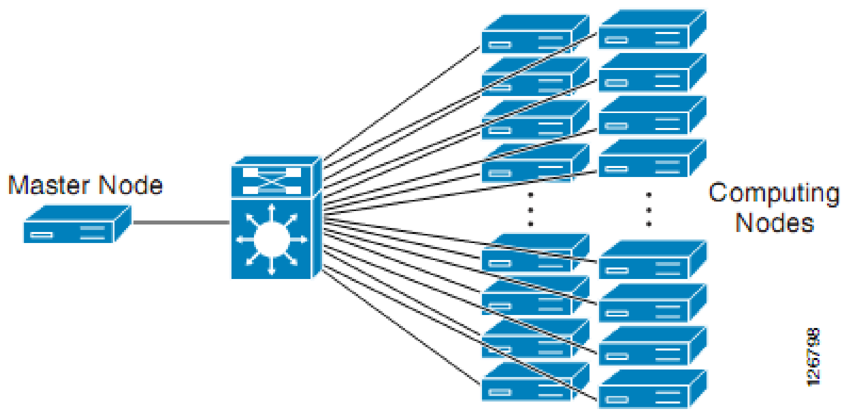
Nodes: Nodes of the cluster system implies about the different computers that are connected. All of these processors can be of intels or AMD 64 bit.

4. CLUSTER OPERATION

4.1 Cluster Nodes

Node technology has migrated from the conventional tower cases to single rack-unit multiprocessor systems and blade servers that provide a much higher processor density within a decreased area. Processor speeds and server architectures have increased in performance, as well as solutions that provide options for either 32-bit or 64-bit processors systems. Additionally, memory performance as well as hard-disk access speeds and storage capacities have also increased. It is interesting to note that even though performance is growing exponentially in some cases, the cost of these technologies has dropped considerably. As shown in Figure 4.1 below, node participation in the cluster falls into one of two responsibilities: master (or head) node and compute (or slave) nodes. The master node is the unique server in cluster systems. It is responsible for running the file system and also serves as the key system for clustering middleware to route processes, duties, and monitor the health and status of each slave node. A compute (or slave) node within a cluster provides the cluster a computing and data storage capability. These nodes are derived from fully operational, standalone computers that are typically marketed as desktop or server systems that, as such, are off-the-shelf commodity systems.

Figure 4   Cluster Nodes



(Cluster Nodes)

(Figure- 4.1)

4.2 Cluster Network

Commodity cluster solutions are viable today due to a number of factors such as the high performance commodity servers and the availability of high speed, low-latency network switch technologies that provide the inter-nodal communications. Commodity clusters typically incorporate one or more dedicated switches to support communication between the cluster nodes. The speed and type of node interconnects vary based on the requirements of the application and organization. With today's low costs per-port for Gigabit Ethernet switches, adoption of 10-Gigabit Ethernet and the standardization of 10/100/1000 network interfaces on the node hardware, Ethernet continues to be a leading interconnect technology for many clusters. In addition to Ethernet, alternative network or interconnect technologies include Myrinet, Quadrics, and Infiniband that support bandwidths above 1Gbps and end-to-end message latencies below 10 microseconds (uSec).

4.2.1 Network Characterization

There are two primary characteristics establishing the operational properties of a network: bandwidth and delay. Bandwidth is measured in millions of bits per second (Mbps) and/or billions of bits per-second (Gbps). Peak bandwidth is the maximum amount of data that can be transferred in a single unit of time through a single connection. Bi-section bandwidth is the total peak bandwidth that can be passed across a single switch.
Latency is measured in microseconds (µSec) or milliseconds (mSec) and is the time it takes to move a single packet of information in one port and out of another. For parallel clusters, latency is measured as the time it takes for a message to be passed from one processor to another that includes the latency of the interconnecting switch or switches. The actual latencies observed will vary widely even on a single switch depending on characteristics such as packet size, switch architecture (centralized versus distributed), queuing, buffer depths and allocations, and protocol processing at the nodes.

4.2.2 Ethernet, Fast Ethernet, Gigabit Ethernet and 10-Gigabit Ethernet

Ethernet is the most widely used interconnect technology for local area networking (LAN). Ethernet as a technology supports speeds varying from 10Mbps to 10 Gbps and it is successfully deployed and operational within many high-performance cluster computing environments.

4.3 Cluster Applications

Parallel applications exhibit a wide range of communication behaviors and impose various requirements on the underlying network. These may be unique to a specific application, or an application category depending on the requirements of the computational processes. Some problems require the high bandwidth and low-latency capabilities of today's low-latency, high throughput switches using 10GbE, Infiniband or Myrinet. Other application classes perform effectively on commodity clusters and will not push the bounds of the bandwidth and resources of these same switches. Many applications and the messaging algorithms used fall in between these two ends of the spectrum. Currently, there are four primary categories of applications that use parallel clusters: compute intensive, data or input/output (I/O) intensive, and transaction intensive. Each of these has its own set of characteristics and associated network requirements. Each has a different impact on the network as well as how each is impacted by the architectural characteristics of the underlying network. The following subsections describe each application types.

4.3.1 Compute Intensive Applications

Compute intensive is a term that applies to any computer application that demands a lot of computation cycles (for example, scientific applications such as meteorological prediction). These types of applications are very sensitive to end-to-end message latency. This latency sensitivity is caused by either the processors having to wait for instruction messages, or if transmitting results data between nodes takes longer. In general, the more time spent idle waiting for an instruction or for results data, the longer it takes to complete the application.

Some compute-intensive applications may also be graphic intensive. Graphic intensive is a term that applies to any application that demands a lot of computational cycles where the end result is the delivery of significant information for the development of graphical output such as ray-tracing applications.
These types of applications are also sensitive to end-to-end message latency. The longer the processors have to wait for instruction messages or the longer it takes to send resulting data, the longer it takes to present the graphical representation of the resulting data.

4.3.2 Data or I/O Intensive Applications

Data intensive is a term that applies to any application that has high demands of attached storage facilities. Performance of many of these applications is impacted by the quality of the I/O mechanisms supported by current cluster architectures, the bandwidth available for network attached storage, and, in some cases, the performance of the underlying network components at both Layer 2 and 3.
Data-intensive applications can be found in the area of data mining, image processing, and genome and protein science applications. The movement to parallel I/O systems continues to occur to improve the I/O performance for many of these applications.

4.3.3 Transaction Intensive Applications

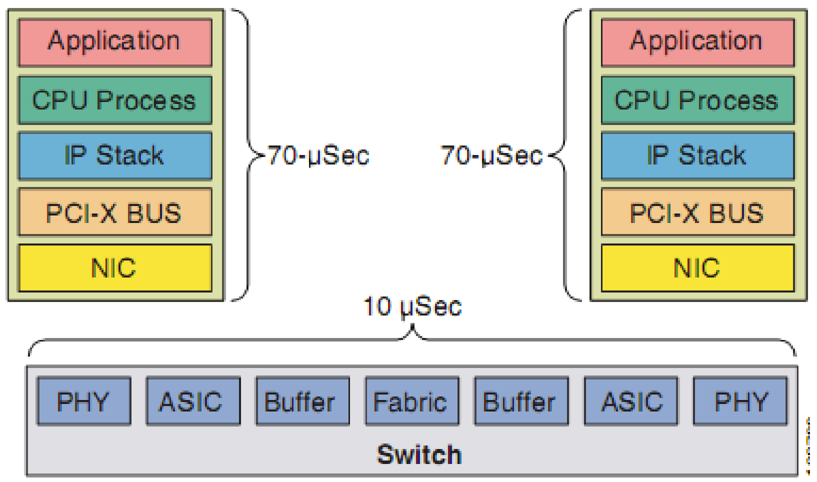
Transaction intensive is a term that applies to any application that has a high-level of interactive transactions between an application resource and the cluster resources. Many financial, banking, human resource, and web-based applications fall into this category.
There are three main care abouts for cluster applications: message latency, CPU utilization, and throughput. Each of these plays an important part in improving or impeding application performance. This section describes each of these issues and their associated impact on application performance.

4.4 Message Latency

Message latency is defined as the time it takes to send a zero-length message from one processor to another (measured in microseconds). The lower the latency for some application types, the better.

Message latency is made up of aggregate latency incurred at each element within the cluster network, including within the cluster nodes themselves (see Figure 4.4.1). Although network latency is often focused on, the protocol processing latency of message passing interface (MPI) and TCP processes within the host itself are typically larger. Throughput of today's cluster nodes are impacted by protocol processing, both for TCP/IP processing and the MPI. To maintain cluster stability, node synchronization, and data sharing, the cluster uses message passing technologies such as Parallel Virtual Machine (PVM) or MPI. TCP/IP stack processing is a CPU-intensive task that limits performance within high speed networks. As CPU performance has increased and new techniques such as TCP offload engines (TOE) have been introduced, PCs are now able to drive the bandwidth levels higher to a point where we see traffic levels reaching near theoretical maximum for TCP/IP on Gigabit Ethernet and near bus speeds for PCI-X based systems when using 10 Gigabit Ethernet. These high-bandwidth capabilities will continue to grow as processor speeds increase and more vendors build network adapters to the PCI-Express specification.

Figure 5 End-to-End Message Latency Example

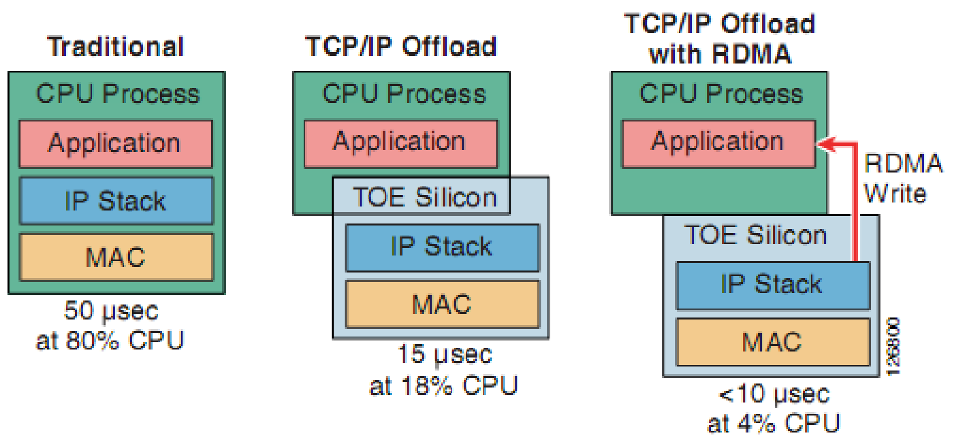


(Message Latency)

(Figure- 4.4.1)

To address host stack latency, reductions in protocol processing have been addressed somewhat through the implementation of TOE and further developments of combined TOE and Remote Direct Memory Access (RDMA) technologies are occurring that will significantly reduce the protocol processing in the host. See Figure 4.4.2 through Figure 4.4.4 below for examples.

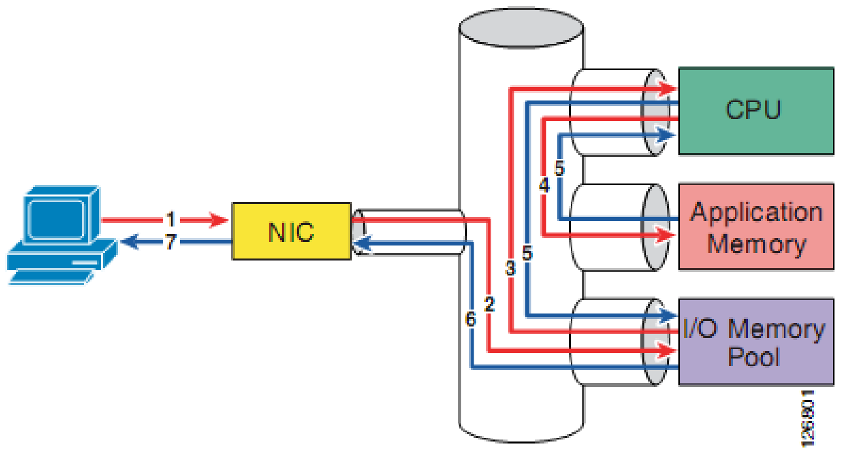
Figure 6 Progression of Change for Protocol Processing in the Host



(Progression)

(Figure- 4.4.2)

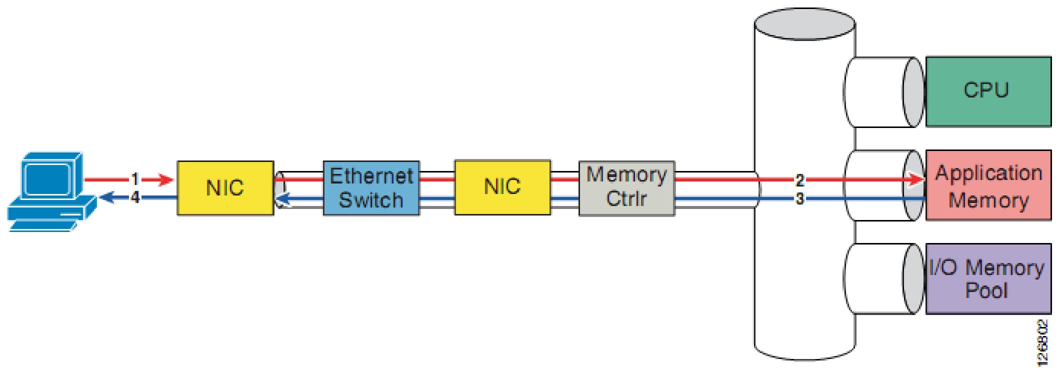
Figure 7 Message Path Without TOE and RDMA Implementation



(Message path Without TOE and RDMA)

(Figure- 4.4.3)

Figure 8 Message Path with TOE and RDMA Implementation



(Message path with TOE and RDMA)

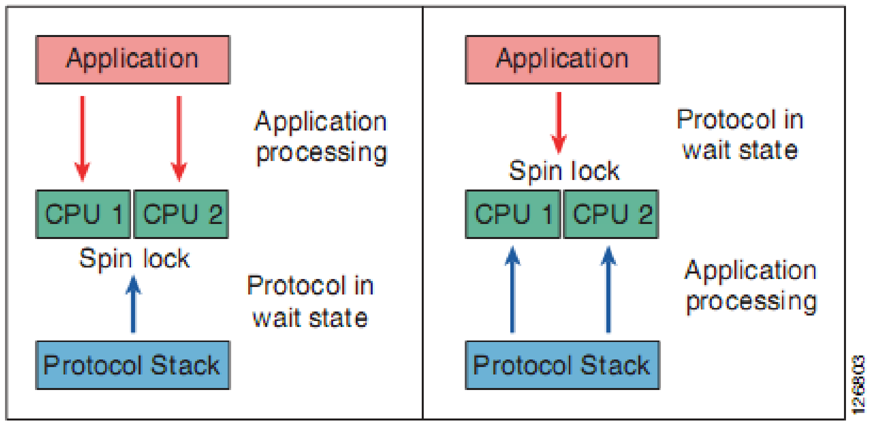
(Figure- 4.4.4)

4.5 CPU Utilization

One important consideration for many enterprises is to use compute resources as efficiently as possible. As increased number of enterprises move towards realtime and business-intelligence analysis, using compute resources efficiently is an important metric. However, in many cases compute resource is underutilized. The more CPU cycles committed to application processing the less time it takes to run the application. Unfortunately, although this is a design goal, this is not obtainable as both the application and protocols compete for CPU cycles.

As the cluster node processes the application, the CPU is dedicated to the application and protocol processing does not occur. For this to change, the protocol process must interrupt a uniprocessor machine or request a spin lock for a multiprocessor machine. As the request is granted, CPU cycles are then applied to the protocol process. As more cycles are applied to protocol processing, application processing is suspended. In many environments, the value of the cluster is based on the run-time of the application. The shorter the time to run, the more floating-point operations and/or millions of instructions per-second occur, and, therefore, the lower the cost of running a specific application or job.

Figure 9 CPU Utilization

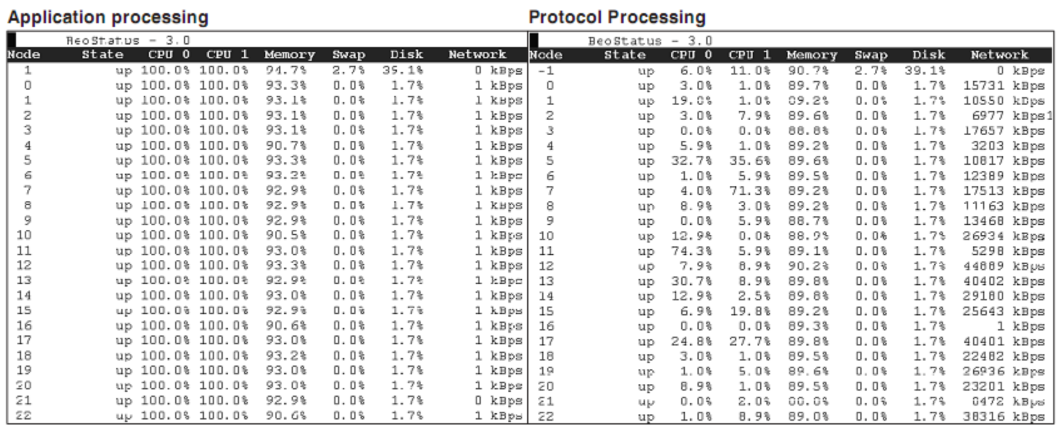


(CPU Utilization)

(Figure- 4.5.1)

The example on the left side of Figure 4.5.1 shows that when there is virtually no network or protocol processing going on, CPU 0 and 1 of each node are 100% devoted to application processing. The right side of Figure 4.5.1 shows that the network traffic levels have significantly increased. As this happens, the CPU spends cycles processing the MPI and TCP protocol stacks, including moving data to and from the wire. This results in a reduced or suspended application processing. With the increase in protocol processing, note that the utilization percentages of CPU 0 and 1 are dramatically reduced, in some cases to 0.

Figure 10 Application and Protocol Processing



Application processing

```
        BeoStatus - 3.0
Node        State   CPU 0   CPU 1  Memory   Swap    Disk     Network
  1            up 100.0% 100.0%   94.7%   2.7%   35.1%      0 kBps
  0            up 100.0% 100.0%   93.3%   0.0%    1.7%      1 kBps
  1            up 100.0% 100.0%   93.1%   0.0%    1.7%      1 kBps
  2            up 100.0% 100.0%   93.1%   0.0%    1.7%      1 kBps
  3            up 100.0% 100.0%   93.1%   0.0%    1.7%      1 kBps
  4            up 100.0% 100.0%   90.7%   0.0%    1.7%      1 kBps
  5            up 100.0% 100.0%   93.3%   0.0%    1.7%      1 kBps
  6            up 100.0% 100.0%   93.2%   0.0%    1.7%      1 kBps
  7            up 100.0% 100.0%   92.9%   0.0%    1.7%      1 kBps
  8            up 100.0% 100.0%   92.9%   0.0%    1.7%      1 kBps
  9            up 100.0% 100.0%   92.9%   0.0%    1.7%      1 kBps
 10            up 100.0% 100.0%   90.5%   0.0%    1.7%      1 kBps
 11            up 100.0% 100.0%   93.0%   0.0%    1.7%      1 kBps
 12            up 100.0% 100.0%   93.3%   0.0%    1.7%      1 kBps
 13            up 100.0% 100.0%   92.9%   0.0%    1.7%      1 kBps
 14            up 100.0% 100.0%   93.0%   0.0%    1.7%      1 kBps
 15            up 100.0% 100.0%   92.9%   0.0%    1.7%      1 kBps
 16            up 100.0% 100.0%   90.6%   0.0%    1.7%      1 kBps
 17            up 100.0% 100.0%   93.0%   0.0%    1.7%      1 kBps
 18            up 100.0% 100.0%   93.2%   0.0%    1.7%      1 kBps
 19            up 100.0% 100.0%   93.0%   0.0%    1.7%      1 kBps
 20            up 100.0% 100.0%   93.0%   0.0%    1.7%      1 kBps
 21            up 100.0% 100.0%   92.9%   0.0%    1.7%      0 kBps
 22            up 100.0% 100.0%   90.6%   0.0%    1.7%      1 kBps
```

Protocol Processing

```
        BeoStatus - 3.0
Node        State   CPU 0   CPU 1  Memory   Swap    Disk     Network
 -1            up    6.0%   11.0%   90.7%   2.7%   39.1%      0 kBps
  0            up    3.0%    1.0%   89.7%   0.0%    1.7%  15731 kBps
  1            up   19.0%    1.0%   09.2%   0.0%    1.7%  10550 kBps
  2            up    3.0%    7.9%   89.6%   0.0%    1.7%   6977 kBps1
  3            up    0.0%    0.0%   88.8%   0.0%    1.7%  17657 kBps
  4            up    5.9%    1.0%   89.2%   0.0%    1.7%   3203 kBps
  5            up   32.7%   35.6%   89.6%   0.0%    1.7%  10817 kBps
  6            up    1.0%    5.9%   89.5%   0.0%    1.7%  12389 kBps
  7            up    4.0%   71.3%   89.2%   0.0%    1.7%  17513 kBps
  8            up    8.9%    3.0%   89.2%   0.0%    1.7%  11163 kBps
  9            up    0.0%    5.9%   88.7%   0.0%    1.7%  13468 kBps
 10            up   12.9%    0.0%   88.9%   0.0%    1.7%  26934 kBps
 11            up   74.3%    5.9%   89.1%   0.0%    1.7%   5298 kBps
 12            up    7.9%    8.9%   90.2%   0.0%    1.7%  44889 kBps
 13            up   30.7%    8.9%   89.8%   0.0%    1.7%  40402 kBps
 14            up   12.9%    2.5%   89.8%   0.0%    1.7%  29180 kBps
 15            up    6.9%   19.8%   89.2%   0.0%    1.7%  25643 kBps
 16            up    0.0%    0.0%   89.3%   0.0%    1.7%      1 kBps
 17            up   24.8%   27.7%   89.8%   0.0%    1.7%  40401 kBps
 18            up    3.0%    1.0%   89.5%   0.0%    1.7%  22482 kBps
 19            up    1.0%    5.0%   89.6%   0.0%    1.7%  26936 kBps
 20            up    8.9%    1.0%   89.5%   0.0%    1.7%  23201 kBps
 21            up    0.0%    2.0%   00.0%   0.0%    1.7%   0472 kBps
 22            up    1.0%    8.9%   89.0%   0.0%    1.7%  38316 kBps
```

(Application and Protocol Processing)

(Figure- 4.5.2)

5. PERFORMANCE IMPACTS AND CARE ABOUTS

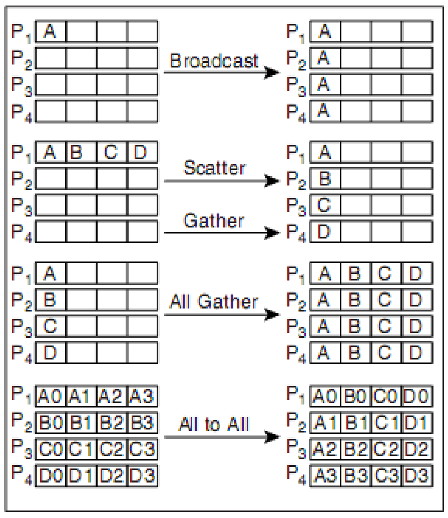
5.1 Throughput

Data throughput begins with a calculation of a *theoretical* maximum throughput and concludes with *effective* throughput. The effective throughput available between nodes will always be less than the theoretical maximum. Throughput for cluster nodes is based on many factors, including the following:

- Total number of nodes running
- Switch architectures
- Forwarding methodologies
- Queuing methodologies
- Buffering depth and allocations
- Noise and errors on the cable plant

As previously noted, parallel applications exhibit a wide range of communication behaviors and impose various requirements on the underlying network. These behaviors may be unique to individual applications and the requirements for inter-processor/inter-nodal communication. The methods used by the application programmer, as far as the passing of messages using MPI, vary based on the application requirements. The various MPI message-method gathering methodologies are show in Figure 5.1 below.

Figure 11 Throughput



MPI Message Collective Routines

MPI_Bcast() – broadcast from the root to all other processes

MPI_Gather() – gather values from the group of processes

MPI_Scatter() – scatters buffer in parts to group of processes

MPI_ Alltoall() – sends data from all processes to all processes

MPI_Reduce() – combine values on all processes to a single value

(Throughput)

(Figure- 5.1)

As shown in the examples in Figure 5.1, there are both simple and complex collective routines. As more scatter-gather, all gather, and all-to-all routines are used, multiple head-of-line blocking instances may occur within the switch, even within non-blocking switch architectures. Additionally, the buffer architectures of the underlying network, specifically the depth and allocation of ingress and egress

buffers, become key to throughput levels. If buffers fill, congestion management routines may be invoked. In the switch, this means that pause frames will be sent resulting in the sending node discontinuing sending traffic until the congestion subsides. In the case of TCP, the congestion avoidance algorithms comes into effect.

5.1.1 Slow Start

In the original implementation of TCP, as soon as a connection was established between two devices, they could each send segments as fast as they liked as long as there was room in the other device's receive window. In a busy network, the sudden appearance of a large amount of new traffic could exacerbate any existing congestion.

To alleviate this problem, modern TCP devices are restrained in the rate at which they initially send segments. Each sender is at first restricted to sending only an amount of data equal to one “full-sized”segment that is equal to the MSS value for the connection. Each time an acknowledgment is received, the amount of data the device can send is increased by the size of another full-sized segment. Thus, the device “starts slow” in terms of how much data it can send, with the amount it sends increasing until either the full window size is reached or congestion is detected on the link. In the latter case, the congestion avoidance feature, described below, is used.

5.1.2 Congestion Avoidance

When potential congestion is detected on a TCP link, a device responds by throttling back the rate at which it sends segments. A special algorithm is used that allows the device to drop the rate at which segments are sent quickly when congestion occurs. The device then uses the Slow Start algorithm, described above, to gradually increase the transmission rate back up again to try to maximize throughput without congestion occurring again.

In the event of packet drops, TCP retransmission algorithms will engage. Retransmission timeouts can reach delays of up to 200 milliseconds, thereby significantly impacting throughput.

6. CLUSTER APPLICATIONS

Few important cluster application are:

- Google Search Engine.
- Petroleum Reservoir Simulation.
- Protein Explorer.
- Earthquake Simulation.
- Image Rendering.

6.1 Google Search Engine

Internet search engines enable Internet users to search for information on the Internet by entering specific keywords. A widely used search engine, Google uses cluster computing to meet the huge quantity of worldwide search requests that comprise of a peak of thousands of queries per second. A single Google query needs to use at least tens of billions of processing cycles and access a few hundred megabytes of data in order to return satisfactory search results.

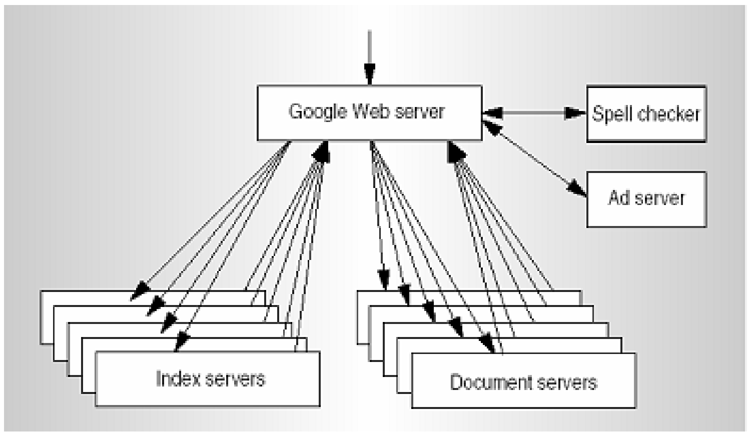
Google uses cluster computing as its solution to the high demand of system resources since clusters have better price-performance ratios than alternative high-performance computing platforms, and also use less electrical power. Google focuses on 2 important design factors: reliability and request throughput.

Google is able to achieve reliability at the software level so that a reliable computing infrastructure can be constructed on clusters of 15,000 commodity PCs distributed worldwide. The services for Google are also replicated across multiple machines in the clusters to provide the necessary availability. Google maximizes overall request throughput by performing parallel execution of individual search requests. This means that more search requests can be completed within a specific time interval.

A typical Google search consists of the following operations:

1. An Internet user enters a query at the Google webpage.
2. The web browser searches for the Internet Protocol (IP) address via the www.google.com Domain Name Server (DNS).
3. Google uses a DNS-based load balancing system that maps the query to a cluster that is geographically nearest to the user so as to minimize network communication delay time. The IP address of the selected cluster is returned.
4. The web browser then sends the search request in Hypertext Transport Protocol (HTTP) format to the selected cluster at the specified IP address.
5. The selected cluster then processes the query locally.
6. A hardware-based load balancer in the cluster monitors the available set of Google Web Servers (GWSs) in the cluster and distributes the requests evenly within the cluster.
7. A GWS machine receives the request, coordinates the query execution and sends the search resultback to the user's browser.

Figure shows how a GWS operates within a local cluster. The first phase of query execution involves index servers consulting an inverted index that match each query keyword to a matching list of documents. Relevance scores are also computed for matching documents so that the search result returned to the user is ordered by score. In the second phase, document servers fetch each document from disk to extract the title and the keyword-in-context portion of the document. In addition to the 2 phases, the GWS also activates the spell checker and the ad server. The spell checker verifies that the spelling of the query keywords is correct, while the ad server generate advertisements that relate to the query and may therefore interest the user.



(Google query-serving architecture)

(Figure- 6.1)

6.2 Petroleum Reservoir Simulation

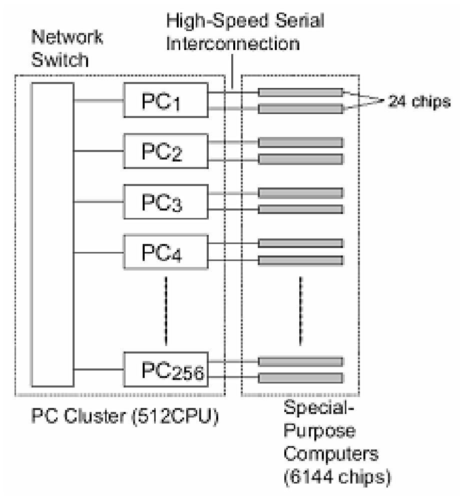
Petroleum reservoir simulation facilitates a better understanding of petroleum reservoirs that is crucial to better reservoir management and more efficient oil and gas production. It is an example of GCA as it demands intensive computations in order to simulate geological and physical models. For example, The Center for Petroleum and Geosystems Engineering of the University of Texas at Austin is constructing a new parallel petroleum reservoir simulator called General Purpose Adaptive Simulator (GPAS) using a cluster of 64 dual-processor servers with a total of 128 processors.

A typical petroleum reservoir simulator consists of a coupled set of non-linear partial differential equations and constitutive relations that describe the physical processes occurring in a petroleum reservoir. There are 2 most widely used simulators. The first is the black oil simulator that uses water, oil, and gas phases for modeling fluid flow in a reservoir. The second is the compositional simulator that uses phases with different chemical species for modeling physical processes occurring in a reservoir. Previously, compositional simulators were used less often since they are more complicated and thus require more intensive memory and processing requirements. With the advent of cluster computing, more researchers are using compositional simulators that use more data to characterize reservoirs.

The GPAS is a compositional petroleum reservoir simulator that can perform more accurate, efficient and high-resolution simulation of fluid flow in permeable media. It uses a finite-difference method which divides a continuous domain into smaller cells to solve the governing partial differential equations. The higher number of cells produces more accurate results, but requires more computation time. A fully implicit solution results in a structure of non-linear equations that are then resolved using Newton's method. However, large sparse linear systems of equations are needed to obtain numerical solution of these non-linear equations. Therefore, the Portable Extensible Toolkit for Scientific Computation (PETSc), a set of tools for solving partial differential equations, is used to solve these linear systems. To handle the parallel processing requirements, an Integrated Parallel Accurate Reservoir Simulator (IPARS) framework has been developed to separate the physical model development from parallel processing. IPARS provides input and output, memory management, domain decomposition, and message passing among processors to update overlapping regions. Communications between the simulator framework and a physical model are carried out through FORTRAN subroutine calls provided within the IPARS, thus hiding the complexities from the physical model developers who only need to call the FORTRAN subroutines to perform corresponding tasks.

6.3 Protein Explorer

The Bioinformatics Group at RIKEN Genomic Sciences Center in Japan is currently building the world-first petaflops supercomputer – the 'Protein Explorer' (PE) system will be a specialized system for molecular dynamics simulations, specifically, protein simulations, and is expected to be ready in early 2006. The PE system will be a PC cluster equipped with special-purpose engines to calculate non-bonded interactions between molecular atoms. These calculations constitute the most time-consuming portion of the simulations. The PE project is motivated by the national ‘Protein 3000’ project in Japan that was initiated in 2002 with the goal of solving the structures of 3,000 proteins by the year 2007.


Network Switch
High-Speed Serial Interconnection
PC1
PC2
PC3
PC4
PC256
24 chips
PC Cluster (512CPU)
Special-Purpose Computers (6144 chips)

(Block diagram of Protein Explorer system)

(Figure- 6.3)

Figure shows the components of the PE system. It will be a cluster of 256 dual-processor nodes giving a total of 512 processors, connected via Gigabit Ethernet. Each cluster node has 2 special-purpose engine boards (with 12 MDGRAPE-3 chips on each board) connected to it, giving it a total of 6,144 chips.

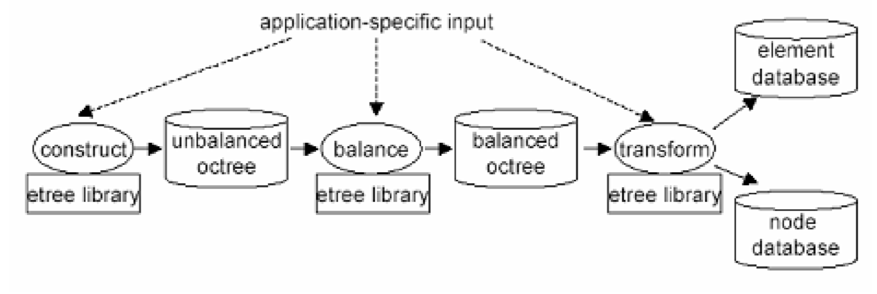
The cluster nodes will transmit the coordinates and the other data of particles for the molecular dynamics simulation to the special-purpose engines, which then calculate the non-bonded forces, such as Coulomb force and van der Walls force between particles before returning the results to the hosts. In other words, the special-purpose engines only focus on computing the most complex portion of the simulation that is calculating the non-bonded forces. All the coordination and other calculations are handled by the cluster nodes themselves.

6.4 Earthquake Simulation

Earthquake simulation is classified as a GCA given its high modeling and computational complexities. First, multiple spatial scales characterize the earthquake source and basin response ranging from tens of kilometers for the basin dimensions to hundreds of kilometers for earthquake sources. Second, temporal scales differ from the hundredths of a second for depicting the highest frequencies of the earthquake source to several minutes of shaking within the basin. Third, many basins have highly irregular geometry. Fourth, the soils in the basins comprise heterogeneous material properties. And fifth, there remains great uncertainty into the modeling process due to the indirect observation of geology and source parameters.

An ongoing research in the United States focuses on developing the capability for generating realistic inversion-based models of complex basin geology and earthquake sources. This capability can then be used to model and forecast strong ground motion during earthquakes in large basins such as Los Angeles (LA). Ground motion modeling and forecasting is essential to studying which structures will become vulnerable during the occurrence of an earthquake. This can be used to design future earthquake-resistant structures and retrofit existing structures so as to mitigate effects of an earthquake. The Los Angeles region is chosen as the case study because it is the most highly populated seismic region in the USA, has well-characterized geological structures (including a varied fault system), and has extensive records of past earthquakes.

The earthquake simulation is conducted using a terra-scale HP AlphaServer cluster which has 750 quadruple-processor nodes at the Pittsburgh Supercomputing Center (PSC). It simulates the 1994 Northridge earthquake in the Greater LA Basin at 1 Hz maximum frequency resolution and 100 m/s minimum shear wave velocity. The resulting unstructured mesh contains over 100 million grid points and 80 million hexahedral finite elements, ranking it as one of the largest unstructured mesh simulations ever conducted. This is also the most highly resolved simulation of the Northridge earthquake ever done. It sustains nearly a teraflops over 12 hours in solving the 300 million wave propagations.



(The etree method of generating octree meshes)

(Figure-6.4)

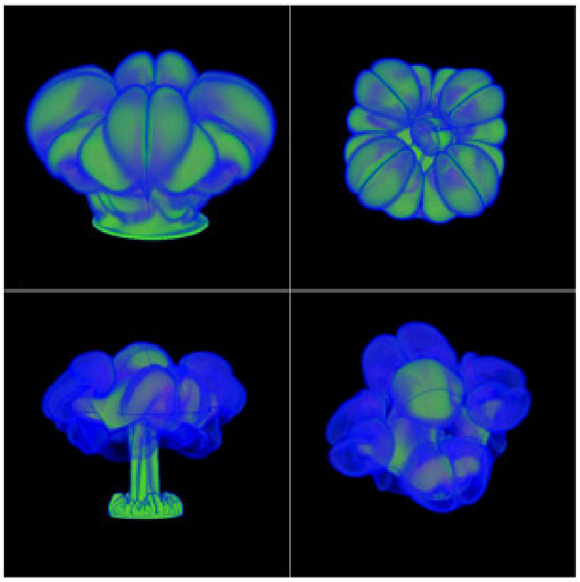
The simulations are based on multi-resolution mesh algorithms that can model the wide range of length and time scales depicting the earthquake response. Figure 6.4 shows the process of generating a mesh using the etree method. That method is used for earthquake simulations in heterogeneous basins where the shear wave velocity and maximum resolved frequency determine the local element size. At the initial “construct” step, an octree is constructed and stored on disk. The decompositions of the octants are dependent on the geometry or physics being modeled, thus resulting in an unbalanced octree. Then, the balance step recursively decomposes all the large octants that violate the 2-to-1 constraint until there are no more illegal conditions, thus creating a balanced octree. Finally, in the transform step, mesh-specific information such as the element-node relationship and the node coordinates are derived from the balanced octree and separately stored in two databases: one for the mesh elements, another for the mesh nodes.

For the balancing step, the whole domain is first partitioned into equal-size blocks. Then, internal balancing enforces the 2-to-1 constraint within each block. Finally, boundary balancing is used to resolve interactions between adjacent blocks. This local balancing step is very effective since it can achieve a speed-up ranging from 8 to 28, depending on the size of the meshes being balanced.

6.5 Image Rendering

The Scientific Computing and Imaging (SCI) Institute at University of Utah has explored cluster-based scientific visualization using a 32-node visualization cluster composed of commodity hardware components connected with a high-speed network. The OpenGL scientific visualization tool Simian has been modified to create a cluster-aware version of Simian that supports parallelization by making explicit use of remote cluster nodes through a message-passing interface (MPI). Simian is able to generate 3D images for fire-spread simulations that model scenarios such as when a missile located within a pool of jet fuel catches fire and explodes. Using image rendering for fire-spread simulations enables researchers to have a better visualization of the destructive effects.

Normally, Simian uses a swapping mechanism to manage datasets that are too large to load into the available texture memory, resulting in low performance and interactivity. For the cluster-aware Simian, large datasets are divided into sub-volumes that can be distributed across multiple cluster nodes, thus achieving the interactive performance. This "divide-and-conquer" technique first decomposes the dataset into sub-volumes before distributing the sub-volumes to multiple remote cluster nodes. Each node is then responsible for rendering its sub-volume using the locally available graphics hardware. The individual results are finally combined using a binary-swap compositing algorithm to generate the final image. This enables the cluster-aware Simian to visualize large-scale datasets to maintain interactive rates without the need of texture swapping.Figure shows the visualization of two fire-spread datasets simulating a heptane pool fire, generated by the cluster-aware version of Simian using 8 cluster nodes. The top row of Figure shows two views (side and top views) of the h300_0075 dataset, while the bottom row shows the h300_0130 dataset.



(Visualization of fire-spread datasets)

(Figure-6.5)

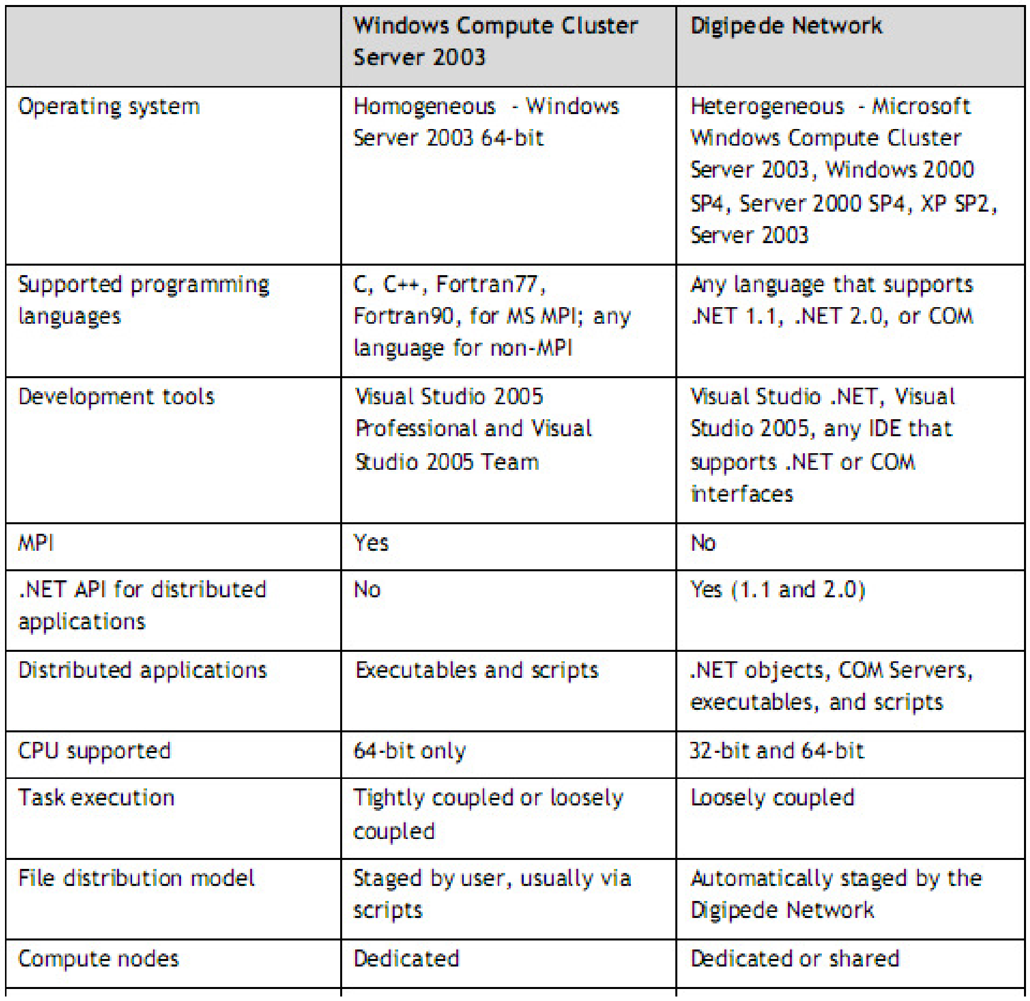
7. Comparison between Cluster Computing and Grid Computing.

The computers (or "nodes") on a cluster are networked in a tightly-coupled fashion--they are all on the same subnet of the same domain, often networked with very high bandwidth connections. The nodes are homogeneous; they all use the same hardware, run the same software, and are generally configured identically. Each node in a cluster is a dedicated resource--generally only the cluster applications run on a cluster node. One advantage available to clusters is the Message Passing Interface (MPI) which is a programming interface that allows the distributed application instances to communicate with each other and share information. Dedicated hardware, high-speed interconnects, and MPI provide clusters with the ability to work efficiently on “fine-grained” parallel problems, including problems with short tasks, some of which may depend on the results of previous tasks.

In contrast, the nodes on a grid can be loosely-coupled; they may exist across domains or subnets. The nodes can be heterogeneous; they can include diverse hardware and software configurations. A grid is a dynamic system that can accommodate nodes coming in and dropping out over time. This ability to grow and shrink at need contributes to a grid’s ability to scale applications easily. Grids typically do not require high-performance interconnects; rather, they usually are configured to work with existing network connections. As a result, grids are better suited to relatively “coarse-grained” parallel problems, including problems composed primarily of independent tasks. There is no dominant programming paradigm in grid computing today, and a key challenge to increasing the acceptance of grid computing is creating grid-enabled applications with familiar programming models. Digipede’s object-oriented programming for grid (OOP-G) is one such model.

Grids can incorporate clusters. Often the best way to make use of all available resources is to manage the cluster resources as part of a larger grid, assigning jobs and tasks to the resources best suited to those jobs and tasks. For example, jobs requiring MPI would be assigned exclusively to the cluster, while loosely-coupled jobs could be assigned to all grid nodes, including those in the cluster (when available). Indeed, cluster compute nodes make excellent grid nodes, and many grids are composed exclusively of dedicated servers. On the Windows operating system compute clusters are supported by Windows Compute Cluster Server 2003 and grid computing is supported by the Digipede Network™. The chart below gives an overview of the two solutions.

Both systems use similar terminology to define submitted requests: A job defines the work submitted to the system which includes the required resources and the tasks to execute. A task is an individual unit of work that can be executed concurrently with other tasks.



	Windows Compute Cluster Server 2003	Digipede Network
Operating system	Homogeneous - Windows Server 2003 64-bit	Heterogeneous - Microsoft Windows Compute Cluster Server 2003, Windows 2000 SP4, Server 2000 SP4, XP SP2, Server 2003
Supported programming languages	C, C++, Fortran77, Fortran90, for MS MPI; any language for non-MPI	Any language that supports .NET 1.1, .NET 2.0, or COM
Development tools	Visual Studio 2005 Professional and Visual Studio 2005 Team	Visual Studio .NET, Visual Studio 2005, any IDE that supports .NET or COM interfaces
MPI	Yes	No
.NET API for distributed applications	No	Yes (1.1 and 2.0)
Distributed applications	Executables and scripts	.NET objects, COM Servers, executables, and scripts
CPU supported	64-bit only	32-bit and 64-bit
Task execution	Tightly coupled or loosely coupled	Loosely coupled
File distribution model	Staged by user, usually via scripts	Automatically staged by the Digipede Network
Compute nodes	Dedicated	Dedicated or shared

(Clusters and Grids)
(Table-7.1)

8. CONCLUSION

High-performance cluster computing is enabling a new class of computationally intensive applications that are solving problems that were previously cost prohibitive for many enterprises. The use of commodity computers collaborating to resolve highly complex, computationally intensive tasks has broad application across several industry verticals such as chemistry or biology, quantum physics, petroleum exploration, crash test simulation, CG rendering, and financial risk analysis. However, cluster computing pushes the limits of server architectures, computing, and network performance.

Due to the economics of cluster computing and the flexibility and high performance offered, cluster computing has made its way into the mainstream enterprise data centers using clusters of various sizes. As clusters become more popular and more pervasive, careful consideration of the application requirements and what that translates to in terms of network characteristics becomes critical to the design and delivery of an optimal and reliable performing solution.

Knowledge of how the application uses the cluster nodes and how the characteristics of the application impact and are impacted by the underlying network is critically important. As critical as the selection of the cluster nodes and operating system, so too are the selection of the node interconnects and underlying cluster network switching technologies. A scalable and modular networking solution is critical, not only to provide incremental connectivity but also to provide incremental bandwidth options as the cluster grows. The ability to use advanced technologies within the same networking platform, such as 10 Gigabit Ethernet, provides new connectivity options, increases bandwidth, whilst providing investment protection.

The technologies associated with cluster computing, including host protocol stack-processing and interconnect technologies, are rapidly evolving to meet the demands of current, new, and emerging applications. Much progress has been made in the development of low-latency switches, protocols, and standards that efficiently and effectively use network hardware components.

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