A Hardware Implementation of the MCAS Synchronization Primitive

***Abstract*—Lock-based parallel programs are easy to write. However, they are inherently slow as the synchronization is blocking in nature. Non-blocking lock-free programs, that use atomic instructions such as compare-and-set (CAS), are significantly faster. However, lock-free programs are notoriously difficult to design and debug. This can be greatly eased if the primitives work on multiple memory locations. We propose MCAS, a hardware implementation of a multi-word compare-and-set primitive. Ease of programming aside, MCAS-based programs are 13.8X and 4X faster on an average than lock-based and traditional lock-free programs respectively. The area overhead, in a 32-core 400mm^2 chip, is a mere 0.046%.**

I. Introduction

Creating efficient programming models for multicore processors is a very significant problem that researchers in academia and industry are trying their best to solve. There is a clear consensus [1] on the fact that to take parallel programming to the masses, it is necessary to create fast parallel libraries that novice programmers can use. Numerous steps have been taken in this direction such as better parallel programming libraries, software and hardware transactional memory, and novel parallel languages such as Mozilla Rust or Google Go.

To create parallel libraries it is necessary to provide parallel implementations of typical data structures that programmers tend to use such as heaps, stacks, and queues. The fastest possible implementations of such operations are typically non-blocking implementations where the algorithms do not use locks. They instead rely on built-in hardware synchronization primitives that allow conditional updations such as atomic compare-and-set (CAS) and load-link/store-conditional (LL/SC). Such non-blocking algorithms have a rich literature and are typically several orders of magnitude faster than comparable implementations that use locks especially if there is high contention. They have also been shown to be much faster than implementations with transactional memory[2].

Sadly, writing such algorithms is fairly hard and complicated, even for experienced programmers. It is very difficult to debug such programs, and guarantee their performance. Consider the example of a queue. Below is a lock-free implementation of the enqueue operation implemented using only CAS instructions (as in the popular Boost C++ library).

```
enqueue(newNode) {
    while( true ) {
        last = tail ;          // ‘ tail ’ is the queue’s tail
        next = last →next;
        if ( last == tail ) {
            if (next == NULL) {
                if (CAS( &(last→next), next, newNode) == next) {
                    CAS( &tail, last , newNode);
                    return ;
                }
            }
            else {
                CAS( &tail, last , next);
            }
        }
    }
}
```

As can be seen, getting the intricacies of atomic updations to a shared data structure right is a very tricky process. A myriad of bugs may be introduced, whose manifestations may not be deterministic. The problem is even harder for more complicated structures like doubly-linked lists and trees. Searching for a solution to this problem, Doherty et al. [1] observed that if we provide a single instruction called *MCAS* in hardware, the job of writing such non-blocking programs will become much easier. An *MCAS* instruction is a generalization of the traditional compare and set instruction(CAS). It compares the contents of k variables with k memory locations (pairwise), and if all the pairs match, then it atomically overwrites the k memory locations with k new values. We will refer to k as the arity of the MCAS instruction. Returning to our example, implementing the enqueue operation with MCAS instructions is much simpler.

```
enqueue(newNode) {
    do {
        last = tail ;
        next = last →next;
        result = MCAS( 2, &(last→next), &tail, next, last , newNode,
            newNode); // first argument (=2) is the arity
    } while( result == false );
}
```

We present implementations of six commonly used data structures using all three approaches: lock-based, CAS-based lock-free and MCAS-based lock-free, in the appendix section. The MCAS-based approach reduces the lines of code by 51% on average as compared to the CAS-based one. Lines of code is a popular metric to quantify the ease of programming, debugging and maintaining software. As is clearly evident from the statistics, the availability of an MCAS primitive greatly simplifies the task of a programmer.

To the best of our knowledge, there has been no work done by the hardware community to provide the implementation of an MCAS instruction in hardware. This paper proposes one such implementation, which is very simple (far simpler that hardware transactional memory), and needs minimal changes in the toolchain (compiler + linker). The area overhead of our implementation is a mere 0.046%.

With this simple mechanism, we show that it is possible to realize the gains that Doherty et al. had speculated. We show improvements of 13.8X on average for a set of concurrent data structures over lock based implementations, and 4X on average over CAS-based lock-free implementations. We then propose an optimization for cases of high contention, that requires a small compiler pass and a minor hardware augmentation.

II. Related Work

Greenwald and Cheriton [3] first spoke of the advantages of having a double-word compare-and-swap (DCAS) primitive. Subsequently, the seminal work by Doherty et al. [1] made the case that even a two-word synchronization primitive may not be enough. We need an arity of at least 3 or 4 for implementing non-blocking variants of most commonly used data structures. To the best of our knowledge, there is no work that has proposed a realization of this idea in hardware.

There is however related work for supporting other synchronization primitives, notably barriers. Chandran et al. [4] proposed a hardware unit for implementing both centralized and distributed barriers in chips with optical networks. Their barrier unit records all requests, and then grants them in order, or uses algorithms based on distributed mutual exclusion to grant barriers. There is similar work by Sampson et al. [5] and Sartori et al. [6] for traditional electrical networks. They also propose dedicated barrier units and custom protocols for them to communicate.

III. Proposed Implementation of the MCAS Primitive in Hardware: MCAS-BASE

The basic realization of the MCAS primitive is through *two-phase locking*. We first acquire *locks* on *all* concerned memory locations, and then perform the comparisons. If the values at *all* the locations are equal to the recorded old values, we then update *all* the locations to the new values. We set the zero-flag (ZF) to 1 to indicate that the MCAS succeeded. If any of the comparisons fail, we set ZF to 0 to indicate failure. We then release *all* the locks.

A. ISA Augmentation

The programmer's interface to using the MCAS primitive consists of two instructions: (i) MCAS Table Store (`MTS`) and (ii) `MCAS`.

`MTS` instructions are used to set up the parameters of the MCAS primitive, one instruction per memory location. The `MTS` instruction allows the programmer to specify the address of the memory location, the recorded old value against which the comparison must be made, and the new value it must be set to if the comparison evaluates to equal.

An `MCAS` instruction is used to direct the hardware to perform the MCAS primitive, based on the parameters already set up using `MTS` instructions. If all the comparisons evaluate to equal, the writes are performed and the *zero-flag* is set to 1; else it is set to 0. The `MCAS` instruction is also interpreted as a memory fence instruction in the pipeline. The operation is issued to the cache only when all preceding loads, stores, `MTS`s and `MCAS`s in the pipeline have been committed. Also, all loads, stores, `MTS`s and `MCAS`s succeeding the current `MCAS` instruction are issued only after the latter commits. Therefore, at any given point in time, there can be only one active `MCAS` instruction per core.

B. Hardware Augmentation

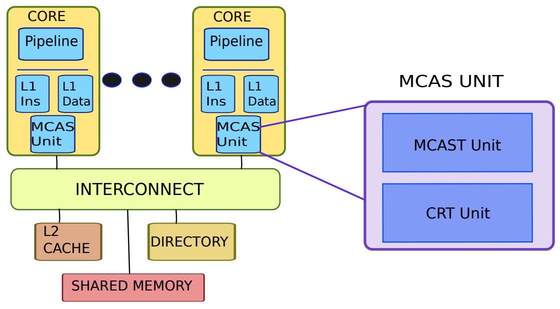
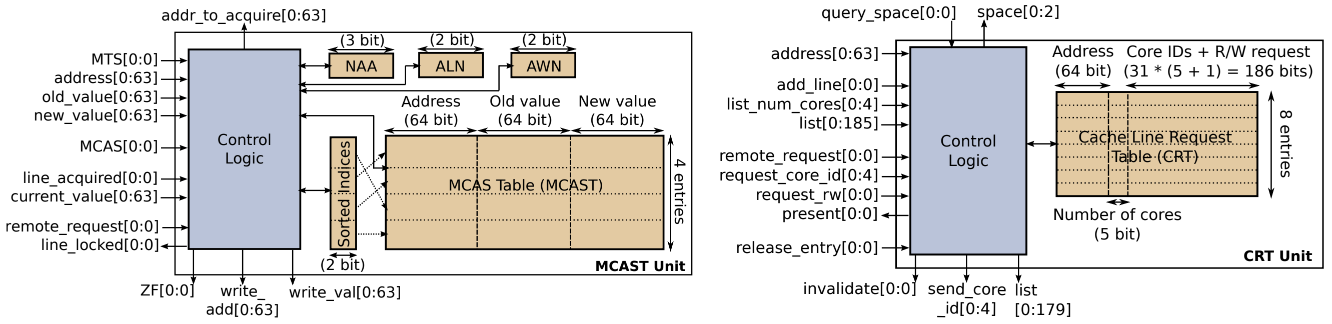


Fig. 1: Hardware Architecture

Figure 1 shows the hardware architecture. The additional hardware required by our proposal is limited to an *MCAS unit* per core. Each MCAS unit consists of two sub-units: an MCAS Table (MCAST) Unit (Figure 2a) and a Cache Line Request Table (CRT) Unit (Figure 2b).

The MCAS Table stores the parameters of the MCAS instruction (note that a core can have at most one outstanding MCAS instruction). Each entry in the table corresponds to one memory location associated with the MCAS primitive. An entry in the table consists of the location's address, the recorded old value of the word, and the new value to be written. Note that the protocol we propose does not pose any limit on the arity. However, we have noticed that arities > 4 are rarely useful. Consequently, we assume an arity of 4 to draw area estimates of our proposed units. Our proposed protocols process the entries in the MCAS Table in ascending order of the address field (see Section III-C1). Sorting the entries of the MCAS Table directly would mean moving entire table entries. We avoid this by storing the indices of the entries in an auxiliary table called "Sorted Indices". These indices are then sorted according to the address field of the MCAS Table entries they point to. Traversing the Sort Indices Table in-order and using the indices to access the MCAS Table is equivalent to traversing the MCAS Table in the required sorted order. The MCAST Unit additionally contains three registers: "Number of Addresses Added" (NAA), "Address to Lock Next" (ALN) and "Address to Write Next" (AWN).

Each entry in the CRT is composed of a cache line address (64 bit) and its corresponding *Cache Line Request List*. This is a list of cores that have requested for this cache line (detailed in Section III-C2). Each entry in this list is composed of two fields: (i) core ID (5 bit) and (ii) request type (read or write) (1 bit). The number of entries is also maintained. The



(a) MCAST Unit (b) CRT Unit

Fig. 2: Components of the MCAS Unit

maximum number of entries in the list is 31, assuming a 32-core processor. Again, this assumption is made just for the sake of drawing up an area estimate. Our protocol places no restrictions on the number of cores. If a core is to process a miss in its private caches, it must first check if there is space in its CRT. If there is no space, it must stall until there is. In our experiments, we observed that with a table size of 8, operations on standard data structures suffered no stalls.

C. Operation

1) Execution of an MCAS *Instruction:* The execution of MCAS instructions consists of four phases: (i) Setup, (ii) Acquire Lock and Compare, (iii) Write and (iv) Exit.

Setup Phase: As discussed earlier (Section III-A), MTS instructions are used to set up the parameters of the MCAS. On encountering an MTS, the pipeline reads the relevant registers, and signals the MCAST Unit (Figure 2a). The MCAST Unit makes an entry (address, old value, new value) in the MCAS Table. The NAA maintains how many entries are in the MCAS Table, and specifies at what position in the MCAS Table the new entry must be made. The index of the new entry is inserted in the Sorted Indices Table at the appropriate position to maintain the sorted order.

```
for nextToLock = 0; nextToLock <MCAS_Table.length;
nextToLock++ do
    Cache_address_line= Cache_line(memory_location);
    if !Cache_Hit(Cache_address_line) then
        //Cache Miss
        waiting for the cache line to be loaded ;
    end
    //Cache Hit. Acquire Lock
    Lock the Cache_address_line;
    if state of Cache_address_line == Shared OR state of
    Cache_address_line == Exclusive then
        Change state to modified;
    end
    if *memory_location!=old_value then
        //MCAS fail
        ZF=0;
        MCAS EXIT;
    end
end
//All memory locations have been locked
MCAS Write;
```
Algorithm 1: Acquire Lock and Compare

Acquire Lock and Compare Phase: Algorithm 1 describes the protocol. For each entry in the MCAS Table (processed in ascending order of address), the cache line is brought in the *modified* (M) state of the MESI coherence protocol. The current value of the memory location is compared with that recorded in the MCAS Table. If the values are equal, the line is deemed *locked*. The ALN is incremented (the ALN maintains which entry has to be locked next) and the next entry is then processed. If the values are not equal, the MCAS is deemed a *failure*. The *zero-flag* (ZF) is set to 0 to indicate this. The Exit Phase protocol is then executed.

Write Phase: This phase is executed only when the MCAS is a success – that is, all entries in the MCAS Table have their lines locked. The MCAST Unit issues write requests to the cache to write the new values to the memory locations. The AWN maintains which line has to be written to next. ZF is set to 1.

Exit Phase: The entries of the MCAS Table are now processed in descending order of the addresses. If there is an entry in the CRT related to this address, it is processed (see Section III-C2). Once all the MCAS Table entries are processed, the MCAS Table contents are purged. The pipeline is signalled that the MCAS has *completed*, so that subsequent memory operations can be issued.

2) Staggered Cache Line Forwarding: When a cache line has been locked by a core, it possesses the cache line in the modified state. The cache coherency protocol ensures that no other core has a copy of this line. It must be ensured that this locked line is not evicted until the MCAS is completed. To ensure this, the way the cache responds to cache line requests from other private caches is modified. Whenever a cache receives a request from another private cache to forward a cache line, the former checks if (i) that cache line is locked (by querying the MCAST Unit – the line is locked if the requested address is present in the MCAS Table and the position of its index in the Sorted Indices Table is less than ALN), or (ii) an entry corresponding to that line is present in the CRT. If either of these are true, then the cache line is not sent to the requester. Instead, this request is added to the end of the Cache Line Request List corresponding to that address in the CRT.

The processing of the list is done on any of the three events:

(i) when an MCAS associated with the address completes, (ii) when a read associated with the address completes, (iii) when a write associated with the address completes. The processing of the list is as follows. If the list contains any write request, then the line in the cache is invalidated. Otherwise, the line in the cache is marked as *shared*. Next, the line is forwarded to the first core in the list. Along with the line, the rest of the list (having removed the first entry) is also sent to the first core. The latter adds the line to its cache and the list to its CRT.

The designs of the MCAST Unit and the CRT Unit were implemented in VHDL and synthesized using the Cadence Encounter RTL compiler and the 65nm technology standard cell library. Due scaling to 14nm was performed according to [7]. The area overhead for a 32-core, 400 mm^2 chip is 0.0456%. The units can operate at 3.4 GHz, while (i) servicing MTS requests at the rate of 1 per cycle, (ii) issuing lock acquire requests at the rate of 1 per cycle, (iii) issuing cache write requests at the rate of 1 per cycle, and (iv) processing Cache Line Request Lists at the rate of 1 per cycle.

IV. Optimized Implementation: MCAS-OPT

In this section, we improve upon our base implementation MCAS-BASE with an optimized implementation MCAS-OPT. In the former, the `MTS` instructions to populate the MCAS Table were executed just before the `MCAS` instruction. However, analyzing common concurrent data structures, we observed that the addresses of the MCAS-related memory locations are known much earlier in the program. Thus, at runtime, it is possible to make the MCAS Table entry much earlier. This is extremely useful because in the time interval between when the entry was made and the `MCAS` instruction, through tracking of the cache coherence messages, we can know if the concerned memory location was written to by some other core. If so, then it is highly likely that this MCAS will fail when executed. We can thus perform an *"early back-off"* and avoid executing the Acquire Lock and Compare Phase.

A. Placement of `MTS` Instructions

We design a compiler pass that statically analyzes the program and places `MTS` instructions as *high* up in the program as possible, while maintaining functional correctness. The proposed method is a Worklist algorithm for iterative forward data-flow analysis. The function containing the MCAS invocation is considered as a graph of basic blocks $G = \langle N, E \rangle$. Let the maximum arity of the MCAS primitive be k. Each basic block B is associated with two vectors in_B and out_B, each of size k – in_B represents the data-flow information reaching the entry to B, while out_B represents the data-flow information leaving B. The concerned data-flow information consists of the instruction points (IP) values (one for each MCAS memory location)‘ of the earliest instruction after which it is safe to place the `MTS` instruction for that address. Algorithm 2 shows the working of the pass.

The operator $\sqcap$ essentially combines the output data-flows of predecessor basic blocks to give the input data-flow of the current block. Let A and B be the output flows of two predecessor blocks. For any i, let a and b be the i^{th} elements of A and B respectively. $headIP$ is the IP of the first instruction of the current basic block. $\sqcap$ is defined as follows:

$$\sqcap(a,b) = \begin{cases} -1 & \text{if } a=b=-1 \\ a & \text{if } a \neq -1, b=-1 \\ b & \text{if } b \neq -1, a=-1 \\ \text{a} & \text{if } a=b, a\neq -1, b \neq -1 \\ \text{headIP} & \text{if } a \neq b, a \neq -1, b \neq -1 \end{cases}$$

The local analysis within a basic block is done by the flow function $F()$. It updates the resultant vector if any new definition of the address field is encountered in that basic block.

```
Input: $N$: set of basic blocks
$entry$: the entry basic block of the function
$exit$: the basic block containing the MCAS invocation
$k$: the maximum arity of an MCAS instruction
Output: $result$: vector of IP addresses of length $k$
Variables: $in$: set of vectors of IP addresses of length $k$, one vector per basic block
$B$: basic block
$worklist$: set of basic blocks
$effect$, $totaleffect$: vectors of IP addresses of length $k$
$worklist = N$
for each $B \epsilon N$ do
    initialize vector $in_B$ to -1
end
repeat
    $B$ = first node of $worklist$
    $worklist = worklist - B$
    $totaleffect$: initialize vector to -1
    for each $P \epsilon Predecessors(B)$ do
        $effect = F(in_B)$
        $totaleffect = totaleffect \sqcap effect$
    end
    if $in_B \neq totaleffect$ then
        $in_B = totaleffect$
        $worklist = worklist \cup successors(B)$
    end
until $worklist$ = $\phi$
$result = in_{exit}$
return $result$
```

Algorithm 2: Worklist_Iterate($N, entry, exit, k$)

B. Early Back-Off

The compiler algorithm helps us place `MTS` instructions as soon as the address is unambiguously known. However, at this point, the old value and new value may not be known. The `MTS` instruction therefore sets these to -1 (an arbitrary value deemed illegal). As in MCAS-BASE, just before the MCAS instruction, when all parameters of the MCAS have been resolved, `MTS` instructions are again placed by the compiler. These *later* `MTS`s contain all legal values. The MCAS Table is augmented with an extra 1-bit flag *MCAS Invalid Flag* (MIF) (1 flag per MCAS Table). When a cache receives an *invalidate* message from the directory, due to some other core writing to the same line, the former cache checks its MCAS Table to see if it has an entry corresponding to the same address. If it does, it sets the MCAS Invalid Flag

TABLE I: Parameters of the simulated architecture

Parameter	Value	Parameter	Value
Number of cores	32	Frequency	3.4GHz
Pipeline			
Retire width ROB size IW size	4 168 54	Issue width LSQ size Predictor	6 128 TAGE
Private L1 caches			
Size Associativity Write mode	32 KB 8 Write back	Latency Block size	3 cycles 64 Bytes
Shared L2			
Size Associativity Write mode	8 MB 8 Write back	Latency Block size	32 cycles 64 Bytes
NOC			
Topology Flit size	2-D Torus 32 Byte	Routing Algorithm Hop latency	dyn X-Y 2 cycles
Main memory		Latency	200 cycles
MCAS Table (one per core)		Entries	4
Cache Line Request Table (one per core)		Entries	8

(MIF) to 1. Now, at any point in time when the Lock Acquire and Compare Phase is in progress, if the MIF is found to be 1, the phase is aborted. The MCAS is deemed to be failed, and the Exit Phase is executed.

MCAS-OPT was implemented and synthesized. The hardware overhead increased marginally, amounting to 0.0466%.

V. Evaluation

We use the Java-based multicore architectural simulator Tejas [8] for evaluating our proposals (cycle accurate and verified against hardware). Table I lists the processor configuration.

The concurrent data structures used for our evaluation are: Binary Search Tree, Sorted List, Doubly Linked List, HashSet, Queue and Stack. There are two reasons for choosing this set of benchmarks. Firstly, these data structures are widely used in many real-world applications, and hence provide credibility to the proposal. Secondly, each of these benchmarks requires MCASs of different arity. This helps us gain a better insight into the behavior of a hardware implementation of such a primitive. Each benchmark is composed of 32 threads. Each thread makes a total of 300 operations (empirically found to reach steady state) on the shared data structure – alternate insertions and deletions of random elements to the data structure. We use three versions of benchmarks (most optimal implementations known in literature [9] [10]): with locks, CAS-based lock-free, and MCAS-based lock-free (henceforth referred to as "lock", "lock-free" and "MCAS" respectively). The benchmarks are implemented in C++, and compiled with GCC version 4.7.2, with the -std=c++0x option. The source code can be found at https://sites.google.com/site/hardwaremcas/.

A. MCAS v/s Lock

Figure 3 compares the simulation time of the MCAS benchmarks (both MCAS-BASE and MCAS-OPT primitives) relative to the Lock benchmarks.

As expected, since lock based benchmarks are blocking and perform synchronization in a serial fashion, speed-ups of up to $30X$ are observed when the non-blocking MCAS primitives are employed. Each thread remains blocked for long periods while waiting to acquire the lock, as shown in Table II.

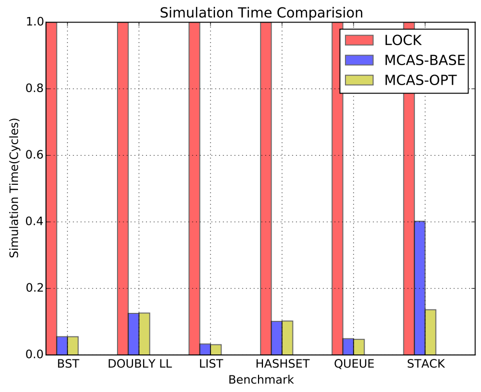


Fig. 3: Simulation Time Comparision (Lock VS MCAS-BASE VS MCAS-OPT)

TABLE II: Average waiting time (in cycles) per lock instruction

Benchmark	Waiting Time
BST	40.64
DOUBLYLL	82.56
HASHSET	108.8
LIST	163.2
QUEUE	182.4
STACK	345.6

B. MCAS v/s Lock-Free

Figure 4 compares the simulation time of the MCAS benchmarks (both MCAS-BASE and MCAS-OPT primitives) relative to the Lock-Free benchmarks. Employing MCAS primitives provided gains of up to $7X$ as compared to the Lock-Free benchmarks, which are non-blocking as well. The large gains are due to two artefacts present in the Lock-Free benchmarks and absent in the MCAS ones. Firstly, multiple single word CAS instructions are required for each operation

TABLE IV: Success rates of different primitives

Benchmark	Success rate		
	Lock-free	MCAS-BASE	MCAS-OPT
BST	0.91	0.866	0.857
DOUBLYLL	0.29	0.746	0.742
HASHSET	0.25	0.849	0.853
LIST	0.42	0.888	0.881
QUEUE	0.1	0.408	0.448
STACK	0.37	0.049	0.394

TABLE V: Average execution time of MCAS variants

Benchmark	Average execution time	
	MCAS-BASE	MCAS-OPT
BST	26.15	21.89
DOUBLYLL	98.08	132.62
HASHSET	22.27	31.44
LIST	23.74	23.54
QUEUE	25.09	17.77
STACK	107.57	22.74

TABLE III: Instruction mix of the different benchmarks (sync instructions: lock, CAS (in Lock-free), MCAS)

Benchmark	Total Instructions (relative to Lock)				Percentage of sync instructions			
	Lock	**Lock-free**	**MCAS-BASE**	**MCAS-OPT**	**Lock**	**Lock-free**	**MCAS-BASE**	**MCAS-OPT**
BST	1.00	2.90	0.98	0.98	0.29	0.22	0.34	0.34
DOUBLYLL	1.00	7.76	2.06	2.07	0.12	0.11	0.07	0.08
HASHSET	1.00	0.61	0.64	0.64	0.22	1.40	0.40	0.40
LIST	1.00	3.56	0.57	0.57	0.21	0.29	0.42	0.42
QUEUE	1.00	2.49	0.93	0.91	0.33	1.84	0.87	0.80
STACK	1.00	0.91	1.45	0.90	0.31	0.91	4.31	0.87

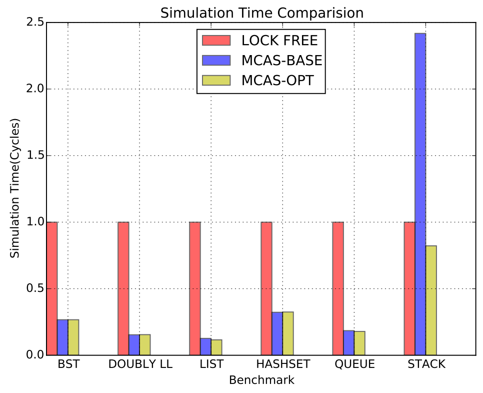


Fig. 4: Simulation Time Comparision (Lock-Free VS MCAS-BASE VS MCAS-OPT)

(Table III compares the percentage of synchronization operations in the benchmark). This results in greater time spent in synchronization, leading to greater contention and lower CAS success rates (Table IV compares the success rates of the different primitives). Secondly, Lock-free benchmarks employ inter-thread helping to achieve progress and atomicity, thereby increasing the number of instructions executed (Table III compares the number of instructions executed by each benchmark).

In the case of the stack data structure, it can be seen (Figure 4) that the Lock-Free benchmark performs better than MCAS-BASE. The reason for this is twofold: (i) the Lock-Free benchmark is quite simple and does not contain any helping mechanisms like in the case of the other data structures (Table III compares the number of instructions executed), and (ii) the Lock-Free benchmark requires a single CAS instruction per push operation, while our encoding of the MCAS benchmark employs an MCAS of arity 2. Although unnecessary, we chose to do this simply to exercise the MCAS hardware. Increasing the arity increases the contention between threads, thereby reducing performance. MCAS-OPT, however, reduces this contention and achieves a speed-up of 22% over the Lock-Free benchmark.

C. MCAS-BASE v/s MCAS-OPT

MCAS-OPT is advantageous (up till 4.9X faster than MCAS base) when the contention between threads is high – that is, in the queue and stack benchmarks. In these benchmarks, the different threads are trying to operate on the same set of addresses (*top* pointer in the stack, *head* and *tail* pointers in the queue). Consequently, the MCAS success rate is low. The optimization reduces the contention, thus improving the MCAS success rate, as shown in Table IV. This reduces the number of MCAS instructions executed, as well as the time spent on each MCAS, as shown in Table III, V. This results in a net increase in performance.

VI. Conclusion

The design of efficient concurrent data structures, which are possibly deadlock-free and starvation-free, is a complex process. The effort of design and verification can be greatly reduced if a hardware-provided, multi-word synchronization primitive is available. We have presented a detailed design of a multi-word compare-and-set primitive (MCAS), which has a minimal area overhead of 0.0016%. We have analyzed the working of the MCAS primitive and proposed an optimization that reduces the contention between threads. We show that MCAS-based concurrent data structures are not only easy to write, but are also 13.8X and 4X faster on an average than lock-based and lock-free implementations respectively.

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APPENDICES

A. Benchmarks

The concurrent data structures used for our evaluation are: Binary Search Tree, Sorted List, Doubly Linked List, HashSet, Queue and Stack. There are two reasons for choosing this set of benchmarks. Firstly, these data structures are widely used in many real-world applications, and hence provide credibility to the proposal. Secondly, each of these benchmarks requires MCASs of different arity. This helps us gain a better insight into the behavior of a hardware implementation of such a primitive. Each benchmark is composed of 32 threads. Each thread makes a total of 300 operations (empirically found to reach steady state) on the shared data structure – alternate insertions and deletions of random elements to the data structure. We use three versions of benchmarks (most optimal implementations known in literature [9] [10]): with locks, lock-free, and with MCAS. The benchmarks are implemented in C++. They have been compiled with GCC version 4.7.2, with the -std=c++0x option to enable C++11 support.

	Lock-based	**CAS-based Lock-free**	**MCAS-based Lock-free**
Binary Search Tree	111	320	162
Doubly Linked List	53	171	51
Hashset	87	245	85
Ordered List	77	101	83
Queue	40	66	36
Stack	33	46	46
Average	66.83	158.17	77.00

TABLE VI: Lock-based v/s CAS-based Lock-free v/s MCAS-based Lock-free : Lines of code comparison

Table VI shows a comparison between the different implementations in terms of lines of code. Lines of code is a popular metric to compare the ease of programming, debugging and maintaining software. As is clearly evident from the statistics, the availability of an MCAS primitive greatly simplifies the task of a programmer.

B. Lock Implementation

Before each operation, the thread has to acquire a lock on the structure, which it releases once it completes performing the operation.

1) Binary Search Tree (BST): Each thread in the benchmark performs alternate insertions and deletions in the binary search tree. The tree is initially populated with 15 elements. Each thread performs 300 operations.

```
pthread_mutex_t mutex1 = PTHREAD_MUTEX_INITIALIZER;
struct bst {
  int data;
  struct bst *left;
  struct bst *right;
};
typedef struct bst bst_t;

bst_t *get_new_node(int val) {
  bst_t *node = (bst_t *) malloc(sizeof(bst_t));
  node->data = val;
  node->left = NULL;
  node->right = NULL;
  return node;
}
bst_t *root = NULL;

bst_t *insert(bst_t *root, int val) {
  if (!root)
    return get_new_node(val);
  bst_t *prev = NULL, *ptr = root;
  char type = ' ';
  while (ptr) {
    prev = ptr;
    if (val < ptr->data) {
      ptr = ptr->left;
      type = 'l';
    } else {
      ptr = ptr->right;
      type = 'r';
    }
  }
  if (type == 'l')
    prev->left = get_new_node(val);
  else
    prev->right = get_new_node(val);
  return root;
}

int find_minimum_value(bst_t *ptr) {
  int min = ptr ? ptr->data : 0;
  while (ptr) {
    if (ptr->data < min)
      min = ptr->data;
    if (ptr->left) {
      ptr = ptr->left;
    } else if (ptr->right) {
      ptr = ptr->right;
    } else
      ptr = NULL;
  }
  return min;
}

bst_t *deleter(bst_t *root, int val) {
  bst_t *prev = NULL, *ptr = root;
  char type = ' ';
  while (ptr) {
    if (ptr->data == val) {
      if (!ptr→left && !ptr→right) { // node to be removed has no children's
        if (ptr != root && prev) { // delete leaf node
          if (type == 'l')
            prev→left = NULL;
          else
            prev→right = NULL;
        } else
          root = NULL; // deleted node is root
      } else if (ptr→left && ptr→right) { // node to be removed has two children's
        ptr→data = find_minimum_value(ptr→right); // find minimum value from right subtree
        val = ptr→data;
        prev = ptr;
        ptr = ptr→right; // continue from right subtree delete min node
        type = 'r';
        continue;
      } else { // node to be removed has one children
        if (ptr == root) { // root with one child
          root = root→left ? root→left : root→right;
        } else { // subtree with one child
          if (type == 'l')
            prev→left = ptr→left ? ptr→left : ptr→right;
          else
            prev→right = ptr→left ? ptr→left : ptr→right;
        }
      }
    }
    prev = ptr;
    if (val < ptr→data) {
      ptr = ptr→left;
      type = 'l';
      height++;
    } else {
      ptr = ptr→right;
      type = 'r';
      height++;
    }
  }
  return root;
}

void enq(int value) {
  pthread_mutex_lock(&mutex1);
  root = insert(root, value);
  pthread_mutex_unlock(&mutex1);
}

void deq(int value) {
  pthread_mutex_lock(&mutex1);
  root = deleter(root, value);
  pthread_mutex_unlock(&mutex1);
}
```

2) Doubly Linked List:

```c
pthread_mutex_t mutex1 = PTHREAD_MUTEX_INITIALIZER;
struct node {
  int data;
  struct node *next;
  struct node *prev;
};
struct node* head = NULL;

void insertAfter(struct node* prev_node, int new_data) {
  if (prev_node == NULL)
  {
    printf("the given previous node cannot be NULL");
    return;
  }
  struct node* new_node = (struct node*) malloc(sizeof(struct node));
  new_node->data = new_data;
  new_node->next = prev_node->next;
  prev_node->next = new_node;
  new_node->prev = prev_node;
  if (new_node->next != NULL)
    new_node->next->prev = new_node;
}

void insert(int key) {
  pthread_mutex_lock(&mutex1);
  struct node *prev = head, *curr = prev;
  while (curr->data < key) {
    prev = curr;
    curr = curr->next;
  }
  insertAfter(prev, key);
  pthread_mutex_unlock(&mutex1);
}

void deleteNode(struct node *del) {
  if (del == NULL)
    return;
  del->next->prev = del->prev;
  del->prev->next = del->next;
  del = NULL;
  free(del);
}

void deleten(int key) {
  pthread_mutex_lock(&mutex1);
  struct node *prev = head, *curr = prev;
  while (curr->data < key) {
    prev = curr;
    curr = curr->next;
  }
  deleteNode(curr);
  pthread_mutex_unlock(&mutex1);
}
```

3) Hash Set:

```
pthread_mutex_t mutex1 = PTHREAD_MUTEX_INITIALIZER;
static vector<struct node*> table;
struct node {
  int data;
  struct node *next;
};

void linkadd(int num, int index) {
  struct node *temp;
  temp = (struct node *) malloc(sizeof(struct node));
  temp->data = num;
  if (table[index] == NULL)
  {
    table[index] = temp;
    table[index]->next = NULL;
  } else {
    temp->next = table[index];
    table[index] = temp;
  }
}

bool linkdelete(int num, int index) {
  struct node *temp, *prev;
  temp = table[index];
  if (temp != NULL)
  {
    table[index] = temp->next;
    return true;
  }
  return false;
}

bool linkcontain(int num, int index) {
  if (table[index] == NULL)
  {
    return false;
  }
  struct node* r = table[index];
  while (r != NULL) {
    if (r->data == num)
      return true;
    r = r->next;
  }
  return false;
}

class CoarseHashSet {
  int size;
public:
  CoarseHashSet(int capacity) {
    size = 0;
    for (int i = 0; i < capacity; i++) {
      struct node *temp = NULL;
      table.push_back(temp);
    }
  }

  bool contains(int x) {
    std::tr1::hash<int> hash_fn;
    int a = hash_fn(x);
    int myBucket = abs(a % table.size());
    bool ans = linkcontain(x, myBucket);
    return ans;
  }

  void add(int x) {
    pthread_mutex_lock(&mutex1);
    std::tr1::hash<int> hash_fn;
    int a = hash_fn(x);
    int myBucket = abs(a % table.size());
    linkadd(x, myBucket);
    size = size + 1;
    pthread_mutex_unlock(&mutex1);
    if (size / table.size() > 4)
      resize();
  }

  void remove(int x) {
    pthread_mutex_lock(&mutex1);
    std::tr1::hash<int> hash_fn;
    int a = hash_fn(x);
    int myBucket = abs(a % table.size());
    bool result = linkdelete(x, myBucket);
    size = result ? size - 1 : size;
    pthread_mutex_unlock(&mutex1);
  }
};
```

4) List:

```
pthread_mutex_t mutex1 = PTHREAD_MUTEX_INITIALIZER;

class LockedList {

public:
  class Node {
  public:
    int item;
    int key;
    Node *next;
    Node(int item) {
      this->item = item;
      this->key = item;
    }
  };
  Node *head;
  Node *tail;

  LockedList() {
    // Add sentinels to start and end
    head = new Node(INT_MIN);
    tail = new Node(INT_MAX);
    head->next = this->tail;
  }

  bool add(int item) {
    Node *pred, *curr;
    int key = item;
    bool flag;

    pthread_mutex_lock(&mutex1);
    pred = head;
    curr = pred->next;
    while (curr->key < key) {
      pred = curr;
      curr = curr->next;
    }

    Node *node = new Node(item);
    node->next = curr;
    pred->next = node;
    flag = true;
    pthread_mutex_unlock(&mutex1);
    return flag;
  }

  bool remove(int item) {
    Node *pred, *curr;
    int key = item;
    bool flag;
    pthread_mutex_lock(&mutex1);
    pred = this->head;
    curr = pred->next;
    while (curr->key < key) {
      pred = curr;
      curr = curr->next;
    }
    pred->next = curr->next;
    flag = true;
    pthread_mutex_unlock(&mutex1);
    return flag;
  }

  bool contains(int item) {
    Node *pred, *curr;
    int key = item;
    pthread_mutex_lock(&mutex1);
    pred = head;
    curr = pred→next;
    while (curr→key < key) {
      pred = curr;
      curr = curr→next;
    }
    pthread_mutex_unlock(&mutex1);
    return (key == curr→key);
  }
};
```

5) Queue:

```
pthread_mutex_t mutex1 = PTHREAD_MUTEX_INITIALIZER;
struct qNode {
  int value;
  struct qNode *next;
};

struct qNode *front = NULL, *rear = NULL;

void enq(int item) {
  pthread_mutex_lock(&mutex1);
  struct qNode *newN = new struct qNode;
  newN->value = item;
  newN->next = NULL;
  if (front == NULL && rear == NULL) {
    front = newN;
    rear = newN;
  } else {
    rear->next = newN;
    rear = newN;
  }
  pthread_mutex_unlock(&mutex1);
}

int deq() {
  int t;
  pthread_mutex_lock(&mutex1);
  if (front != NULL) {
    struct qNode *temp = front;
    t = temp->value;
    if (front == rear) {
      front = NULL;
      rear = NULL;
    } else
      front = front->next;
  } else {
    cout << "queue is empty" << endl;
  }
  pthread_mutex_unlock(&mutex1);
  return t;
}
```

6) Stack:

```
pthread_mutex_t mutex1 = PTHREAD_MUTEX_INITIALIZER;
class stack {
public:
  class Node {
  public:
    int item;
    Node *next;
    Node(int item) {
      this->item = item;
      this->next = NULL;
    }
  };
  Node *top;

  void push(int value) {
    Node *node = new Node(value);
    pthread_mutex_lock(&mutex1);
    node->next = top;
    top = node;
    pthread_mutex_unlock(&mutex1);

  }

  void pop() {
    int t;
    pthread_mutex_lock(&mutex1);
    if (top != NULL) {
      t = top->item;
      top = top->next;
    }
    pthread_mutex_unlock(&mutex1);
  }
};
```

C. CAS-based Lock-free Implementation

Library Used by all Benchmarks:

```
static size_t compareAndExchange( volatile size_t* addr, size_t oldval, size_t newval ){
  size_t ret;
  __asm__ volatile( "lock cmpxchg %2, %1\n\t":"=a"(ret), "+m"(*addr): "r"(newval),
     "0"(oldval): "memory" );
  return ret;
}

static size_t compareAndExchangeTid( volatile size_t* addr, int oldval, int newval ){
  int ret;
  __asm__ volatile( "lock cmpxchg %2, %1\n\t":"=a"(ret), "+m"(*addr): "r"(newval),
     "0"(oldval): "memory" );
  return ret;
}
static size_t AtomicExchange(volatile size_t* ptr, size_t new_value) {
 __asm__ __volatile__("xchg %1,%0": "=r" (new_value): "m" (*ptr), "0" (new_value): "memory");
 return new_value; // Now it's the previous value.
}

template<typename T,unsigned N=sizeof (uint32_t)>
struct DPointer {
public:
  union {
    uint64_t ui;
    struct {
      T* ptr;
      size_t mark;
    };
  };

  DPointer() : ptr(NULL), mark(0) {}
  DPointer(T* p) : ptr(p), mark(0) {}
  DPointer(T* p, size_t c) : ptr(p), mark(c) {}

  bool cas(DPointer<T,N> const& nval, DPointer<T,N> const & cmp)
  {
    bool result;
    __asm__ __volatile__(
      "lock cmpxchg8b %1\n\t"
      "setz %0\n"
      : "=q" (result)
       ,"+m" (ui)
      : "a" (cmp.ptr), "d" (cmp.mark)
       ,"b" (nval.ptr), "c" (nval.mark)
      : "cc"
    );
    return result;
  }

  // We need == to work properly
  bool operator==(DPointer<T,N> const&x) { return x.ui == ui; }

};

template<typename T>
struct DPointer <T,sizeof (uint64_t)> {
public:
  union {
    uint64_t ui[2];
    struct {
      T* ptr;
      size_t mark;
    } __attribute__ (( __aligned__( 16 ) ));
  };
  DPointer() : ptr(NULL), mark(0) {}
  DPointer(T* p) : ptr(p), mark(0) {}
  DPointer(T* p, size_t c) : ptr(p), mark(c) {}

  bool cas(DPointer<T,8> const& nval, DPointer<T,8> const& cmp)
  {
    bool result;
    __asm__ __volatile__ (
      "lock cmpxchg16b %1\n\t"
      "setz %0\n"
      : "=q" ( result )
       ,"+m" ( ui )
      : "a" ( cmp.ptr ), "d" ( cmp.mark )
       ,"b" ( nval.ptr ), "c" ( nval.mark )
      : "cc"
    );
    return result;
  }

  // We need == to work properly
  bool operator==(DPointer<T,8> const&x) { return x.ptr == ptr && x.mark == mark; }
};
```

1) Binary Search Tree:

```
class Node {
public:

  long key;
  long value;
  DPointer<Node, sizeof(size_t)> lChild;
  DPointer<Node, sizeof(size_t)> rChild;
  Node() {
  }

  Node(long key, long value) {
    this→key = key;
    this→value = value;
  }

  Node(long key, long value, DPointer<Node, sizeof(size_t)> lChild
      , DPointer<Node, sizeof(size_t)> rChild) {
    this→key = key;
    this→value = value;
    this→lChild = lChild;
    this→rChild = rChild;
  }
};

class SeekRecord {
public:
  Node *ancestor;
  Node *successor;
  Node *parent;
  Node *leaf;

  SeekRecord() {
  }
  SeekRecord(Node *ancestor, Node *successor, Node *parent, Node *leaf) {
    this→ancestor = ancestor;
    this→successor = successor;
    this→parent = parent;
    this→leaf = leaf;
  }
};

class LockFreeBST {
public:
  static Node *grandParentHead;
  static Node *parentHead;
  static LockFreeBST *obj;

  LockFreeBST() {
    createHeadNodes();
  }

  long lookup(long target) {
    Node *node = grandParentHead;
    while (node→lChild.ptr != NULL) //loop until a leaf or dummy node is reached
    {
      if (target < node→key) {
        node = node→lChild.ptr;
      } else {
        node = node→rChild.ptr;
      }
    }

    if (target == node→key)
      return (1);
    else
      return (0);
```

```
}

void add(long insertKey) {
  int nthChild;
  Node *node;
  Node *pnode;
  SeekRecord *s;
  while (true) {
    nthChild = -1;
    pnode = parentHead;
    node = parentHead->lChild.ptr;
    while (node->lChild.ptr != NULL) //loop until a leaf or dummy node is reached
    {
      if (insertKey < node->key) {
        pnode = node;
        node = node->lChild.ptr;
      } else {
        pnode = node;
        node = node->rChild.ptr;
      }
    }

    Node *oldChild = node;

    if (insertKey < pnode->key) {
      nthChild = 0;
    } else {
      nthChild = 1;
    }

    //leaf node is reached
    if (node->key == insertKey) {
      //key is already present in tree. So return
      return;
    }

    Node *internalNode, *lLeafNode, *rLeafNode;
    if (node->key < insertKey) {
      rLeafNode = new Node(insertKey, insertKey);
      internalNode = new Node(insertKey, insertKey, DPointer<Node, sizeof(size_t)>(node,
          0), DPointer<Node, sizeof(size_t)>(rLeafNode, 0));
    } else {
      lLeafNode = new Node(insertKey, insertKey);
      internalNode = new Node(node->key, node->key, DPointer<Node,
          sizeof(size_t)>(lLeafNode, 0), DPointer<Node, sizeof(size_t)>(node, 0));
    }

    if (nthChild == 0) {
      if (pnode->lChild.cas(DPointer<Node, sizeof(size_t)>(internalNode, 0), oldChild)) {
        return;
      } else {
        //insert failed; help the conflicting delete operation
        if (node == pnode->lChild.ptr) { // address has not changed. So CAS would have
            failed coz of flag/mark only
          //help other thread with cleanup
          s = seek(insertKey);
          cleanUp(insertKey, s);
        }
      }
    } else {
      if (pnode->rChild.cas(DPointer<Node, sizeof(size_t)>(internalNode, 0), DPointer<Node,
          sizeof(size_t)>(oldChild, 0))) {
        return;
      } else {
        if (node == pnode->rChild.ptr) {
          s = seek(insertKey);
          cleanUp(insertKey, s);
          }
        }
      }
    }
  }

  void remove(long deleteKey) {
    bool isCleanUp = false;
    SeekRecord *s;
    Node *parent;
    Node *leaf = NULL;
    while (true) {
      s = seek(deleteKey);
      if (!isCleanUp) {
        leaf = s->leaf;
        if (leaf->key != deleteKey) {
          return;
        } else {
          parent = s->parent;
          if (deleteKey < parent->key) {
            if (parent->lChild.cas(DPointer<Node, sizeof(size_t)>(leaf, 2), leaf)) {
              isCleanUp = true;
              //do cleanup
              if (cleanUp(deleteKey, s)) {
                return;
              }
            } else {
              if (leaf == parent->lChild.ptr) {
                cleanUp(deleteKey, s);
              }
            }
          } else {
            if (parent->rChild.cas(DPointer<Node, sizeof(size_t)>(leaf, 2), leaf)) {
              isCleanUp = true;
              //do cleanup
              if (cleanUp(deleteKey, s)) {
                return;
              }
            } else {
              if (leaf == parent->rChild.ptr) {
                //help other thread with cleanup
                cleanUp(deleteKey, s);
              }
            }
          }
        }
      } else {
        if (s->leaf == leaf) {
          //do cleanup
          if (cleanUp(deleteKey, s)) {
            return;
          }
        } else {
          //someone helped with my cleanup. So I'm done
          return;
        }
      }
    }
  }

  int setTag(int stamp) {
    switch (stamp) // set only tag
    {
    case 0:
      stamp = 1; // 00 to 01
      break;
    case 2:
```

```
    stamp = 3; // 10 to 11
    break;
  }
  return stamp;
}

int copyFlag(int stamp) {
  switch (stamp) //copy only the flag
  {
  case 1:
    stamp = 0; // 01 to 00
    break;
  case 3:
    stamp = 2; // 11 to 10
    break;
  }
  return stamp;
}

bool cleanUp(long key, SeekRecord *s) {
  Node *ancestor = s→ancestor;
  Node *parent = s→parent;
  Node *oldSuccessor;
  size_t oldStamp;
  Node *sibling;
  size_t siblingStamp;

  if (key < parent→key) { //xl case
    if (parent→lChild.mark > 1) { // check if parent to leaf edge is already flagged. 10 or
       11
      //leaf node is flagged for deletion. tag the sibling edge to prevent any modification
         at this edge now
      sibling = parent→rChild.ptr;
      siblingStamp = parent→rChild.mark;
      siblingStamp = setTag(siblingStamp); // set only tag

      parent→rChild.cas(DPointer<Node, sizeof(size_t)>(sibling, siblingStamp), sibling);
      sibling = parent→rChild.ptr;
      siblingStamp = parent→rChild.mark;
    } else {
      //leaf node is not flagged. So sibling node must have been flagged for deletion
      sibling = parent→lChild.ptr;
      siblingStamp = parent→lChild.mark;
      siblingStamp = setTag(siblingStamp); // set only tag

      parent→lChild.cas(DPointer<Node, sizeof(size_t)>(sibling, siblingStamp), sibling);
      sibling = parent→lChild.ptr;
      siblingStamp = parent→lChild.mark;
    }
  } else { //xr case
    if (parent→rChild.mark > 1) { // check if parent to leaf edge is already flagged. 10 or
       11
      //leaf node is flagged for deletion. tag the sibling edge to prevent any modification
         at this edge now
      sibling = parent→lChild.ptr;
      siblingStamp = parent→lChild.mark;
      siblingStamp = setTag(siblingStamp); // set only tag

      parent→lChild.cas(DPointer<Node, sizeof(size_t)>(sibling, siblingStamp), sibling);
      sibling = parent→lChild.ptr;
      siblingStamp = parent→lChild.mark;
    } else {
      //leaf node is not flagged. So sibling node must have been flagged for deletion
      sibling = parent→rChild.ptr;
      siblingStamp = parent→rChild.mark;
      siblingStamp = setTag(siblingStamp); // set only tag
```

```
        parent→rChild.cas(DPointer<Node, sizeof(size_t)>(sibling, siblingStamp), sibling);
        sibling = parent→rChild.ptr;
        siblingStamp = parent→rChild.mark;
      }
    }

    if (key < ancestor→key) {
      siblingStamp = copyFlag(siblingStamp); //copy only the flag
      oldSuccessor = ancestor→lChild.ptr;
      oldStamp = ancestor→lChild.mark;
      return (ancestor→lChild.cas(DPointer<Node, sizeof(size_t)>(sibling, siblingStamp),
          DPointer<Node, sizeof(size_t)>(oldSuccessor, oldStamp)));
    } else {
      siblingStamp = copyFlag(siblingStamp); //copy only the flag
      oldSuccessor = ancestor→rChild.ptr;
      oldStamp = ancestor→rChild.mark;
      return (ancestor→rChild.cas(DPointer<Node, sizeof(size_t)>(sibling, siblingStamp),
          DPointer<Node, sizeof(size_t)>(oldSuccessor, oldStamp)));
    }
  }

  SeekRecord* seek(long key) {
    DPointer<Node, sizeof(size_t)> parentField;
    DPointer<Node, sizeof(size_t)> currentField;
    Node *current;

    //initialize the seek record
    SeekRecord *s = new SeekRecord(grandParentHead, parentHead, parentHead,
        parentHead→lChild.ptr);

    parentField = s→ancestor→lChild;
    currentField = s→successor→lChild;

    while (currentField.ptr != NULL) {
      current = currentField.ptr;
      //move down the tree
      //check if the edge from the current parent node in the access path is tagged
      if (parentField.mark == 0 || parentField.mark == 2) { // 00, 10 untagged
        s→ancestor = s→parent;
        s→successor = s→leaf;
      }
      //advance parent and leaf pointers
      s→parent = s→leaf;
      s→leaf = current;
      parentField = currentField;
      if (key < current→key) {
        currentField = current→lChild;
      } else {
        currentField = current→rChild;
      }
    }
    return s;
  }

  void createHeadNodes() {
    long key = LONG_MAX;
    long value = LONG_MIN;
    parentHead = new Node(key, value, DPointer<Node, sizeof(size_t)>(new Node(key, value), 0),
        DPointer<Node, sizeof(size_t)>(new Node(key, value), 0));
    grandParentHead = new Node(key, value, DPointer<Node, sizeof(size_t)>(parentHead, 0),
        DPointer<Node, sizeof(size_t)>(new Node(key, value), 0));
  }
};
Node * LockFreeBST::grandParentHead = NULL;
Node * LockFreeBST::parentHead = NULL;
LockFreeBST *LockFreeBST::obj = NULL;
```

2) Doubly Linked List:

```
class doublylinked {
public:
  class Node {
  public:
    int value;
    DPointer<doublylinked::Node, sizeof(size_t)> after;
    Node *before;

    Node() {
    }
    Node(int key) {
      this→value = key;
      this→before = NULL;
      this→after = DPointer<doublylinked::Node, sizeof(size_t)>();
    }
  };
  Node *headdummy, *taildummy;

  bool deleten(int key) {
    Node *pred = headdummy, *curr;
    curr = pred→after.ptr;
    while (curr→value < key) {
      pred = curr;
      curr = curr→after.ptr;
    }
    return deleteNode(curr, true);
  }

  bool deleteNode(Node *thisNode, bool retry) {
    DPointer<doublylinked::Node, sizeof(size_t)> nextref;
    while (true) {
      nextref = thisNode→after;
      if (nextref.mark)
        return false;
      Node *next = nextref.ptr;
      if (thisNode→after.cas(DPointer<Node, sizeof(size_t)>(next, true), next));
      break;
      if (!retry)
        return false;
    }
    getBack(thisNode);
    return true;
  }

  Node* getBack(Node *refNode) {
    Node *prevref = refNode→before;
    Node *currentNode = refNode;
    while (true) {
      prevref = currentNode→before;
      Node *backnode = prevref;
      DPointer<doublylinked::Node, sizeof(size_t)> backAtref = backnode→after;
      Node *backAftNode = backAtref.ptr;
      if (backAtref.mark)
        currentNode = backnode;
      else if (backAftNode == refNode)
        return backnode;
      else {
        Node *maybeback = fixforwarduntil(backnode, refNode);
        if ((maybeback == NULL) && (backnode→after.mark))
          currentNode = backnode;
        else
          return maybeback;
      }
    }
  }
```

```
Node* fixforwarduntil(Node *thisNode, Node *laterNode) {
  Node *nextnode, *worknode = thisNode;
  DPointer<doublylinked::Node, sizeof(size_t)> thisnodeAtref, workNodeAtref, laternodeAtref;

  while (true) {
    thisnodeAtref = thisNode->after;
    if (thisnodeAtref.mark)
      return NULL;
    laternodeAtref = laterNode->after;
    if ((laternodeAtref.ptr != NULL) && (laternodeAtref.mark))
      return NULL;
    workNodeAtref = worknode->after;
    if (workNodeAtref.ptr == NULL)
      return NULL;
    if (!(workNodeAtref.mark)) {
      fixforward(worknode);
      workNodeAtref = worknode->after;
    }
    nextnode = workNodeAtref.ptr;
    if (nextnode == laterNode)
      return worknode;
    else if (nextnode->after == NULL
      ) return NULL;
    else
      worknode = nextnode;
  }
}

void initialise() {
  Node *a = new Node(0);
  headdummy = a;
  taildummy = a;
  Node *b = new Node(100000000);
  b->before = a;
  a->after = DPointer < doublylinked::Node, sizeof(size_t) > (b, 0);
}

bool add(int key) {
  Node *mynode = new Node(key);
  Node *pred = headdummy, *curr;
  curr = pred->after.ptr;
  while (curr->value < key) {
    if (pred == curr)
      break;
    pred = curr;
    curr = curr->after.ptr;
  }
  if (headdummy == pred)
    return insertafter(headdummy, mynode);
  else
    insertafter(pred, mynode);
}

bool insertafter(Node *previous, Node *mynode) {
  while (true) {
    DPointer<doublylinked::Node, sizeof(size_t)> prevAtref = previous->after;
    if (prevAtref.mark)
      return false;
    Node *prevafter = fixforward(previous);
    if (insertBetween(mynode, previous, prevafter))
      return true;
  }
}

bool insertBetween(Node *thisNode, Node *prev, Node *after) {
  thisNode->before = prev;
  thisNode->after = DPointer < doublylinked::Node, sizeof(size_t) > (after, 0);
```

```
      if (prev→after.cas(DPointer<Node, sizeof(size_t)>(thisNode, false), after)) {
        reflectforward(thisNode);
        return true;
      }
      return false;
    }

    Node* fixforward(Node *thisNode) {
      DPointer<doublylinked::Node, sizeof(size_t)> thisAtref = thisNode→after;
      Node *laterNode = thisAtref.ptr;
      Node *laterLater;
      while (true) {
        DPointer<doublylinked::Node, sizeof(size_t)> nextref = laterNode→after;
        if (nextref == NULL || !nextref.mark) {
          reflectforward(thisNode);
          return laterNode;
        } else {
          laterLater = nextref.ptr;
          thisNode→after.cas(DPointer<Node, sizeof(size_t)>(laterLater, false), laterNode);
          laterNode = laterLater;
        }
      }
    }

    void reflectforward(Node *previous) {
      DPointer<doublylinked::Node, sizeof(size_t)> prevAtref = previous→after;
      if (prevAtref.mark)
        return;
      Node *afterNode = prevAtref.ptr;
      Node *afterBeforeref = afterNode→before;
      Node *afterBeforeNode = afterBeforeref;
      if (afterBeforeNode == previous)
        return;
      DPointer<doublylinked::Node, sizeof(size_t)> afterAtref = afterNode→after;
      if (afterAtref == NULL && !afterAtref.mark)
        afterNode→before = previous;
    }
  };
```

3) Hash Set:

```
class Lockprogram {
public:
  class LockFreehash {
  public:
    class Node {

    public:
      int item;
      int key; //item's hash code
      DPointer<LockFreehash::Node, sizeof(size_t)> next;
      Node() {
      }
      Node(int item1) { // usual constructor
        this→key = item1;
        this→next = DPointer<LockFreehash::Node, sizeof(size_t)>();
      }
      Node(int key, int x) {
        this→key = key;
        this→item = x;
        this→next = DPointer<LockFreehash::Node, sizeof(size_t)>();
      }

      Node* getnext() {
        bool cMarked[] = { false };
        bool sMarked[] = { false };
        Node* succ;
        Node* entry = this→next.ptr;
        cMarked[0] = this→next.mark;
        while (cMarked[0]) {
          succ = entry→next.ptr;
          sMarked[0] = entry→next.mark;
          this→next.ptr = succ;
          this→next.mark = sMarked[0];
          entry = this→next.ptr;
          cMarked[0] = this→next.mark;
        }
        return entry;
      }
    };
  public:
    class Window {
    public:
      Node *pred;
      Node *curr;
      Window() {
      }
      Window(Node *pred, Node *curr) {
        this→pred = pred;
        this→curr = curr;
      }
    };
    const static int WORD_SIZE = 24;
    const static int LO_MASK = 0x00000001;
    const static int HI_MASK = 0x00800000;
    const static int MASK = 0x00FFFFFF;
    Node *head;
    LockFreehash() {
      this→head = new Node(0);
      Node *tail = new Node(2147483647);
      while (!head→next.cas(DPointer<LockFreehash::Node, sizeof(size_t)>(tail, 0),NULL));
    }
    LockFreehash(Node* e) {
      this→head = e;
    }

    int hashcode(int x) {
```

```
    std::tr1::hash<int> hash_fn;
    int a = hash_fn(x);
    return a & MASK;
  }

  int reverse(int key) {
    int loMask = LO_MASK;
    int hiMask = HI_MASK;
    int result = 0;
    for (int i = 0; i < WORD_SIZE; i++) {
      if ((key & loMask) != 0) { // bit set
        result |= hiMask;
      }
      loMask <<= 1;
      hiMask >>= 1; // fill with 0 from left
    }
    return result;
  }

  int makeRegularKey(int x) {
    std::tr1::hash<int> hash_fn;
    int a = hash_fn(x);
    int code = a & MASK; // take 3 lowest bytes
    return reverse(code | HI_MASK);
  }

  int makeSentinelKey(int key) {
    return reverse(key & MASK);
  }

  Window* find(Node* head, int key) {
    Node* pred = head;
    Node* curr = head→getnext();
    while (curr→key < key) {
      pred = curr;
      curr = pred→getnext();
    }
    return new Window(pred, curr);
  }

  bool add(int x) {
    int key = makeRegularKey(x);
    bool splice;
    while (true) {
      Window* window = find(head, key);
      Node* pred = window→pred;
      Node* curr = window→curr;
      Node* entry = new Node(key, x);
      entry→next = DPointer < LockFreehash::Node, sizeof(size_t) > (curr, 0);
      splice = pred→next.cas(DPointer<Node, sizeof(size_t)>(entry, 0), curr);
      if (splice)
        return true;
      else
        continue;
    }
  }

  bool remove(int x) {
    int key = makeRegularKey(x);
    bool snip;
    while (true) {
      Window* window = find(head, key);
      Node* pred = window→pred;
      Node* curr = window→curr;
      if (curr→key != key) {
        return false;
      } else {
        snip = pred→next.cas(DPointer<Node, sizeof(size_t)>(curr, true), curr);
        if (snip)
          return true;
        else
          continue;
      }
    }
  }

  bool contains(int x) {
    int key = makeRegularKey(x);
    Window* window = find(head, key);
    Node* pred = window→pred;
    Node* curr = window→curr;
    return curr→key == key;
  }

  LockFreehash* getsentinel(int index) {
    int key = makeSentinelKey(index);
    bool splice;
    while (true) {
      Window* window = find(head, key);
      Node* pred = window→pred;
      Node* curr = window→curr;
      // is the key present?
      if (curr→key == key) {
        return new LockFreehash(curr);
      } else {
        // splice in new entry
        Node* entry = new Node(key);
        entry→next = DPointer < LockFreehash::Node, sizeof(size_t) > (pred, 0);
        splice = pred→next.cas(DPointer<Node, sizeof(size_t)>(entry, false), curr);
        if (splice) {
          return new LockFreehash(curr);
        } else
          continue;
      }
    }
  }
};

vector<LockFreehash*> bucket;
int bucketSize;
int setSize;
const static double THRESHOLD = 4.0;
LockFreehash lfh;
Lockprogram() {
}
Lockprogram(int capacity) {

  for (int i = 0; i < capacity; i++) {
    LockFreehash* temp = new LockFreehash();
    this→bucket.push_back(temp);
  }
  this→bucketSize = 2;
  this→setSize = 0;
}

LockFreehash* getBucketList(int myBucket) {
  if (this→bucket[myBucket] == NULL
    )
    initializeBucket(myBucket);
  return this→bucket[myBucket];
}

int getparent(int myBucket) {
  int parent = this→bucketSize;
```

```
    do {
      parent = parent >> 1;
    } while (parent > myBucket);
    parent = myBucket - parent;
    return parent;
  }

  void initializeBucket(int myBucket) {
    int parent = getparent(myBucket);
    if (this→bucket[parent] = NULL
      )
      initializeBucket(parent);
    LockFreehash* b = this→bucket[parent]→getsentinel(myBucket);
    if (b != NULL
      )
      this→bucket[myBucket] = b;
  }

  bool add(int x) {
    int mybucket = abs(lfh.hashcode(x) % this→bucketSize);
    LockFreehash* b = getBucketList(mybucket);
    if (!b→add(x))
      return false;
    int setSizeNow = this→setSize + 1;
    int bucketSizeNow = this→bucketSize;
    if (setSizeNow / (double) bucketSizeNow > THRESHOLD)
      this→bucketSize = 2 * bucketSizeNow;
    return true;
  }

  bool remove(int x) {
    int myBucket = abs(lfh.hashcode(x) % bucketSize);
    LockFreehash* b = getBucketList(myBucket);
    if (!b→remove(x))
      return false;
    return true;
  }

  bool contains(int x) {
    int myBucket = abs(lfh.hashcode(x) % bucketSize);
    LockFreehash* b = getBucketList(myBucket);
    return b→contains(x);

  }
};
```

4) List:

```
class LockFreeList {
public:
  class Node {

  public:
    int item;
    int key; //item's hash code

    DPointer<LockFreeList::Node, sizeof(size_t)> next;
    Node() {
    }
    Node(int item1) { // usual constructor
      this→item = item1;
      this→key = item1; //instead of hashcode(), we have used the item itself as the key.
      this→next = DPointer<LockFreeList::Node, sizeof(size_t)>();
    }
  };

  Node *head;

  LockFreeList() {
    this→head = new Node(0);
    Node *tail = new Node(1000000);
    while (!head→next.cas(DPointer<LockFreeList::Node, sizeof(size_t)>(tail, 0), NULL));
  }

  bool add(int item) {
    int key = item;
    bool splice;
    while (true) {
      Window *window = find(head, key);
      Node *pred = window→pred, *curr = window→curr;
      Node *node = new Node(item);
      node→next = DPointer < LockFreeList::Node, sizeof(size_t) > (curr, 0);
      if (pred→next.cas(DPointer<LockFreeList::Node, sizeof(size_t)>(node, 0), curr)) {
        return true;
      }
    }
  }

  bool remove(int item) {
    int key = item;
    bool snip;
    while (true) {
      Window *window = find(head, key);
      Node *pred = window→pred, *curr = window→curr;
      Node *succ = curr→next.ptr;
      snip = curr→next.cas(DPointer<LockFreeList::Node, sizeof(size_t)>(succ, 1),succ);
      if (!snip)
        continue;
      pred→next.cas(DPointer<LockFreeList::Node, sizeof(size_t)>(succ, 0), curr);
      return true;
    }
  }

  bool contains(int item) {
    int key = item;
    Window *window = find(head, key);
    Node *pred = window→pred, *curr = window→curr;
    return (curr→key == key);
  }

  class Window {
  public:
    Node *pred;
    Node *curr;
    Window(Node *pred, Node *curr) {
      this→pred = pred;
      this→curr = curr;
    }
  };

  LockFreeList::Window* find(Node *head, int key) {
    Node *pred = NULL, *curr = NULL, *succ = NULL;
    bool marked[] = { false }; // is curr marked?
    bool snip;
    int flag = 0;
    retry: while (true) {
      pred = head;
      curr = pred→next.ptr;
      while (true) {
        succ = curr→next.ptr;
        marked[0] = curr→next.mark;

        while (marked[0]) { // replace curr if marked
          snip = pred→next.cas(DPointer<Node, sizeof(size_t)>(succ, false),curr);
          if (!snip) {
            goto retry;
          }
          curr = pred→next.ptr;
          succ = curr→next.ptr;
          marked[0] = curr→next.mark;
        }
        if (curr→key >= key)
          return new LockFreeList::Window(pred, curr);
        pred = curr;
        curr = succ;
      }
    }
  }
};
```

5) Queue:

```
class Queue {
  class Node {
  public:
    int value;
    Node *next;

    Node(int value) {
      this->value = value;
      this->next = NULL;
    }
  };
private:
  Node *head;
  Node *tail;
public:

  Queue() {
    Node *sentinel = new Node(-1);
    this->head = sentinel;
    this->tail = sentinel;
  }

public:
  void enqueue(int item) {
    Node *node = new Node(item);
    Node *last, *next;

    while (true) {
      last = tail; // read tail
      next = last->next;
      if (last == tail) {
        if (next == NULL)
        {
          if (reinterpret_cast<Node*>(compareAndExchange(reinterpret_cast<volatile
              size_t*>(&last->next), reinterpret_cast<size_t>(next),
              reinterpret_cast<size_t>(node))) == next) {
            compareAndExchange(reinterpret_cast<volatile size_t*>(&tail),
                reinterpret_cast<size_t>(last), reinterpret_cast<size_t>(node));
            return;
          }
        } else {
          compareAndExchange(reinterpret_cast<volatile size_t*>(&tail),
              reinterpret_cast<size_t>(last), reinterpret_cast<size_t>(next));
        }
      }
    }
  }

  int dequeue() {
    int c = 0;
    while (true) {
      Node *first = head;
      Node *last = tail;
      Node *next = first->next;
      if (first == head) { // are they consistent?
        if (first == last) { // is queue empty or tail falling behind?
          if (next == NULL || head->value == -1) { // is queue empty?
            cout << "\nqueue is empty";
            return -1;
          }
          compareAndExchange(reinterpret_cast<volatile size_t*>(&tail),
              reinterpret_cast<size_t>(last), reinterpret_cast<size_t>(next));
        } else {
          int value = next->value;
          if (reinterpret_cast<Node*>(compareAndExchange(reinterpret_cast<volatile
              size_t*>(&head), reinterpret_cast<size_t>(first),
                 reinterpret_cast<size_t>(next))) == first)
                return value;
            }
        }
    }
  }
};
```

6) Stack:

```
struct Node {
  int value;
  struct Node* next;
};

struct Node* top = NULL;

bool tryPush(Node* node) {
  Node* oldTop = top;
  node->next = oldTop;
  return (reinterpret_cast<struct Node*>(compareAndExchange( reinterpret_cast<volatile
      size_t*>(&top), reinterpret_cast<size_t>(oldTop), reinterpret_cast<size_t>(node))));
}

void push(int value) {
  Node* node = (struct Node*) malloc(sizeof(struct Node));
  while (true) {
    if (tryPush(node)) {
      return;
    }
  }
}

Node* tryPop() {
  Node* oldTop = top;
  if (oldTop == NULL)
  {
    cout << "\nEmpty Stack";
    return NULL;
  }
  Node* newTop = oldTop->next;
  if (reinterpret_cast<struct Node*>(compareAndExchange(reinterpret_cast<volatile
      size_t*>(&top), reinterpret_cast<size_t>(oldTop), reinterpret_cast<size_t>(newTop))) ==
      oldTop) {
    return oldTop;
  } else {
    return NULL;
  }
}

int pop() {
  while (true) {
    Node *returnNode = tryPop();
    if (returnNode != NULL)
    {
      return returnNode->value;
    }
  }
}
```

D. MCAS-based Lock-free Implementation

Library Used by all Benchmarks: This library is essentially a software implementation of the MCAS primitive. Calls to the `mcas()` function are replaced with a hardware MCAS call during simulation.

```
#define LOCKTABLESIZE 819412

int lock[LOCKTABLESIZE];
void sort(volatile size_t *list[], volatile size_t oldV[],
    volatile size_t newV[], int length) {
  for (int i = 0; i < length; i++) {
    for (int j = 0; j < length - (i + 1); j++) {
      if (list[j] > list[j + 1]) {
        volatile size_t *temp = list[j + 1];
        list[j + 1] = list[j];
        list[j] = temp;
        volatile size_t tV = oldV[j + 1];
        oldV[j + 1] = oldV[j];
        oldV[j] = tV;
        tV = newV[j + 1];
        newV[j + 1] = newV[j];
        newV[j] = tV;
      }
    }
  }
}

void initialiseLockArray() {
  int i;
  for (i = 0; i < LOCKTABLESIZE; i++) {
    int falseValue = 0;
    lock[i] = falseValue;
  }
}

void acquireLock(volatile size_t *location) {
  volatile size_t index = (volatile size_t) location;

  int hashIndex = index % LOCKTABLESIZE;
  int falseValue = 0;
  int trueValue = 1;
  while ((compareAndExchange(
      reinterpret_cast<volatile size_t*>(&lock[hashIndex]), falseValue,
      trueValue)) != falseValue) {
  }

}

void releaseLock(volatile size_t *location) {
  volatile size_t index = ((volatile size_t) location) % LOCKTABLESIZE;
  int hashIndex = index % LOCKTABLESIZE;
  int falseValue = 0;
  lock[hashIndex] = falseValue;

}
void fail(volatile size_t **addressArray, unsigned int index) {
  unsigned int i;
  for (i = index; i > 0; i--) {
    releaseLock(addressArray[i]);
  }
}

bool mcas(int n, volatile size_t *m0, volatile size_t old0,
    volatile size_t new0) {
  initialiseLockArray();
  int i;
  volatile size_t *address[1] = { m0 };
  volatile size_t oldV[1] = { old0 };
  volatile size_t newV[1] = { new0 };
  sort(address, oldV, newV, 1);

  for (i = 0; i < n; i++) {
    acquireLock(address[i]);
    if ((unsigned long int) *address[i] != (unsigned long int) oldV[i]) {
      fail(address, i);
      return false;
    }
  }

  if (i == n) {
    for (i = n - 1; i >= 0; i--) {
      *address[i] = newV[i];
      releaseLock(address[i]);
    }
    return true;
  }
}

bool mcas(int n, volatile size_t *m0, volatile size_t *m1, volatile size_t old0,
    volatile size_t old1, volatile size_t new0, volatile size_t new1) {
  initialiseLockArray();
  int i;
  volatile size_t *address[2] = { m0, m1 };
  volatile size_t oldV[2] = { old0, old1 };
  volatile size_t newV[2] = { new0, new1 };
  sort(address, oldV, newV, 2);

  for (i = 0; i < n; i++) {
    acquireLock(address[i]);
    if ((unsigned long int) *address[i] != (unsigned long int) oldV[i]) {
      fail(address, i);
      return false;
    }
  }

  if (i == n) {
    for (i = n - 1; i >= 0; i--) {
      *address[i] = newV[i];
      releaseLock(address[i]);
    }
    return true;
  }
}

bool mcas(int n, volatile size_t *m0, volatile size_t *m1, volatile size_t *m2,
    volatile size_t old0, volatile size_t old1, volatile size_t old2,
    volatile size_t new0, volatile size_t new1, volatile size_t new2) {
  initialiseLockArray();
  int i;
  volatile size_t *address[3] = { m0, m1, m2 };
  volatile size_t oldV[3] = { old0, old1, old2 };
  volatile size_t newV[3] = { new0, new1, new2 };
  sort(address, oldV, newV, n);

  for (i = 0; i < n; i++) {
    acquireLock(address[i]);
    if ((unsigned long int) *address[i] != (unsigned long int) oldV[i]) {
      fail(address, i);
      return false;
    }
  }

  if (i == n) {
    for (i = n - 1; i >= 0; i--) {
      *address[i] = newV[i];
      releaseLock(address[i]);
    }
    return true;
  }
}

bool mcas(int n, volatile size_t *m0, volatile size_t *m1, volatile size_t *m2,
    volatile size_t *m3, volatile size_t old0, volatile size_t old1,
    volatile size_t old2, volatile size_t old3, volatile size_t new0,
    volatile size_t new1, volatile size_t new2, volatile size_t new3) {
  initialiseLockArray();
  int i;
  volatile size_t *address[4] = { m0, m1, m2, m3 };
  volatile size_t oldV[4] = { old0, old1, old2, old3 };
  volatile size_t newV[4] = { new0, new1, new2, new3 };
  sort(address, oldV, newV, n);

  for (i = 0; i < n; i++) {
    acquireLock(address[i]);
    if ((unsigned long int) *address[i] != (unsigned long int) oldV[i]) {
      fail(address, i);
      return false;
    }

  }

  if (i == n) {
    for (i = n - 1; i >= 0; i--) {
      *address[i] = newV[i];
      releaseLock(address[i]);
    }
    return true;
  }
}

bool mcas(int n, volatile size_t *m0, volatile size_t *m1, volatile size_t *m2,
    volatile size_t *m3, volatile size_t *m4, volatile size_t *m5,
    volatile size_t old0, volatile size_t old1, volatile size_t old2,
    volatile size_t old3, volatile size_t old4, volatile size_t old5,
    volatile size_t new0, volatile size_t new1, volatile size_t new2,
    volatile size_t new3, volatile size_t new4, volatile size_t new5) {
  initialiseLockArray();
  int i;
  volatile size_t *address[6] = { m0, m1, m2, m3, m4, m5 };
  volatile size_t oldV[6] = { old0, old1, old2, old3, old4, old5 };
  volatile size_t newV[6] = { new0, new1, new2, new3, new4, new5 };
  sort(address, oldV, newV, n);

  for (i = 0; i < n; i++) {
    acquireLock(address[i]);
    if ((unsigned long int) *address[i] != (unsigned long int) oldV[i]) {
      fail(address, i);
      return false;
    }

  }

  if (i == n) {
    for (i = n - 1; i >= 0; i--) {
      *address[i] = newV[i];
      releaseLock(address[i]);
    }
    return true;
  }
}
```

1) Binary Search Tree:

```
struct bst {
  int data;
  struct bst *left;
  struct bst *right;
};
typedef struct bst bst_t;
bst_t *root = NULL;

bst_t *get_new_node(int val) {
  bst_t *node = (bst_t *) malloc(sizeof(bst_t));
  node->data = val;
  node->left = NULL;
  node->right = NULL;
  return node;
}

bst_t *insert(bst_t *root, int val) {
  if (!root)
    return get_new_node(val);
  bst_t *prev = NULL, *ptr = root, *last, *temp, *node;
  node = get_new_node(val);
  char type = ' ';
  while (true) {
    while (ptr) {
      prev = ptr;
      if (val < ptr->data) {
        ptr = ptr->left;
        type = 'l';
      } else {
        ptr = ptr->right;
        type = 'r';
      }
    }
    if (type == 'l') {
      last = prev->left;
      if(mcas(1, reinterpret_cast<volatile size_t*>(&prev->left), reinterpret_cast<volatile
         size_t>(last), reinterpret_cast<volatile size_t>(node)))
        return root;
    } else {
      last = prev->right;
      if(mcas(1, reinterpret_cast<volatile size_t*>(&prev->right), reinterpret_cast<volatile
         size_t>(last), reinterpret_cast<volatile size_t>(node)))
        return root;
    }
  }
}

int find_minimum_value(bst_t *ptr) {
  int min = ptr ? ptr->data : 0;
  while (ptr) {
    if (ptr->data < min)
      min = ptr->data;
    if (ptr->left) {
      ptr = ptr->left;
    } else if (ptr->right) {
      ptr = ptr->right;
    } else
      ptr = NULL;
  }
  return min;
}

bst_t *deleter(bst_t *root, int val) {
  bst_t *prev = NULL, *ptr = root, *last, *present, *temp;
  char type = ' ';
  while (ptr) {
```

```
if (ptr→data == val) {
  if (!ptr→left && !ptr→right) { // node to be removed has no children's
    if (ptr != root && prev) { // delete leaf node
      if (type == 'l') {
        while (flag1) {
          last = prev;
          present = ptr;
          temp = NULL;
          if(mcas(2, reinterpret_cast<volatile size_t*>(&ptr), reinterpret_cast<volatile
              size_t*>(&prev→left), reinterpret_cast<volatile size_t>(present),
              reinterpret_cast<volatile size_t>(present), reinterpret_cast<volatile
              size_t>(temp), reinterpret_cast<volatile size_t>(temp)))
            return root;
        }
      } else {
        while (flag1) {
          last = prev;
          present = ptr;
          temp = NULL;
          if(mcas(2, reinterpret_cast<volatile size_t*>(&ptr), reinterpret_cast<volatile
              size_t*>(&prev→right), reinterpret_cast<volatile size_t>(present),
              reinterpret_cast<volatile size_t>(present), reinterpret_cast<volatile
              size_t>(temp), reinterpret_cast<volatile size_t>(temp)))
            return root;
        }
      }
    } else {
      last = root;
      temp = NULL;
      if(mcas(1, reinterpret_cast<volatile size_t*>(&root), reinterpret_cast<volatile
          size_t>(last), reinterpret_cast<volatile size_t>(temp)))
        return root;
    } // deleted node is root
  } else if (ptr→left && ptr→right) { // node to be removed has two children's
    ptr→data = find_minimum_value(ptr→right); // find minimum value from right subtree
    val = ptr→data;
    prev = ptr;
    ptr = ptr→right; // continue from right subtree delete min node
    type = 'r';
    continue;
  } else { // node to be removed has one children
    if (ptr == root) { // root with one child
      if (root→left) {
        last = root;
        temp = root→left;
        if(mcas(1, reinterpret_cast<volatile size_t*>(&root), reinterpret_cast<volatile
            size_t>(last), reinterpret_cast<volatile size_t>(temp)))
          return root;
      } else {
        last = root;
        temp = root→right;
        if(mcas(1, reinterpret_cast<volatile size_t*>(&root), reinterpret_cast<volatile
            size_t>(last), reinterpret_cast<volatile size_t>(temp)))
          return root;
      }
    } else { // subtree with one child
      if (type == 'l') {
        if (ptr→left) {
          while (flag1) {
            present = ptr;
            temp = NULL;
            if(mcas(2, reinterpret_cast<volatile size_t*>(&prev→left),
                reinterpret_cast<volatile size_t*>(&ptr), reinterpret_cast<volatile
                size_t>(present), reinterpret_cast<volatile size_t>(present),
                reinterpret_cast<volatile size_t>(present→left),
                reinterpret_cast<volatile size_t>(temp)))
              return root;
              }
            } else {
              present = ptr;
              temp = NULL;
              if(mcas(2, reinterpret_cast<volatile size_t*>(&prev->right),
                  reinterpret_cast<volatile size_t*>(&ptr), reinterpret_cast<volatile
                  size_t>(present), reinterpret_cast<volatile size_t>(present),
                  reinterpret_cast<volatile size_t>(present->right),
                  reinterpret_cast<volatile size_t>(temp)))
                return root;
            }
          } else {
            if (ptr->left) {
              last = ptr->left;
              present = ptr;
              temp = NULL;
              if(mcas(2, reinterpret_cast<volatile size_t*>(&prev->left),
                  reinterpret_cast<volatile size_t*>(&ptr), reinterpret_cast<volatile
                  size_t>(present), reinterpret_cast<volatile size_t>(present),
                  reinterpret_cast<volatile size_t>(last), reinterpret_cast<volatile
                  size_t>(temp)))
                return root;
            } else {
              last = ptr->right;
              present = ptr;
              temp = NULL;
              if(mcas(2, reinterpret_cast<volatile size_t*>(&prev->right),
                  reinterpret_cast<volatile size_t*>(&ptr), reinterpret_cast<volatile
                  size_t>(present), reinterpret_cast<volatile size_t>(present),
                  reinterpret_cast<volatile size_t>(last), reinterpret_cast<volatile
                  size_t>(temp));
                return root;
            }
          }
        }
      }
    }
    prev = ptr;
    if (val < ptr->data) {
      ptr = ptr->left;
      type = 'l';
    } else {
      ptr = ptr->right;
      type = 'r';
    }
  }
  return root;
}

void enq(int value) {
  root = insert(root, value);
}

void deq(int value) {
  root = deleter(root, value);
}
```

2) Doubly Linked List:

```
struct node {
  int data;
  struct node *next;
  struct node *prev;
};
struct node* head = NULL;

void insertAfter(struct node* prev_node, int new_data) {
  struct node* new_node = (struct node*) malloc(sizeof(struct node));
  new_node->data = new_data;
  new_node->next = NULL;
  new_node->prev = NULL;
  struct node *temp = NULL, *next_l, *prev_l;
  while (true) {
    next_l = prev_node->next;
    prev_l = prev_node;

    if(mcas(4, reinterpret_cast<volatile size_t*>(&new_node->next), reinterpret_cast<volatile
        size_t*>(&new_node->prev), reinterpret_cast<volatile size_t*>(&prev_node->next),
        reinterpret_cast<volatile size_t*>(&prev_node->next->prev), reinterpret_cast<volatile
        size_t>(temp), reinterpret_cast<volatile size_t>(temp), reinterpret_cast<volatile
        size_t>(next_l), reinterpret_cast<volatile size_t>(prev_node),
        reinterpret_cast<volatile size_t>(next_l), reinterpret_cast<volatile
        size_t>(prev_node), reinterpret_cast<volatile size_t>(new_node),
        reinterpret_cast<volatile size_t>(new_node)))
      return;
  }
}

void insert(int key) {
  struct node *prev = head, *curr = prev;
  while (curr->data < key) {
    prev = curr;
    curr = curr->next;
  }
  insertAfter(prev, key);
}

void deleteNode(struct node *del) {
  struct node *prev_l, *next_l;
  while (true) {
    prev_l = del->next->prev;
    next_l = del->prev->next;

    if(mcas(2, reinterpret_cast<volatile size_t*>(&del->next->prev), reinterpret_cast<volatile
        size_t*>(&del->prev->next), reinterpret_cast<volatile size_t>(prev_l),
        reinterpret_cast<volatile size_t>(next_l), reinterpret_cast<volatile
        size_t>(del->prev), reinterpret_cast<volatile size_t>(del->next)))
      return;
  }
  free(del);
}

void deleten(int key) {
  struct node *prev = head, *curr = prev;
  while (curr->data < key) {
    prev = curr;
    curr = curr->next;
  }
  deleteNode(curr);
}
```

3) Hash Set:

```
static vector<struct node* > table;
struct node {
  int data;
  struct node *next;
};

void linkadd(int num, int index) {
  bool mcast = false;
  struct node *temp, *a1, *a2;
  temp = (struct node *) malloc(sizeof(struct node));
  temp->data = num;
  while (!mcast) {
    if (table[index] == NULL) {
      table[index] = temp;
      table[index]->next = NULL;
      return;
    } else {
      a1 = temp->next;
      a2 = table[index];
      mcast = mcas(2, reinterpret_cast<volatile size_t*>(&temp->next),
          reinterpret_cast<volatile size_t*>(&(table[index])), reinterpret_cast<volatile
          size_t>(a1),    reinterpret_cast<volatile size_t>(a2), reinterpret_cast<volatile
          size_t>(table[index]), reinterpret_cast<volatile size_t>(temp));
    }
  }
}

bool linkdelete(int num, int index) {
  struct node *temp, *prev;
  while (true) {
    temp = table[index];
    if (temp != NULL)
    {
      if (mcas(1, reinterpret_cast<volatile size_t*>(&(table[index])),
          reinterpret_cast<volatile size_t>(temp), reinterpret_cast<volatile
          size_t>(temp->next)))
        return true;
    } else {
      return false;
    }
  }
}

bool linkcontain(int num, int index) {
  if (table[index] == NULL) {
    return false;
  }
  struct node* r = table[index];
  while (r != NULL) {
    if (r->data == num)
      return true;
    r = r->next;
  }
  return false;
}

class CoarseHashSet {
  int size;
public:
  CoarseHashSet(int capacity) {
    size = 0;
    table.clear();
    for (int i = 0; i < capacity; i++) {
      struct node *temp = NULL;
      //temp=(struct node *)malloc(sizeof(struct node));
      table.push_back(temp);
```

```
        }
    }

    bool contains(int x) {
        std::tr1::hash<int> hash_fn;
        int a = hash_fn(x);
        bool ans = linkcontain(x, abs(a % table.size()));
        return ans;
    }

    void add(int x) {
        std::tr1::hash<int> hash_fn;
        int a = hash_fn(x);
        linkadd(x, abs(a % table.size()));
        size = size + 1;
    }

    void remove(int x) {
        std::tr1::hash<int> hash_fn;
        int a = hash_fn(x);
        bool result = linkdelete(x, abs(a % table.size()));
        size = result ? size - 1 : size;
    }
};
```

4) List:

```
class List {
public:
  class Node {
  public:
    int item;
    int key;
    Node *next;
    Node(int item) {
      this->item = item;
      this->key = item;
    }
  };
  Node *head;
  Node *tail;

  List() {
    head = new Node(-2147483648); // Add sentinels to start and end
    tail = new Node(2147483647);
    head->next = this->tail;
  }

  bool add(int item) {
    Node *pred, *curr, *last, *temp;
    int key = item;
    bool flag, mcast = false;
    Node *node = new Node(item);
    while (true) {
      pred = head;
      curr = pred->next;
      while (curr->key < key) {
        pred = curr;
        curr = curr->next;
      }
      last = curr;
      temp = NULL;
      mcast = mcas(2, reinterpret_cast<volatile size_t*>(&pred->next),
          reinterpret_cast<volatile size_t*>(&node->next), reinterpret_cast<volatile
          size_t>(last), reinterpret_cast<volatile size_t>(temp), reinterpret_cast<volatile
          size_t>(node), reinterpret_cast<volatile size_t>(last));
      if (mcast) {
        flag = true;
        return flag;
      }
    }
  }

  bool remove(int item) {
    Node *pred, *curr, *last, *temp, *prev;
    int key = item;
    while (true) {
      pred = this->head;
      curr = pred->next;
      while (curr->key < key) {
        pred = curr;
        curr = curr->next;
      }
      last = curr->next;
      prev = pred->next;
      mcas(1, reinterpret_cast<volatile size_t*>(&pred->next), reinterpret_cast<volatile
          size_t>(prev), reinterpret_cast<volatile size_t>(last));
      return true;
    }
  }

  bool contains(int item) {
    Node *pred, *curr, *last, *prev, *temp;
    int key = item;
    pred = head;
    curr = pred→next;
    while (curr→key < key) {
      prev = pred;
      last = curr;
      mcas(2, reinterpret_cast<volatile size_t*>(&pred), reinterpret_cast<volatile
          size_t*>(&curr), reinterpret_cast<volatile size_t>(prev), reinterpret_cast<volatile
          size_t>(last), reinterpret_cast<volatile size_t>(last), reinterpret_cast<volatile
          size_t>(last→next));
    }
    return (key == curr→key);
  }

  int size() {
    Node *pred = head;
    int l = 0;
    while (pred != tail) {
      l++;
      pred = pred→next;
    }
    return l;
  }
};
```

5) Queue:

```
struct node
{
  int data;
  node *next;
}*front = NULL, *rear = NULL, *p = NULL, *np = NULL, *last = NULL, *first = NULL, *next1 =
   NULL;

void enqueue(int x) {
  bool result = false;
  np = new node;
  np->data = x;
  np->next = NULL;
  while (!result) {
    last = rear;
    first = front;
    if (front == NULL) {
      front = rear = np;
    } else {
      next1 = last->next;
      result = mcas(2, reinterpret_cast<volatile size_t*>(&rear->next),
          reinterpret_cast<volatile size_t*>(&rear), reinterpret_cast<volatile size_t>(next1),
          reinterpret_cast<volatile size_t>(last), reinterpret_cast<volatile size_t>(np),
          reinterpret_cast<volatile size_t>(np));
    }
  }
}

void dequeue() {
  bool result = false;
  while (true) {
    if (front == NULL) {
      return;
    } else {
      p = front;
      result = mcas(1, reinterpret_cast<volatile size_t*>(&front), reinterpret_cast<volatile
          size_t>(p), reinterpret_cast<volatile size_t>(front->next));
      if (result)
        return;
    }
  }
}
```

6) Stack: We chose to employ an MCAS of arity 2, although a single address CAS is sufficient. We chose to do this simply to exercise our design of the MCAS hardware.

```
class stack {
public:
  class Node {
  public:
    int item;
    Node *next;
    Node(int item) {
      this->item = item;
      this->next = NULL;
    }
  };
  Node *top;

  void push(int value) {
    bool flag = false;
    Node *node = new Node(value);
    Node *topd, *temp = NULL;
    while (true) {
      topd = top;
      flag = mcas(2, reinterpret_cast<volatile size_t*>(&node->next),
          reinterpret_cast<volatile size_t*>(&top), reinterpret_cast<volatile size_t>(temp),
          reinterpret_cast<volatile size_t>(topd), reinterpret_cast<volatile size_t>(topd),
          reinterpret_cast<volatile size_t>(node));
      if (flag) {
        return;
      }
    }
  }

  void pop() {
    int t;
    Node *topd;
    int temp;
    bool result = false;
    while (true) {
      if (top != NULL) {
        t = top->item;
        topd = top;
        result = mcas(1, reinterpret_cast<volatile size_t*>(&top), reinterpret_cast<volatile
            size_t>(topd), reinterpret_cast<volatile size_t>(top->next));
        if (result) {
          return;
        }
      } else {
        return;
      }
    }
  }
};
```