ActiveMonitor: Non-blocking Monitor Executions for Increased Parallelism

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We present a set of novel ideas on design and implementation of monitor objects for multi-threaded programs. Our approach has two main goals: (a) increase parallelism in monitor objects and thus provide performance gains (shorter runtimes) for multi-threaded programs, and (b) introduce constructs that allow programmers to easily write monitor-based multi-threaded programs that can achieve these performance gains. We describe the concepts of our framework, called ActiveMonitor, and its prototype implementation using futures[11]. We evaluate its performance in terms of runtimes of multi-threaded programs on linked-list, bounded-buffer, and other fundamental problems implemented in Java. We compare the runtimes of our implementation against implementations using Java’s reentrant locks [29], recently proposed automatic signaling framework AutoSync [23], and some other techniques from the literature. The results of the evaluation indicate that monitors based on our framework provide significant gains in runtime performance in comparison to traditional monitors implemented using Java’s reentrant locks.

1 Introduction

Monitors are the prevalent programming technique for synchronization between threads in shared-memory parallel programs. They were designed [21] with two primary goals: (i) to ensure safety of shared data by enforcing mutual exclusion in critical sections, and (ii) to enable conditional synchronization using the wait-notify mechanism. Monitors ensure that while a thread is executing a critical section, other threads that cannot access the critical section wait for it to become available. Waiting threads are notified by some thread exiting the critical section. We argue that this monitor design has certain drawbacks:

(a) For executions on multi-core CPUs, a thread’s update to the shared data may cause a cache invalidation for some other thread running on a different core, specially if the thread was waiting for the critical section. Thus, the penalty incurred due to cache misses would slow down the program on multi-core CPUs.

(b) If threads do not require the result of their updates on shared data immediately after performing these updates, then the blocking executions of critical sections for these updates may become a bottleneck, and could reduce the program throughput. For example, consider a thread that inserts items in a linked-list. If this thread does not need the result of the insert operation then blocking insert operations lead to slower runtimes.

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In this paper, we focus on monitors methods that perform updates on shared data. Thus, the solution of using Read/Write locks [29] is not applicable. Observe that the design of monitors to enforce blocking executions was envisioned in 1970’s when processors were single-core, processing power was scarce and saving processor cycles was a primary concern for programmers. Under these settings, making the critical section executions blocking was not a performance issue. The current situation is drastically different: not only multi-core processors are now ubiquitous, but they are also significantly cheaper and faster. Therefore, it is important to explore alternate design and implementation of monitors to exploit the availability of multi-core processors. Given that the blocking executions of monitor methods seem to form a bottleneck for performance, we pose the following question: can monitor design and implementation be altered to allow non-blocking executions and thus improve the throughput of conditionally synchronized multi-threaded programs on multi-core machines? The motivation here is that non-blocking executions can increase parallelism by allowing more instructions to be executed in fixed time from the perspective of the thread(s). For this purpose, we propose two novel techniques:

1. A monitor object is instantiated as a thread, and invocation of monitor methods by application (worker) threads is replaced by submissions of equivalent tasks to the monitor thread. The monitor thread assumes the responsibility of executing these tasks and returning the result (if required) to the application threads.

2. The monitor methods, replaced by tasks in representation, can be executed in non-blocking manner. The non-blocking executions are explicitly indicated in the code.

These two changes together tackle the drawbacks discussed above. Under our proposed design, the worker threads do not directly access the shared data, only monitor thread does, which helps in improving the data cache locality; and non-blocking executions reduce runtime due to parallelism. This paper presents our experience with design and implementation of these ideas. We propose a framework, called ActiveMonitor, that explores non-blocking executions of monitor methods — possibly at the expense of cheap and abundant processor and memory resources.

Fig. 1 compares the implementation of a bounded-buffer monitor written using: (a) Java’s Reentrant locks [29], and (b) our proposed framework and its constructs. We propose two new keywords: activemonitor and nonblocking. The activemonitor keyword, in class declaration at line 1 of Fig. 1(b), is used to declare that this bounded-buffer is implemented as an ‘active’ monitor object, that is: it would exist as an independent thread. The nonblocking keyword in the method signature of put(), at line 6, indicates that the execution of this method can be non-blocking. As our experiments show (Section 4), this implementation provides ~ 33% faster runtime in comparison to the conventional implementation of Fig. 1(a). Lastly, our implementation is shorter, cleaner, and more intuitive. This is because we use the waituntil construct (at lines 9,15 in Fig. 1(b)) that provides implicit/automatic signaling mechanism for threads [23]. This keyword and the automatic signaling is not a contribution of this paper; we merely use it in our framework’s implementation to exploit the performance benefits it provides.

An immediate criticism of our approach is the need for additional resources for its realization. Creating a new thread for a monitor object consumes additional memory in the form of its stack allocation, as well as increases the demand for CPU time slices. However, it is well known that the processing power of the modern multi-core CPUs remains commonly under utilized. Additionally, with the trends of ever increasing data and computation size, most users tend to favor faster runtimes even at the cost of somewhat increased consumption of processor and memory resources. Our approach provides much faster runtimes for many multi-threaded use cases. In addition, we claim that with careful resource

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1Appendix A briefly covers the automatic signaling mechanism

2we collected resource usage data, at 10 min. intervals, of Stampede supercomputer over a period of three days. The mean CPU idle time was 86%.
Figure 1: Comparison of Bounded-Buffer programs written using (a) Java’s locks and (b) our approach

management by the means of a dynamic thread creation policy that considers the processor/memory utilization, coupled with the automatic thread signaling mechanism [23], our approach’s performance improvements come at an acceptable cost of additional CPU and memory usage. In short, the key contributions of this paper are following:

• we propose a new monitor design, based on two new keywords: `activemonitor` and `nonblocking`, that facilitates non-blocking executions of data updates within their critical sections. We describe the concepts required for this design’s implementation in Java.

• we define rules to ensure correctness in presence of non-blocking operations, and show that with our proposed design, despite additional concurrent executions, the executions are linearizable [20] as per their non-blocking interpretation.

• we evaluate the runtimes of some fundamental multi-threaded problems using our prototype implementation and Java’s Reentrant locks [29]. For majority of these problems, our design and implementation provides $\sim 30 - 40\%$ faster runtimes in comparison to reentrant locks.

The rest of this paper is organized as follows. Section 2 briefly covers the background concepts. Section 3 discusses the key concepts of the framework and correctness of executions. Section 4 presents experimental evaluation of our approach. We discuss some limitations of our approach, and future work in Section 5. Section 6 presents the related work, and Section 7 offers concluding remarks.
2 Background

We use the concept of *futures* [11] to achieve non-blocking executions of critical sections.

**Futures:** Futures [11] were proposed as a mechanism to facilitate task submissions (to threads) in shared memory parallel programs. In a task submission based model some threads, called *executors*, provide task execution as a service. Under this model, a thread makes an asynchronous call to some executor thread, and a *future* object is returned to the caller thread as a pointer to the computation and its possible result. The executor thread performs a task for the caller thread, and updates the returned future object with the result of the computation of the task. The caller thread can collect the result by *evaluating* the future. Evaluation of a future, i.e. the collection of the result, is performed by invoking a blocking method on the future object. Hence, if needed the thread would have to wait for the task computation to complete. In our framework, we use futures to realize non-blocking executions of monitor methods by treating method invocations as task submissions.

**Blocking and Non-Blocking methods:** By design, methods provided by monitor objects are usually blocking (*synchronous*). If a thread invokes a blocking method \( m \), then the thread can not execute its next instruction until it has exited \( m \); whether by normally returning from the method or exiting the method due to an exception. Whereas, if a thread invokes a non-blocking method \( m' \) then it would be able to execute its next instruction immediately after, while the non-blocking method is being executed in parallel, possibly by another thread.

3 **ActiveMonitor** Concepts

In this section, we discuss the key concepts of the *ActiveMonitor* framework. The relevant implementation details are presented in Appendix D. We first explain our approach using the bounded-buffer monitor of Fig. 1(b). Observe that apart from using the implicit-signal construct of waituntil, the code uses two additional keywords that we propose: *activemonitor* and *nonblocking*. By including the *activemonitor* keyword in the declaration (eg. line 1), the programmer indicates that this monitor is an ‘active’ object, i.e. it should be instantiated as a thread. However, if there are many monitor objects in a user’s program we limit the number of monitor threads — this is an implementation detail, and discussed in Appendix D.2. In the conventional monitor design, worker threads, i.e. threads explicitly created by the user program, execute the instructions of the critical section and update the data protected by the monitor. In contrast, as per our design, once the monitor is instantiated as a thread, it executes its own critical sections on behalf of worker threads. For this, at compile time method calls made to the monitor are treated as task submissions to the monitor thread. Thus, for the program in Fig. 1(b), a producer thread’s call to the *put* method, as well as a consumer thread’s call to the *take* method, are converted to submission of equivalent tasks to the monitor thread by our framework. The worker threads now have the option to perform blocking (*synchronous*) or non-blocking (*asynchronous*) executions of monitor methods. Asynchronous executions are made possible by using our second keyword proposal, *nonblocking*, that allows for non-blocking (asynchronous) execution of instructions of the method using this keyword. We first describe how monitor tasks are generated from monitor methods, and then discuss their asynchronous or synchronous executions.

3.1 Monitor Tasks

In our framework, every monitor method call corresponds to an equivalent task. At compile-time, invocations of monitor methods by worker threads are replaced by submissions of the equivalent tasks to the monitor thread.
Definition 1 (Monitor Task). A monitor task t consists of a boolean predicate P and a set of statements S. If the precondition defined by P is true then t is ‘executable’ and statements in S can be executed to complete t. Otherwise, t is ‘unexecutable’.

Observe that the syntax of a monitor task is similar to that of a guarded command [8]. Consider the put method (lines 8–13) of the bounded-buffer in Fig. 1b. For this monitor method, the equivalent monitor task T is defined by the code of lines 9–12. Here, the precondition P is (itemCount < buffer_size); and it checks if the buffer has any space to insert the item. If this condition is false, the waituntil construct ensures that any thread trying to complete this task has to wait unless the buffer is not full. Lines 10 and 11 together form the set of statements S. As indicated by the nonblocking keyword in the method signature at line 8, the generated task would be submitted for a non-blocking execution to the monitor thread. Removal of this keyword from the method signature makes the execution blocking.

The details of compile time generation of tasks for monitor method calls are in Appendix D.1. Appendix B discusses some special cases of monitor tasks. Our current prototype cannot convert some particular types of monitor methods to equivalent tasks – for example, methods with waituntil not at the beginning of the critical section, or waituntil in a conditional branch. They are also discussed in Appendix D.1.

3.2 Monitor Tasks: Execution and Correctness Guarantees

In the ActiveMonitor framework, monitor threads are responsible for executing monitor tasks. Based on the availability of resources, the framework tries to create one thread per monitor object. The implementation details for limiting the monitor thread count are in Appendix D.2. Monitor threads execute monitor tasks while observing the following rules.

Rule 1 (Mutex Invariant). All the tasks of a single monitor object are executed by the same monitor thread.

Thus, Rule 1 maintains the mutual exclusion of critical sections of a monitor. However, for correctness of executions, we require additional rules. Let proc(t) denote the thread that submits the task t to a monitor; sub(t) be the time at which the task t is submitted to the monitor, and exe(t) indicate the time when the monitor thread starts executing t.

Rule 2. For a pair of tasks s and t submitted to a monitor M, if proc(s) = proc(t), then sub(s) < sub(t) ⇒ exe(s) < exe(t).

Rule 3. Let n1, n2 be two successive method invocations by a worker thread on two different monitors M1 and M2 in the user program, and let t1, t2 be the corresponding task submissions at runtime. Then, at runtime t1 must be completed before t2’s submission.

The notions of method invocation and response used to define linearizability [20] need a different interpretation under non-blocking executions. In short, invocation now corresponds to submission of the equivalent task to monitor thread, and response corresponds to this tasks completion. With this interpretation, the following result establishes correctness of executions by proving linearizable executions.

Lemma 1. With rules 1, 2, and 3 we get an execution that is equivalent to a lock-based execution.

Proof. Sketched in Appendix C.1.

Observe that Rule 3 forces a worker thread to wait for the previous task to finish even if that task was on a different monitor object. In many applications, a programmer may not require this constraint.
on different monitor objects. Hence, to improve performance, we can drop Rule 3 for such applications. We show that the execution is still linearizable with the new interpretation of invocation and response.

Note that in the standard model of concurrent history [20], the thread history is always sequential although the object history may not be sequential. In our model, due to non-blocking executions, we have the dual property: an object history is always sequential whereas a thread history may not be so. We first define the thread order in presence of non-blocking operations. Let \( s_1, s_2, \ldots, s_m \) be \( m \) operations performed on a monitor object by a worker thread. Let \( s_i < s_j \) denote that \( s_i \) was executed before \( s_j \). In the standard model, all operations are blocking and we get that \( s_i < s_{i+1} \) for all \( i \). In our model, we define the order as follows. If \( s_i \) is blocking, then \( s_i < s_j \) for all \( j > i \). If \( s_i \) and \( s_j \) are operations on the same object and \( i < j \), then \( s_i < s_j \). If \( s_i \) is non-blocking and the result of \( s_i \) is required before \( s_k \), then \( s_i < s_j \) for all \( j \geq k \).

**Lemma 2.** With Rules 1 and 2, we get an execution that is linearizable.

*Proof.* Sketched in Appendix C.2.

Observe that the legal sequential history we get may not preserve the order of invocation of operations, but only the thread order.

## 4 Evaluation

We now present the experimental evaluation of our proposed approach. We evaluate our prototype implementation on five multi-threaded problems. The first problem is a bounded-buffer problem with multiple producers and consumers, the second is a sorted linked-list (of integers) on which threads perform updates. The remaining three are conditional synchronization problems involving varying levels of complexity in their conditional predicates. We implemented the problems using the `ActiveMonitor` framework, Java’s reentrant locks, and `AutoSynch` [23]. Additional use-case specific implementations (details given in problem descriptions below) are also compared for bounded-buffer, and the linked-list problem. For all the problems, we use a benchmark in which each worker thread performs 512000 operations on shared data protected by monitors. All the experiments are conducted on a machine with 1 socket, 2 AMD Opteron 6180 SE 12 Core, 2.5 GHz CPUs (= 24 hardware threads) and 64 GBs memory running Linux 2.6.18. We vary the number of worker threads, and measure the time required for all of them to complete their operations. All threads perform a fixed number of warm-up operations on shared data before starting the time measurements. For each problem, we measure runtimes for 25 runs, and report the mean values after removing the highest and the lowest values.

For all the experiments, we restrict the `ActiveMonitor` framework to create only one monitor thread.

We now discuss the setup of experiments and their results in a problem specific manner. Across all results, we denote the implementation techniques with the following notation: LK: Reentrant locks, AS: `AutoSynch`, AM: `ActiveMonitor` (this paper). For each problem, all the runtimes reported in their results exhibit negligible variance (< 5% of the mean value) across runs.

### 4.1 Bounded-Buffer (BB) problem [6, 7]

**Setup:** Items are plain Java objects. Every producer’s `put` invocation is non-blocking, and every consumer’s `take` is blocking. We also compare runtimes of Java’s `ArrayBlockingQueue` [29], denoted by ABQ, based implementation. Number of producers (= number of consumers) is varied from 2 to 24. We perform three types of experiments, and measure: (a) runtimes with varying number of threads for a buffer of fixed size (=4). (b) runtimes with varying buffer-size for fixed number of producers/consumers (=16 each). (c) runtimes with varying limit on non-blocking tasks allowed on the buffer of size 4 with 16 producers and consumers each.
Results

Collective results are shown in Fig. 2. Fig. 2a plots the runtimes for experiment (a). Fig. 2b shows the runtimes for experiment (b). This result highlights the benefits of non-blocking executions. Recall that only put calls are non-blocking for AM; all take calls are blocking. For small size buffers, LK, AS, and ABQ are much slower in comparison to AM due to their blocking insert operations. For larger buffer sizes, LK and ABQ implementations perform slightly faster than AM. On larger buffer sizes, the frequency of threads getting blocked out is much lower, and both LK and ABQ benefit from greedy implementation of Java in lock acquisition; but AM ends up performing slightly more work in enforcing order on tasks (as per Rules 1, 2).

Fig. 2c shows the results for experiment (c). ‘Limit’ on the size of task queue means that whenever the queue maintained by the monitor thread to store tasks, reaches the ‘limit’ value then even a non-blocking task submission to the monitor is force to block. Making all the invocations blocking (queue size limit = 0) leads to an overall runtime (for completion) of ~ 5 seconds, whereas with no limit on the size of task queue the runtime is ~ 3 seconds. This observations clearly shows that our non-blocking task based approach is beneficial. However, an unbounded task queue might grow quite large. But as shown by the plot, even for a short limit (around 20) on the size of this queue, the runtime performance converges to optimal performance (of unbounded size). Thus, this result establishes that only a small number of non-blocking tasks can provide significant performance benefit.

4.2 Sorted Linked-List (SLL) Problem

**Setup:** A linked-list of integers sorted in non-decreasing order. The number of worker threads is varied from 2 to 24. The list is pre-populated with 5000 integers. Each worker thread inserts or removes (with equal probability) a random integer. For a fair comparison, seeds are used for randomization so that the threads generate the same sequence of random integers across runs as well as across different monitor implementations. We make every thread execute some local instructions, simple mathematical computations, outside the critical section between any successive calls on the monitor. This is done in attempt to simulate some practical program behavior in which generation of data takes some time.

Both insert and remove operations are non-blocking. Additional techniques used for performance comparison: lock-free implementation (LF) [18, 13, 32], fine-grained locking (FG) [18], and transactional memory (TM) implementation in Java [28]. We measured runtimes for two types of experiments: (a) runtimes with varying number of threads, when each thread performed 250 mathematical computations

Moreover, The results for the BB problem already showed that we perform better than conventional monitors for saturation tests.
Results

Fig. 3a shows the results for experiment (a). For this experiment, the ActiveMonitor implementation (AM) clearly outperforms the reentrant lock based monitor (LK), and AutoSynch (AS). However, lock-free (LF) and transactional memory (TM) based implementations perform better. This is because both of them use optimized algorithm for the linked-list data structure. Whereas, we do not use any linked-list specific optimization, and only use non-blocking executions on critical sections.

Fig. 3b plots the ratio of runtimes using LK implementation and AM implementations for experiment (b). The ratio with no operations outside the critical section is close to 1, i.e. our approach provides no performance benefit. This is expected because no operations can be performed concurrently with the non-blocking updates to the list, and the opportunity of parallelism is effectively absent. As the number of operations outside the critical section is increased, we see significant performance gains with our approach, upto ∼30%, due to increased parallelism introduced by non-blocking executions.

4.3 Conditional Synchronization Problems

We used three thread synchronization problems that involve different levels of complexity in their conditional predicates. For all three, we measured the time taken for all the worker threads to complete the designated number (512000) of operations on the monitor.

Round-Robin (RR) Access: Every worker thread accesses the monitor in round-robin order. All operations on the monitor are non-blocking. The number of worker threads is varied from 2 to 24.

Parametrized Bounded-Buffer (PBB) [6, 7]: Producers put a collection of items into a shared buffer, while consumers remove a number of items from the buffer. For producers, the number of items to be inserted, and for consumers, the count of items to be removed, both are randomly decided at runtime. Similar to the SLL problem, seeds are used for randomization for fair evaluation across implementations. The number of producers (= number of consumers) is varied from 2 to 24.

Ticketed-Readers/Writers (TRR) [4, 3, 12]: A ticket is used to maintain the access order for readers and writers [3]. Every reader/ writer gets a ticket number indicating its arrival order. Readers/writers wait on the monitor for their turn. On their turn, they enter the monitor but do not
perform any computation inside the monitor, and immediately exit. Operations for arrival on monitor and waiting for turn to access the monitor are blocking, whereas operations after getting access to critical sections are non-blocking. The number of writer threads is varied from 2 to 24. The number of readers is kept 5 x the number of writers.

Results

Fig. 4 presents the runtimes of LK, AS, and AM based implementations for the three problems. For the RR problem, the performance of AM is 6 and 5 times faster than that of AS, and LK, respectively. This is due to better cache locality and fewer context switches. For this problem, after accessing the critical section, every thread is forced to wait unless all other threads have accessed the critical section. This constraint leads to poor cache locality and more context switches for conventional monitor design. However, in our approach, the monitor thread continuously executes all monitor accesses for each thread; therefore, there is minimal number of context switches between each monitor method invocation and that results in excellent cache locality.

For the TR/W problems, AM performs poorly in comparison to LK. This is primarily due to the nature of the problem and its underlying implementation requirements. The problem requires conditional synchronization in the middle of the method calls, and thus our task based approach has to create two tasks per method call. In fact, any family of problems with such characteristics would lead to much higher number of tasks than the actual method calls.

4.4 CPU and Memory Consumption

Table 1 presents the results on the CPU and memory usage by LK, AS, and AM for all the evaluated problems. For each problem, the CPU ratio stands for the ratio of an implementation’s mean (across runs) CPU consumption and mean (across runs) CPU consumption of LK implementation. As per memory usage, we report the maximum memory (in MBs) consumed across any of the runs performed by the implementations for each problem. As expected, our approach consumes more CPU resources. However, the maximum memory consumed by our approach is only incrementally larger than that of Java’s reentrant lock based approach. Thus, we have backed our claim that with careful resource management the cost for the performance benefit is relatively small.

5 Discussion & Future Work

The benefits of our approach are manifold: improved runtime performance, better control over desired program behavior, and increased opportunities for applying optimizations such as execution re-ordering,
operation combining, etc. However, some aspects of our framework are open to criticism. First and foremost, based on the design assumptions as well as the experimental results, it is evident that at present, our approach does not suit systems on which processor and memory resources are scarce. Even though our evaluation results indicate slightly increased memory consumption, the increase in CPU consumption is more drastic. Hence, an important future work is an improved implementation of our framework that lowers the CPU usage. Another future work is to address the issue of task generation for problems that require conditional synchronization in the middle of the method call, e.g., Ticket-R/W, and causes large number of tasks to be created. It is important to note that our approach extends conventional multi-threaded programs and their constructs, and thus provides a programmer the choice of an implementation she thinks is most suited for her needs.

We showed that we provide linearizability of executions — interpreted under the non-blocking execution model. Although it is desirable in most of the cases, there are situations when this requirements can be relaxed to certain extents for even faster performance. Such relaxations are very much dependent on the use-cases and the expectations of the programmer. As shown by Kogan et al. in [25], having ‘weak’ consistency requirements could lead to significant performance gains. In fact, for specific use-cases programmers may only need eventual consistency [37], which requires that any update to shared data is eventually committed, in their programs. However, allowing weak or eventual consistency is not possible for all use-cases. For example, consider multi-threaded implementations (in shared memory model) of Dijkstra’s single-source-shortest-path algorithm [5, 31]. Weak or eventual consistency based implementations for this algorithm cannot guarantee correct results. However, for a large number of problems, approximate solutions are good enough, and their parallel implementations exhibit significant gains in performance. Thus, this opens up two interesting future problems for our work. First of them is evaluating performance of our non-blocking execution approach for problems that admit approximate solutions, and the second is to extend our evaluation to the weak consistency model of [25].

When it comes to evaluating the performance of our proposed design and its implementation, the exploration space is large. Not only there is a large number of problems related to multi-threaded updates on data structures, but the set of parameters that affect the runtime for these problems is also large. We also plan to perform experiments by varying more parameters such as load distributions of methods, size of shared data, etc. Another key experiment is to analyze the cache locality of our approach — in terms of cache miss rates per operation and per instruction — for different experiments, and comparing it to cache locality achieved by other techniques.

Lastly, note that our current implementation does not use ideas such as operation combining [15], execution re-ordering, and batch updates [25]. Intuitively, incorporating these strategies in our implementation could lead to even better results than those observed in this paper.

### 6 Related Work

The idea of having monitor objects execute as independent threads is not completely novel. Hoare proposed a similar mechanism, in which all objects are active, of communicating sequential processes (CSP) in [22] long ago. However, the proposal was a formal language for interactions between processes.

| Problem | BB | SLL | RR | PBB | TR/W |
|---------|----|-----|----|-----|------|
| Approach | LK | AS | AM | LK | AS | AM | LK | AS | AM | LK | AS | AM |
| CPU Ratio | 1.00 | 1.11 | 1.95 | 1.00 | 0.86 | 3.49 | 1.00 | 1.10 | 2.97 | 1.00 | 2.39 | 2.47 |
| Max Mem. | 196 | 236 | 197 | 135 | 135 | 145 | 236 | 224 | 250 | 196 | 227 | 251 |

Table 1: CPU and memory consumption with Reentrant locks (LK), AutoSynch (AS), and ActiveMonitor (AM).
Its constructs are still mostly used for formal analysis. Our work focuses on making parallel programs faster by using futures to provide selective non-blocking executions on monitor methods.

Research efforts to increase parallelism in programs have been continuous almost since the advent of computing. With the arrival of multi-core processors, improving multi-threaded programming with syntactic changes, as well as with novel designs of data structures and algorithms, has been the focus of many research efforts in the last decade. Transactional memory \[17, 34\] is a well-known research effort that proposes modified syntax for ease of writing multi-threaded programs. The prominent contributions in algorithmic direction are: lock-free data structures \[13, 32, 16\], and wait-free data structures \[26, 27, 36\]. Some other research efforts have explored increased parallelism for data structures by operation re-ordering and combining complementary operations (insert and remove) \[14\].

Transactional memory \[17, 34\] introduced an elegant and much needed design for writing multi-threaded programs on shared memory. The promising feature in transactional memory proposal was to provide simplified syntax that guarantees correctness, and delegates the handling of mutual exclusion to the library providing the implementation. Our approach and ideology is similar on these goals. However, constructs for conditional waiting under transactional memory are limited \[35, 30, 9\]. Hence, writing many conditional synchronization based multi-threaded programs is rather difficult. Also, unlike transactional memory, our approach merely transfers the responsibility of data manipulation to a single monitor thread and does not require any complicated rollback mechanism for resolving conflicting updates on the shared data.

Designing lock-free and wait-free algorithms is a challenging problem for any use-case. In addition, lock-free and wait-free implementations are currently available for a small set of data structures \[10, 19\]. Even though there is a lot of ongoing research to grow this set, the growth is slow. By using our approach, the end user benefits by an additional level of abstraction and does not have to deal with the complications involved in understanding and correctly implementing wait-free and lock-free algorithms.

We use the concept of futures \[11, 29\] to realize the idea of non-blocking/asynchronous executions. The work by Kogan et al. \[25\] is similar to our approach, and makes use of futures for non-blocking executions. However, there are few key differences between our work and \[25\]. We explore changes to the paradigm of monitors, especially for conditional synchronization problems, whereas \[25\] focuses on throughputs, under saturation scenarios, of data structures such as stacks, queues, and linked-lists. Hence, our approach provides a more generic tool for performing safe updates and synchronization between threads.

Frameworks such as Legion \[2\] and Galois \[33\] focus on improving runtime performance of parallel programs on scientific simulations and large graphs, respectively. Thus, they do not directly relate to thread synchronization and notification based use-cases such as bounded-buffer. Secondly, both of these libraries require advanced skills and familiarity with the features and syntactic details exposed by the libraries. Hence, the performance gains achieved by using them are highly correlated with a programmer’s knowledge of the involved optimization parameters needed to tweak the executions for optimal performance.

7 Conclusion

Proposing changes to a well established programming paradigm is an ambitious goal. Moreover, convincing programmers to adopt a new programming framework in favor of the conventional one, usually requires the proposed approach to offer gains in terms of runtime performance as well as programming ease/productivity. The ActiveMonitor framework is a step in this direction. In almost all of the problems used in our evaluation, monitors with non-blocking executions outperform Java’s reentrant lock based monitors. Additionally, this gain is achieved by a simple mechanism of using only two new
keywords in existing Java programs. At present, our prototype implementation is costly in terms of processor usage. However, with the ubiquity of multi-core processors, optimized implementations of our proposed technique could lead to significant advantages at reduced costs. In this paper, our initial exploration in a new direction, that is: non-blocking executions on monitors, has showed promising results. We hope that with further research in this direction, our approach would lead to even stronger results.

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**Appendix**

A Implicit/Automatic signal monitors:

Monitors can be divided into two categories according to the different implementations of conditional synchronization: explicit-signal monitors and implicit-signal monitors [3]. In explicit-signal monitors, condition variables are used along with `wait`, and `notify/notifyAll` statements for conditional synchronization between threads. Programmers need to associate assertions with condition variables manually. When a thread wants to execute a set of instructions under a critical section, it first checks some condition variable(s), and waits if the predicate is not true. Once a thread enters the waiting state, another thread on detecting that the conditional predicate has become true, explicitly notifies the waiting thread. The bounded-buffer implementation in Fig. 1(a) that uses Java’s reentrant locks is an explicit-signal monitor. In fact, almost all of the prevalent programming languages, including Java, use the explicit-signal design for monitors.

Implicit-signal monitors, also called automatic-signal monitors, require the underlying system to handle thread synchronization and wait/notification. Recently, Hung et al. [24] showed that implicit-signal monitors can be beneficial when implemented on modern multi-core processors. In an implicit-signal design, programmers need to use `waituntil` statements (line 9, 15 in automatic-signal program in Fig. 1(b)) instead of condition variables for synchronization. In this monitor design, a thread will wait as long as the condition of a `waituntil` statement is false, and execute the remaining instructions only after the condition becomes true. The responsibility of identifying a waiting thread to signal, and then signaling it, is that of the underlying system/framework rather than of the program logic explicitly put in the thread by a programmer. The details of design and implementations of such monitors is beyond the scope of this paper, and we refer the interested reader to [21, 23].
B Monitor Task Examples

Here, we highlight some key aspects of our framework’s handling of monitor tasks. First, note that the set of statements, $S$, of a task may be empty. Such a task serves as a barrier; and is legal in our framework. Second, the precondition can either be absent or appear later, and not as the first statement, in the monitor method. When a monitor method has no precondition, our framework creates a task with the precondition as tautology, indicating that the task can be executed at any time. If a monitor method does not start with a `waituntil` statement but has some such statement in between, then the precondition of the first derived task is a tautology. In Fig. 5, the method `bar()` has two corresponding tasks $T_1$ and $T_2$, where $T_1$ has the precondition as tautology and the set of statements $S_1$; $T_2$ has the precondition $P$ and the set of statements $S_2$.

Furthermore, monitor tasks are compositional in nature. Consider the method `foo()` in Fig. 5. If a method declares $n$ sets of preconditions and statements, then the framework would generate $n$ tasks such that each task $T_i$, $1 \leq i \leq n$, has a precondition $P_i$ and a corresponding set of statements $S_i$. Appendix B presents some detailed examples of these cases.

```c
void foo() {
    waituntil($P_1$);
    $S_1$;
    waituntil($P_2$);
    $S_2$;
    ...
    waituntil($P_n$);
    $S_n$;
}

void bar() {
    $S_1$;
    waituntil($P$);
    $S_2$;
}
```

Figure 5: Examples of methods leading to compositional tasks and tautology as precondition

C Lemma Proofs

C.1 Proof Sketch for Lemma 1

We show that for any execution in our model there exists an equivalent lock-based execution. Since all tasks of any monitor object are executed by a single thread due to Rule 1, mutual exclusion is preserved just as in any lock-based execution. We only need to show that the order of execution of the tasks corresponds to a schedule in which worker threads execute the tasks.

It is sufficient to show that all tasks submitted by a single worker thread execute in the order of submissions. Let $s$ and $t$ be two consecutive tasks submitted by a worker thread. If they are submitted for the same monitor, then the Rule 2 preserves the order. If $s$ is a blocking task, then by definition of blocking task, $t$ cannot be submitted before $s$ is completed. Hence, execution of $s$ precedes execution of $t$. If $s$ is a non-blocking task and is on a different monitor object from $t$, then due to Rule 3 we wait for $s$ to finish before submission of $t$.

C.2 Proof Sketch for Lemma 2

It is sufficient to show that for every thread history there exists an equivalent sequential thread history that is consistent with the execution by the monitor thread. We get this sequence by considering as linearization point for an operation the instant at which the monitor thread finishes executing the corresponding task. We show that this order is consistent with the thread order.
Let $s < t$ denote that operation (i.e., its corresponding task) $s$ was executed before $t$. First consider the case when $s < t$ because $s$ is a blocking operation. In this case, task $t$ cannot be submitted before task $s$ is executed. Hence, the order of execution of monitor tasks preserves the thread order. Second, consider the case when $s < t$ because they are operations on the same monitor object and $s$ is invoked before $t$. In this case Rule 2 guarantees that the order of execution is $s$ followed by $t$. Finally, consider the case when $s$ and $t$ are tasks submitted by the same thread, $s$ is non-blocking but its results are used by $t$. In this case, the execution would have to block for collecting the results of $s$ before executing any further. Hence $t$ would be submitted later than the execution of $s$.

D Implementation Details

The translation of the code written with our two proposed keywords to an equivalent Java code is performed by using a pre-processor. For our implementation, we use JavaCC [24] pre-processor. We convert all the monitor methods to equivalent tasks, and use a threadpool based executor service framework for monitor threads. Here, we first discuss the pre-processing steps.

D.1 Pre-processing

We briefly summarize the concepts applied for compiling the code, using the ActiveMonitor framework, in which the two proposed keywords are used.

First, our pre-processor identifies the waituntil statements that capture the preconditions of monitor tasks. Recall that the waituntil keyword is used for automatic signaling between threads, and the predicate provided as its argument forms the precondition for execution of monitor tasks. In the corresponding generated code (in Java) every predicate is created as an inner class with a method called isTrue(), which returns a boolean value as the result of the predicate evaluation. At runtime, our system invokes the isTrue() method to evaluate the predicate when deciding which task should be executed.

Next, the pre-processor creates a Callable [29] or Runnable [29] object that contains the set of statements for each task inside its call() or run() method. If the return value of the original monitor method is void, then we create a Runnable object; otherwise, we create a Callable object. Note that if a non-blocking monitor method has been divided into multiple tasks, the resulting tasks may have some shared variables. To handle these variables, our system creates a data object to store them and all the tasks can access them through this data object.

Finally, we replace the invocations of monitor methods by submitting monitor tasks to threadpool executor (Appendix D.2). The executor returns $f$, an instance of Java’s Future object [29], to the invoker thread when a task is submitted. If the task is blocking, then the thread needs to wait for the computation in $f$ to finish; this is done by evaluating $f$ within the task and returning the result. Otherwise, $f$ is registered with the threadpool executor for exception checking and handling.

In Section 3 we mentioned that our current implementation does not admit a particular family of methods for task based executions. Specifically, it does not admit recursive blocking calls, monitor methods in which conditional synchronization guards using automatic thread signaling (waituntil) are not initial statements of the program, or are present in conditional branches. This does not mean that programs requiring such method implementations are not allowed in our framework; just that at present we do not support task generation of such methods. A programmer can implement them using conventional Java syntax, and still use our framework for other methods.
D.1.1 Discussion: Thread Dependent Variables and Functions

In our current implementation, thread dependent variables and functions within a monitor method cannot be used directly in the Runnable or Callable object that is used in task generation by our approach. This is because the tasks are executed by the monitor thread and not by the worker thread. For example, suppose there is a monitor method that invokes Thread.currentThread(), if we directly add this statement to the generated Runnable object (in the task), then this method’s invocation at runtime will return the reference to the monitor thread when it is executed. However, it is obvious that the intent of this call inside the monitor method was to refer to the worker thread. To handle this situation, currently, we require the programmer to perform reference copy and storage and storage in thread-local variables. For read operations of thread dependent variables and functions, the worker thread would need to evaluate them outside the monitor, and store the result with final variables. These final variables can be accessed by the runnable and callable objects. An additional constraint/limitation applies for the case of write operation on thread dependent variables. For write operations, if the monitor method is non-blocking then the results can be stored as intermediate data. The worker thread then writes these results back to its local variable after the task is executed.

D.1.2 Discussion: Blocking recursive method

Our current pre-processing implementation does not support a blocking recursive method on monitors. This is because the number of the method invocations to be made at the runtime is non-deterministic. Thus, we cannot know how many tasks we need to create at pre-processing time. In addition, since the method is blocking, the monitor thread will get blocked when it recurs.

D.2 Limiting Monitor Threads using ThreadPools

A threadpool is a collection of threads to execute tasks that are units of computation. These threads are usually created together at the start-up, and remain in the pool to provide executor service. For task execution based programs, the use of a threadpool can significantly improve the runtime performance by having an already existing thread ready to execute the tasks as they arrive. Generally, tasks are stored in a collection, and free threads are responsible for finishing the unexecuted tasks. If there is no task that is eligible for execution, the threads in the pool wait for one to arrive. This approach is especially beneficial when the number of tasks is greater than the number of threads in a pool. Thus, the size of the threadpool is a crucial factor as the timing of creating or destroying a thread may have a significant impact on performance. Given that we spawn a new thread for a monitor object, programs with a large number of monitors could be adversely affected by having too many additional threads in the ActiveMonitor framework.

To keep the overhead of monitor threads relatively low, we control the number of monitor threads created by querying the operating system for available resources and managing the monitor threads dynamically. A component, called Monitor ThreadPool Executor, manages this process. This component instantiates monitor threads as threads of a threadpool at the start of the execution. The pre-processing phase collects the information about number of monitor objects in the program, and the threadpool executor uses this information for creating a threadpool balancing the resource consumption and performance benefit.

D.2.1 Exception Handling

For a non-blocking method invocation, after submitting its corresponding task to the executor, the invoker does not need to wait for the completion of the task. The task is executed in parallel by a thread of the monitor threadpool. Thus, if an exception occurs during its execution, the thread
that submitted it must be notified of this exception. The *ActiveMonitor* framework has an exception handler that keeps a log of every exception and provides different mechanisms for programmers to handle exceptions in the non-blocking method. The users may choose to ignore the exceptions or they can specify a maximum number of times a task may be considered for automatic re-tries. Furthermore, our system also provides a hook so that the programmer can write their custom exception handler.