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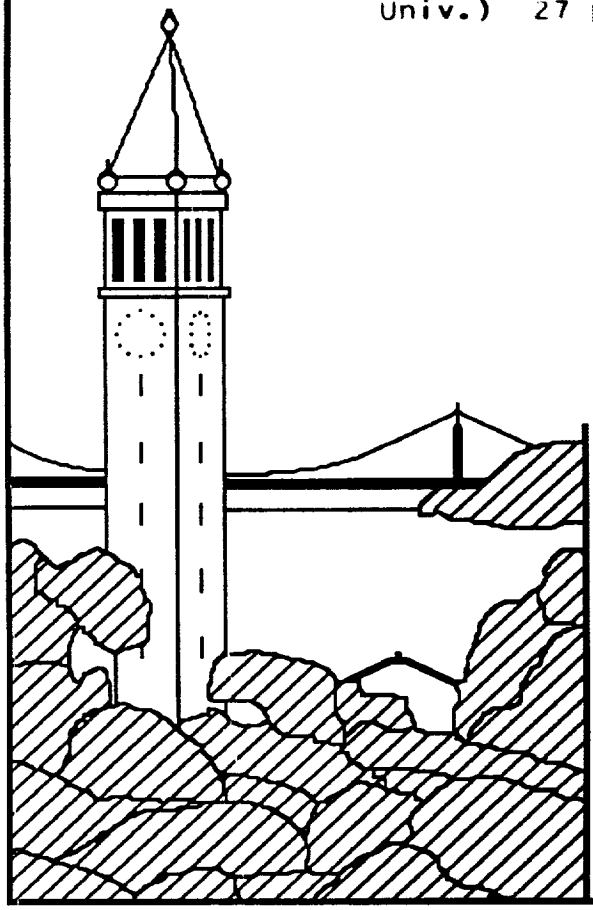

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Abstract: Rapid advances in high performance computing are making possible more complete and accurate computer-based modeling of complex physical phenomena, such as weather front interactions, dynamics of chemical reactions, numerical aerodynamic analysis of airframes, and ocean-land-atmosphere interactions. Many of these "grand challenge" applications are as demanding of the underlying storage system, in terms of their capacity and bandwidth requirements, as they are on the computational power of the processor. A global view of the Earth's ocean chlorophyll and land vegetation requires over 2 terabytes of raw satellite image data [ISTP91]!

In this paper, we describe our planned research program in high capacity, high bandwidth storage systems. The project has four overall goals. First, we will examine new methods for *high capacity* storage systems, made possible by low cost, small formfactor magnetic and optical tape systems. Second, access to the storage system will be *low latency and high bandwidth.* To achieve this, we must interleave data transfer at all levels of the storage system, including devices, controllers, servers, and communications links. Latency will be reduced by extensive caching throughout the storage hierarchy. Third, we will provide *effective management of a storage hierarchy,* extending the techniques already developed by Ousterhout for his Log Structured File System. Finally, we will construct a *prototype high capacity file server,* suitable for use on the National Research and Education Network (NREN). Such research must be a cornerstone of any coherent program in high performance computing and communications.

1. Introduction

The past decade has witnessed stunning increases in the computational power available for a broad spectrum of applications and users. Timeshared machines serving dozens of users with a performance rating of 1 SPECmark have been replaced by workstations that dedicate 50 SPECmarks or more to a single user. In the supercomputing arena, $10-million machines capable of 200 megaFLOPS have given way to machines in the same price range capable of almost 12,000 megaFLOPS. Furthermore, the explosion in computing power seems likely to continue for many more years. By the mid- to late-1990s we will see workstations containing multiple 500-SPECmark CPUs and supercomputers offering performance in the teraFLOPS range. The increases in CPU power will revolutionize not only Computer Science, but many other fields that use computers, such as Physics, Chemistry, Earth Sciences, and Economics.

Processing power alone does not make a computing system, however. Every increase in CPU power must be accompanied by an increase in the capacity and bandwidth of its storage system in order to provide the additional information that will be manipulated by faster CPUs. There is already some evidence that new systems are unbalanced in their storage capacities relative to their processing power. For example, the Intel Touchstone machine is 500% faster than the Cray-YMP, yet it has only 4% to 8% as much storage on-line (secondary plus tertiary) as typical Cray-YMP supercomputers centers.

Over the past four years, our group has pursued a successful research program to develop new high-performance I/O architectures to match the ever higher performance processors. Our major research achievements are RAID, Redundant Arrays of Inexpensive Disks, and Log Structured File Systems. The

latter overcomes the one disadvantage of RAIDs and lays the groundwork for very wide application of RAID technology. The Berkeley RAID project probably represents the single largest coordinated hardware-software research program in I/O architectures.

So far, we have focussed on I/O performance, and in particular on bandwidth. We took this approach because we saw the raw performance of CPUs increasing much faster than the raw performance of I/O devices, and we were afraid that slow I/O devices would become a performance bottleneck. We now believe, however, that capacity is as important an issue as bandwidth. Very fast computers not only need to access information quickly, but they need to incorporate an ever-increasing amount of information into their calculations. Unfortunately, current storage systems are woefully inadequate for storing and accessing information on the scale that is needed for future computing systems. Only a few large-scale storage systems exist, such as the Storage Technology Automated Cartridge System (ACS); they are very expensive, they don't use the most capacious and cost effective storage technology, they are not widely available, and they are somewhat restrictive in their system integration. New developments in storage technology, such as helical-scan tapes and optical disks and tape, offer the prospect of storage systems containing tens or hundreds of terabytes. This represents a thousand-fold increase in storage capacity relative to most of today's systems. We believe that such massive increases in on-line storage will be at least as revolutionary as the increases in computing power.

Storage capacity is probably even more important for applications outside of Computer Science than for applications in the field. [ISTP91] describes several "Grand Challenge" scientific applications that will drive high-performance computing and communications in the coming decade, and many of these challenges are limited as much by storage capacity as by computational power. One of the most interesting grand challenges involves the analysis of satellite data to understand global effects such as weather front interactions and ocean-land-atmosphere interactions. The data requirements for such studies are truly massive: for example, a global view of the Earth's ocean chlorophyll and land vegetation requires over two terabytes of raw satellite image data [ISTP91]. Over the next ten years the Earth Observation System will provide enormous amounts of new data for earth scientists (approximately one terabyte per day when it is fully functional). Efficient access to this massive information base is an enabling technology for research in global change and the earth sciences.

Our research group is actively participating in a project, called Sequoia 2000, which attacks the grand challenge of global change. It involves global change researchers at U.C. Santa Barbara, U.C. Los Angeles, and the Scripps Institute, plus computer scientists from Berkeley and other U.C. campuses. The Sequoia 2000 project brings together computer scientists and global change researchers to develop new storage systems and make them available over high-speed networks to scientists studying satellite data. Sequoia 2000 provides us with the exciting opportunity to work closely with demanding users in one of the most important research areas of this decade. Digital Equipment Corporation and the University of California have provided core funding for the Sequoia 2000 project in the form of workstations and telecommunications resources to interconnect the participating institutions.

In this paper, we describe a program of research to complement the Sequoia 2000 project. Our goal is to develop system architectures for secondary and tertiary storage systems and high-speed networks that will allow storage systems with 100-1000 terabytes total capacity to become practical and widely used by the mid- to late-1990s. We will test our ideas by building a prototype named "Bigfoot," that will store 10-100 terabytes (depending on the maturation of emerging storage technologies) for Sequoia global change researchers. We will evaluate our ideas and the Bigfoot prototype using Sequoia applications as benchmarks. Bigfoot will provide a thousand-fold increase in on-line storage capacity over today's disk-based systems, and it will provide a 10-100x improvement in capacity/cost over today's tertiary storage systems. Figure 1 demonstrates the area of investigation of our research program.

Our research program extends the RAID work in three directions: *tertiary storage*, *network integration*, and *application support*. The first new dimension is the inclusion of tertiary storage, such as robotical-

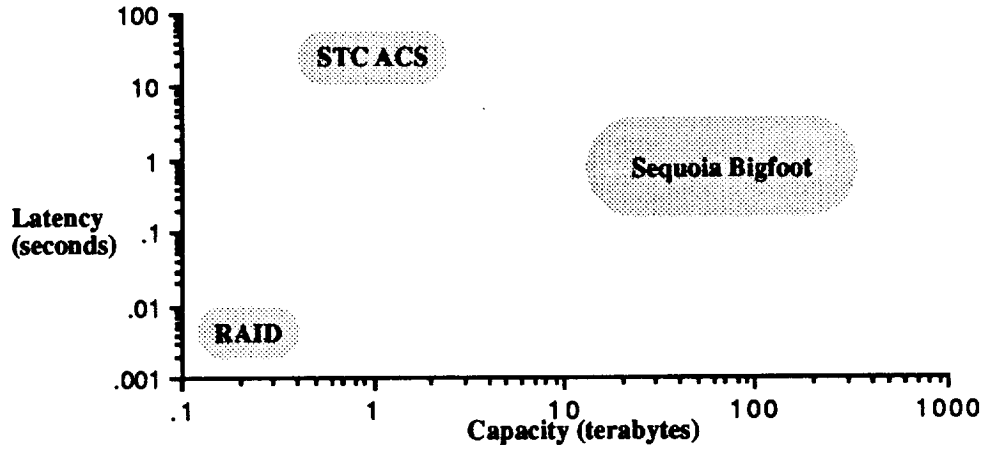

Figure 1: *Relationship of Sequoia "BigFoot" and STC ACS in terms of latency and capacity*
For systems costing $250,000 to $500,000. Bigfoot relies on several latency lowering techniques: this graph assume 80% to 85% of accesses go to disk cache, 10% to 15% write to a logging tape system, and 1% to 5% are random tape reads.

ly-controlled libraries of helical-scan tapes or optical disks. Such systems are necessary to provide multi-terabyte capacity at low cost, but they have serious performance limitations both in terms of latency and bandwidth. For example, the latency of a single access can be measured in tens to hundreds of seconds; this is so high that it can make demand fetches intolerable. One of the themes of our work is a multi-faceted attack on the latency of tertiary storage to make it as "on-line" as possible. In addition, the transfer speed of tertiary storage is almost two orders of magnitude worse than that of disk arrays. Another of our research themes is to use compression and interleaving at a number of levels to amplify the capacity and bandwidth of storage systems.

The second new dimension to our work here is techniques for integrating storage systems into a networked environment. This includes a number of research thrusts, such as striping data across servers and across networks in order to increase performance and using compression to amplify the limited bandwidth of long-haul networks.

The third way in which the research extends and improves upon the RAID work is that it couples us tightly to the global change scientists of Sequoia 2000. This application coupling provides us with a source of measurement data to guide our designs. It also allows us to focus our efforts on problems whose solution will provide the greatest benefit. At present the global change researchers have no viable alternative for their storage requirements, so we are guaranteed that our research results will be used and evaluated.

The rest of this paper is organized as follows. In the next section, we describe the trends in the underlying storage and network technologies that are making possible our vision of very large storage systems on a network. Section 3 describes our technical approach in detail, focussing on our strategies for library management, reduced latency, increased bandwidth, and geographic distribution. Section 4 compares our approach with other related research efforts. Our summary and conclusions are given in Section 6.

2. Technical Rationale

2.1. Introduction

In this section, we describe the detailed technology trends in storage systems hardware and software, applications, and compression that lead us to believe that significant new results can be achieved in distributed storage systems. These trends provide the technical underpinings of the research discussed in the next section.

The rest of this section is organized as follows. In Section 2.2, we review the trends in storage systems

technology. We concentrate on how the storage hierarchy has evolved over the past decade, and predict how we see it continuing to evolve through the end of this decade. The key technical developments, such as disk arrays, robo-line storage, tape technology, and storage systems on network-based interconnect, are also described. Section 2.3 describes the developments in software for managing the storage hiearchy, in particular, the Mass Storage System Reference Model. Section 2.4 reviews the needs of scientific applications, the most likely clients for kinds of massive storage systems described in this proposal. Compression technology, a key element of our approach for managing image data across geographically distributed sites, is discussed in Section 2.5.

2.2. State of the Art in Storage Systems Technology

2.2.1. Evolution of Storage Hierarchies

The storage hierarchy is traditionally modeled as a pyramid, with a small amount of expensive, fast storage at the pinnacle and larger capacity, lower cost, and lower performance storage as we move towards the base. In general, there are orders of magnitude differences in capacity, access time, and cost among the layers of the hierarchy.

A typical minicomputer of 1980 had a very simple memory hierarchy: perhaps 4 - 8 MBytes of main memory, 100 MBytes of magnetic disk, and essentially unlimited magnetic tape. The primary storage, at least as seen from the viewpoint of the I/O system, was a small file cache allocated in the main memory. This held data likely to be accessed in the near future. Secondary storage was universally provided by magnetic disk, with transfer rates in the 1 MByte/second range and access times of approximately 50 ms. Magnetic tape provided the tertiary storage off-line, primarily for archive/back-up. Nine track, 6250 BPI tapes, able to hold about 140 MBytes, were the dominant technology.

By 1990, the environment shifted to workstation/server computing, and with it, a more complex and distributed storage hierarchy. A primary performance limitation is the added latency of network accesses to obtain data from a remote server. With the advances in semiconductor technology, it is not unusual to find today's client workstations with 4 - 8 MBytes (of 32 MBytes) dedicated for use as a client cache. Most of the server's memory, perhaps 128 MBytes, is also dedicated to a cache function. Much of the active portion of the file system, especially the file system "meta-data," can be held in the server's fast semiconductor memory, thus avoiding the latency of a disk access in servicing user requests.

The success of client/server computing in the workstation environment suggests that a similar approach can work in the high performance arena given sufficiently fast interconnect between the client processor and the storage server. Figure 2 depicts one possible scenario for the storage hierarchy of 1995. Three major technical innovations shape the organization: disk arrays, storage subsystems based on optical disk or automated tape libraries, and high bandwidth wide area networks. To understand why these will become pervasive components of the future storage hierarchy, it is necessary to review the progress in the underlying storage and network technologies.

2.2.2. Disk Arrays, "Robo-Line" Storage Systems, and Network Integration

Because of the rapidly decreasing formfactor of magnetic disks, it is becoming attractive to replace a small number of large disk drives with very many small drives. This is called a *disk array*. The resulting secondary storage system can have much higher capacity since small format drives traditionally obtain the highest areal densities. And since the performance of both large and small disk drives is limited by mechanical delays, it is no surprise that performance can be dramatically improved if the data to be accessed is spread across many disk actuators. Disk arrays provide a method of organizing many disk drives to appear logically as a small number of very reliable drives of high capacity and high bandwidth [Katz 89].

Unlike conventional archival tape, which is meant to be written once and (hopefully) never read, *robo-line storage systems* (also called *near-line* storage systems) are designed to provide a very large storage ca-

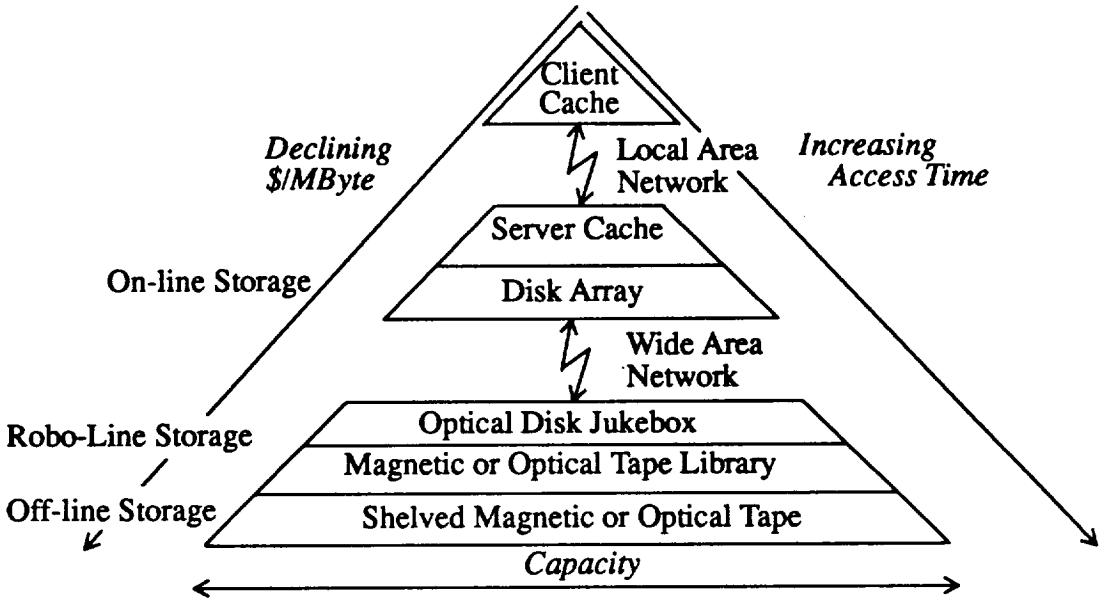

Figure 2: *Typical Storage Hierarchy, Circa, 1995.*
Conventional disks have been replaced by disk arrays, a method of obtaining much higher I/O bandwidth by striping data across multiple disks. A new level of storage emerges between on-line disk and off-line tape. It provides very high capacity, but at access times measured in seconds due to the mechanical robot. Hence the names "robo-line" or "near-line." For robo-line storage, optical disk jukeboxes have faster access times than tape-oriented systems, but lower capacity. We expect the storage hierarchy to span local and wide area networks.

pacity that can be frequently read and potentially rewritten. This is accomplished through the use of very densely recorded media, such as optical disk or high capacity tape, in conjunction with robotic "pickers" to stage media between shelves and readers. Access times are measured in milliseconds to seconds for data that has already been loaded in a reader to tens of seconds for data on the shelf. The name "robo-line" suggests a compromise in both latency and cost between directly connected on-line storage and off-line storage which requires the assistance of a human operator.

Optically recorded disks have long been thought to be ideal for filling this level of the storage hierarchy [Ranade 90]. They combine improved storage capacity (2 GBytes per platter surface originally to over 6 GBytes per side today) with access times that are approximately a factor of ten slower than conventional magnetic disks (several hundred milliseconds). The first generation of optical disks were written once, but could be read many times, leading to the term "WORM" to describe the technology. The write once nature of optical storage actually makes it better suited for an archival medium than robo-line storage, since it is impossible to accidently overwrite data once it has been written. A problem has been its relatively slow transfer rate, 100K – 200K bytes per second. Newer generations of optical drives now exceed one megabyte per second transfers.

Magneto-optical technologies, based on a combination of optical and magnetic recording techniques, have recently led to the availability of erasable optical drives. Read transfer rates are comparable to those of conventional magnetic disks. Access times are still slower than a magnetic disk due to the more massive read/write mechanism holding the laser optics. The write transfer rate is worse in optical disk systems because (1) the disk surface must first be erased before new data can be recorded, and (2) the written data must be reread to verify that it was written correctly to the disk surface. Thus, a write operation could require three disk revolutions before it completes.

Nevertheless, as the formfactor and price of optical drives continue to decrease, optical disk libraries will become more pervasive. Table 1 describes the system parameters of two alternative optical disk juke-

Vendor	Formfactor (inches)	Drives	Platters	Capacity (per platter)	Data Transfer (KBytes/second)	Access Time (second)
HP 6300 Model 20GB/A	5.25"	2	32	600 MB	340 - 680	7.0 (pick) 4.0 (load) 2.4 (spin-up) 0.1 (seek)
Kodak 6800 Automated Disk Library	14"	1 - 3	50 - 150	6800 MB	1000	6.5 (disk change) 0.1 - 0.7 (seek)

Table 1. Relevant Metrics for Alternative Optical Disk Jukeboxes.

box systems, the Hewlett-Packard Series 6300 Model 20GB/A Optical Disk Library System [Hewlett-Packard 89] and the Kodak Optical Disk System 6800 Automated Disk Library [Kodak 90]. Despite an order of magnitude difference in the price of these two systems, the expected access time only varies between 7 and 14 seconds!

2.2.3. Tape Technology

The success of automated tape libraries has demonstrated that tape can also be used to implement a robo-line storage system. The most pervasive magnetic tape technology available today is based on the IBM 3480 half-inch tape cartridge, storing 200 MBytes and providing transfer rates of 3 MBytes per second. However, there has been an enormous increase in tape capacity, driven primarily by *helical scan recording* methods. The technology is based on the same tape transport mechanisms developed for video cassette recorders in the VHS and 8 mm tape formats and the newer 4 mm digital audio tape (DAT) systems.

Each of these systems provide a very high storage capacity in a small easy-to-handle cartridge. The small formfactor makes them particularly attractive as the basis for automated data libraries, because of the simpler robots that can be used. Tape systems from Exabyte, based on the 8 mm video tape format, can store 5 GBytes and transfer at approximately 500 KBytes per second. A tape library system based on a 19" rack can hold up to four tape readers and over one hundred 8mm cartridges, thus providing a storage capacity of 500 GBs [Exabyte90] for less than $40,000 (OEM pricing).

DAT tape provides smaller capacity and bandwidth than 8 mm, but enjoys other advantages [Tan 89]. Low cost tape readers in the 3.5" formfactor, the size of a personal computer floppy disk drive, are readily available. This makes possible the construction of tape libraries with a higher ratio of tape readers to tape media, increasing the aggregate bandwidth to the robo-line storage system. In addition, the DAT tape formats support subindex fields which can be searched at speed two hundred times greater than the normal read/write speed. A given file can be found on a DAT tape in an average search time of only 20 seconds. Due to competitive pressures, 8mm tape systems have recently incorporated a similar fast search capability.

Helical scan techniques are not limited to consumer applications, but have also been applied for certain instrument recording applications, such as satellite telemetry, which require high capacity and bandwidth. The Ampex TeraStore Data D-2 (DD-2) cassette recorder features a 15 MByte/second transfer rate from tape cassettes that can hold from 25 GBytes (small cassette) to 165 GBytes (large cassette). An associated tape robot can hold up to 6.4 TBytes of data (256 small cassettes) in 21 square feet (306 GBytes/sq. ft.). Because of their relatively low production volumes, such systems are very expensive.

A new recording technology that appears promising is optical tape. The recording medium is called *digital paper*, a material constructed from an optically sensitive layer that has been coated onto a substrate similar to magnetic tape. The basic recording technique is similar to write once optical disk storage. One 12 inch diameter by 2400 foot reel holds 1 TB of data, can be read or written at the rate of 3 MBytes per second, and can be accessed in a remarkable average time of 28 seconds. Two companies are developing tape readers for digital paper: CREO Corporation [Spencer 88] and LaserTape Corporation. CREO makes use of a

Technology	Capacity (MB)	Media Cost (Removable)	Density (Mb/in^2)	Data Xfer (KB/s)	Access Time (1/3 full seek)	Xchg Time (unload/load)	Media Limits (Reads)	(Writes)
Conventional Tape								
Reel-to-Reel (1/2")	140	$5	0.11	549	minutes	minutes	∞	∞
Cartridge (1/4")	150	$15	1.25	92	minutes	minutes	∞	∞
IBM 3480 (1/2")	200	$5	0.87	3,000	15 secs	10 secs	∞	∞
Helical Scan Tape								
VHS (1/2")	15,000	$29	?	4,000	45 secs	6 secs	500	500
Video (8mm)	4,600	$14	70.56	492	45 secs	100 secs	500	500
DAT (4mm)	1,300	$8	114.07	183	20 secs	55 secs	500	500
DD-2 (19mm)	25,000	$140	46.00	15,000	15 secs	5 secs	1,000	1,000
Optical Tape								
CREO (35mm)	1,000,000	$5000?	224.00	3,000	30 secs	minutes	∞	1
LaserTape (1/2")	50,000	$35	224.00	3,000	15 secs	10 secs	∞	1
Magnetic Disk (fixed media)								
Seagate Elite (5.25")	1,200	n.a.	63.01	3,000	18 ms	n.a.	∞	∞
IBM 3390 (10.5")	3,800	n.a.	62.44	4,250	20 ms	n.a.	∞	∞
Optical Disk								
Sony MO (5.25")	640	$100	453.54	500	100 ms	8 secs	∞	∞
Kodak (14")	3,200	$500	296.33	1,000	100's ms	7 secs	∞	1

Table 2. Relevant Metrics for Alternative Storage Technologies.
Latency of robo-line storage is determined by Exchange Time (Xchg Time: the time to unload the removable media and then load a new unit and get it ready to read) plus the time for an average seek (time to seek 1/3 of the full storage on the media.) Helical scan tapes wear out after 1000 to 2000 accesses.

12 inch tape reels and a unique laser scanner array to read and write multiple tracks 32-bits at a time. The system sells for over $200,000. LaserTape places digital paper in a conventional 3480 tape cartridge (50 GBytes capacity, 3 MBytes per second transfer rate). A 3480 tape reader that is "retrofitted" costs approximately $25,000 compared to the $15,000 for the older model. Existing tape library robotics for the 3480 cartridge formfactor can be adapted to LaserTape without changes.

Table 2 summarizes the relevant metrics of the alternative storage technologies. The metrics displayed are the capacity, removable media cost, areal density (in millions of bits per square inch), data transfer rate (KBytes per second for sustained transfers), average positioning times, exchange times of removable media (time to unload an old tape and load a new one), and maximum number of reads and writes the media can sustain. Exchange times and access times are especially important for evaluating robo-line storage media. The table shows that while helical scan media are very inexpensive, especially for consumer markets such as VHS, video, or DAT, the helical scan heads wear out the tapes in 500 to 1000 accesses. The long switch and access times plus limited accesses before the tape must be replaced decrease the attraction of helical scan for robo-line storage. The price per megabyte of optical disk media, on the other hand, is 30 to 80 times worse than helical scan tapes. Overall, optical tape appears to be the most promising technology in terms of capacity, latency, and bandwidth, but the optical tape technology is the least mature of all the technologies in Table 2.

The key technical challenges are how to build a storage system with the low-cost capacity of tape with the access times of optical disk. We intend to overcome the low bandwidth of robo-line storage systems by leveraging interleaving and compression techniques. And we will reduce the latency to robo-line storage

Operation	Machine	SPECMarks	Network	Raw B/W (Mb/s)	Latency (ms)
Sprite RPC	Sun-3	2	Ethernet	10	2.5
Sprite RPC	DS5000	18	Ethernet	10	0.8
Sprite RPC	Sun-3	2	Ultranet	1000	3.5
UW RPC	DS5000	18	Ethernet	10	0.34
UW RPC	DS5000	18	FDDI	100	0.38
Nectar	Sun-4	9	Nectar	100	0.45

Table 3. Bandwidth and Latency of Some Workstations and Networks.
Note that the higher bandwidths of the FDDI and UltraNetwork do not yield lower network latencies. While faster processor will reduce latency, it does not do so at the same rate as its processing power increases. Latency overhead is expected to dominate network overhead.

system by constructing a storage hierarchy that migrates infrequently accessed data to the tape while keeping frequently accessed data on disk.

2.2.4. Networks

The 1980's were the Ethernet decade. Ten-megabit Ethernet became widely available in the early 1980's, and interface chips quickly became cheap enough to include with all engineering workstations. Ethernet, as the dominant technology for local-area networks, spurred the development of network file systems and a variety of other network software, and played a large role in the emergence of high performance engineering workstations.

By the end of the 1980's it was clear that 10 Mbits/second was not enough bandwidth to support the high-speed RISC workstations of the 1990's. In the last few years a number of high-speed networking technologies have appeared, including the FDDI standard (100 Mbits/s), UltraNet (100 MByte/second), and a number of research efforts such as CMU's Nectar (100 Mbit/second) [Arnould 89] and DEC's Autonet (100 Mbit/second per link with higher aggregate network bandwidth) [Schroeder 90]. Our rule of thumb, based on experience with file systems at U. C. Berkeley for example, is that a local area network connecting 50-100 workstations should have 1 Mbit/second of bandwidth for each SPECmark of computing power in a single workstation. Thus today's state-of-the-art workstations with 20-50 SPECmarks can easily overload Ethernet. Given that workstations with 100-500 SPECmarks will be available within a few years, it seems likely that FDDI will be a short-lived standard and will be superceded very soon by a networking technology in the 1 Gbit range.

We see two overall trends in networking technology. First, bandwidths in the gigabit range seem certain to become widely available in the next 5-10 years. At this speed, network bandwidth will be comparable to the memory bus bandwidth of the machines attached to the network, so there becomes very little performance distinction (at least in terms of bandwidth) between a device attached to an individual machine and a device accessed over the network.

The second overall trend is that network latency is not improving as rapidly as either network bandwidth or processor speed; in many cases, networks with higher bandwidth actually have *worse* latency than Ethernet. We measured the bandwidth and latency of a number of different networks (see Table 3). The commercially available UltraNetwork has much higher raw bandwidth than Ethernet, but the round trip latency for RPC is actually 30% worse. Also, note that a DECStation 5000 shows only a 3-fold reduction in network latency relative to a SUN-3, even though it has 10 times the processing power. Researchers at the University of Washington measured latencies 10% worse for FDDI than for Ethernet [Levy 91] even on a small FDDI network; a larger FDDI network will have higher latency due to the additional links packets must traverse. CMU's Nectar project has made an aggressive attack on both latency and bandwidth; it improved bandwidth by nearly a factor of 10 relative to other systems, but improved latency by only about a factor of 2.

The lack of improvement in network latency presents potential problems for future networked systems. Even in scientific environments with many large files, there are also many small files; typically, large files account for most of the bytes transferred, but most accesses are to small files. Furthermore, the increases in network bandwidth make more and more transfers latency dominated. For example, the median file size in an engineering environment is about 5 KBytes. On a 1 GBit/second network, such a file requires 0.04 milliseconds of transmission time. Given the latencies from Table 3, the cost of reading or writing such a file will be totally dominated by network latency. Even a 100-KByte file requires only 0.8 milliseconds of transmission time; more than one-third of the time to transfer such a file will be due to network latency.

2.3. Mass Storage System Reference Model

Supercomputer users have long had to deal with the problem that high performance machines do not come with scalable I/O systems. As a result, each of the major supercomputer centers has been forced to develop its own mass storage system, typically a network-based storage organization in which files are staged from the back-end storage server, usually a robo-line subsystem, to the front-end supercomputer.

The Mass Storage System (MSS) Reference Model was developed by the managers of these supercomputer centers, to promote more interoperability among mass storage systems and to influence vendors to build such systems to a "standard." The purpose of the reference model is to provide a framework within which standard interfaces can be defined. They begin with the fundamental underlying premise that the storage system will be distributed over multiple machines potentially running different operating systems.

The MSS Reference Model defines six elements of the mass storage system: Name Server, Bitfile Client, Bitfile Server, Storage Server, Physical Volume Repository, and Bitfile Mover. Bit files are the model's terminology for uninterpreted bit data streams. There are different ways to assign these elements to underlying hardware. For example, the Name Server and Bitfile Server may run on a single Mass Storage control processor, or they may run on independent communicating machines.

An application's request for I/O service begins with a conversation with the Name Server. The name service maps a user-readable file name into an internally recognized bitfile ID. The client's requests for data are then sent to the Bitfile Server, identifying the desired files through their IDs. The Bitfile Server maps these into requests to the Storage Server. It handles the logical aspects of file storage and retrieval, such as directories and descriptor tables. The Storage Server handles the physical aspects of file storage, and manages the physical data volumes. It may request the Physical Data Repository to mount volumes if they are off-line. For example, one storage server may be specialized for tape handling while another manages disk. The Bitfile Mover is responsible for moving data between the Storage Server and the client, usually over a network. It provides the components and protocols for high-speed data transfer.

The MSS Reference Model has been incorporated into at least one commercial product: the Unitree™ File Management System sold by General Atomics, Inc. This is a UNIX-based hierarchical storage management system, based on software originally developed at the Lawrence Livermore National Laboratory. This, and other similar systems, are described in Section 4.2.

2.4. Applications Needs

[ISTP91] describes several "Grand Challenge" scientific applications that will drive high performance computing and communications in the coming decade. As faster, more powerful processors become available, scientists will use them to compute over ever larger data sets with even finer time steps. These computations will place enormous demands, both for capacity and performance, on the underlying storage systems.

We highlight a particular applications areas of considerable interest to the Earth System Scientists with whom we are participating on the Sequoia 2000 project: the numerical simulation and remote sensing-based analysis of large scale land-ocean-atmosphere interactions. Much of what these scientists need to do is similar to defense applications: remote sensing, high definition systems, simulation of physical phenomena,

weather prediction, and scientific visualization.

Earth System Science researchers need access to geophysical and biological information, as well as raw data from spaceborne instruments or in situ sensors. The researchers must be able to collate and cross-correlate data sets about the Earth by processing the data from the satellite and aircraft observatories and other selected sources. For example, Prof. Dozier of U.C.S.B. routinely examines images from the Thematic Mapper satellite to determine the water content of the snow cover in the mountains. Each image requires 300 MB, and he is interested in both the long term history and the most recent broadcasts. An additional application is in models of the dynamics, physics, and chemistry of climatic subsystems which are accomplished through coupled General Circulation Models (GCMs). These can generate huge data sets of output that represent grids of variables denoting atmospheric, oceanic, and land surface conditions. The models need to be analyzed and validated by comparison with values generated by other models, as well as with those values actually measured by sensors in the field.

To get a feeling for the kinds of data sets involved in evaluating global change over the last century, consider the following. The archives of the National Meteorological Center (NMC) contain daily weather analyses from 1946, and collectively measure 2×10^{11} bits (20 GBytes). A second data set contains the weather observations from the logs of over 72 million ships between the years 1854 and 1979. In addition, high resolution satellite data collected since 1968 brings the total data volume to 1×10^{13} bits (1 TByte). As of late 1988, the mass storage system at NCAR in Boulder, Colorado stored almost 300,000 bit files and managed 50,000 3480 tape cartridges, for a total of 55 TBytes of data.

[Halem89] describes some of the computational challenges to be addressed by Earth System Science researchers in this decade. NASA's Earth Observing System (EOS) is expected to archive 1 to 10 petabits (100 to 1000 TBytes) per year for the 20 year lifetime of the program starting in the mid-1990s! This is on the order of 1 TByte per day.

A key limitation for Earth System Science researchers is the lack of a storage system that meets their need for capacity and remote access. Much of the critical data for the analysis of long term climate changes are inaccessible to the average researcher. By working closely with Earth System Science research community, it becomes feasible for us to think of filling a multi-terabyte tertiary store.

2.5. Compression

Compression has long been of interest in computer systems as a method for increasing the capacity of the storage system. Algorithms can be characterized as being *lossless* or *lossy*. Lossless algorithms lose no information during the compression and decompression process. Lossy algorithms achieve higher compression ratios by losing information, and thus are only of use for image or video data where such losses can be tolerated.

One of the most extensively used lossless compression algorithms is the Lempel-Ziv method. A one pass algorithm, it builds a translation table on the fly, recoding variable length data strings with shorter length codewords built up in the translation table. For typical ASCII text, Lempel-Ziv yields compression ratios in the range of 2 to 3 (i.e., the compressed file is 1/2 to 1/3 the size of the uncompression file). The algorithm is fast enough to be implemented as software utilities on many systems. Industry standard derivatives of the Lempel-Ziv method are now being embedded in a variety of tape drive systems, primarily to increase the storage capacity of the medium.

For image data in which some loss of resolution can be tolerated, the alternative lossy compression strategies are very attractive. Two emerging industry standards are the JPEG (still image) and MPEG (video image) methods. We describe the JPEG (Joint Photographic Expert Group) method first.

JPEG begins by dividing an image into 8 x 8 pixel blocks. RGB values are then converted to an alternative colorspace representation based on luminance, chrominance, and intensity (UVY). This representation has better compression properties. At this point, an optional subsampling information losing step can be inserted. Basically, alternative rows and columns of pixels are deleted from the image.

The next step is to apply the forward discrete cosine transform (DCT), mapping the pixels into a frequency representation. Since most of the picture's information content is captured by the lower frequencies (upper lefthand corner of the 8x8 matrix), many of the higher frequency entries contain small values or zero.

The next step, quantization, introduces most of the information loss. The matrix entries are rescaled by dividing the 8 x 8 transform matrix by an 8 x 8 quantization matrix and then rounding. The quantization matrix is the major "parameter" to the compression algorithm that controls the level of loss in the image. The effect of the quantization step is to introduce zeros into the higher frequency entries of the matrix.

The final step is a Huffman encoding, which can apply run-length encoding to the streams of 0's. This significantly reduces the number of bits needed to encode the image. By choosing the degree of subsampling and quantization, it is possible to vary the quality of the image. Lossless compression will typically yield a compression ratio of approximately 2:1, "excellent" image quality is approximately 8:1, "high" quality is 15:1, "good" quality is 20:1, and "fair" quality is 40:1. Depending on the sharpness and contrast in the image, much higher compression ratios can be achieved.

JPEG compression/decompression algorithms have recently become available as software utilities, and while these are acceptable for occasional image manipulation, they are not yet fast enough for 30 frame per second video decompression. Several companies, including CCube, Storm Technologies/Micron, and LSI Logic have produced special purpose hardware to accelerate JPEG compression/decompression.

The MPEG (Moving Picture Experts Group) method builds on top of the JPEG standard to apply compression to video image streams. MPEG adds new techniques to reduce temporal redundancy, while using JPEG methods to reduce spatial redundancy.

MPEG organizes a video stream into three different kinds of pictures: intrapictures (I), predicted pictures (P), and bidirectional pictures (B). An intrapicture carries enough information to be decompressed without reference to proceeding or following frames. It can be the target of a random access, but obtains only a moderate degree of compression. Predicted pictures are computed as a difference from a previous picture in the sequence. This obtains better compression for the forward translation of localized motion. Bidirectional pictures are computed in terms of differences between previous and future pictures. This obtains better compression for uncovered regions and exhibits better error recovery behavior. To decompress bidirectional pictures, the algorithm needs access to pictures before it and after it in the video sequence.

Compression ratios in the range of 50 to 100:1 are claimed for MPEG. The first hardware accelerator chip sets for MPEG, from CCube, have recently been demonstrated.

3. Technical Approach

3.1. Overview

The classic goals of a storage system are greater capacity, lower latency, greater bandwidth, and high reliability. We have four main approaches to towards these goals (see Table 4):

1. **Massive Storage Laboratory**: Massive storage is currently facing a revolution in new technologies, and there is little information on the performance/reliability trade-offs of these new options. We will create a laboratory containing several different storage systems, evaluate the tradeoffs between the different technologies, and develop support software that can be used on multiple storage systems. The purpose of the lab is to give us head-start in evaluating the emerging technologies and in developing the software for them, as well as to give us a forum to influence future offerings from the industry.
2. **Managing Storage Latency**: While these emerging technologies make tremendous improvements in capacity, they do this at tremendous cost to latency. By taking a systems approach to the problem, we hope to overcome some of the latency problems. Ideas include avoiding tertiary accesses via caching and abstracting, lowering media latency by revising controller software, and designing hybrid massive storage systems.

3. **Compression**: Data compression acts as a multiplier both for the capacity of a storage system and the bandwidth of interconnect. Traditional approaches to compression have focussed on isolated portions of a system, such as a single link or storage device. In this project we will take a system-level approach to compression: more data will stay compressed longer, and different compression algorithms will be used, depending on the nature of the data. By doing this we hope to increase the benefits provided by compression.
4. **Interleaving Across Multiple Components**: Interleaving provides a method to scale I/O bandwidth. If the transfer rate of a single disk is insufficient for the application, in the RAID project we spread the data over multiple disks and perform the transfers in parallel. This same basic argument applies to all aspects of the I/O system: it is possible to increase bandwidth by interleaving across multiple tapes, multiple robo-line storage subsystems, multiple file servers, and even multiple network interconnections.
5. **Redundant Components**: The opportunity to replace large disks by small ones in RAID enabled both the interleaving to get higher bandwidth and the redundant drives to give higher reliability. The same approach applies here: multiple components in a massive storage system allow higher bandwidth via interleaving and higher reliability by providing more components than the absolute minimum. The extra components allow failures to be detected, corrected, and then avoided until repaired.

Each of these five approaches can potentially improve several of the storage system metrics. Table 4 shows the impact of each approach on the classic goals for storage systems.

3.2. Massive Storage Laboratory

One difficulty with massive storage is that the newest and most exciting technologies are being offered by essentially start-up companies. Many candidate technologies are coming to market for the first time in 1991 or 1992, and each technology is usually associated with a single company. So unlike the RAID project we have no body of knowledge on performance, reliability, or even the reality of some of the options that appear in trade magazines.

One solution is to wait two to three years for the dust to settle, and then work with the winners. This approach has several drawbacks:

- **Time to General Acceptance**: By waiting three years before starting with the technology, we delay its inclusion into computing systems; in particular, we delay the creation of the software that can put the technology to work, which is typically the obstacle to the success of any new computer technology.
- **Influencing the Next Generation**: By cooperating with these emerging companies and reporting the results of our experiments, we can be in a position influence the next generation of these products to be more effective in high performance, scalable computer systems.
- **False Starts**: With the wide variety of options, several groups will likely pick ones that prove to be white elephants. Sour initial experiences can result in rejection of an entire industry. Early evaluation by an unbiased research group can avoid wasting the time and money of many people making false starts, as well as avoid initial negative impressions that are difficult to overcome to gain acceptance of a

	Capacity	*Latency*	*Bandwidth*	*Reliability*
Massive Storage Laboratory	High	High	Medium	High
Managing Storage Latency	Medium	High	Low	--
Compression	High	Medium	High	--
Interleaving Multiple Components	--	Low	High	--
Redundant Components	--	--	Medium	High

Table 4. Impact of our four approaches on each of the four classic storage metrics.

new technology.

We believe that we will more quickly reach the goal of terabytes of storage being readily available by acting immediately. Hence our plan is to get several initial examples of this emerging technology and put them to work:

- Small robot and reader for 3480 cartridges using Digital Paper; each cartridge has 50 GB storage capacity in a write-once medium and the drives transfer at 3 MB/S bandwidth;
- Small robot and reader for 19 mm helical scan tapes (DD2), each with 25 GB capacity and 15 MB/S bandwidth;
- Small robot and reader for 1/2 inch helical scan tapes (T-120), each with 15 GB capacity and 4 MB/S bandwidth;
- Small robot and reader for 8 mm helical scan tapes, such as the EXB -120
- Stackers containing 4mm or 8mm helical scan tapes (DAT or video), each with 1 to 5 GB capacity and 0.5 MB/S bandwidth;
- Low cost robot for Read/Write optical disks, each with 0.65 GB capacity and 1 MB/S read bandwidth.

Hands-on experience with these systems will allow us to understand the strengths and the weaknesses of each option. Moreover, the software we create must work with several technologies because the "winners" may be application dependent, and our experience is that software is difficult to port unless it is developed in a heterogeneous environment.

As users of these new technologies we hope to be able answer questions about their reliability, based both on our experience and in working with the manufacturers to answer our questions. We found that getting reliability numbers on individual disks was nearly impossible when we asked as researchers, but that customers had a leverage with the company and could get the data. We believe this will be especially true of this emerging massive storage industry, as companies need to address the customer's problems to survive. Moreover, we can run experiments ourselves to verify the answers we get from these start-up companies. And one clear goal in our interactions with companies is to influence the next version of the technology, particularly in making it work well in high performance, scalable computer systems.

This experience with these first system lays the foundation to construct a high capacity massive storage system that has low latency, scalable bandwidth, and high reliability.

3.3. Low Latency via Caching on the Local File Server

One of the first latency hiding techniques we call *abstraction*. It lowers latency by completely avoiding the access to tertiary storage. Our assumption is that many file accesses are for browsing rather than reading the file in full. To permit fast browsing without tertiary storage accesses, we will keep small *abstracts* on disk. An abstract is a highly-compressed version of a file, where the exact information kept in the abstract is chosen based on the type of the file. For an image, the abstract might be a sampled reduction of the image. In Dozier's case we might supply only the 3 most important spectral bands, reduce the grid to 1000 x 850 via averaging, and then compress. Just as we intend to use different compression algorithms depending on the type of data in a file (see Section 3.6 below), we can invoke different abstraction programs depending on that file type. Abstraction could reduce the size of the image by 7/3 x 7000/1000 x 6000/850 x 8 or 920. Hence Dozier could maintain almost 1000 abstracts on his local file server for the cost of one full image. His latency is limited only by the speed of the local area network, the speed of decompression, and the RAID on his file server.

Another application of abstraction is with text files, such as browsing through electronic mail messages. By keeping a subset of the information on the file server—such as the date, sender, subject line, and selected index terms from the body of the message—and then compressing that data, keeping a fraction of the message on the disk may serve to avoid many accesses to tertiary storage. For example, a message on the outline of this proposal contained 2011 characters. The author, subject line, date, and a few words from the

body took 54 characters. If this data were compressed 3:1, then this abstract would represent less than 1% of the original message. In this case the user's response time would be limited only by the latency of the local area network and the file server.

A second latency lowering technique is *anticipatory fetching*. Anticipatory fetching hides latency by reading the data in advance of its demand. This can take several flavors: reading all the files in a directory versus a single file on a request, reading all the files in a makefile versus sequential requests, passive learning of the probabilities of access to other files given past history, and user hints. As an example in this last category, assume a window pops up at 5PM to ask if Dozier will be in tomorrow, and if so what geographic areas and time periods might he be interested in. He would answer this question by browsing through the abstracts of the images he is likely to work on next. His estimate of usage is sent to the massive storage system which merges this request with all other users. Data is then shipped overnight to local file servers using the most economical means of data transfer. The data is on his file server when he comes in the next morning, available as fast as his machine can read the data over the network.

The third technique is *file caching*. Based on the use of files at a site, the data is kept on disk, in main memory of the local file server, or in the main memory of the workstation. Dozier wins when requesting a file that he has requested previously, and it appears nearly instantaneously depending on the its location in the hierarchy.

These ideas bring new challenges for the file system. While there exist well known techniques with two-level storage hierarchies, managing three-levels of storage offers new opportunities for the systems designer. In particular, we must balance the storage requirements and latency-hiding benefits of file caching with those of abstraction and anticipatory fetching. These issues can only be addressed by evaluating the patterns of access of real users, modeling the benefits of each option, and subjecting proposed policies to actual use. Sequoia 2000 provides us the framework to see how well these ideas will work.

3.4. Low Latency Helical Scan Tape Readers

As mentioned above, one obstacle to making inexpensive storage useful is the long load/unload times. While not a problem for archival applications, where data is written once and almost never read, it directly conflicts with the repeated unpredictable reads needs of robo-line storage. Preliminary investigations suggest that these long times are a function of the anticipated application rather than the technology. For example, some of this long load/unload time is spent checking to see if the tape has been written before. Another obstacle is rewinding the tape. Rewinding is used to set the read head over a dataless leader of the tape. Since tape wear and stretching are most likely to occur while the tape and heads are coming up to speed, the leader acts to reduce the chance of damaging data.

To turn archival storage into robo-line storage we will modify the controller firmware, ideally in cooperation with a controller manufacturer, to improve these characteristics. For example, a computer system knows if the tape is written or not in advance, thereby skipping the time for seeing is the tape is written. A second idea is to add multiple "leaders" interspersed throughout the tape, lowering the storage capacity by, say, 10% but avoiding the need of a full rewind before a tape is unloaded. Another benefit of multiple leaders is that the head would be closer to the middle of the tape then the beginning, thereby cutting the average time to find a file. Multiple leaders could potentially halve the long load/unload and seek time of 8mm helical scan tapes.

The difficulty of these proposals is that so little is known about helical scan media beyond the few companies with helical scan products that there well may be technical roadblocks to such suggestions. Again the massive storage laboratory (Section 3.2 above) should address these issues. Our intent is to try to enhance these characteristics in part to improve the prototype and in part to make the needs of robo-line known to the tape controller industry.

For Capacity:	Use Tape
For Writes:	Use Tape
For Repeated Reads:	Use Optical Disk
For High Write Bandwidth:	Use Striped Tape Readers/Writers (See Section 3.7)
For High Read Bandwidth:	Use Striped Optical Disk Readers (See Section 3.7)

Table 5. Responsibilities in a hybrid optical disk/helical scan tape massive storage system.

3.5. Low Latency via Another Level of the Storage Hierarchy

Helical scan tapes are cheaper, rewritable, and on a faster curve of density improvement than optical disks, but they have long load/unload and seek times (see Table 2 above) and limitations as to the number of reads or writes before the tapes must be replaced. Optical disks, on the other hand, have low load times and have no limits to the number of reads but they are more expensive, their density is improving slowly, and they write slowly. Hence the strengths and weaknesses of tapes and optical disks do not overlap. Another interesting fact is that many of the global change applications write much more data than is ever read.

One latency lowering technique that we will pursue is to use an optical disk jukebox as a cache on the helical scan tape libraries. The tapes would be used in a log structured file system, which is optimized for writes. (A log structured file system simply appends writes to the end of a sequential media, with reads causing seeks that access data in proper order to get the most recent version of a file.) Hence long latency of the tape load/unload and seek would normally only occur when a tape is full. The first time the data is read the long latency of the helical scan tapes must be overcome, and the data is transferred to the magnetic disk of the file servers. Then a copy of the data will be placed on an optical disk in the jukebox. If the data is reread the request will be satisfied by the jukebox in a second.

One promising jukebox comes from a new company that promises 7 second access to any of 700 5.25" disks for about $100,000. When complemented by the low cost helical scan tapes, this combination may offer low latency for reads and writes with high capacity. When multiple optical and tape readers are striped together, this combination may also offer high read bandwidth and high write bandwidth. This hybrid storage system may offer performance-capacity-price characteristics that cannot be matched by homogenous tertiary storage system. Table 5 below illustrates the individual roles of the components in the hybrid organization.

Once again these ideas can only be validated by interactions with real users, such as the Sequoia 2000 community. The threshold of when to make an optical copy will be determined by the relative costs of the media, write speeds, and patterns of use by the global change scientists.

3.6. Compression

3.6.1. Basic Concept of Compression

Compression in storage systems has traditionally been used to increase the capacity of the system. However, compression can also be used to amplify the bandwidths of communication channels. Many peripheral manufacturers are placing lossless compression hardware into their embedded device controllers. This has the effect of increasing tape capacity while maintaining the interchangeability of the tape media, at least among drives of the same manufacturer. (An industry standard algorithm for lossless compression has been proposed, and is being adopted by most peripheral manufacturers). Conventional unencoded data enters and exits the tape drive, and there is no change to the driver software on the host.

Unfortunately this architecture does little to improve the overall transfer bandwidth of the I/O system. From a system viewpoint, it is advantageous to keep the data compressed until it is actually delivered to the

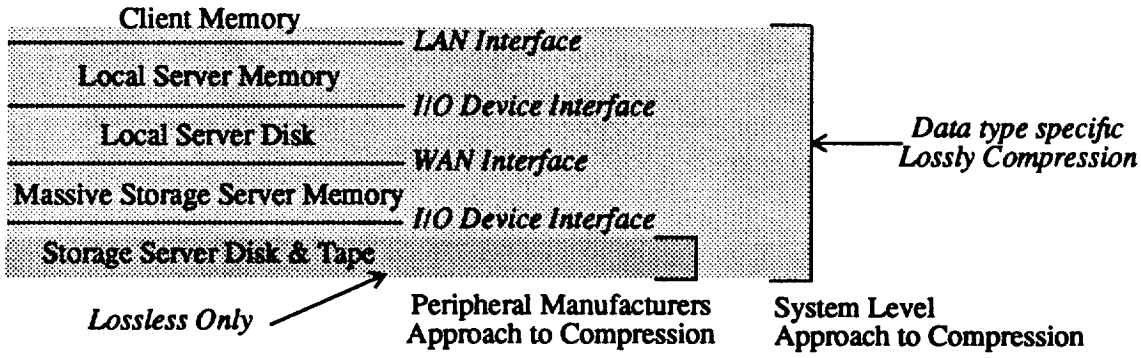

Figure 3: *Improved Transfer Rate via Data Compression*
Peripheral manufacturers are embedding lossless compression hardware into individual I/O devices, such as tape drives. A system level approach can support compression/decompression along any of the interfaces of the system, such as the local area network (LAN), local device, wide area network (WAN), and remote device. In addition, the system level approach can leverage information about the types of files to apply more effective data type specific lossy compression strategies.

application. Compressed data can be exploited to increase I/O system, memory system, and network bandwidth as well as storage device bandwidth.

Further, at a system level, knowledge of the file type can be used to choose among a variety of different compression algorithms, some of which may be most effective for text while others are better suited for video or image compression (see Figure 3). Even without application hints, it is often enough to examine the beginning of the file to heuristically determine its type. For example, the UNIX command "file" guesses the type of file contents by examining the its first 512 bytes.

3.6.2. Technical Challenges of Compression

There are many challenges associated with embedding support for compression within the system. The first is whether it is necessary to include hardware accelerators for decompression. To some extent, this depends on the kind of data and compression algorithm, as well as the application's tolerance for latency. Decompression of ASCII text files probably do not require hardware support while 30 frame per second video playback is impossible without it.

We expect the server to have full capabilities for compression and decompression. But the second challenge is how to support a heterogeneous environment in which some clients have special purpose hardware for compression/decompression while others do not. The file system must have knowledge of where the compression or decompression is to be done, based on the capabilities of the clients.

The industry standard compression algorithms, such as JPEG, offer an interesting possibility for variable resolution playback. Data can be placed in the storage system in lossless, encoded form. Depending on the available bandwidth available in the I/O path, the image can be played back at full resolution or at degraded resolution, by performing the quantization step and Huffman encoding "on the fly." We expect to explore the dynamic interplay between available bandwidth, bandwidth/resolution guarantees, and variable playback resolution.

Another interesting interaction exists between compression and error correction in the storage system. A bit error within a compressed file renders unreadable the portion of the file after the point of the error. Error correction schemes must be integrated with compression strategies to minimize the impact of bit errors. One possibility is to improve the error correction capabilities of data stored in the storage system, perhaps by using parallel error correct (see the discussion of interleaved tape and disk in the next section). Another is to partition the compressed data into units with which error correction is associated, rather than

spreading the correction across the entire file.

We propose to develop an architecture in which to support system-level compression and decompression in an internetworked storage environment. Both hardware and software strategies will be examined, supported at the level of I/O controllers, file server software, and hardware/software in the clients.

3.7. Interleaving Multiple Components

3.7.1. Interleaved Tape

Interleaving is a technique that increases bandwidth by using multiple storage or communication elements operating in parallel. Interleaving usually introduces slight additional latency and makes less efficient use of system resources than non-interleaved approaches, so it is does not make sense unless bandwidth is the performance bottleneck. The tertiary storage systems we are considering have relatively low bandwidth in comparison to the disk arrays used for secondary storage, which makes interleaving attractive. However, they also have relatively high latency, which lessens the benefit of interleaving. In this research we will apply to tertiary storage the same kinds of striping techniques that we have pioneered for disk storage and evaluate the architectural issues, benefits, and costs associated with interleaving.

Rather than construct a tape handling system of our own design, we will make use of commercially available robotics. Figure 4 shows the elements of one such system, an Exabyte EXB-120 Cartridge Handling System. We describe this system for the purposes of illustration; we are not yet ready to commit to a particular tertiary storage technology. The standard 19" rack can be configured with four 8mm tape readers, up to 116 x 5 GByte tape cartridges, and a tape handling robot that can pick any cartridge and deliver it to any tape reader in under 20 seconds. The robot mechanism and each tape reader are on independent SCSI (Small Computer System Interface) interfaces, making it possible to control the robot while independently reading from or writing to any of the tape drives. Exabyte is in the process of developing a 5.25" half-height tape reader, which will make it possible to place eight tape drives into the subsystem. The tape handler also has an integrated bar code reader, making it possible to inventory the contents of library with ease.

Using a cartridge handling system such as the EXB-120, we propose to demonstrate the viability of striped tape as a method for improving the transfer bandwidth of helical scan tape. The concept is shown in Figure 5. Each tape transport has its own embedded controller that supports the SCSI command set. An individual Exabyte tape drive has the potential to sustain 512 KBytes/second. By striping data from the same

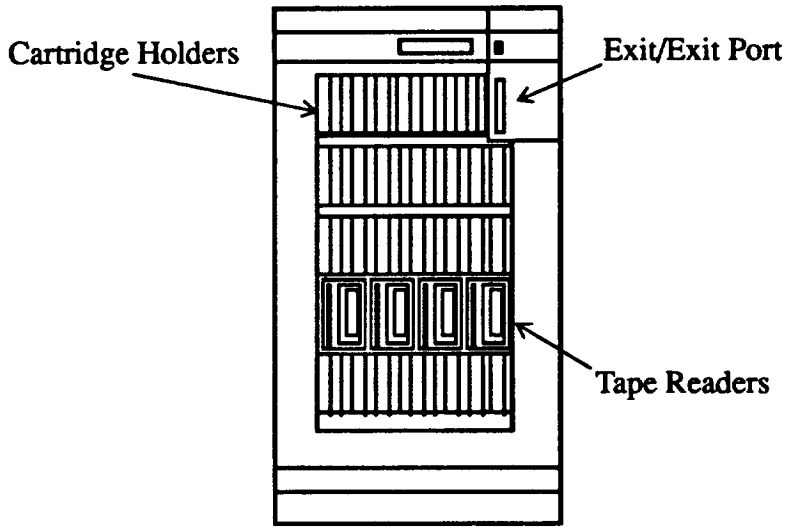

Figure 4: *EXB-120 Cartridge Handling System*
The system provides 580 Gigabytes (116 cartridges, 5 GB per cartridge) and 4 tape readers in a standard 19" rack.

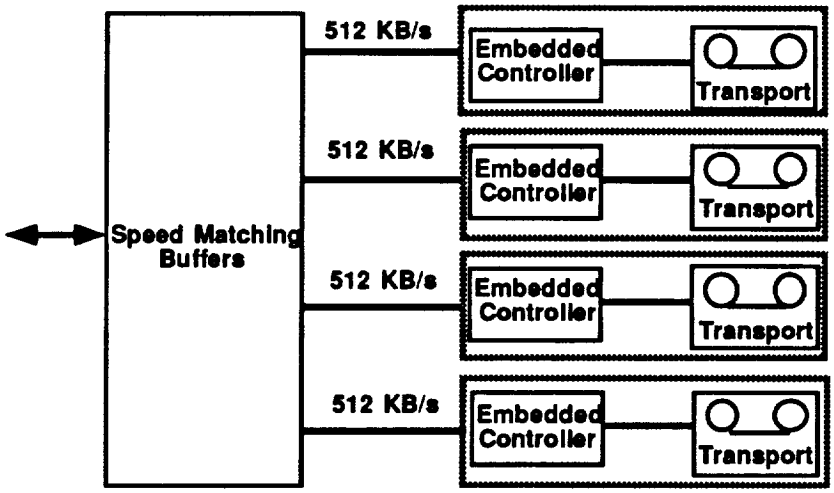

Figure 5: *Tape Striping*
Bandwidth can be improved by spreading data over multiple tapes in a parallel. The EXB-120 has the potential for 2-MByte/second sequential transfers. The next generation has the potential for 4-MByte/second transfers.

file across multiple drives, we can get a multiplicative speed-up in the transfer rate to a single file.

Actually achieving this speed-up will be difficult, however. There are a number of aspects that make striping tapes more difficult than striping disks. First, it is more difficult to synchronize the actions of several tape drives than several disks. With disks it is possible to synchronize the rotations of the drives so that they truly operate in lock-step. With tapes, no such synchronization is possible. Furthermore, the error correction techniques used by the Exabyte system add variability to the speed of each drive. The Exabyte system performs a verifying read after each write, and if errors are detected (even correctable ones) a new copy of the data is written to tape after the original copy. This leaves two copies of the data on tape, which slows down both the write and later reads.

This variation in drive speed makes it more difficult to achieve the full benefits of interleaving, since it could result in one or more drives sitting idle while slower drives catch up. If a drive stays idle too long, the tape system will unload the tape in order to reduce wear, and this results in a delay of several seconds to reload the tape before the next operation. The result is even greater variation in drive speed. We believe that the skew problems can be solved with adequate buffering, but we expect that experimentation will be required to determine the right sizes for buffers and the right algorithms for staging data into and out of them. An important aspect of our research will be to quantify the effect of tape skew in striped tape systems by constructing a software striping driver for a multiple tape drive system and measuring its performance. We have at our disposal several SCSI-bus analyzers that can be used to monitor activities on the interfaces between the host bus adapters (SCSI controllers designed to couple the host to the SCSI bus) and the tape drives. In addition, Exabyte will provide us with software that will allow us to monitor error correction events within the tape drives themselves.

The long load times for tape systems also work against interleaving. For example, once the robot arm has placed one tape in a drive, it takes about 5-10 seconds for it to load a second tape in a second drive. This means that the first drive will be able to start transferring about 5-10 seconds before the second drive, and during this 5-10 seconds it will be able to transfer 2.5-5 MBytes of data (for the Exabyte system). This implies that there is no benefit to striping within a single tape robot for files that are smaller than 2.5-5 MBytes. Furthermore, the long load times for tape, 100 seconds or more for the Exabyte system, result in very poor drive utilization if only a few MBytes of data are transferred per drive. This also argues for striping only very large files. Most likely a hybrid approach to striping will be necessary, where very large files are striped and small ones are not, or perhaps small files can be clustered into large groups which can then be striped. The availability of several kinds of optical disk and tape libraries in the Massive Storage Laboratory

will allow us to experiment with a wide range of interleaving strategies.

Tape arrays face the same kinds of reliability challenges as disk arrays. The tape drive mechanisms, due to their complex electromechanical nature, are even less reliable than magnetic disks. Spreading data across multiple transports reduces the reliability even further. In addition, tape wear, and the eventual loss of the ability to read previously written data, is an important consideration. To guarantee that data in the array is kept available, a scheme comparable to parity striping for disk arrays is attractive. Tapes are organized into stripe groups of N+1 tapes, with parity redundancy computed horizontally bitwise across N tapes and stored on the N+1st tape. The striping software must keep track of which tapes form a stripe group. If a tape reader fails, the contents of tapes in that stripe position can still be read by inverting the parity calculation. Writes can continue as before, even though one tape cannot be accessed, but its contents will need to be reconstructed after the tape reader is repaired.

Tape data redundancy can also be exploited for the lagging tape problem described above, at least for reads. Rather than waiting for a slow tape to catch up, its contents can be reconstructed from the other tapes in its stripe group.

3.7.2. Interleaved Disks

RAID, or redundant arrays of inexpensive disks, was developed at U. C. Berkeley as an organization for high performance disk systems based on replacing a small number of large formfactor disk drives with very many small formfactor drives. Parallelism within the disk system is exploited by transferring in parallel data to and from the I/O devices in "stripes" that span multiple disk actuators.

Because of the large number of mechanical components within such a system, reliability becomes an overriding concern. If a single disk fails, then the data spread across the disks becomes unavailable. Disk arrays are therefore partitioned into recovery groups in which redundant data is introduced to protect against data loss. Our solution introduces low capacity cost data redundancy into the system: we compute parity redundancy for each stripe and store it within the recovery group as part of the data stripe. Should a disk fail, its contents can be reconstructed from the data and parity information stored on the remaining disks in the recovery group. This strategy protects against a single failure per recovery group. If the system includes a hot spare, to which the contents of a failed disk can be reconstructed as a background task, then very high mean-time-to-data-loss can be achieved.

It is clear that the RAID concepts developed for magnetic disks are just as relevant for optical disk systems. Although the media cannot fail due to head crashes, the more complex mechanism of the optical disk drive reader makes them significantly more prone to failures. To maintain high transfer rates from striped optical drives in the face of drive failures, we expect to be able to apply our parallel error correction techniques.

3.7.3. Interleaved Robots

For the purposes of reliability, it is important that storage robots have a degree of redundancy. If a robot breaks, it is disastrous if the storage system becomes unavailable. Further, in the striped tape organizations described above, the robo-line storage system could become unavailable should one of the tape drive mechanisms fail. Given these observations, it is attractive to interleave across multiple robots as well as readers. The organization is suggested by Figure 6, using the Exabyte EXB-120 as an example. A "stripe" is formed from individual tapes/readers controlled by different robots. This "orthogonal" organization protects against both reader and robot failures.

Striping across robots has the additional advantage of eliminating the problem of sequential tape loads described in Section 3.7.1. Each of the robots in the stripe can load its tape in parallel with the other robots, so that all the tapes become ready to transfer at about the same time.

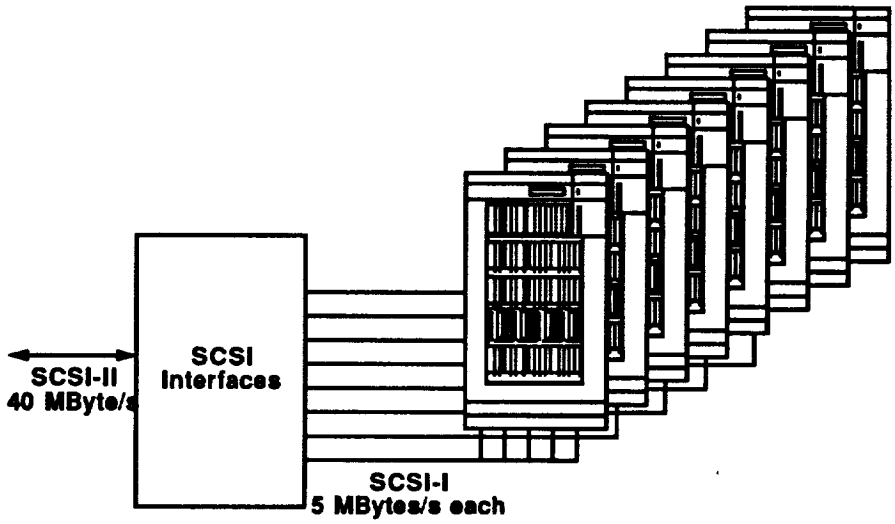

Figure 6: *Striped Tape Across Multiple Robots*
A tape stripe consist of tapes loaded in parallel by independent robots. Media pick and load operations take place in parallel, as do data transfers. The orthogonal organization, coupled with parallel data redundancy, provides protection against tape reader and robot failures.

3.7.4. Interleaved Servers

Another way to scale the bandwidth of a network file system is to stripe individual files across multiple server machines. This allows the overall bandwidth of file transmission to exceed the memory bandwidth of any one machine. Such striping is simple in principle, but a practical implementation must resolve two management issues: centralized versus decentralized control, and large files versus small files.

The first management issue is the degree to which the striped servers are controlled centrally. One approach is to have a single server that controls the others. It might store access times, sizes, and permissions for files and determine which portions of the file are stored on which other servers. All clients might be required to talk to this central server before accessing files. This approach is probably the simplest to implement and is used by existing striped storage systems such as Swift, developed at the IBM Almaden Research Center. Unfortunately, the central server could turn into a performance bottleneck, especially if there are small file accesses as well as large ones. Another approach is a decentralized one, where the individual file servers are relatively autonomous, without centralized control. However, this approach may lead to complexities in management: where are the access time and permissions stored for a file, and how do clients locate this information? If it is replicated on all servers, then there will be increased costs for updates. Intermediate approaches between these two extremes are also possible. For example, each file might be managed centrally by one server, but the choice of server might be different for different files.

The second issue concerns the relationship between large files and small ones. Although striping is advantageous for large files, it is disadvantageous for small ones. For small files, striping is likely to increase latency over a non-striped implementation, since it requires contacting more servers. One goal is to maintain low latency for small files while increasing the bandwidth for large ones. This will require varying the degree of striping, depending on file size.

3.7.5. Interleaved Networks

The theme throughout this section is to increase bandwidth by striping across multiple objects. We do this at the level of devices (disks and tapes) and media handling robots, as well as servers. If one component cannot provide enough bandwidth, we simply add additional components in parallel and interleave accesses across them.

We need not stop at the level of interleaving across servers. If the network bandwidth is the bottleneck,

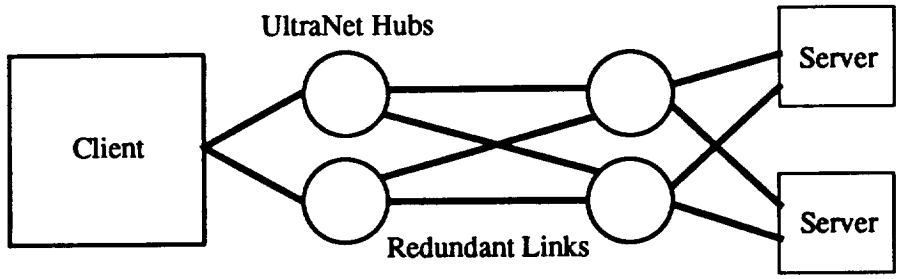

Figure 7: *Storage Server Clusters*
If the client demands more bandwidth than that which can be obtained by a single network link, data transfers can be striped across multiple network paths between multiple servers and the client.

then it should be possible to stripe accesses across multiple network interfaces as well. Figure 7 shows a possible testbed to investigate striped transfers over the network. It makes use of the hub-based UltraNetwork, but the concept is not limited to the UltraNetwork. (For example, a similar topology is supported by the Digital Equipment Corporation's AutoNet). Since both clients and servers have multiple network interfaces, it is possible to send packets over alternative routings where they can be reassembled at the destination. Large client caches are critical for hiding skewing delays.

An interesting issue in disributed control is how to get the servers participating in a common interleaved transfer to use different pathways to the client. This requires a different approach than the standard network routing literature. The existing algorithms are optimized for gradual load balancing and congestion avoidance. In the environment given above, the algorithms must make rapid routing decisions, geared towards maximizing the network bandwidth available to related transfers.

3.8. Redundant Components

The sparkle of thousand-fold increase in capacity dims when confronted with the possibility that data may be lost, or that data may be unavailable for long periods due to hardware failures. An unreliable storage system is a useless storage system; hence we must address reliability and availability.

We need to understand the failures of the components to understand how to create a highly available system, and we have no body of knowledge on reliability to guide us. For example, all of the following are plausible solutions, depending on the needs of the users and the weaknesses of the technology:

- Users must never lose data but can live with occasional unavailability, and the tape media is determined to be the weak link of the reliability chain. One solution is to simply make copies using the least expensive media and save the copies as off-line storage.
- Readers are the weak link in the chain, so every robot must have multiple readers.
- Robots are the weak link in the chain. One solution is to use a stacker as the building block. Each stacker has a reader, simple robot, and a limited set of tapes. The stackers are used in a parity scheme, much like disks are used in RAID.
- The error recovery scheme we invent to overcome whatever weakness are inherent in the technology is also sufficient to handle normal tape read/write errors. The ECC mechanism for tapes is simplified to offer higher tape write bandwidth (no read after write) and greater tape capacity (reduce the 25% of storage dedicated to ECC).

Table 6 lists a number of metrics that we would like to characterize for each storage technology. The results of the Massive Storage Laboratory, both via our experimentation and our interaction with industry as customers, will help answer these questions.

- Typical failures of media (e.g., scratches, breakage)
- Read error rate
- Shelf life of media (e.g., time until unreadable)
- Number of reads/writes before wear-out of media
- Typical failures of readers/writers(e.g., electronic failures)
- MTBF of reader/writer
- Use before wear-out of reader/writer head
- Preventative maintenance schedule for reader
- Typical failures of robots
- MTBF of robots
- Grab Error Rate/ Place Error Rate of robots
- Preventative maintenance schedule for robot

Table 6. List of Reliability Questions for Massive Storage Technologies.

4. Comparison with Related Research

4.1. File Migration

File migration studies were a topic of considerable research interest in the 1970s and early 1980s. The work focused on analyzing the mainframe file accesses of the time, in order to determine effective strategies for migrating files between the levels of the storage hierarchy. These include policies for when to fetch a file from archive to disk, where a file should be placed on disk or in the archive, and when to replace the file from disk to archive storage.

Typical of this work are the papers by Smith [Smith 81a, Smith 81b] and Lawrie [Lawrie 82]. These papers evaluated a variety of alternative fetch, placement, and replacement policies within the context of high performance computing environments of the time. For example, Lawrie demonstrated the validity of clusting files by user ID within the archive, while Smith developed a replacement policy that used file size as well as time of last access.

We believe that this work has become seriously outdated by advances in technology. The evaluations and development of algorithms were performed in an environment that preceeded the invention of the workstations, the wide spread use of local area networks, networked-based storage, automated data storage libraries, and disk arrays. A fresh look at the new distributed computing environment is needed to determine whether the existing policies are still valid and whether new algorithms may be effective. Because of the tremendous growth of computer CPU performance and storage capacities in the last decade, along with system topologies, it would not be unreasonable to assume that the patterns of system use have changed. More specifically, evaluations of distributed systems, consisting of workstations and file servers, and comparisons with existing supercomputing-type installations are needed.

4.2. Mass Storage Systems

The 1980s saw the wide-spread development of mass storage systems at the nation's supercomputer centers. Some of these systems are described in papers by Collins [Collins 88], Nelson [Nelson 88], and Tweten [Tweten 90]. As a typical example, consider the storage system as developed by the National Center for Atmospheric Research in Boulder Colorado. Their system is built around an IBM mainframe running the MVS operating system. It manages twenty four IBM 3380 large formfactor disk drives (100 GBytes), a StorageTek Automated Cartridge System containing four cartridge readers and approximately 6000 cartridges (1 TByte of tertiary storage), and 69,000 manually-loadable cartridges on shelves (12.5 TBytes of off-line storage). The system manages 450,000 files of an average size of 26 MByte each. On a given day, 2000 files are read from the system while 1000 are written [Merrill 90].

The mass storage systems developed at the various supercomputer centers implement many of the elements of the Mass Storage System Reference Model already described in Section 2.3. This is no surprise, as this is the precisely the community that has been working to define the reference model. The systems have been designed to support the kinds of local area network-based mass storage for a heterogeneous collection of supercomputers, minicomputers, and workstations that characterize these large-scale supercomputer centers. And they are reasonably effective at doing so, supporting large numbers of scientists performing important computations. Even commercially available versions of the systems developed at Los

Alamos and Livermore have recently become available (DataTree™ and UniTree™ [McClain 90]; see the more detailed discussion below on the relationship between the proposed file system work and UniTree™).

However, the existing mass storage systems are not without their limitations. They are production systems, developed by computer center support staff. A body of knowledge has yet to be created that would assist a developer to create his or her own mass storage system (to a large extent, this is the primary motivation for the development of the Mass Storage System Reference Model). From a research perspective, the major limitations of existing mass storage system can be summarized as: (1) no support for geographically distributed storage hierarchies, (2) use of non-scalable, high cost technologies, and (3) lack of strategies for high reliability and fault tolerant storage. We examine each of these in the following paragraphs.

First, existing mass storage systems provide no special support for geographically distributed access to hierarchical storage, having been architected for large scale computer centers, such as those at Los Alamos, Lawrence Livermore, NCAR, and the NASA Ames NAS facility (of course, it is possible to log in from anywhere in the country to gain access to these centers). A major component of the current proposal is directed specifically at this difficiency in the existing work, by proposing a coordinated attack on the issues of network latency in mass storage systems. In this proposal, we have described our ideas on providing pervasive support for compression within the storage system as well as local abstracts and data staging strategies.

Second, solutions suitable for supercomputing data centers are not often applicable to other, more cost sensitive environments. The approaches for high bandwidth and high capacity tertiary storage described in this proposal are based on scalable and inexpensive technologies. To our knowledge, there has been no serious investigation of interleaved tape, robot, file server, or network interconnection as a means to incrementally increase the bandwidth of tertiary storage. We have been successful in the past in transferring some of our ideas on interleaved disk to the mass storage system community (e.g., [Henderson 89]), and believe we can again be successfully with our ideas on interleaving tertiary storage and robotics.

Lastly, with the possible exception of the NAS facility [Tweten 90], existing mass storage systems do not specifically address the issues of high reliability and fault tolerance. For example, the reliability of existing tertiary storage technologies or media handling robots is not well documented. We believe that there is a significant need to investigate the reliabilitty requirements and to better understand the abilities of storage devices to meet these requirements. Interleaving schemes in conjunction with parallel error correcting codes, such as those used in disk arrays, provide one element of the solution. Additional schemes, such as backup methods to be used in conjunction with automated migration, replication of critical hardware, and guidelines for regular media replacement, must also be considered, and we intend to do so within the context of the proposed work.

4.3. File Systems

There are several efforts in the operating system and file system areas that are closely related to the proposed research. These include the Andrew File System (AFS), UniTree™, and the MACH-based OS release from the Open Software Foundation (OSF/1). We describe these related developed in the following paragraphs.

The main foci of the AFS file system project have been distribution and scalability: how to support very large networks with many clients and servers. The key contribution of AFS is its mechanism for caching files on local disks to reduce server traffic. This mechanism has worked so well that AFS has been extended to a "national file system" with clients using files whose official disk storage is thousands of miles away. Our proposed research addresses a different set of issues than AFS: extensions to tertiary storage and support for very large files. AFS has not addressed issues of tertiary media such as optical disks and tapes, and it has focussed primarily on small files. For example, the first versions of AFS required clients to transfer entire files to their disks before the files could be accessed; this approach would not be practical with the large files managed by our servers. Although this restriction was lifted in later versions of AFS, the use

of local disks as a staging point remains, and this probably doesn't make sense for files that are much larger than the local disk.

The UniTree™ system has been very successful at creating a multi-level file system that spans main-memory caches, disks, and tertiary storage such as tape and optical disk. One of the strengths of UniTree™ is that it does this transparently using caches. Applications see a traditional view of disk-based file storage even when information is actually stored on tertiary storage. However, the caching approach breaks down when dealing with files that are actually stored on high-latency devices such as videocassettes: if users pretend that such files are on disk, they will receive terrible performance.

One of the main thrusts of our work is to explore other, non-transparent, approaches to managing multi-level hierarchies, such as storing short abstracts on disk to avoid references to the main file altogether, or providing more control to applications over where files are stored. These approaches are less convenient to applications than the UniTree™ approach, but we think they will be a necessary supplement to UniTree-like techniques for storage systems of the future.

The OSF/1 and DCE projects of the Open Software Foundation include a substantial amount of effort in the areas of networks and file systems. However, most of this work follows along the lines of the AFS file system with special efforts at standardizing a number of supporting areas of network protocols such as remote procedure calls. As far as we know, OSF does not currently have any major projects addressing the issues of tertiary storage.

5. Summary and Conclusions

In this paper, we have described the underlying trends towards higher speed networks, higher capacity tape systems, hardware-assisted compression, and low cost robot-managed data libraries.Our goal is to understand how to structure a geographical distributed mass storage system, based on these technologies. We intend to build a low latency, high capacity, network-attached mass storage system as part of our commitment to the Sequoia 2000 Earth Scientists.

Our research approach is founded on developing new techniques for managing latency, integrating compression, leveraging interleaving, providing redundancy within the storage system. Some of the latency management strategies we have discussed include access hints and caching, reduced load times on tape media, and mixing optical disk and tape within the same hierarchy.

Our methods for increasing bandwidth include compression and interleaving. With the advent of new compression hardware, we believe that it will provide an important new element of storage technology. The question that remains is how effectively compression can be applied to scientific data sets. Interleaving has proved effective in disk array organizations. We think that the concept can be generalized to other media, I/O controllers, file servers, and network connections to scale up the bandwidth of the I/O system.

Reliability remains a major unknown for tertiary storage devices. This is one of the primary motivations for establishing a massive storage laboratory, to better understand the failure mechanisms of the various storage technologies. Tape media and read/write heads suffer from much more pronounced wear-out than comparable disk systems. By combining parallel error correction with an interleaved approach, we can obtain storage systems with much higher levels of availability.

With ever increasing processor power, we believe the future limit to performance in computer systems will be the storage system, both in terms of its aggregate bandwidth and its capacity. All too often computer architects have concentrated on processor performance, without a comparable investment in the development of the memory and storage subsystems. The research program described in this paper is one effort to redress the balance.

6. References

[Adachi 87] Adachi, T., et. al., "A Fast Random Accessing Scheme for R-DAT," *IEEE Transactions on Consumer Electronics*, Vol. CE-33, No. 3, (August 1987), pp. 275 – 285.

[Collins 88] Collins, B., C. Mexal, "The Los Alamos Common File System," Proc. Ninth IEEE Symp. on Mass Storage Systems, Monterey, CA, (Nov. 1988), pp. 61 - 67.

[Exabyte 90] Exabyte Corporation, "EXB-120 Cartridge Handling Subsystem Product Specification," Part No. 510300-002, 1990.

[Fahnestock 90] Fahnestock, J., T. Myers, E. Williams, "Summary of the Intelligence Community's Mass Storage Requirements," SRC Technical Report 90-026, (December 1990).

[Henderson 89] Henderson, R. L., A. Poston, "MSS-II and RASH: A Mainframe UNIX based Mass Storage System with a Rapid Access Storage Hierarchy File Management System," Proc. USENIX Conference, (Winter '89), pp. 65 - 85.

[Hewlett-Packard89] Hewlett-Packard Corporation, "HP Series 6300 Model 20GB/A Rewritable Optical Disk Library System Product Brief," 1989.

[Hitomi 86] Hitomi, A., "Servo Technology of R-DAT," *IEEE Transactions on Consumer Electronics*, Vol. CE-32, No. 3, (August 1986), pp. 425 – 432.

[Itoh 86] Itoh, F., "Magnetic Tape and Cartridge of R-DAT," *IEEE Transactions on Consumer Electronics*, Vol. CE-32, No. 3, (August 1986), pp. 442 – 452.

[Katz 89] Katz, R., G. Gibson, D. Patterson, "Disk System Architectures for High Performance Computing," *Proceedings of the IEEE*, Special Issue on Supercomputing, (December 1989).

[Kodak 90] Kodak Corporation, "Optical Disk System 6800 Product Description," 1990.

[Lawrie 82] Lawrie, D. H., J. M. Randal, R. R. Barton, "Experiments with Automatic File Migration," *IEEE Computer*, (July 1982), pp. 45 - 55.

[Lelewer 87] Lelewer, D., D. Hirschberg, "Data Compression," *ACM Computing Surveys*, V. 19, N. 3, (September 1987).

[LSI 90a] LSI Logic, "L64760 Inter-Frame Processor," Product Specification, (September 27, 1990).

[LSI 90b] LSI Logic, "Video Compression Chip Set," Product Specification, (September 27, 1990).

[Markoff91] Markoff, J., "A System to Speed Computer Data ," New York Times, Wednesday, (January 23, 1991), p. C7.

[McClain 90] McClain, F., "DataTree™ and UniTree™: Software for File and Storage Management," Proc. Tenth IEEE Symp. on Mass Storage Systems, Monterey, CA, (Nov. 1990), pp. 126 - 128.

[Mee 88a] Mee, C. D., E. D. Daniel, *Magnetic Recording, Volume II: Computer Data Storage*, McGraw–Hill, New York, 1988.

[Mee 88b] Mee, C. D., E. D. Daniel, *Magnetic Recording, Volume III: Video, Audio, and Instrumentation Recording*, McGraw–Hill, New York, 1988.

[Merrill 90] Merrill, J., E. Thanhardt, "Early Experiences with Mass Storage on a UNIX-based Supercomputer," Proc. Tenth IEEE Mass Storage Systems, Monterey, CA, (Nov. 1990), pp. 117 - 121.

[Nelson 87] Nelson, M. D. L. Kitts, J. H. Merrill, G. Harano, "The NCAR Mass Storage System," Proc. Eighth Symp. on Mass Storage Systems, (May 1988), pp. 12 - 20.

[Nelson 88] Nelson, M., J. K. Ousterhout, B. Welch, "Caching in the Sprite Network File System," *A.C.M. Transactions on Computer Systems*, V. 6, N. 1, (February 1988), pp. 134-154.

[Pollard 88] Pollard, A., "New Storage Function for Digital Audio Tape," New York Times, Wednesday, (May 25, 1988), p. C10.

[OSTP 91] Office of Science and Technology Policy, "Grand Challenges: High Performance Computing and Communications," Report by the Committee on Physical, Mathematical, and Engineering Sciences, FCCSET, (1991).

[Ousterhout 89] J. K. Ousterhout, F. Douglas, "Beating the I/O Bottleneck: A Case for Log-Structured File Systems," ACM Operating Systems Review, V 23, N 1, (January 1989), pp. 11-28.

[Ranade 90] Ranade, S., J. Ng, *Systems Integration for Write-Once Optical Storage*, Meckler, Westport, CT, 1990.

[Rosenblum 90] M. Rosenblum and J. Ousterhout, "The LFS Storage Manager," Proc. USENIX Summer Conference, June 1990, pp. 315-324.

[Schroeder 90] Schroeder, M., A. D. Birrell, M. Burrows, H. Murray, R. M. Needham, T. L. Rodeheffer, E. H. Satterthwaite, C. P. Thacker, "Autonet: A High-Speed Self-configuring Local Area Network Using Point-to-Point Links," DEC SRC Tech. Rep. #59, (April 1990).

[Spencer 88] Spencer, K., "The 60-Second Terabyte," *Canadian Research Magazine*, (June 1988).

[Smith 81a] Smith, A. J., "Analysis of Long Term File Reference Patterns for Application to File Migration Patterns," *IEEE Trans. on Software Engineering*, SE-7 (4), pp. 403 - 417, (1981).

[Smith 81b] Smith, A. J., "Long Term File Migration: Development and Evaluation of Algorithms," *Comm. ACM*, 24 (8), pp. 521 - 532, (1981).

[Tan 89] Tan, E., B. Vermeulen, "Digital Audio Tape for Data Storage," *IEEE Spectrum*, V. 26, N. 10, (October 1989), pp. 34 - 38.

[Tweten 90] Tweten, D., "Hiding Mass Storage Under UNIX: NASA's MSS-II Architecture," Proc. Tenth IEEE Symp. on Mass Storage Systems, (May 1990), pp. 140 - 145.

[Wood 90] Wood, R., "Magnetic Megabytes," *IEEE Spectrum*, V. 27, N. 5, (May 1990), pp. 32 - 38.