

The MIT Alewife Machine

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Invited Paper

A variety of models for parallel architectures, such as shared memory, message passing, and data flow, have converged in the recent past to a hybrid architecture form called distributed shared memory (DSM). By using a combination of hardware and software mechanisms, DSM combines the nice features of all the above models and is able to achieve both the scalability of message-passing machines and the programmability of shared memory systems. Alewife, an early prototype of such DSM architectures, uses a hybrid of software and hardware mechanisms to support coherent shared memory, efficient user-level messaging, fine-grain synchronization, and latency tolerance.

Alewife supports up to 512 processing nodes connected over a scalable and cost-effective mesh network at a constant cost per node. Four mechanisms combine to achieve Alewife's goals of scalability and programmability: software-extended coherent shared memory provides a global, linear address space; integrated message passing allows compiler and operating system designers to provide efficient communication and synchronization; support for fine-grain computation allows many processors to cooperate on small problem sizes; and latency-tolerance mechanisms—including block multithreading and prefetching—mask unavoidable delays due to communication.

Extensive results from microbenchmarks, together with over a

dozen complete applications running on a 32-node prototype, demonstrate that integrating message passing with shared memory enables a cost-efficient solution to the cache coherence problem and provides a rich set of programming primitives. Our results further show that messaging and shared memory operations are both important because each helps the programmer to achieve the best performance for various machine configurations. Block multithreading and prefetching improve performance significantly, and language constructs that allow programmers to express fine-grain synchronization can improve performance by over a factor of two.

Keywords— Active messages, cache coherence, distributed shared memory, fine-grain synchronization, large-scale multiprocessors, message passing, parallel processing, rapid context switching, shared-memory multiprocessors.

I. INTRODUCTION

The last few years have seen the introduction of a number of parallel-processing systems with truly impressive maximum performance. The amount of raw computation packaged in a single chassis is quickly approaching a trillion operations per second. Unfortunately, end users rarely benefit from the advertised maximum performance of today's massively parallel systems. Any application that actually exploits the full potential of a machine typically requires months of careful programming, painful debugging, and relentless tuning.

By integrating mechanisms from shared memory, message passing and data flow architectures into a hybrid distributed shared memory (DSM) model, the Massachusetts Institute of Technology (MIT) Alewife machine [4] shows that a parallel architecture can yield a rich shared memory programming environment on a scalable hardware base. The hardware, compiler, and operating system combine to achieve the goal of programmability by solving problems that traditionally burden multiprocessor programmers, namely, scheduling computation and moving data between processing elements. Features of this environment include a globally shared address space, a scalable cache coherence mechanism, a compiler that automatically partitions regular

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programs with loops, a library of efficient synchronization and communication routines, distributed garbage collection, and a parallel debugger. Statistics-gathering tools help to optimize performance.

These features allow programmers to write high-performance applications quickly. A shared address space relieves the programmer of the burden of address computation for distributed data, caching eliminates the need for explicit data movement, and automatic data partitioning further simplifies the task of managing communication requirements. Distributed garbage collection gives programmers the option of avoiding a traditional source of many bugs in parallel applications: explicit memory allocation and deallocation. Efficient synchronization and communication routines—together with statistics-gathering tools—help programmers tune performance once they have programs working correctly.

The goal of scalability addresses both the cost of building the machine and its ability to run programs efficiently. The Alewife architecture permits a physically scalable implementation. Similar to earlier message passing systems, Alewife machines are built by replicating a single, modular processing node. Passive backplanes provide the wires to connect the nodes in a low-cost, two-dimensional mesh network. In order to provide I/O facilities, Versamodule-European (VME) and small computer systems interface (SCSI) interface boards plug into the edges of the mesh. Whether an Alewife machine has one node or 512 nodes, this physical layout results in a constant cost per node. In the prototype, despite unit quantity purchasing, a single node costs only about \$2000. With volume fabrication, this cost could be reduced substantially.

This paper shows how the hardware and software components of Alewife provide good performance on parallel applications, without sacrificing physical scalability or programmability. Indeed, most applications were written for other machines and run on Alewife without significant porting effort. On any DSM architecture, the primary challenge to achieving these goals simultaneously is the latency of interprocessor communication, which dominates the time required for intranode memory accesses. Unlike other DSM architectures, Alewife provides four classes of architectural mechanisms—each popularized by various computational models such as shared memory, message passing, and data flow—that implement an automatic locality management strategy. This strategy seeks to maximize the amount of local communication by consolidating related blocks of computation and data and attempts to minimize the effects of nonlocal communication when it is unavoidable. The four classes of mechanisms are: coherent caches for shared memory; integrated message passing; support for fine-grain computation; and latency tolerance.

A. Coherent Shared Memory

Although Alewife provides the abstraction of globally shared memory to programmers, the system's physical memory is statically distributed over the nodes in the machine. On each node, a communications and memory

management unit (CMMU) [20] receives memory requests from a Sparcle processor [2] and directs the requests to local or remote memory. When necessary, the CMMU synthesizes messages that fetch memory from remote nodes.

The memory hardware helps manage locality by caching both private and shared data on each node. Caching involves making a local copy of the remote data so that future accesses do not incur network traffic. Systems with caches, however, suffer the coherence problem. The coherence problem arises when cached copies of data are modified locally, resulting in an inconsistent view of memory. Solutions to the coherence problem generally involve protocols that allow multiple cached copies of read-shared data but disallow sharing when a cached copy must be written by invalidating all other copies. Invalidations are facilitated in DSM's by a distributed memory directory that keeps track of the locations of each cached copy. Alewife uses a scalable, software-extended scheme called LimitLESS [10] (limited directories locally extended with software support) to maintain the coherence of cached data. The LimitLESS scheme handles common-case memory accesses in the CMMU hardware but relies on software traps to enforce coherence for memory blocks that are shared by a large number of processors. The software traps invoke software protocol handlers that extend the directory into software managed memory, thereby limiting the amount of dedicated directory memory.

B. Integrated Message Passing

While the programmer sees a shared memory programming model, for performance reasons much of the underlying software is implemented using message passing. The performance of all of the layers of software that help manage locality (including the compiler, libraries, run-time system, and LimitLESS handlers) depend on an efficient communication mechanism. Features in Sparcle and the CMMU provide a streamlined interface for transmitting and receiving messages: both system and user code can quickly describe and atomically launch a packet directly into the interconnection network; a direct memory access (DMA) mechanism allows data to flow between the network and memory; and a fast interrupt mechanism speeds message reception and simplifies the task of writing message-passing programs by eliminating the need to poll the network frequently.

The Alewife hardware supports a seamless interface between the various software layers by integrating the shared memory and message-passing mechanisms. To do so, the system provides forward progress guarantees to shared memory accesses in the face of message reception interrupts. In addition, the DMA engine maintains the coherence between the data in messages and the data in local caches [18].

C. Fine-Grain Computation

Given a fixed-size data set, the granularity of computation (the time between events that require interprocessor

communication) decreases as the number of processors in a system increases. A system that cannot handle small tasks efficiently must attempt to increase synchronization and communication granularity artificially, possibly defeating attempts to maximize parallelism. Alewife's support for fine-grain computation includes mechanisms popularized by data flow and message passing architectures, namely, fast user-level messages and support for full/empty bit synchronization. User-level messages allow the processor direct access to the network queues. Full/empty bit synchronization associates a synchronization bit with each word of memory and allows synchronization and data access to be accomplished simultaneously.

Alewife's programming languages, parallel C and Multi, include constructs for expressing fine-grain synchronization. These constructs allow a thread to synchronize implicitly upon every memory access.

D. Latency Tolerance

Block multithreading and prefetching provide the last line of defense in Alewife's locality management strategy. These mechanisms attempt to tolerate the latency of interprocessor communication when it cannot be avoided. Prefetching allows code to anticipate communication by requesting data or locks before they are needed. Block multithreading allows a processor to switch between threads of computation on a cache miss or a failed synchronization attempt.

Latency tolerance requires support from Alewife's hardware and software components. Prefetching and block multithreading both require lockup-free caches [17]. Prefetching requires support in the compiler and special memory operations. Block multithreading requires a fast context switch [3] and a solution to the window of vulnerability problem created by interleaved threads of execution [19].

Although it is helpful to think of Alewife's four mechanisms as being distinct, the machine's implementation integrates them tightly. For example, the CMMU's transaction buffer closes the window of vulnerability opened not only by multithreading, but also by fast message handling and software-extended coherence. The transaction buffer also provides storage for prefetching and support for correct ordering of messages. Similarly, Sparcle's fast interrupt mechanism accelerates LimitLESS event handling, message reception, fine-grain synchronization events, and context switching.

This paper describes the experience gained by designing, fabricating, and running a complete parallel DSM system. Specifically, it evaluates the effectiveness of the Alewife architecture and its locality management strategy. Section II describes the machine's implementation and its programming environment to show how the mechanisms combine to produce a coherent system. Section III describes Alewife's primitive mechanisms and uses microbenchmarks to measure the base performance of the mechanisms in terms of the latency and bandwidth of primitive functions. Section IV presents detailed case studies of several applications that illustrate the benefits of Alewife's approach and examines

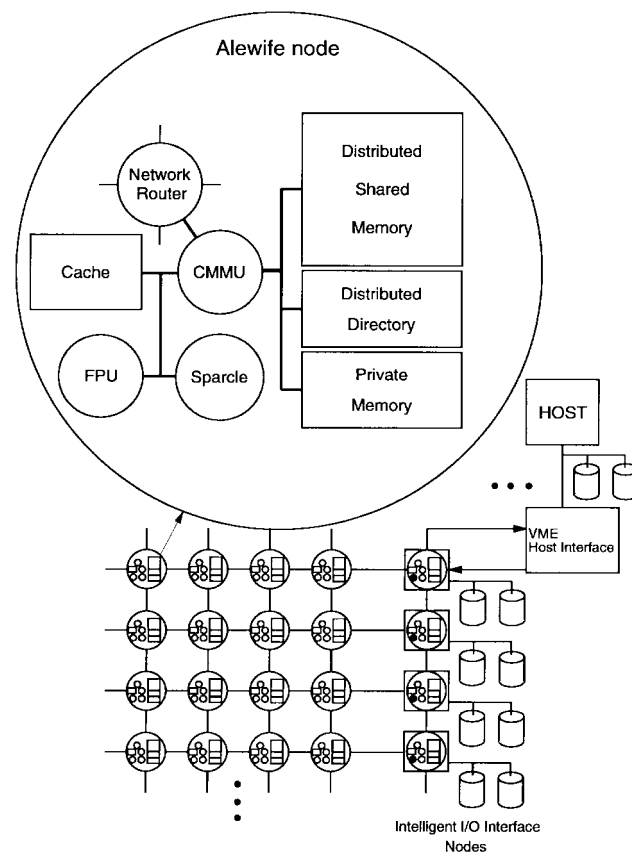


Fig. 1. The Alewife machine.

the relative benefits of DSM mechanisms when technology changes the ratio of computation to communication speed. Section V discusses related work on parallel architectures. Finally, Section VI summarizes the insight gained from implementing Alewife and briefly discusses results from research that followed the Alewife experiment.

II. THE ALEWIFE MACHINE

The Alewife architecture is organized as shown in Fig. 1. Memory is physically distributed over the processing nodes, which use a mesh network for communication.

Each Alewife node consists of a Sparcle [2] processor, 64 Kbytes of direct-mapped cache, 4 Mbytes of data, and 2 Mbytes of directory (to support a 4-Mbyte portion of shared memory), 2 Mbytes of private (unshared) memory, a floating-point coprocessor, and an Elko-series mesh routing chip (EMRC) from California Institute of Technology (Caltech). Both the cache memories and floating-point unit (FPU) are off-the-shelf, SPARC-compatible components. The EMRC network routers use wormhole routing and are connected to form a direct network with a mesh topology. The nodes communicate via messages through this network. A single-chip CMMU services data requests from the processor and network. Intelligent I/O Interface nodes in Fig. 1 are attached to the edges of the mesh network, and provide SCSI-based interfaces to disks and local area networks (LAN's). These I/O nodes are modified versions of the compute nodes.

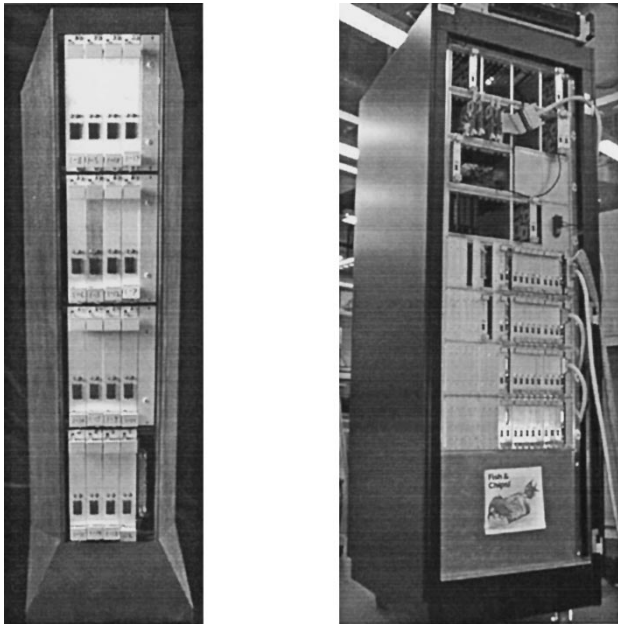


Fig. 2. Sixteen-node machine and 128-node chassis populated with a 32-node machine.

Fig. 2 shows the physical realization of both a 16-node Alewife system and a 32-node system within a chassis scalable to 128 nodes. The 16-node system, complete with two internal 3 1/2-in disk drives, is about $74 \times 12 \times 46$ cm, roughly the size of a floor-standing workstation. Packaging for a 128-node machine occupies a standard 19-in rack. Timing numbers in this paper reflect the 32-node Alewife machine, packaged in the lower right quarter of the 128-node chassis.

User access to an Alewife machine is through a host workstation. Client interface software connects to the Alewife machine via UNIX sockets to a server process running on the host. External network file system (NFS) file access is also provided by the host.

The first Alewife machine became operational in May 1994. Results in this paper were obtained using first-silicon versions of Sparcle and the CMMU. Although there are a few bugs in the CMMU, all of them have software work arounds. However, one of the bugs involves a timing conflict with the FPU, requiring operation at 20 MHz when floating point is in use. Integer codes run at 30 MHz. For consistency, the remainder of this paper will quote performance numbers at a 20-MHz system speed.

A. Sparcle Processor

Sparcle was derived from an industry-standard SPARC (version 7) processor. It provides an efficient and tight coupling between the processor pipeline and the communications network. Many of the features of the underlying SPARC implementation are exploited directly by Alewife: for example, the SPARC external coprocessor interface is used for fast messaging, interrupt control, and fine-grained synchronization. SPARC also provides register windows

that can be exploited as separate contexts for block multithreading.

Sparcle augments the basic SPARC architecture with a few simple mechanisms to facilitate rapid messaging, block multithreading, and fine-grain synchronization.

- *User-Level Colored Loads and Stores:* The SPARC architecture defines an 8-bit Alternate Space Indicator (ASI) that serves to tag all load and store operations with one of 256 different “colors.” Sparcle allocates the top 128 ASI values to the user and defines new load and store instructions that emit these ASI values.
- *Extra Synchronous Trap Lines:* These lines enable unique trap vectors for context-switch and fine-grain synchronization traps.
- *Context Management Instructions:* New instructions allow rapid switching between active hardware contexts. The SPARC current window pointer is visible at the pins, permitting context-dependent state in the CMMU and FPU.

These changes require an increase of fewer than 2000 gates over the unmodified SPARC design. Together, they yield a processor with support for low-overhead communication, including a 14-cycle context-switch time for a remote data cache miss.

B. The Alewife CMMU

The Alewife CMMU [20] implements most of the unique functionality of Alewife. In an Alewife node, the CMMU is connected directly to the first-level cache bus and serves much the same functionality as a cache-controller/memory-management unit in a uniprocessor. It contains tags for the cache, provides dynamic random access memory (DRAM) refresh and error correcting codes (ECC) and handles cache fills and replacements. In addition, it implements the architectural mechanisms described in this paper. The CMMU also provides asynchronous queuing for the EMRC network chips and a number of hardware statistics facilities.

Fig. 3 shows a block diagram of this chip. The *Processor Glue Logic* is responsible for interpreting colored memory operations and coprocessor instruction requests. The *Cache Management and Invalidation Control* and *Memory Coherence and DRAM Control* blocks comprise, respectively, the processor and memory portions of the cache coherence protocol. In addition, both blocks service requests from the *Network Interface and DMA Control* block, which provides user-level message passing with locally coherent DMA [18]. Since the processor and memory sides of the cache coherence protocol as well as the message-passing interfaces share the same network queues, message passing and shared memory are integrated [16].

The *Transaction Buffer* is a 16-entry, fully associative data store that tracks outstanding cache coherence transactions, holds prefetched data, and stages data in transit between the cache, network, and memory. It is integrated closely with the mechanism for removing livelock in the face of block multithreading [19]. The transaction buffer is also responsible for making the Alewife coherence pro-

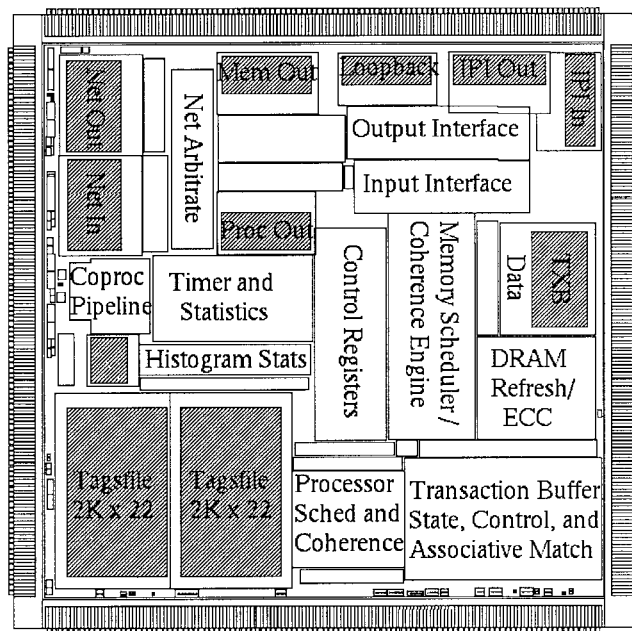
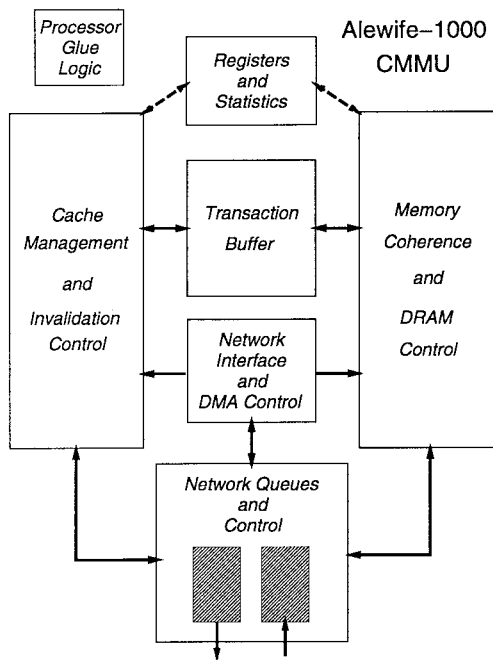


Fig. 3. Block diagram and floor plan for the CMMU (15 mm × 15 mm).

toloc insensitive to reordering in the network. It does this by tracking in-progress memory transactions, retaining sufficient processor-side information to reconstruct the message order intended by a memory node even when messages arrive at the processing node out of order. Among other things, this information enables a scheme called *deferred invalidation* to untangle misorderings between data messages and subsequent invalidations—a critical type of misordering that can lead to incoherence: invalidations that arrive prematurely when data are expected are simply deferred until the data arrive. The *Registers and Statistics* block contains a dedicated cycle counter, a timer, and a number of statistics facilities. The *Network Queues and Control* block contains asynchronous interfaces for the EMRC network routers.

Fig. 3 also shows a floor plan of the CMMU. This chip is implemented with three layers of metal in the LEA-300K hybrid gate-array technology from LSI Logic. Shaded blocks are standard-cell memories. The rest of the chip is implemented in a sea-of-gates style; costs for the gate-array portion of the chip are given in Table 1. In this technology, an NAND gate is one (1) gate, while a scan flip-flop takes nine (9) gates.

C. Programming Model

Although the fast-message capability of Alewife makes it a good vehicle for executing programs written in a message-passing style, it is better viewed by the programmer as a shared-memory machine. The Alewife hardware mechanisms, including fast messages, are combined in support of the shared-memory programming model. To facilitate programming, Alewife provides tools that inform programmers when poor performance is caused by widely shared data objects, and which parts of the application are

Table 1

Functional Block Sizes (in Gates) for the Alewife CMMU, as Well as Contributions to Shared Memory (SM), Message Passing (MP), Latency Tolerance (LT), and Fine-Grain Synchronization (FG) [Total Chip Resources: 100 Kgates and 100 Kbits of Static Random Access Memory (SRAM)]

Category	Gate Count	%	Mechanism			
			SM	MP	LT	FG
Processor Requests	11686	12	✓		✓	✓
Full/Empty Decode	2157	2				✓
Memory Service	13351	13	✓	✓		
DRAM Control	8720	9	✓	✓		
Livelock Removal	2108	2	✓		✓	
Transaction Buffer	17399	17	✓	✓	✓	
IPI interface	11805	12	✓	✓		
Network Queueing	7363	7	✓	✓	✓	✓
CMMU Registers	9308	9	✓	✓		
Statistics	11958	12				
Miscellaneous	4627	5				

affected. Programmers can then fine tune performance by using the direct message-passing interface integrated with shared memory.

Alewife has compilers for a parallel version of ANSI C and a parallel version of LISP called Mul-T [15]. For parallel C, Alewife supports the p4 library from Argonne National Laboratory as well as parallel loops and distributed arrays. Automatic partitioning can be used when a program uses parallel loops and arrays [1].

Parallelism in Mul-T is specified with the *future* construct. Low thread creation overhead is achieved using lazy task creation [24], a method for dynamic partitioning and load balancing. The Alewife run-time system includes a parallel stop-and-copy garbage collector.

D. Alewife Debugging and Tuning

Alewife provides a number of facilities to aid in program debugging and performance tuning. An Alewife version of

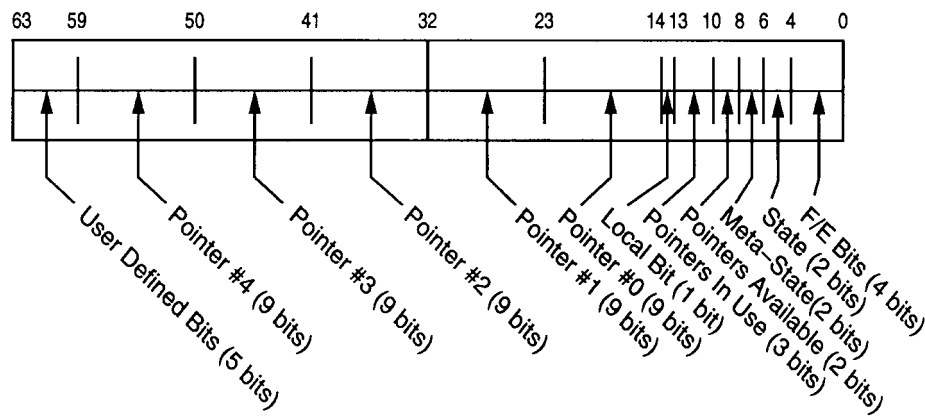


Fig. 4. A hardware directory entry in Alewife.

GNU debugger (GDB) allows symbolic program debugging, complete with the ability to set break points, examine data and registers on individual nodes, and inspect threads, both active and blocked.

The programmer can make use of two distinct facilities in Alewife for performance debugging. First, the LimitLESS cache coherence mechanism can be configured to collect information about which memory locations are being shared and accessed in a pattern that causes poor performance. A tool is available that traces errant memory behavior directly to source variables.

Second, the Alewife CMMU provides extensive facilities for performance monitoring. Four 32-bit statistics counters and a histogram array can be configured to measure a wide variety of hardware events: examples include cache hits and misses, instruction counts, and network throughput statistics. A graphical interface allows users to specify a set of statistics and displays static and dynamic views of the results.

III. MECHANISMS AND MICROBENCHMARKS

This section describes the implementation of the mechanisms introduced in Section I. It presents the cost and the raw performance of each of the mechanisms in isolation.

A. DSM

The Alewife machine provides hardware support for distributed, cache-coherent shared memory. Cache lines in Alewife are 16 bytes in size and are kept coherent through a software-extended scheme called LimitLESS [9], [10]. This scheme implements a full-map directory protocol by supporting up to five readers per memory line directly in hardware and by trapping into software for more widely shared data. Consequently, LimitLESS involves a close interaction between hardware and software. The hardware invokes software handling for remote requests by making use of the Alewife message-passing interface: faulted coherence requests are forwarded to the processor in the same way as any other message. The queuing inherent in the message-passing interface permits multiple pending LimitLESS coherence requests.

Shared memory is distributed, in the sense that the shared address space is physically partitioned among nodes. Each 16-byte memory line has a home node that contains storage for its data and coherence directory. All coherence operations for a given memory line, whether handled by hardware or software, are coordinated by its home node. Each Alewife node contains the data and coherence directories for a 4-Mbyte portion of shared memory.

The Alewife directory entry format is shown in Fig. 4. Directories are 64-bits wide and are stored in off-chip DRAM. Each entry contains five 9-bit pointers, two bits of state, two bits of metastate, and four full/empty bits (one for each word in the line). The Local Bit provides an optimization which guarantees that the local node can always acquire a pointer. The Pointers In Use field indicates the number of other pointers that are in use. The number of pointers available to the hardware may be adjusted from two to five with the Pointers Available field. Since the Pointers In Use field can be set by software, the cost of the LimitLESS read handler is amortized over up to six different read requests: when invoked to handle a read request, the handler resets the Pointers In Use field, allowing the next five requests to be handled without software intervention.

Sparcle employs a single-ported, unified first-level cache, with no on-chip instruction cache. Consequently, 32-bit loads and stores that hit in the cache take two and three cycles, respectively, (one cycle for the instruction fetch). Doubleword (64-bit) loads and stores that hit in the cache take one additional cycle.

Table 2 shows the cost incurred when memory references miss in the cache. These values were obtained with a sequence of experiments run on an otherwise idle Alewife system. All remote misses or invalidations are between adjacent nodes. Each additional “hop” of communication distance increases these latencies by approximately 1.6 cycles.

For a simple load miss to remote memory handled in hardware, 58% of the 38-cycle miss penalty is due to network latency (1.1 out of 1.9 μ s). Roughly three-quarters of the network latency is time spent transferring flow-control units (flits) between the CMMU and the interconnection

Table 2
Typical Shared Memory Miss Penalties

Miss Type	Home Location	# Inv. Msgs	hw/sw	Miss Penalty	
				Cycles	μ sec
Load	local	0	hw	11	0.55
	remote	0	hw	38	1.90
	remote (2-party)	1	hw	42	2.10
	remote (3-party)	1	hw	63	3.15
	remote	-	sw [†]	425	21.25
Store	local	0	hw	12	0.60
	local	1	hw	40	2.00
	remote	0	hw	38	1.90
	remote (2-party)	1	hw	43	2.15
	remote (3-party)	1	hw	66	3.30
	remote	5	hw	84	4.20
	remote	6	sw	707	35.35

[†] This sw read time represents the throughput seen by a single node that invokes LimitLESS handling at a sw-limited rate.

Table 3
Rough Breakdown of 38-Cycle Clean Read-Miss to Neighboring Node

Action	Count
Cache-miss to request in network	2
Request transit time (8 bytes)	7
Request at memory to output header transmit	7
Data return in network (24 bytes)	15
Response arrival to beginning of cache fill	3
Cache fill time	4

network (36 flits at 22.5 ns/flit). Table 3 gives a breakdown of the various latencies involved in satisfying a remote read-miss.

Misses handled in software represent the access time seen when a cache line is shared more widely than is supported in hardware (five pointers), so that the home node processor must be interrupted to service the request. In the case of a load, the software time represents the maximum throughput available when every request requires software servicing. Because of the read-ahead optimization and amortized read handling, this latency number will rarely be experienced by a requesting node. The software store latency represents an actual latency seen by a writer; it includes the time required for the software handler to send six invalidations, for these invalidations to be received by the hardware, and for an exclusive copy to be returned.

B. Message Passing

Message passing is both a crucial component of the LimitLESS cache coherence protocol and a mechanism to be used in cooperation with software-extended shared memory. Some communication operations, such as file I/O, remote task dispatch, and the inner loops of typical scientific codes, can often be implemented more efficiently with message passing than with shared memory. Further, since Alewife provides a protected user-level message-passing interface, compilation targets such as active messages [32] are naturally supported.

Messages in Alewife are sent through a two phase process: first *describe*, then *launch*. A message is described by writing directly to an output descriptor array with a

```

stio header,    $ipiout0
stio dataword, $ipiout1
stio address,  $ipiout2
stio length,   $ipiout3
ipilaunch 2, 1

```

Fig. 5. Machine code implementing a message send. In addition to the required header, this message includes one explicit data word, and one block of data from memory.

colored store instruction called *stio*. The output descriptor array consists of 16 memory-mapped network registers in the CMMU. Writes into this array incur the same cost as write hits in the cache. Once a message is described, it is launched via an atomic, single-cycle instruction called *ipilaunch*. This two-phase process permits direct, user-level access to the network queues.

Fig. 5 illustrates code for launching a message that consists of a header, one word of data from a register, and a block of data from memory (to be transferred via DMA). The header, dataword, address, and length are aliases for arbitrary Sparcle registers. On entry to this code sequence, *header* contains the packet header, *dataword* contains the word of data, *address* points to the start of the data block, and *length* gives the number of double-words in the data block. This packet descriptor is two double-words long and contains one double-word of explicit data (*header* and *dataword*). Alewife maintains local coherence for the data block specified by *address* and *length*: data are acquired from the local cache at the source and invalidated from the local cache at the destination.

When a message arrives at its destination, it typically causes an interrupt. The CMMU overlaps message arrival with interrupt processing by posting the interrupt as soon as it has received the header of a message. Since the operating system reserves one of the four Sparcle hardware contexts for message processing (as in [26] and [29]), no register saves or restores are necessary. The first 16 words of an incoming message are presented in the memory-mapped input packet array. Consequently, an interrupt handler may either load words directly from this array via the *ldio* instruction, or initiate a DMA sequence to store the message into memory.

The Alewife message-passing interface has low overhead. A simple, two-word message (one header, one data word), can be transmitted with three instructions, or seven cycles. Message reception can use polling or interrupts. The cost of reception is more expensive when an interrupt must be fielded at the receiving end. Using interrupts, a system-level handler for a two-word message can be entered in approximately 35 cycles. This time includes reading the message from the network, dispatching on an opcode in the header, and setting up for a general call to handler routines written in C.

Adding user-level message protection increases this entry time by another 15 cycles to approximately 50 cycles. A null user-level message handler requires a total of 95 cycles. Much of this time is associated with saving and restoring

Table 4
Examples of Alewife’s Data-Access Instructions

Name	Meaning
ldn	Load and examine full/empty bit.
stn	Store and examine full/empty bit.
lden	Load, set empty, examine original value.
stfn	Store, set full, examine original value.
ldet	Load, set empty, and trap if already empty.
stft	Store, set full, and trap if already full.

the system-level timer (to time out an errant user-level handler and prevent a user from locking up the machine), preventing access to shared memory before the current message has been removed from the queue, and checking for user-requested atomicity. Simple modifications to the CMMU can combine these three functions into a single mechanism and reduce the overhead of protected message passing considerably.

Measurements of Alewife’s mesh network show that each channel provides a peak bandwidth of approximately 356 Mbits/s (22.5 ns per 8-bit flow-control unit). For a 16-node machine, this rate yields a maximum possible bisection bandwidth of 2.8 Gbits/s.

C. Fine-Grain Synchronization

The primary advantage of fine-grain synchronization is that more parallelism can be exposed to the underlying hardware or software system than if coarse-grain synchronization techniques, such as barriers, were employed. For example, a thread synchronizing at a barrier has to wait for the arrival of all other synchronizing threads before proceeding, regardless of whether that thread depends on results computed by the other threads. By synchronizing on exactly the data words to be consumed, fine-grain synchronization eliminates false dependencies and allows a thread to proceed as soon as the data it needs are available.

The Alewife machine provides both hardware and software support for fine-grain synchronization. Hardware support consists of a full/empty bit [31] for each 32-bit data word. To access these bits, colored load and store instructions are provided that perform full/empty test-and-set operations. Table 4 presents a sample of Alewife data-access instructions. All of these instructions return the original full/empty bit in the coprocessor status word. Two Sparcle instructions, `bempty` (branch on empty) and `bfull` (branch on full), can then be used to examine this bit.

In Alewife, the odd data width introduced by full/empty bits does not impact DRAM, cache, or network data widths. At memory side, full/empty bits are stored in the bottom four bits of the coherence directory entry (see Fig. 4). At cache side, they are stored as an extra field in the cache tags. In data packets, they are transmitted in the bottom four bits of the address and take advantage of the 16-byte cache-line width.

The system provides several language extensions for fine-grain synchronization in the form of J-structures and L-structures. Patterned after I-structures [7], J-structures support producer-consumer style synchronization on vector

Table 5
Costs in Cycles of Fine-Grain, Producer-Consumer Synchronization In Alewife (“hw” Represents the Use of Full Hardware Support; “sw” Represents Explicit Checking in Software)

Event	hw	sw
Read success	2	6
Read failure	21	6
Write	3	6
Unload thread	120–130	
Reload thread	90–100	

elements, with full/empty bits associated with each vector element. A J-structure read waits until the element is full before returning its value. A J-structure write updates the element and sets it to full. An L-structure supports mutual-exclusion style synchronization on vector elements with full/empty bits associated with each vector element. L-structures support three operations: a locking read; an unlocking write; and a nonlocking read.

Table 5 compares the costs (in cycles) of implementing J-structure read and write operations, with and without hardware support. The hardware implementation (hw) relies on traps to signal a failed read and uses a separate, centralized waiting queue. It allows successful reads and writes to proceed at the speed of normal Sparcle loads and stores. The software-based implementation (sw) uses an additional memory word to emulate a full/empty bit for each J-structure element.

D. Latency Tolerance

Latency tolerance in Alewife takes two forms: block multithreading and nonbinding software prefetching. By supporting both block multithreading and prefetching, Alewife provides a platform for directly comparing these two latency tolerance mechanisms.

Three different mechanisms in the Alewife CMMU help support block multithreading. First, the CMMU takes advantage of as much parallelism as possible when servicing a remote cache miss by generating a context-switch trap in parallel with message generation. Second, the CMMU implements lockup-free caches. Third, the CMMU implements a livelock avoidance technique to prevent the livelock that can arise when cache-coherent shared memory is coupled with context switching and LimitLESS.

Software prefetch is implemented in Alewife as two different colored load instructions, one for read prefetch and the other for write prefetch; the value returned from the prefetch instructions is ignored. Prefetched data are returned in the transaction buffer.

To measure the benefit of latency tolerance using context switching and prefetching, an experiment runs a small loop on one processor that adds numbers fetched from the memory of another processor. Fig. 6 shows the number of cycles per loop iteration as a function of the number of outstanding requests. As expected, one outstanding request incurs the same overhead using either prefetching or context switching. As the prefetch depth is increased, the performance improves until the limit of network bandwidth is

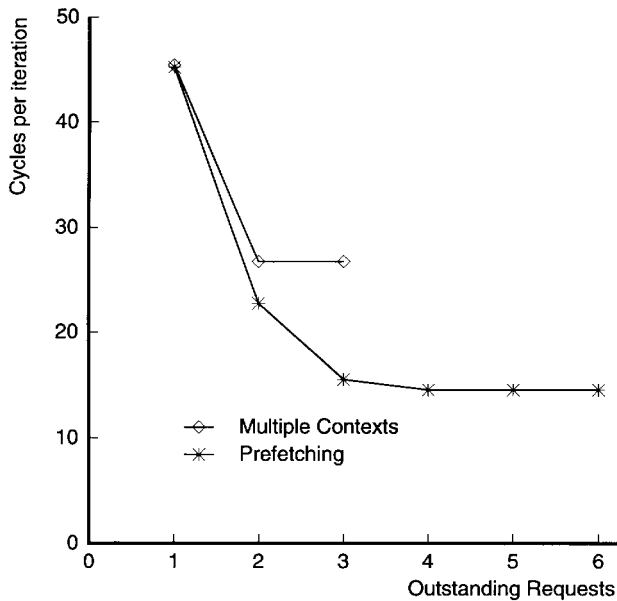


Fig. 6. Effectiveness of latency tolerance mechanisms.

reached. For context switching, the limiting factor is the overhead of the mechanism, not bandwidth. Because the loop performs remote reads which have a relatively low latency (~ 40 cycles), the 14-cycle context switch time hides all of the latency with two contexts. For longer remote latencies that can occur in real programs, three contexts may be beneficial.

Although the absolute performance of prefetching is better due to low overhead, its use is limited to places where cache-miss behavior can be predicted statically. Results in Section IV show that context switching can increase the performance of a parallel application, even when prefetching has been carefully used.

IV. APPLICATION PERFORMANCE

This section presents the performance of a number of applications and demonstrates the efficacy of the mechanisms in the machine. It starts by summarizing the performance of a dozen applications written in a shared-memory style. Section IV-A presents details of an application case study using MP3D. Section IV-C uses EM3D to compare the relative benefits of shared memory and message passing.

A. DSM Performance

Shared-memory applications perform well on Alewife, proving the viability of both the software-extended coherence mechanism and the low-dimensional communication substrate provided by the mesh network. Table 6 summarizes the main characteristics of the applications evaluated on Alewife. The first five applications shown in the table are from the SPLASH suite [30], the three following ones are from the NAS parallel benchmarks [8], the next four are engineering kernels, and the last solves a numerical problem.

Table 7 presents the running time and speedup performance of these applications on Alewife. The table includes

Table 6
Main Application Characteristics

Program	Input Size
MP3D	18k particles, 6 iterations
Barnes-Hut	16k bodies, 4 iterations
LocusRoute	3817 wires, 20 routing channels (Primary2)
Cholesky	3948 \times 3948 floats, 56934 non-zeros (TK15)
Water	729 molecules, 5 iterations
Appbt	20 \times 20 \times 20 floats
Multigrid	56 \times 56 \times 56 floats
CG	1400 \times 1400 doubles, 78148 non-zeros
EM3D	20000 nodes, 20% remote neighbors
Gauss	512 \times 512 floats
FFT	80k floats
SOR	512 \times 512 floats, 50 iterations
MICCG3D	32 \times 32 \times 32 and 64 \times 64 \times 64 floats

results for “Mod MP3D,” which is a version of the original MP3D application that eliminates some useless code and improves locality by modifying the mapping of particles to processors. Section IV-B discusses both the original and modified versions of MP3D in detail.

All the speedups presented in Table 7 are based on the parallel implementation of each program running on one processor except those that are marked in the table with asterisks and the different versions of MICCG3D. These exceptions ran with input sizes that do not fit on a single node’s memory.¹ The experiments with an asterisk assume that the speedup is linear at the smallest number of nodes that can hold the data set. The MICCG3D speedups are computed using a best sequential running time that is obtained by assuming that sequential running time grows linearly with problem size. The Alewife compiler, used for all applications, produces code with a sequential running time that is within 10% of gcc at the “-O2” level of optimization.

The results show that Alewife usually achieves good application performance, especially for the computational kernels, even for relatively small input sizes. In particular, MP3D (an application with a difficult shared-memory work load) achieves extremely good results. In contrast, a comparison between the two entries for Cholesky in the table demonstrates the importance of the input size for the performance of this application; a fivefold input size increase leads to a significant improvement in speedup. The modest speedups of CG and Multigrid result from load imbalance and bad cache behavior, which can be addressed by using larger input sizes and the latency tolerance mechanisms in Alewife.

Table 7 presents the performance of the 32 \times 32 \times 32 and 64 \times 64 \times 64 input sizes for MICCG3D (labeled MICCG3D-32 and MICCG3D-64, respectively) using coarse-grain and fine-grain synchronization. The speedups appear low because they are measured against the best sequential implementation of the application, rather than a uniprocessor run of the parallel algorithm. Versions of MICCG3D using fine-grain synchronization perform significantly better than those using coarse-grain synchronization. We observed that

¹Barnes-Hut was run with 32k bodies as input, while Cholesky was run with five times as many nonzeros as the base input size.

Table 7

Performance of Shared-Memory Applications on Alewife

Program	Running Time (Mcycles)						Speedup					
	1P	2P	4P	8P	16P	32P	1P	2P	4P	8P	16P	32P
Orig MP3D	67.6	41.7	24.8	13.9	7.4	4.3	1.0	1.6	2.7	4.9	9.2	15.7
Mod MP3D	47.4	24.5	12.4	6.9	3.5	2.2	1.0	1.9	3.8	6.9	13.4	21.9
Barnes-Hut	9144.6	4776.5	2486.9	1319.4	719.6	434.2	1.0	1.9	3.7	6.9	12.7	21.1
Barnes-Hut *	-	10423.6	5401.6	2873.3	1568.4	908.5	-	2.0	3.9	7.3	13.3	22.9
LocusRoute	1796.0	919.9	474.1	249.5	147.0	97.1	1.0	2.0	3.8	7.2	12.2	18.5
Cholesky	2748.1	1567.3	910.5	545.8	407.7	398.1	1.0	1.8	3.0	5.0	6.7	6.9
Cholesky *	-	-	2282.2	1320.8	880.9	681.1	-	-	4.0	6.9	10.4	13.4
Water	12592.0	6370.8	3320.9	1705.5	897.5	451.3	1.0	2.0	3.8	7.4	14.0	27.9
Appbt	4928.3	2617.3	1360.5	704.7	389.7	223.7	1.0	1.9	3.6	7.0	12.6	22.0
Multigrid	2792.0	1415.6	709.1	406.2	252.9	165.5	1.0	2.0	3.9	6.9	11.0	16.9
CG	1279.2	724.9	498.0	311.1	179.0	124.9	1.0	1.8	2.6	4.1	7.1	10.2
EM3D	331.7	192.1	95.5	46.8	22.4	10.7	1.0	1.7	3.5	7.1	14.8	31.1
Gauss	1877.0	938.9	465.8	226.4	115.7	77.8	1.0	2.0	4.0	8.3	16.2	24.1
FFT	1731.8	928.0	491.8	261.6	136.7	71.8	1.0	1.9	3.5	6.6	12.7	24.1
SOR	1066.2	535.7	268.8	134.9	68.1	32.3	1.0	2.0	4.0	7.9	15.7	33.0
MICCG3D-32-Coarse	-	36.6	21.7	11.7	6.9	4.4	-	0.5	0.8	1.5	2.5	3.9
MICCG3D-32-Fine	-	-	11.7	5.8	2.9	1.5	-	-	1.5	3.0	5.9	11.5
MICCG3D-64-Coarse	-	-	-	-	-	32.2	-	-	-	-	-	4.3
MICCG3D-64-Fine	-	-	-	-	-	12.5	-	-	-	-	-	11.1

the ability to express synchronization at a fine granularity has a first-order impact on performance for the MICCG3D application [33]; providing support for the fine-grain synchronization primitives in hardware is a second-order effect.

As a whole, experience with porting a variety of applications in a short period of time shows that Alewife provides a good environment for applications written in a shared-memory style. Programs can be easily ported to the machine and usually achieve good performance.

B. MP3D

On Alewife, MP3D achieves the largest reported speedup for this application. There are two reasons for this result. First, most of the communication traffic in the benchmark is caused by migratory data, and Alewife’s coherence protocol is optimized for this type of data. Second, Alewife has relatively low (~60-cycle) latency for three-party remote read transactions, which results from Alewife’s pipelined memory system and its simple, flat network hierarchy. This low latency pays off when the whole hierarchy must be traversed frequently.

MP3D also serves as a good vehicle for assessing the performance of Alewife’s latency tolerance mechanisms. The original MP3D code is a good candidate for latency tolerance, since improvements in locality for this program are difficult to obtain without significant code restructuring. Accordingly, this section considers the effect of using multiple contexts, software prefetching, and a combination of these two. Fig. 7 presents the speedups of different versions of MP3D. All speedups in this graph are computed with respect to the nonprefetching parallel implementation running on one processor.

In order to investigate the maximum possible benefit of prefetching, software prefetching was inserted by hand. The prefetch instructions concentrate on the data causing the majority of the cache misses in MP3D. As seen in Fig. 7,

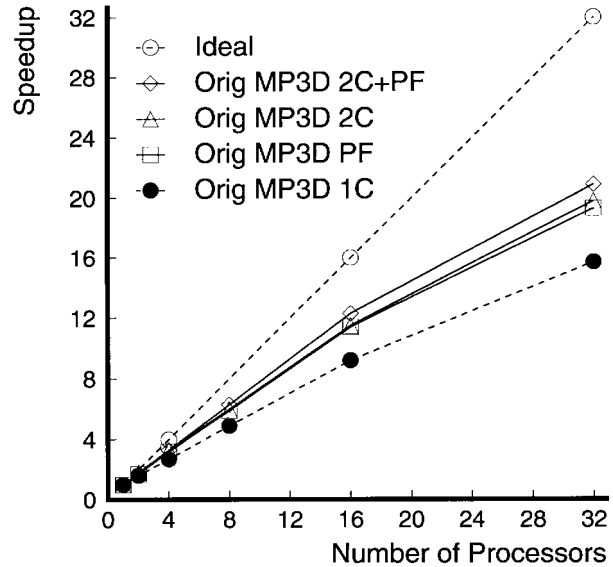


Fig. 7. Speedups for various versions of MP3D: single-context (1C); two contexts (2C); and prefetching (PF).

prefetching achieves a 23% improvement in speedup at 32 processors over the nonprefetching version.

Block multithreading allows MP3D to perform marginally better than hand-crafted software prefetching (26 versus 23%), proving that context switching can help applications achieve performance comparable to versions generated by sophisticated compilers and/or programmers. An interesting observation is that the combination of prefetching and multithreading for MP3D approaches the speedup performance of the hand-optimized version of the application, Mod MP3D (see Table 7). One possible explanation for this effect is that multithreading can tolerate the latency of replacement cache misses, which are difficult to predict when implementing software prefetching.

Fig. 8 presents the cost breakdown (measured by the Alewife statistics hardware) for MP3D and Mod MP3D

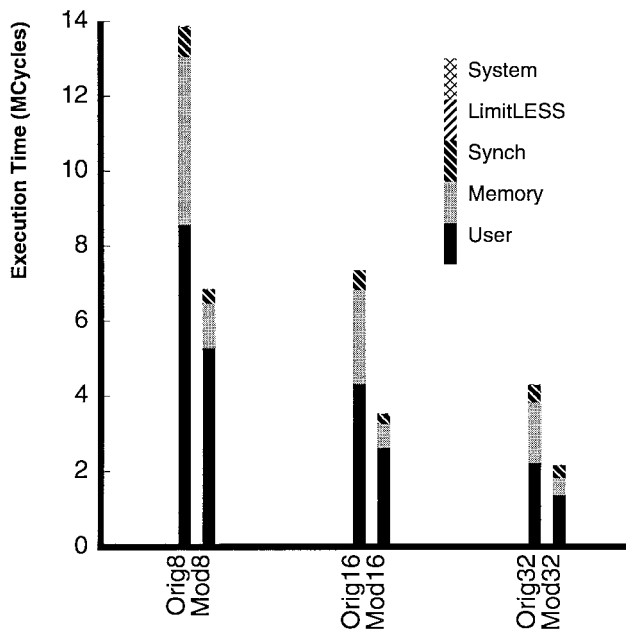


Fig. 8. Orig and Mod MP3D running times, with costs.

for eight, 16, and 32 processors. As shown in this figure, Mod MP3D significantly reduces both the busy time and the memory wait overhead of MP3D. Another interesting observation is that the overhead of handling widely shared cache blocks in software (the LimitLESS component) and the scheduler costs (the system component) are always negligible for the two programs. In fact, none of the shared-memory applications suffer significantly from these two types of overhead.

C. Message Passing, Shared Memory, and Network Bandwidth

The debate about the relative merits of shared memory and message passing has raged between parallel-processing experts for at least two decades. Because Alewife integrates user-level shared memory and message passing, the prototype offers a unique opportunity for providing some insight into the tradeoff between these two programming styles. An important metric for making this tradeoff is network bandwidth: if the processor interconnection fabric can deliver enough bits per second, DSM is a perfectly fine mechanism for almost all applications. However, as processing speeds increase faster than network speeds, programmers must use message-passing techniques to achieve desired levels of performance.

Before attempting the comparison between shared memory and message passing, it is important to verify the performance of each of the mechanisms independently. The microbenchmarks in Section III-A and the previous benchmark studies certainly argue that Alewife's implementation of shared memory is more than adequate for the purpose. Section III-B and the following case study make a similar argument for Alewife's implementation of message passing.

1) *Message-Passing Performance:* In order to verify that Alewife provides reasonable message-passing performance, this case study compares the relative performance of an

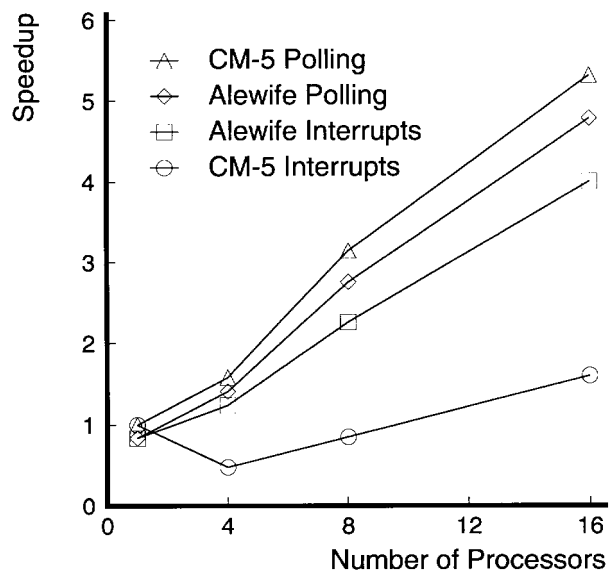


Fig. 9. Performance of a message-passing implementation of the sparse triangular matrix solver.

application running on the Alewife prototype and on the Thinking Machines' CM-5, a commercial message-passing architecture built with contemporary technology. This application is a power grid benchmark from a sparse matrix suite [12] which uses the techniques of [11].

Fig. 9 presents speedups of message-passing implementations of this application on Alewife and the CM-5. Speedups are computed based on the execution time (in cycles) of an optimized sequential code running on a single CM-5 node. The difference between the two polling implementations of the machines is 10%, and can be entirely attributed to the use of an experimental compiler on Alewife. Additionally, the difference between polling and interrupt versions on Alewife is only 16%. In contrast, the interrupt-driven version of this application on the CM-5 suffers more than a factor of three degradation over the polling version.

In summary, Alewife's base performance is comparable to the CM5 when polling is used. However, Alewife's uniqueness stems from its special support for mechanisms such as interrupt-driven messages, whose performance is much better than that of commercial machines. Interrupt-driven message delivery enables a program running on a node to be unaware of when messages are processed by the local node. In contrast, polling requires that the programmer be aware of when messages might need to be processed and ensure that the network is polled frequently enough to allow the messages to be serviced promptly, or else suffer poor performance or even deadlock [14]. Placing this additional burden on programmers has a negative impact on the ease of use of the message passing programming model.

2) *Comparing Communication Volumes:* Having validated shared memory and message passing independently, the next step is to compare their relative merits. Although shared-memory applications in Alewife leverage the messaging mechanisms through their run-time system, applications written in the message-passing style exploit

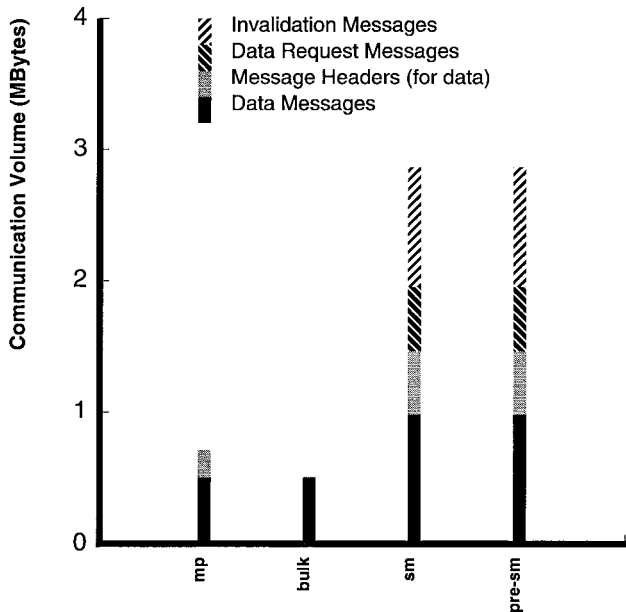


Fig. 10. Breakdown of communication volume per processor node for each communication mechanism.

Alewife’s messaging interface directly. Rewriting the EM3D benchmark as a message-passing application allows a direct comparison between these two styles.

In the following analysis, SM indicates the original EM3D benchmark; PRE-SM indicates a version tuned to use Alewife’s prefetch mechanism; MP is a message-passing polling² version; and BULK is a message-passing version that uses Alewife’s bulk data-transfer mechanism. Fig. 10 shows that the average communication volume—the amount of data injected into the network over the course of an execution—is three to four times higher for the shared memory version of EM3D than the message-passing version. Bulk transfer further reduces the volume by saving on message headers.

Where message passing uses a single message to communicate a value along each edge of a graph problem, shared memory (using an invalidation protocol) must use at least four: the writer must invalidate the reader’s copy, the reader acknowledges the invalidate, the reader later requests a valid copy, and the write responds with valid copy. Additional messages may be required if the writer must invalidate cached copies on more than one reader. Additional traffic is generated when spin locks are necessary to enforce atomic read-modify-writes. While a shared-memory protocol with optimizations for update transactions might reduce the communication volume, such protocols still require at least twice as many messages as optimal message-passing codes. Similarly, prefetching can reduce average memory-access latency, but the mechanism almost always increases communication volume.

3) *Bisection Bandwidth Emulation:* While communication volume measurements are important, the bottom line of DSM performance is application execution time, not

²Since polling performs slightly better than interrupts and communication volume is similar for this application, interrupts are omitted.

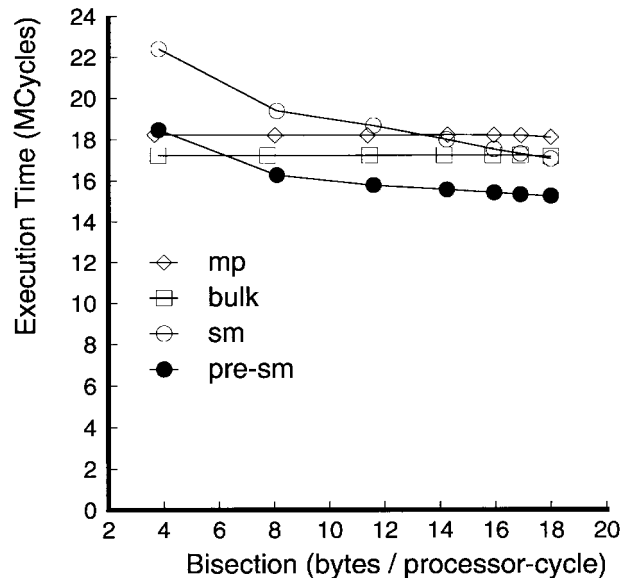


Fig. 11. Execution time (in cycles) on a 32-node system versus bisection bandwidth. Alewife is at 18 bytes/processor-cycle.

network usage. Since the Alewife prototype provides more than adequate interprocessor bandwidth for most applications—including EM3D—shared memory remains the mechanism of choice. However, the current prototype is only one point in a design spectrum. Since it was built, increases in processor speed have dramatically outstripped network transfer rates.

To investigate the effects caused by lower network speed, it is possible to reduce the Alewife prototype’s available network bandwidth artificially. Background cross traffic, generated by the I/O nodes shown in Fig. 1, lowers the effective bandwidth without directly changing the behavior of an application running on the compute nodes. The bisection bandwidth of the emulated system is calculated by taking Alewife’s maximum (18 bytes per processor cycle) and subtracting the amount of cross traffic sent. Experimental factors (such as the size of the cross-traffic messages) limit the minimum effective bisection bandwidth to 4 bytes per processor cycle.

Fig. 11 plots EM3D performance on a 32-node system as the amount of I/O cross traffic varies. The X axis plots bisection bandwidth in bytes per processor cycle. The Y axis plots application run time in processor-cycles. The data points on the right side of the graph indicate the baseline performance of Alewife: even the basic shared-memory version of EM3D performs as well as the optimized message-passing version. Given the increases in processor speed since the prototype was built, only the most expensive DSM systems in the future will have bisection bandwidths closer to the left side of the graph. In this regime, only heroic latency-tolerance techniques (like hand-optimized prefetching or possibly multithreading) allow shared memory to achieve the performance of message passing.

As is the case with most religious debates, the answer depends on the point of view. In this case, the relative merits of shared memory versus message passing depend

on applications' use of communication resources. The best architectural solution to this dilemma is to integrate both mechanisms together, allowing programmers to choose the appropriate model of parallel computation for their own applications.

V. RELATED WORK

A number of other systems provide a shared address space entirely in hardware. DASH [22] is a cache-coherent multiprocessor that uses a full-map directory-based cache coherence protocol. It includes prefetching and a mechanism for depositing data directly in another processor's cache. The KSR1 and DDM [13] provide a shared address space through cache-only memory. These machines also allow prefetching. The Scalable Coherent Interface [6] also specifies mechanisms for implementing large shared address spaces.

Both the J-machine [26] and the CM-5 export hardware message-passing interfaces directly to the user. These interfaces differ from the Alewife interface in several ways. First, in Alewife, messages are normally delivered via an interrupt and dispatched in software, while in the J-machine, messages are queued and dispatched in sequence by the hardware. On the CM-5, message delivery through interrupts is expensive enough that polling is normally used to access the network. Second, neither the J-machine, nor the CM-5 allow network messages to be transferred through DMA. Third, the J-machine does not provide an atomic message send like Alewife does; this omission complicates the sharing of a single network interface between user code and interrupt handlers.

The Cray T3D integrates message passing and hardware support for a shared address space. Message passing in the T3D is flexible and includes extensive support for DMA. However, the T3D does not provide cache coherence.

Several subsequent architectures are based on the integration of shared memory and message passing in some form. FLASH [21] includes a microcoded, kernel-level coprocessor for message handling including shared-memory protocol messages. Bulk transfers in FLASH avoid using the receiving processor, but require prenegotiating memory allocation. FLASH provides a multi-user environment. Typhoon [28] offers user-level message handling and cache coherence, using a second processor dedicated to the network interface. The *T [25] architecture uses a memory coprocessor model as well.

A few architectures incorporate multiple contexts, pioneered by the HEP [31], switching on every instruction. These machines, including Monsoon [27] and Tera [5], do not have caches and rely on a large number of contexts to hide remote memory latency. In contrast, Alewife's block multithreading technique switches only on synchronization faults and cache misses to remote memory, permitting good single-thread performance and requiring less aggressive hardware multithreading support. A number of architectures—including HEP, Tera, Monsoon, and the J-machine—also provide support for fine-grain synchronization in the form of full/empty bits or tags.

VI. CONCLUSION

As one of the first examples of a truly scalable DSM, Alewife represents a step in the maturation of multiprocessing technology. Specifically, it augurs the end of the religious war between proponents of the shared-memory and message-passing models of parallel computation. The working machine demonstrates that both models permit efficient and scalable implementations; moreover, the two models may—and should—be integrated into a unified multimodel framework. Shared memory is easy to program and performs better than message passing when machines have a high ratio of communication bandwidth to processing speed. Message passing, on the other hand, performs better when the machines are upgraded with faster processors, resulting in a lower ratio of communication bandwidth to processing speed. Although previous systems have implemented some of Alewife's mechanisms independently, Alewife is unique in its combination of coherent caches for shared memory, integrated message passing, support for fine-grained computation, and latency tolerance. These four mechanisms provide an integrated solution to the problems of communication and synchronization in parallel systems.

This integration of architectural features results in a multiprocessor that is both programmable and scalable. The case study using the MP3D application illustrates this conclusion: it was easy to port this demanding workload to the architecture, and the application worked and realized acceptable speedups almost immediately. Subsequent performance tuning and invoking Alewife's latency tolerance mechanisms significantly improved MP3D's performance.

Experience with a variety of other workloads confirms this anecdotal evidence. More broadly, experience with applications indicates that a globally shared address space, cache coherence, and a message-based run-time system is instrumental in the quick development of working applications that perform well. Latency tolerance mechanisms, fine-grain synchronization, and explicit message passing help improve performance further.

Although Alewife addresses many of the issues of large-scale multiprocessing, it is essentially a single-user machine. Our recent work has investigated mechanisms for protection and virtual memory in multiprocessors that support fast messaging. Implementing a virtual machine model is challenging because features such as multiprogramming and demand paging tend to interfere with streamlined, tightly-coupled communication. Our FUGU architecture [23] embodies an optimistic approach to message passing in a virtual machine: each application has direct access to a simple, fast, Alewife-like network interface unless immediate conditions (detected in hardware) dictate otherwise. Operating system software maintains the fiction of a virtual machine by transparently buffering messages in virtual memory when required.

We have also investigated the use of clustered DSM's to construct massively parallel processors (MPP's). Packaging constraints and low-volume demand significantly raise the cost of MPP's. Alternatively, the economy of high-

volume production provides a cost-performance advantage to MPP's built out of smaller-scale DSM's. The multigrain shared memory (MGS) project [34] investigates building MPP's by coupling multiple Alewife-like DSM's by a local area network using a page-based software DSM protocol to maintain coherence over the network. Early experience demonstrates that effectively exploiting multigrain sharing leads to performance on cost-effective clustered MPP's that is comparable to the high performance attained on monolithic all-hardware MPP's.

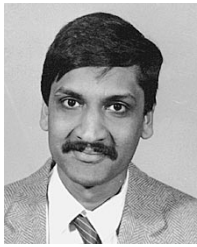
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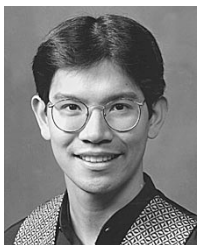
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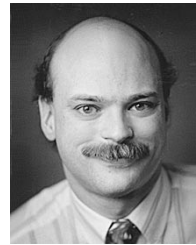


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