

# Observationally Cooperative Multithreading\*

Christopher A. Stone    Melissa E. O’Neill    Sonja A. Bohr    Adam M. Cozzette  
M. Joe DeBlasio    Julia Matsieva    Stuart A. Pernsteiner    Ari D. Schumer

Harvey Mudd College

{stone,oneill,sbohr,acozzette,mdeblasio,jmatsieva,spernsteiner,aschumer}@cs.hmc.edu

## Abstract

Despite widespread interest in multicore computing, concurrency models in mainstream languages often lead to subtle, error-prone code.

*Observationally Cooperative Multithreading* (OCM) is a new approach to shared-memory parallelism. Programmers write code using the well-understood cooperative (i.e., non-preemptive) multithreading model for uniprocessors. OCM then allows threads to run in parallel, so long as results remain consistent with the cooperative model.

Programmers benefit because they can reason largely sequentially. Remaining interthread interactions are far less chaotic than in other models, permitting easier reasoning and debugging. Programmers can also defer the choice of concurrency-control mechanism (e.g., locks or transactions) until *after* they have written their programs, at which point they can compare concurrency-control strategies and choose the one that offers the best performance. Implementers and researchers also benefit from the agnostic nature of OCM—it provides a level of abstraction to investigate, compare, and combine a variety of interesting concurrency-control techniques.

**Categories and Subject Descriptors** D.1.3 [*Programming Techniques*]: Concurrent Programming—Parallel programming; D.3.2 [*Programming Languages*]: Language Classifications—Concurrent, distributed, and parallel languages

**General Terms** Languages, Performance

\* This material is based upon work supported by the National Science Foundation under Grant No. CCF-0917345. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

**Keywords** Observationally cooperative multithreading, cooperative multithreading, transactional memory, lock inference, parallel model, parallel debugging.

## 1. Introduction

Parallel programming is notoriously difficult; it is hard to predict all ways in which threads may interact [32]. Synchronization code to manage these interactions can be complex and error-prone. And when bugs inevitably arise, hard-to-reproduce race conditions make debugging even more difficult than in sequential code. Although there has been valuable progress in making parallel programming more accessible, the models for parallelism in widespread use today are still difficult for many programmers to use effectively [37].

Inspired by traditional Cooperative Multithreading (CM) for uniprocessors, where threads run one at a time and continue until they explicitly yield control, we propose a new model for parallel programming. *Observationally Cooperative Multithreading* (OCM) offers

- Simple semantics and syntax, taken from CM;
- Parallel execution, taking advantage of modern hardware;
- Implementation flexibility, allowing a variety of contention management methods (including transactional memory and lock inference);
- Serializability, simplifying debugging and reasoning.

OCM is not an implementation mechanism, but rather an abstraction for programmers. The observable behavior of programs is consistent with execution on a uniprocessor with cooperative multithreading, even if behind the scenes threads are running simultaneously or preempting one another.

Designed to emphasize correctness over raw performance, OCM may not be suitable for all multithreaded applications. But just as many systems use garbage collection and runtime bounds checking rather than manual memory management and unsafe array accesses, we feel that there is a place for systems like OCM that provide an easier and safer path into parallel programming. And, as with garbage collection and bounds checking, there is wide scope for interesting research and design work to mitigate runtime overhead in OCM systems.

[Copyright notice will appear here once 'preprint' option is removed.]

In this paper, we define OCM and examine some of the issues involved in implementing and using it in practice. In particular, we

- Introduce and define the core OCM model (Section 3);
- Share our experience in building several prototype implementations of the OCM model (Section 4);
- Demonstrate that different concurrency-control mechanisms can be compared by running the same algorithm on different OCM implementations (Section 5);
- Describe how the OCM model can enable simple, reproducible debugging of parallel programs (Section 6).

Readers should be aware that there are also some things that they will *not* find in this paper. In particular, because OCM is a new model for shared-memory parallelism, there is no preexisting storehouse of OCM programs, and thus no large benchmark suite to run (see Section 7). Our goal is not to show how *well* we have implemented OCM (although, anecdotally, we do think it does perform well), but to show there are awkward parallel programs that are more easily expressed in OCM, to demonstrate OCM’s potential, and perhaps encourage you to download an implementation and experiment, or implement OCM with your own concurrency-control mechanism.<sup>1</sup>

## 2. Background

Programmers working with mainstream languages already choose from a number of multithreading models. The choice matters because it can significantly affect whether programmers produce code free of race conditions and deadlock [37].

As a prelude to introducing our own model (in Section 3), we review the strengths and weaknesses of some well-known schemes for multithreading. We use the familiar example of two threads transferring funds within an array of bank accounts, either with each thread doing exactly one transfer,

```
// move $5          | // move $10
acct[x] = acct[x] - 5; | acct[i] = acct[i] - 10;
acct[y] = acct[y] + 5; | acct[j] = acct[j] + 10;
```

or with each thread looping to perform as many transfers as the relevant accounts permit:

```
while (acct[x] >= 5) { | while (acct[i] >= 10) {
  // move $5          | // move $10
  acct[x] = acct[x] - 5; | acct[i] = acct[i] - 10;
  acct[y] = acct[y] + 5; | acct[j] = acct[j] + 10;
}                       | }
```

We would like to ensure that money is neither created nor destroyed, and that the loops cannot cause accounts to become overdrawn.

<sup>1</sup> Downloads are available at [www.ocm-model.org](http://www.ocm-model.org).

## 2.1 Serial Computation with Cooperative Multithreading

Cooperative Multithreading (CM) is a well-known model for writing *uniprocessor* multithreaded programs. In the CM model, exactly one thread runs at a time, and control switches from one thread to another only when a thread either terminates or uses the provided `yield` statement. Programmers place `yield` statements at specific points in the code where it is safe to yield control—either to propagate changes to shared data between threads, or just to be a “good citizen” and let other threads execute.

Under CM, the two code examples above (nonlooping and looping) work perfectly well as written. Neither thread invokes `yield`, so in both cases first one thread will run to completion and then the other, with no interleaving of computations.

In the looping case, if `x` happened to be equal to `i`, one looping thread would transfer out most or all of the money, leaving little or nothing for the other thread to do. We can provide an opportunity for interleaved iterations by adding explicit `yield` statements:

```
while (acct[x] >= 5) { | while (acct[i] >= 10) {
  // move $5          | // move $10
  acct[x] = acct[x] - 5; | acct[i] = acct[i] - 10;
  acct[y] = acct[y] + 5; | acct[j] = acct[j] + 10;
  yield;               | yield;
}                       | }
```

Because the `yields` are at the end of the loops, individual iterations execute without interruption. In the first thread, for example, there is no possibility of `acct[x]` changing between the comparison and the assignments.

**Critique** There are certainly instances where relying on cooperation is inappropriate. Desktop operating systems such as Windows and MacOS formerly employed CM but have long since adopted preemptive scheduling, preventing one uncooperative process from hanging the entire system. But within a single program, a buggy thread failing to `yield` is no worse than an accidental infinite loop in sequential code.

As a programming model for multithreaded applications, CM has some very attractive properties. Most notably, the text of the program specifies exactly where threads may be interrupted. Although CM programs may be nondeterministic, the ways in which nondeterminism can arise are relatively restricted. Further, between `yields` we can reason about code purely sequentially: until a thread `yields`, it will never see the environment being changed by other threads, nor will its changes be visible to other threads.

The composability properties of CM are also quite strong. Two nonyielding operations invoked in sequence automatically form a larger nonyielding combination. Programmers can also programatically control whether code `yields` or not (e.g., having subroutines test a boolean flag to decide whether they should `yield`).

We are not the first to see the CM model as a generally desirable model for programmers [20, 44]. In recent years, it

has been suggested most often to combine the efficiency and simplicity advantages of sequential event-driven code with a more natural programming model [16, 45]. There is still debate about the relative overheads of events and cooperative threads, but there is no doubt that CM can provide an attractive and natural model for systems programming.

The obvious deficiency of CM as a model for multithreaded computation is that it executes only one thread at a time. Our goal for OCM, which we introduce in Section 3, is to retain the many advantages of CM but allow multicore implementations. Before turning to OCM, however, we contrast CM’s relative simplicity with some other common approaches to parallel shared-memory computation.

## 2.2 Parallel Computation with Explicit Locking

Parallel computation with explicit locking is one of the oldest parallel models [10], and is still widely seen today (Pthreads, Java threads, etc.). In this model, multiple threads may execute simultaneously and control may switch between them at unpredictable times. Locks and condition variables, monitors, semaphores, and other similar explicit mechanisms provide concurrency control for shared data. In this section, we will focus on locks.

In our banking examples, observe that money was transferred between accounts specified by variables ( $x, y, i, j$ ), whose values we may not know until runtime. One thread cannot assume that the other thread will not try to access or modify one of the same accounts. Therefore, code that works under CM has race conditions under the traditional preemptive model. Consider our nonlooping example with  $x$  and  $i$  referring to the same account—our hope is that a total of \$15 is removed from that account, but for some executions it might decrease by only \$5 or \$10 (e.g., if the second thread executes in its entirety between the first thread’s read of `acct[x]` and its write to `acct[x]`). To fix this issue, we can add locks to ensure that only one thread at a time can update a particular account. If we naïvely add locks, our example becomes:

<pre>lock(acct[x]); lock(acct[y]);   // move \$5   acct[x] = acct[x] - 5;   acct[y] = acct[y] + 5; unlock(acct[y]); unlock(acct[x]);</pre>	<pre>lock(acct[i]); lock(acct[j]);   // move \$10   acct[i] = acct[i] - 10;   acct[j] = acct[j] + 10; unlock(acct[j]); unlock(acct[i]);</pre>
--	---

But this code is incorrect, being prone to deadlock if  $x == j$  and  $y == i$ . There are well-known techniques to prevent such deadlocks (e.g., acquiring locks in a global total order); but doing so is not always simple. In this case, we cannot know whether to lock `acct[x]` or `acct[y]` first until we know the values of  $x$  and  $y$  at runtime; the problem becomes worse when there are more locks or the locks are not all acquired in one place.

**Critique** Explicit locking comes with an interesting trade-off. A coarse-grained locking scheme that holds a few locks

for a long time (in the limit, “one big lock for everything”) may operate correctly but offer mediocre performance. Finer-grained schemes where locks are held for as little time as possible may offer good performance but be harder to reason about.

Because holding locks limits concurrency, this model often tempts the programmer to write code with race conditions and then add as few locks as possible, held for the shortest time possible. This choice can easily lead to bugs, as it is difficult to mentally model all possible ways that complex lock-based code might execute.

For example, in the case of the looping account transfers, a programmer might acquire and release locks inside the loop (making each individual transfer atomic), and even ensure that locks are acquired in a good order, but not realize this strategy permits account contents to change between the loop test and the body of the loop (permitting overdrawn accounts). Correct lock-based code even for these simple loops requires great care.

Finally, lock-based code does not compose well. If `foo` and `bar` are each atomic because they acquire and release (possibly different) locks, there may be no obvious way to combine both into a single atomic sequence that acquires the correct locks in the correct order [22].

## 2.3 Parallel Computation with Atomic Blocks

An increasingly popular alternative to locks is the `atomic` block [31]. As the name suggests, `atomic` blocks guarantee that the enclosed code appears to execute atomically, even as multiple threads execute in parallel. We can easily express the nonlooping example as

<pre>atomic {   // move \$5   acct[x] = acct[x] - 5;   acct[y] = acct[y] + 5; }</pre>	<pre>atomic {   // move \$10   acct[i] = acct[i] - 10;   acct[j] = acct[j] + 10; }</pre>
---	--

**Critique** Atomic blocks are usually easier to use than explicit locks, as we do not have to worry about which locks to acquire or in what order, or which condition variable to wait on. With `atomic` blocks, there is nothing else to specify—the implementation infers all data dependencies.

Atomic blocks permit multiple underlying implementations. Two popular schemes are to infer and acquire the required locks or to use software transactional memory (discussed as a parallel model in its own right in Section 2.4).

Another advantage of `atomic` blocks over explicit locks is that `atomic` blocks are easy to compose. We can combine individually atomic actions `foo` and `bar` into an atomic sequence simply by placing them inside an `atomic` block. But this approach requires explicit action by the programmer, and one might easily forget that a sequence of atomic operations is not itself automatically atomic.

Further, just as programmers working with locks may feel pressured to hold locks for as short a time as possible,

programmers working with `atomic` blocks may feel pressured to keep their `atomic` sections short, keeping as much code as possible in the “unprotected” outside area, again increasing the chances that the programmer will introduce errors.

Finally, the `atomic`-block construct is not always as elegant in practice as it may first appear. Adapting the looping example to use `atomic` blocks, permitting interleaving but keeping the tests and assignments atomic, demonstrates how much less intuitive and straightforward this model can be:

```
bool loop1;
do {
  atomic {
    loop1 = acct[x] >= 5;
    if (loop1) {
      // move $5
      acct[x] = acct[x] - 5;
      acct[y] = acct[y] + 5;
    }
  }
} while (loop1);

bool loop2;
do {
  atomic {
    loop2 = acct[i] >= 10;
    if (loop2) {
      // move $10
      acct[i] = acct[i] - 10;
      acct[j] = acct[j] + 10;
    }
  }
} while (loop2);
```

## 2.4 Parallel Computation with Software Transactional Memory

Although software transactional memory (STM) may be used as an implementation technique for `atomic` blocks, it is often seen as a parallelism model in its own right, not necessarily tied to `atomic` blocks.

In this model, shared data is accessed inside *transactions* (analogous to database transactions). Once a transaction starts, reads and writes of shared data operate atomically with respect to other transactions (i.e., as if they are taking place in isolation). When a transaction ends, the STM system will attempt to *commit* the transaction, but such a commit may *fail* due to conflicting changes made by other concurrent transactions. In this case, it is *rolled back* (i.e., all its work is undone) and may be retried.

The STM model provides an extension to the concept of `atomic` blocks, but one in which the programmer is given more control over the (now mandatory) implementation mechanism. Atomic blocks may be provided under an STM model, equating the opening brace of an `atomic` block with `beginTransaction` and the closing brace with `endTransaction`. Users of STM libraries might also begin and end transactions directly; for example, implementing the looping code as:

```
beginTransaction();
while (acct[x] >= 5) {
  // move $5
  acct[x] = acct[x] - 5;
  acct[y] = acct[y] + 5;
  endTransaction();
  beginTransaction();
}
endTransaction();

beginTransaction();
while (acct[i] >= 10) {
  // move $10
  acct[i] = acct[i] - 10;
  acct[j] = acct[j] + 10;
  endTransaction();
  beginTransaction();
}
endTransaction();
```

**Critique** The STM model allows other constructs beyond `atomic` blocks. For example, Automatic Mutual Exclusion (see Section 8.1) provides `unprotected` blocks, in which the opening of the block corresponds to `endTransaction` and the end of the block to `beginTransaction`.

Programmers may further be allowed or encouraged to take advantage of other transaction-based facilities, such as the ability to explicitly `retry` (i.e., fail) transactions, or chain transactions together with an `orElse` construct that begins a second transaction only if the first decides to `retry`.

Encouraging programmers to construct their own novel and elaborate synchronization schemes using `retry` and `orElse` may also create composability issues. It is also unclear that such schemes are any easier to reason about than similarly elaborate uses of locks and condition variables [37].

As with explicit locks and `atomic` blocks, transactional schemes potentially allow code outside a transaction to access shared data without any concurrency control at all. In some schemes, there may be additional pressure to perform operations (such as I/O) outside of transactions because they cannot be rolled back. For instance, the following code could result in undesired behavior:

```
atomic {
  print("Hello World"); // Do some I/O
  retry;                // Undo that I/O
}
```

Therefore, an STM system might require that I/O take place outside of transactions.

Although transactions are a powerful mechanism, as a parallel model, they can, like locks and `atomic` blocks, lead to programs that are intricate, subtle, and hard to reason about.

## 2.5 Conclusions

The parallel models we have discussed can be difficult to use due to a number of factors. They all allow, encourage, or sometimes even require programs to have portions that run outside the provided concurrency-control mechanisms. They each have subtleties that may trip up unwary or inexperienced parallel programmers, and may encourage programmers to use the provided concurrency-control mechanisms in intricate or fragile ways. Rossbach et al. [37] found that undergraduate students in a systems class had more difficulty understanding the transactional concurrency model than they did the coarse-grained locking model, but those who used locks produced programs with significantly more errors.

“Conscious human thinking appears to us to be sequential, so that there is something appealing about software that can be considered in a sequential way” [40]. The CM model provides significant opportunities for sequential reasoning in an explicitly multithreaded program. It is, we argue, easier to reason about, has fewer subtleties, and allows *nothing* to run outside of the provided concurrency-control mechanism. Unfortunately, the concurrency-control mechanism it provides is harsh indeed—no parallelism at all, only serial interleaving

of threads at `yield` points. We desire a system that provides the benefits of CM *and* the parallelism of the other models.

### 3. Observationally Cooperative Multithreading

We therefore propose a model for parallel computation called Observationally Cooperative Multithreading (OCM). It adopts the simple semantics of cooperative multithreading (CM) discussed in Section 2.1. Unlike CM, the OCM model allows implementations that take advantage of multiprocessor parallelism when possible.

As with CM, under the OCM model the programmer simply specifies locations in their code where it is safe for a thread to yield control; the syntax for an OCM program is the same as for a CM program. For example, the previous banking example written for a CM system is also a correct example written in the style of OCM:

```
while (acct[x] >= 5) {           while (acct[i] >= 10) {
  // move $5                    // move $10
  acct[x] = acct[x] - 5;        acct[i] = acct[i] - 10;
  acct[y] = acct[y] + 5;        acct[j] = acct[j] + 10;
  yield;                        yield;
}                                }
```

But unlike CM, OCM is a model for *parallel* computation. A system implementing the OCM model is free to run programs in parallel, provided that the observable behavior (final results, I/O, etc.) of a program is consistent with a possible execution under some (nonpreemptive, uniprocessor) CM model. We call this requirement *CM serializability*, and it is the fundamental property of OCM.

For the above code, the two loops can execute simultaneously if `x` and `y` are disjoint from `i` and `j`, or be serialized otherwise; either way produces results consistent with CM.

CM serializability also means that the semantics of OCM is by definition that of CM; we can immediately reuse existing formalizations of CM semantics [1], and hence omit formal semantics here.

#### 3.1 A Parallel Perspective on the OCM Model

From a parallel-execution perspective, code between any two dynamically successive `yield` statements executes atomically in OCM. Threads behave as if completely isolated from each other except at `yield` points. Thus, `yield` statements should be placed where a thread needs to publish its changes to the surrounding environment and/or to observe other threads' changes to that environment.

The details of how an OCM system runs code in parallel while retaining CM serializability (and the concurrency-control mechanisms it uses to do so) are implementation decisions, visible to users only insofar as they affect performance. Like `atomic` blocks, OCM may be implemented using a variety of concurrency-control schemes, which can range from basic to elaborate. We examine these options in detail in Section 4.

#### 3.2 Advantages of the OCM Model

OCM offers programmers the same advantages as CM, particularly the ability to reason about parallel threads in serial chunks punctuated by `yield` statements. Yet it also avoids CM's main disadvantage: support for only uniprocessor execution. In addition, OCM benefits from being agnostic about the underlying mechanism.

This agnosticism means, first of all, that a programmer using the OCM model can avoid making a premature commitment to any particular concurrency-control scheme. This flexibility can be particularly useful if a programmer is not sure beforehand whether their application will work best with optimistic concurrency control (e.g., STM) or pessimistic concurrency-control (e.g., locks). If a program is written in OCM, it can be easily ported to OCM systems that provide the same interface but very different underlying implementations. Thus a programmer can test out which mechanism suits the application best. The same program written with explicit locks or transactions would make this comparison much more difficult.

Also, external code written outside the OCM model can generally be used in conjunction with an OCM program, so long as the OCM system treats it conservatively, which means treating external code as possibly `yielding` and/or having appropriate conflicts. For example, we can handle unbuffered I/O operations by going to either extreme: reduce parallelism by serializing I/O access to "the world" (i.e., if another thread is doing I/O, we must wait for it to yield before we can do I/O), or maximize parallelism by treating all I/O as `yielding` before and after. In the latter case, the proviso "`fscanf` will `yield`" can be compared to a typical STM restriction that "calls to `fscanf` may not appear in an atomic block."

#### 3.3 Beyond yield

OCM is consistent with many traditional concurrency primitives, including mutexes, condition variables, and barriers as in the GNU Pth library for CM [13]. If we worry that relying solely on shared-memory concurrency might not scale well to huge numbers of processors, then an OCM implementation can provide channels and primitives for threads to do synchronous or asynchronous message-passing.

One approach is to implement these primitives directly using `yield` and shared data. For example,

```
do
  yield;
while (!p)
```

begins a conditional critical region [21, 26]; any following code executes atomically with the test `p`, once `p` is true.

This idiom is very powerful, and all our prototype OCM implementations provide `yieldUntil(p)` as a built-in operator. We can use it, for example, to implement a simple barrier:

```

void barrier() {
    ++count;
    yieldUntil ( count == NUM_THREADS );
}

```

The OCM code for a more robust and reusable barrier is a little longer, but easily achievable.

A large number of interesting kinds of coordination and synchronization mechanisms can be explained in terms of `yield`. Although we can implement them in this fashion, OCM implementors also have the option of writing more sophisticated and efficient native implementations. Programmers using OCM can largely ignore the difference; it would remain valid to imagine a thread at a barrier repeatedly `yields` until everyone arrives. An STM-based implementation, however, might implement `yieldUntil` as

```

endTransaction();
beginTransaction();
while (!p) retry;

```

because a sophisticated STM might record the shared variables used to evaluate the predicate  $p$  and, if  $p$  is side-effect free, delay `retrying` the transaction until one of those variables has changed [22].

### 3.4 Trade-Offs of the OCM Model

CM serializability imposes a “concurrency control everywhere and always” requirement that may impact performance for some programs. However, this trade-off is deliberate and, we believe, potentially worthwhile if it can improve simplicity and correctness.

In addition, by providing an abstraction that hides the details of the underlying concurrency-control mechanism, OCM makes invisible any unique features that would violate CM serializability. Anything not easily realizable under CM (such as rolling back execution to an earlier point) will not be exposed. Thus, even if the underlying implementation of OCM is transactional, features such as `retry` or `orElse` are hidden. This simplification may limit the level of control the programmer has over their program’s execution, but OCM implementations (and support libraries) may use these features behind the scenes to provide efficient of CM-compatible concurrency primitives.

Finally, like CM, STM, `atomic` blocks, and explicit locking, OCM does not guarantee determinism or the absence of race conditions; multithreaded code remains harder than unthreaded code.

### 3.5 Fairness and Uncooperative Threads

Most implementations of CM provide a `yield`-fairness guarantee: any thread that is suspended because it invokes `yield` will eventually be allowed to resume. This fairness guarantee holds only in the absence of *uncooperative* threads, threads that neither `yield` nor terminate. When an uncooperative thread exists, it either will be scheduled to run (in which case it will monopolize the CPU forever, unfairly halting all other

threads), or the uncooperative thread itself is being unfairly avoided.

In this paper, when referring to CM, we implicitly assume `yield` fairness in the absence of uncooperative threads. (It would be difficult to program under the assumption that an unfair scheduler might arbitrarily refuse to resume a particular thread.) An uncooperative thread in a CM program are almost certainly a programmer error, so permitting unfairness in this case seems reasonable. Unlike some languages where programmer errors mean that all bets are off (“undefined behavior”), there remains a well-defined semantics for programs with uncooperative threads, though with restricted possibilities for interleaving. CM serializability thus requires that in the absence of uncooperative threads, all `yielding` OCM threads will eventually resume.

In a CM system, if an uncooperative thread does exist and begins (observably) executing, it will prevent all other threads from executing. This situation could occur in an OCM implementation as well. But if the uncooperative thread has no observable effects (i.e., no I/O, no shared-data changes, etc.) it is possible that OCM could run it forever on one processor while other processors execute the remaining threads. As `yield` fairness is not guaranteed in the presence of uncooperative threads, we still remain consistent with a CM implementation; specifically, one that is unfair to the uncooperative thread.

## 4. Implementations

Because OCM is implementation agnostic, a variety of techniques can be used to develop a valid OCM system. We have developed several different implementations, which are all available for download at <http://ocm-model.org/>. In creating these implementations, we show that a variety of implementation strategies for OCM are feasible. Doing so also allows us to compare the tradeoffs of these different implementation strategies. In this section, we discuss some of the salient issues that arise from implementing OCM; in Section 5 we will see how these implementations compare in practice.

### 4.1 Naïve Implementations

Possibly the simplest implementation of the OCM model is traditional uniprocessor CM. Although CM does not exploit multiple cores, it has value as a baseline implementation. We would hope that an OCM implementation that exploits multiple cores would quickly outperform CM. But sometimes CM may actually be the best OCM implementation to use (e.g., for programs with massive thread contention, or on a uniprocessor machine).

Naïve parallel implementations are also possible. One such scheme is to use a preemptive implementation with a single global lock to protect all shared data. In this case, `yield` could be implemented as `releaseGlobalLock` followed by `acquireGlobalLock`. Like CM, only one thread would run

at a time, but different threads might execute on different cores.

Interestingly, however, the global-lock scheme can be optimized by delaying `acquireGlobalLock` until shared data is about to be accessed for the first time since `yield`. Likewise, if the system can determine that a `yield` is imminent and that no more accesses to shared data will occur before the next `yield` is reached, it can perform the `releaseGlobalLock` action ahead of the actual `yield`. We call these two lock optimizations *lazy acquire* and *eager release*. Both optimizations preserve CM serializability, yet allow thread executions to overlap in parallel.

Lazy acquire is fairly trivial to implement, but eager release seems to require static analysis. To avoid or enhance static analysis, an OCM system can allow the programmer to make assertions about the behavior of their code. Thus, a programmer may assert that the thread will yield within a specific amount of time and that the program will not use any more shared data until that `yield`. Both assertions can be checked and enforced at run time, and in a global-lock OCM implementation, they may provide enough information for the system to release the lock early.

Using a single global lock is hardly cutting-edge concurrency control, but, like CM, it provides a baseline against which more sophisticated concurrency-control schemes may be compared. Furthermore, it successfully provides some parallelism at low implementation cost.

## 4.2 Nontrivial Lock-Based Implementations

The OCM model can be implemented with far more sophisticated lock-based implementations than one global lock. Much of the work on lock inference for atomic blocks is directly applicable to the problem of executing OCM threads (see Section 8.2). In contrast, in this section we outline a simple scheme based on per-object locks to show that this approach is feasible as an OCM implementation.

As before, the OCM source program does not refer to locks. But if the thread is accessing a shared data, the OCM system must (on the thread's behalf) acquire the proper locks before the thread's access occurs, and release them at the following `yield`. This use of locks guarantees that one thread can never modify an object that is in use by another thread, so a running thread will never observe outside changes to a shared variable between two `yield` statements.

As with most situations that use mutual-exclusion locks, a lock-based OCM implementation must have some mechanism to handle or prevent deadlock. One solution is to impose a global total order for acquiring the locks, although doing so requires that the OCM system know in advance which variables a thread might use between each pair of `yield` statements. Conservative predictions can be obtained via static analysis, augmented by runtime state information.

Like our earlier naïve global-lock-based implementation, our system can make use of programmer-specified assertions to optimize its behavior. For example, if the programmer

asserts that a section of the program will access only a specific range of indices in a shared array, the OCM implementation might choose to use fine-grained locking to allow threads that require access to other parts of the same array to run concurrently. In addition, such assertions can be checked at runtime to detect errors in the program. Similarly, any lock-based scheme can exercise lazy lock acquisition and eager lock release. The only added caveat is that all locks needed between yields must be acquired before any may be released, two-phase locking [14].

### 4.2.1 Dynamic-Language Implementation

We have developed a proof-of-concept lock-based OCM implementation as an extension to the Lua scripting language [27]. This extension is a dynamic library loaded by the Lua interpreter, so it cannot perform static analysis to obtain the information needed for correct locking.

Access to shared data is therefore mediated solely through “proxy objects” obtained through the OCM library—threads are otherwise completely separate. Because the system knows that a thread can only access shared data through proxies, and the system knows which threads are holding which proxies, the OCM scheduler can acquire all necessary locks for a thread before it can run.

The above approach is conservative; just because a thread has expressed interest in a shared value by acquiring its proxy doesn't mean that the thread will necessarily access it before the next `yield`. Lazy acquire can be implemented by waiting to acquire locks until the appropriate proxy is accessed (subject to lock-ordering constraints). Eager release needs the program to tell the system about proxies that will not be accessed before the next `yield`, using informational function calls (much like `assert` is used in C and C++). Run-time checks ensure that these assertions are accurate.

I/O performed by threads must either be to separate files, or also mediated through the OCM library.

This implementation shows that it is workable to create a relatively light-weight OCM extension to an existing language without making significant changes to the language core. But there is a trade-off: this OCM implementation is more syntactically awkward than some of the others we will describe, because declaring and accessing shared data requires function calls. Runtime confirmation of the programmer's assertions imposes further overhead.

### 4.2.2 Compiled-Language Implementation

We have also implemented lock-based OCM in the form of a source-to-source translator for a simple C-like language, a restricted form of C/C++ with the addition of `yield` and `spawn` statements. The translator analyzes the original source code to conservatively determine which variables may be accessed in the future following each `yield` statement—those are the variables that `yield` needs to lock. This information is then used to insert calls to locking and unlocking functions using Pthreads in the necessary locations. Any `spawn` or

`yield` statements are also replaced with calls to library functions. The translator has options to enable lazy locking as well as simple static analysis for eager unlocking.

There is already much work on static analysis to automatically perform *lock inference* for atomic blocks [6, 12, 23, 29, 35], but analyzing a program that `yields` is not quite the same as analyzing one with more traditional atomic blocks. First, atomic blocks have a statically scoped endpoint, whereas the location of the next `yield` may be dynamically determined. Second, atomic blocks have code outside of the atomic block, whereas there is no equivalent code in OCM. Thus, while our proof-of-concept is no doubt far less sophisticated than existing lock-inference schemes, there is value in showing that it can be done for the OCM model.

### 4.3 STM-based Implementations

The OCM model also permits implementations based on software transactional memory. In such an implementation, all reads and writes of shared data are routed through an STM system. Each `yield` statement ends the current transaction and begins a new one, so that changes made by the current thread become visible to others.

Most STM libraries are designed for use with transactions that begin and end in the same lexical scope, so they require modification for use in OCM implementations. For example, OCM may require that a transaction begin in one function and end in another, as shown in the following example:

```
void subroutine() {
    yield;
    :
}

void caller() {
    subroutine();
    :
    yield;
}
```

If the transaction ending at the `yield` at the end of `caller` cannot commit, it must roll back to the `yield` inside `subroutine`, which has since returned and been removed from the stack. Thus, the STM system needs to be able to “unreturn” from functions when a transaction aborts and retries. Unreturning is not conceptually difficult; it simply requires some state saving so that the stack can be restored if a transaction fails [41].

Using STM as an implementation technique also presents problems with I/O and other operations with side effects, which cannot be reversed if a transaction needs to be rolled back. One method commonly used in STM systems is to require that a thread wishing to perform I/O obtains a special lock which guarantees that its transaction always succeeds. Another possibility is to have the OCM system buffer output until a transaction completes successfully and print it before starting the next transaction. This technique is effective, but

it cannot be applied to input. A final method is to force an implicit `yield` before and after I/O operations. This option allows the I/O to be done without rollback.

As we noted in Section 2.4, it is unclear what an STM implementation should do in the event of nested transactions. STM-based OCM implementations avoid this problem because every statement takes place in exactly one transaction.

#### 4.3.1 Dynamic-Language Implementation

As when investigating lock-based implementations, we began with a proof-of-concept modification to Lua. In this case, we implemented the OCM system by requiring the Lua interpreter to use the TinySTM [15] library when accessing global variables. We also modified it to support Pthreads and “unreturning” from Lua functions by tracking changes to the interpreter stack so that they can be rolled back if needed.

Our implementation experience here reveals that it is possible to adapt an existing scripting language to mediate all of its data accesses through an STM system, although the changes required can be quite invasive. But the effort comes with a positive pay-off—to language users, access to shared data is simple and natural.

#### 4.3.2 Compiled-Language Implementation

We have also created an STM-based OCM implementation as a C++ library using Pthreads. This library allows the programmer to indicate that certain global variables are shared, which causes all accesses to those variables to be routed through either the TL2 or TinySTM systems. Our library includes implementations of `yield` and `spawn`, and supports “unreturning” from functions by transparently saving portions of the stack.

Our library approach requires no changes to the underlying language, relying instead on C++ language features (overloading, templates, etc.) to make access to shared data feel natural. As with our dynamic-language OCM system, most of the hard work for concurrency control is done by the STM system, but unlike that system, much of the implementation work is mere shimming. In principle, a transactional approach could also benefit from statically derived information about program behavior, but like more traditional STM systems, our implementation does not perform any static analysis.

Extending an STM library is a quick way to implement a parallel OCM system, can provide one that is highly usable in practice (certainly no more difficult than using an STM library directly), and allows complex programs to be expressed naturally and run in parallel.

### 4.4 Other Implementation Techniques

The only requirement OCM places on its implementation is that it conform to CM serializability. In Sections 4.2 and 4.3, we examined lock-based and STM-based schemes, but other schemes are possible. An OCM system could, for example, use a hybrid of locks and transactions, defaulting to STM-based concurrency control while having the option to fall back on a

```

philosopher(int i):
  for iter in (1..ITERS):
    think();
    yield;

    eat(fork[i], fork[(i+1) % N])
    yield;

```

(a) Philosophers never observe each other holding forks.

```

philosopher(int i):
  for iter in (1..ITERS):
    think();
    yieldUntil (isFree[i] && isFree[(i+1) % N]);

    isFree[i]          = false;    // take left fork
    isFree[(i+1) % N] = false;    // take right fork
    yield;
    eat();
    yield;
    isFree[i]          = true;     // put down forks
    isFree[(i+1) % N] = true;
    yield;

```

(b) Philosophers can observe each other holding forks.

**Figure 1.** Solutions to the Dining Philosophers Problem

lock-based implementation or even CM in the case of high contention for shared data.

Because an OCM implementation can combine statically and dynamically gathered information, possibly augmented with programmer assertions about the behavior of their code, other interesting concurrency-control options may be possible. For example, lock-free techniques such as atomic processor instructions or sequential locking could be used to improve performance. Consider a program that contains a shared variable counter that is always used to initialize a local variable as follows:

```

yield;
int timestamp = ++counter;
yield;

```

In this case, it may be safe to avoid protecting counter with locks or transactions and use a processor instruction for atomic increment.

## 5. Comparing Implementation Strategies

In the previous section, we showed that the OCM model is implementable; in this section, we show that it is possible to compare different concurrency-control techniques underlying the same OCM program.

We therefore turn to that classic problem in concurrency, *dining philosophers*<sup>2</sup> [9, 10]. First suggested in 1965, the problem is still studied to this day [7, 11]. In the problem,  $N$  philosophers are arranged around a table, alternating between *thinking* and *eating*. Eating is complicated, as each philosopher requires two utensils to eat (e.g., forks or chopsticks), but each utensil must be shared by two neighboring philosophers. A solution to the problem should avoid deadlock, livelock, and other forms of starvation.

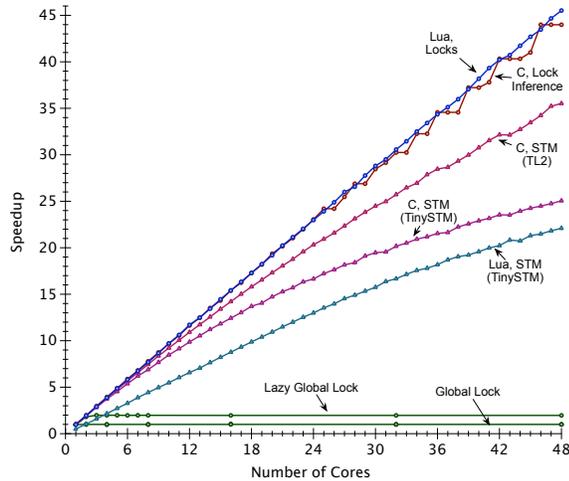
<sup>2</sup>Tanenbaum [43] writes that “everyone inventing a new synchronization primitive has tried to demonstrate how wonderful the new primitive is by showing how elegantly it solves the dining philosophers problem,” making our choice almost *de rigueur*.

Although dining philosophers might seem overfamiliar, it is an easy-to-understand problem whose solutions are often intricate, and one where some widely seen and taught solutions have unexpected subtleties. Gingras [18] observes that Tanenbaum’s semaphore-based solution [43] is not strictly starvation-free, but the behavior of Gingras’s starvation-avoiding solution is also somewhat nonobvious [46]. Despite its apparent simplicity, the problem provides interesting insight into both the OCM model and its implementations.

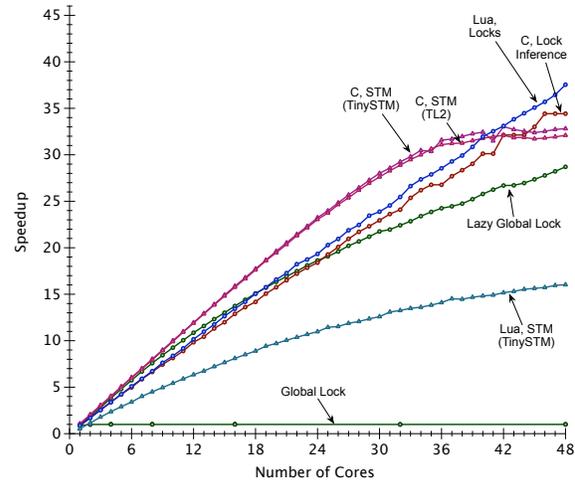
For our tests, we used two OCM-based solutions to the problem. Figure 1(a) shows an almost trivial solution. In a CM implementation, only one philosopher would ever eat at a time, with no interference between neighbors; CM serializability guarantees an indistinguishable result under OCM. In this solution, the philosophers are literally oblivious to each other: while philosophers are using their forks, they do not `yield`, so at every `yield` point all philosophers see all forks on the table. It is up to the OCM system to find and exploit parallelism, and ensure (because of `yield`-fairness) that every philosopher makes progress without any philosophers starving. The code itself is also interesting because it is virtually identical to code that is usually presented as an unworkable race-prone solution attempt [43]; the only difference is the added `yields` and the requirement that it run under the OCM model.

Figure 1(b) shows a more involved solution where philosophers can see their neighbors holding forks, and hence must explicitly wait for their own forks to become available. (Eating itself remains a private affair). The added `yields` give the OCM implementations more latitude for thread interleaving.

This second solution is constructed to be parallel to the first, but is actually prone to the same issue as Tanenbaum’s semaphore based solution [18, 46]—a thread can be starved if its neighbors happen to alternate their eating in a way that always overlaps. We might argue that the simplicity of our code makes the flaw easier to notice, but also note that the perpetual pathological interleaving necessary to starve a philosopher is unlikely in practice. There are a variety of ways to ensure there is no chance of starvation (specifically, avoid situations



(a) Algorithm from Figure 1(a), speedup relative to CM.



(b) Algorithm from Figure 1(b), speedup relative to CM.

**Figure 2.** Performance of Our Dining Philosophers Example.

where we eat again while our neighbor is hungry), but the simplest solution is to use the code in Figure 1(a).

To allow the problem to scale as we add processor cores, our tests use 199 philosophers rather than the more typical five. In addition, our timings are for 1000 iterations (per philosopher)—a reduction from the usual infinite number of iterations.

Figure 2 shows the results of running the two algorithm variants on a 48-core machine.<sup>3</sup> All versions use the same delay loops to simulate eating and thinking, calibrated to take about  $1 \text{ ms} \pm 20\%$  pseudorandom variation, chosen as a point where contention effects start to become visible enough to make the graphs “interesting.”

We show speedup graphs for each algorithm, where speedup is measured compared to a corresponding pure CM implementation—for our Lua-based code, it is an implementation using Lua’s coroutine facility, and for our C-code implementations, the CM system is a thin wrapper around GNU Pth [13].

In Figure 2(a), we see that both STM and lock-inference schemes are finding the potential parallelism in this problem. The performance of our lock-based OCM implementations is nearly identical to that of well-known solutions [18, 43] (not shown on the graph). Interestingly, as we scale to multiple processors there is little difference between C and Lua lock implementations. Our C-code transactional implementation can use either TL2 [8] or TinySTM [15] as its STM back-end; for this program, TL2 seems to perform better with the rather long transactions that arise from this algorithm. Our STM-based Lua implementation is slower, presumably because considerably more state is tracked in transactions for the

<sup>3</sup> Specifically, a SuperMicro H8QGi+-F-based system, with four Opteron 6168 processors running at 1.9 GHz, and 64 GB of RAM running Linux (Ubuntu 10.04). Each processor MCM has two dies, each with six cores. (The effects of the six-core boundaries are visible in some of the graphs.)

interpreter than for C. Finally, as you might expect, the naïve implementations offer little speedup, but interestingly, both do run faster than their CM counterparts on a multiprocessor—the global lazy lock offers a  $1.8\times$  speedup on two cores, and about  $2\times$  on more than two cores (staying essentially flat beyond three cores).

In Figure 2(b), we see the performance for the second variant of the problem. The lock-based implementations again perform well, but are outperformed by both variants of our C-based STM implementation (whose performance is so similar that we only show one line on the graph) until we reach about 38 cores; beyond that point, STM performance does not scale as well. The loss of scalability is largely due to our use of a simple implementation of `yieldUntil`—variants that use `retry` (not shown on the graph) scale much better, but don’t perform as well in absolute time.

The global-lazy-lock implementation also does well in this case. This good performance is largely due to the contrived nature of the task—because the code already explicitly does its own fork arbitration, `eat()` does not actually *use* the forks in any way, and thus no shared data accesses occur during `eat()`, which in turn means that the global lock is never acquired during `eat()`. Nevertheless, this version does show that sometimes naïve solutions perform well; for programs that do most of their computation independently and occasionally coordinate, the global-lazy-lock approach can work surprisingly well.

Readers should not suppose that this one simple program by itself reveals anything particularly noteworthy about the relative strengths of lock-based and transactional implementations, but what we have shown is that we can compare their performance running essentially *the same program*. The comparison in this case reveals what we might expect: which scheme wins out depends on a variety of factors, including the number of cores and the structure of the program. What is

tantalizing about OCM is the potential it provides to adaptively choose the concurrency control scheme that works best; for example, for the second algorithm, we might choose a transactional approach for smaller numbers of cores and switch to locks for very large numbers of cores.

A secondary, largely anecdotal, result we can infer from our measured performance is that there exist programs for which our OCM implementations scale well. Although we do not devote space to it here (creating a full-blown benchmark-suite for OCM is a paper in itself), our results thus far with regard to scalability seem encouraging.

Readers interested in examining a slightly more realistic program written using OCM can consult the appendix to this paper.

## 6. Debugging and Performance Profiling

Although OCM dramatically reduces the potential for race conditions and deadlock compared to, say, explicit locking, it does not eliminate them. The following code uses shared variables `a` and `b` to (atypically) simulate explicit locks in a way that could lead to deadlock, assuming both `a` and `b` are initially 0:

```
yieldUntil (a == 0);   |   yieldUntil (b == 0);
a = 1;                 |   b = 1;
yieldUntil (b == 0);   |   yieldUntil (a == 0);
b = 1;                 |   a = 1;
```

It is possible to write buggy multithreaded code in the OCM model (`yield` fairness does not guarantee that other operations like `yieldUntil` will succeed); debugging and repeatability for parallel programs is a longstanding problem [4, 36, 47].

Fortunately, reproducing bugs is far easier in OCM than in many other models due to reduced opportunities for race conditions. Further, in OCM every execution of a program has at least one corresponding execution under CM. If an OCM system wishes to allow reproducible debugging, it simply has to record a corresponding serial execution for that program. With that *serialization trace*, it is possible to rerun the program serially following that trace and thereby reproduce the exact sequence of interleavings that trigger the bug. We have implemented a proof of concept in our C++ STM-based OCM implementation (described in Section 4.3.2).

For the code above, a human-readable example trace of a failed execution might read as follows:

```
A->B (at A's 'yieldUntil (a == 0);')
B->A (at B's 'yieldUntil (b == 0);')
A->B (at A's 'yieldUntil (b == 0);')
B->A (at B's 'yieldUntil (a == 0);')
... deadlock ...
```

From this trace it is fairly straightforward for programmers to work out what has gone wrong, or for them to simply rerun a failed execution to better understand what happened.

OCM implementations may run threads in parallel, so how can they record a serial execution order that corresponds to their parallel execution? One scheme is to use a global

timestamp service and have each thread record timestamps to create a trace. In the case of a lock-based implementation, the timestamp should be recorded after all locks have been acquired and before any lock has been released. In the case of a transactional implementation, the timestamp should be read during the transaction, and recorded when the transaction is successfully committed.

In fact, no system-level support is necessary. We can achieve tracing just by adding one line of code after every `yield` to record the trace in a large shared array using a shared index

```
yield;
trace[index++] = (thread_id, context_info);
```

but for some OCM implementations, adding this extra code may restrict observable execution orders. For this reason, a low-overhead system-level implementation is preferable.

Recording thread-serialization traces has more potential uses than just supporting debugging. For example, knowing how often one thread runs compared to others can also reveal and explain performance issues with the code, such as when the underlying concurrency-control system fails to achieve the desired level of concurrency.

## 7. Conclusions and Future Work

OCM is a promising solution for shared-memory program development. It retains many of the benefits of currently existing concurrency-control systems, while mitigating the complexity of using these systems. It allows the programmer to concentrate more on the logic of the program and less on the subtle mechanics of concurrency control.

As we have demonstrated with our lock-based and STM-based systems, the OCM model can be implemented with various underlying concurrency-control systems. In this way, an application can be written according to the OCM model and use whichever implementation is best suited for it. It may even be worthwhile to refactor existing multithreaded programs to use OCM in order to make future development or debugging easier.

We would like to see OCM broadly adopted. As we have shown, it is often straightforward to use OCM as a front end for a variety of concurrency-control mechanisms, and so we hope that others will follow our lead and show how their concurrency-control schemes can be used to execute programs written for OCM. We also hope that educators see the value in using OCM as a “kinder gentler” form of multicore parallelism, even if they later introduce other, more challenging, models such as explicit locks or transactions. In fact, OCM can be a springboard for exploring these other techniques; synchronization primitives are easy to write in OCM (e.g., `semWait(i)` is `yieldUntil(i > 0); --i`, and `semSignal(i)` is `++i`), and discussions of efficient OCM implementations naturally lead to topics like transactions. We hope that our available implementations and further examples of OCM in use (which include solutions to a number of other

classic and not-so-classic problems [11]) will provide a good starting point for these efforts.

We are continuing our OCM implementation work, and we plan to take even better advantage of modern research into concurrency control (see Section 8.2). We have, of course, already run somewhat larger examples than dining philosophers (with promising results), but there is still much to learn about scaling efficiently OCM to large systems, including which language extensions and debugging and profiling tools prove most valuable.

In addition, OCM needs a suite of benchmark programs that can be used to assess the performance of different concurrency control techniques and of the OCM approach as a whole. Unfortunately, existing benchmark suites are targeted at prior schemes for parallelism, and although it is possible to recreate other schemes within OCM (e.g., by rolling your own semaphores, locks, or condition variables), doing so misses the OCM’s point of allowing simpler solutions. Thus, new benchmarks must be created from scratch.

## 8. Related Work

As a parallel model, OCM intersects with a significant portion of prior work on parallelism and concurrency. There is a vast literature describing parallel models, concurrency-control mechanisms, debugging techniques, and so forth that could be compared to OCM, but we cannot hope to do them all justice here. Thus, we must restrict our discussion to those techniques that we feel are of most interest because they parallel, influence, or counterpoint OCM in a particularly significant way.

### 8.1 Other Models of Concurrency

There are, of course, many other models for parallel programming besides those discussed in Section 2, including monitors [24] and Java `synchronized` methods [19], communicating sequential processes [25], Threading Building Blocks [34], and OpenMP [33], to name just a few. We cannot compare each in detail here, but to the extent that they provide particular scheduling policies or ways to create new threads (e.g., `parallel for` loops), they may be transferrable to an OCM context. However, three further models deserve specific comparison with OCM.

**Automatic Mutual Exclusion** AME [2, 28] is a variant of software transactional memory. Rather than starting with unsynchronized code and marking particular blocks as `atomic`, AME makes the safer assumption that all code should be executed atomically unless specifically marked `unprotected`. Consequently, atomic code is dynamically delimited by the execution of `unprotected` blocks. An AME system could easily be used to implement OCM (`yield` corresponds to an empty `unprotected` block [2]), and AME has already engendered work on the denotational semantics of uniprocessor cooperative multithreading [1].

While we have found the AME work inspiring, there are two ways in which OCM intentionally differs from AME. Both follow naturally from CM serializability, but the differences make OCM both simpler and safer.

First, AME exposes the underlying STM implementation. Its `blockUntil` operator permits users to roll back and retry in the middle of an atomic transaction, allowing code that is impossible without run-time tracking and undoing side-effects. In contrast, OCM has multiple implementations, including lock-based schemes that are more efficient for some programs.

Second, OCM has no escape hatch for “lower-level” memory operations outside of OCM’s concurrency-control system. Non-empty `unprotected` blocks can improve performance, but they can also be a source of bugs and semantic surprises [39].

**Transactions with Isolation and Concurrency** Compared with traditional STM systems, the main feature of TIC [41] is its ability to “punctuate” atomic transactions.

The `Wait(p)` statement checks whether  $p$  is true; if not, it commits the current transaction, and waits for  $p$  to become true before continuing in a new transaction. Transactions can begin and end in different functions; like STM-based OCM (and like AME), TIC implementations must capture enough of a run-time continuation to undo function-returns.

A motivating example for TIC is a transaction that waits on a barrier; although the number of waiting threads should be incremented before we wait for remaining threads to arrive, inside a transaction this increment would not be visible to any other thread until the transaction ends (after the barrier). The TIC solution is to increment the count and `Wait`; since `Wait(p)` corresponds exactly to `while (!p) yield`; in OCM, OCM provides similar functionality.

TIC has other features not in OCM. It does static checking to ensure that calls to methods that might `Wait` are marked as such. (A similar approach might be desirable for OCM methods that might `yield`.) TIC also lets a program check at run time whether these calls actually `Wait`, and take corrective action if necessary. TIC is otherwise based on `atomic` blocks, and its treatment of nested transactions is slightly subtle. OCM has `yield` but not `atomic`, and has no possibility of nesting.

**Cilk** Cilk [5, 17] is a parallel extension of C. Although Cilk largely relies on the programmer to prevent interference between threads, it is interesting to compare Cilk’s *serial elision* property with CM serializability.

Serial elision guarantees that Cilk keywords can be omitted—replacing spawned function calls with ordinary function calls, and removing all `sync` barriers—to obtain a legal C program with the same semantics as the Cilk version running on one processor. The Cilk version running on a multiprocessor may produce additional behaviors (due to race conditions and other nondeterminism).

The CM serializability guarantee goes in the opposite direction: the behaviors of OCM running on a multiprocessor

cannot exceed the behaviors possible in theory from a uniprocessor CM implementation.

## 8.2 Methods for Reducing OCM Overhead

There are many ways to implement OCM. For example, OCM can use a pessimistic lock-based approach. *Lock Inference* is a method for the system to infer the correct locking actions automatically [6, 12, 23, 29, 35]. Research advances in lock inference can be directly applied to lock-based OCM implementations.

There is also significant ongoing research into *Software Transactional Memory* [30, 38, 42] (and even hardware support for transactional memory [22, 30]). STM has even been adopted by some newer languages such as Sun's Fortress [3]. Switching an STM-based OCM implementation from one STM library to another is not difficult, as long as the STM interfaces are reasonably similar. As a result, an STM-based OCM implementation can choose the STM implementation with the best performance characteristics.

In general, implementation advances in other models of concurrency should permit improved implementations of OCM.

## Acknowledgments

We would like to thank Bartholomew Broad, Kwang Ketcham, Samuel Just, Alejandro Lopez-Lago, and Joshua Peraza for their work prototyping early OCM implementations, and Christine Alvarado, Claire Connelly, and Robert Keller for helpful comments on this paper.

## References

- [1] M. Abadi and G. Plotkin. A model of cooperative threads. In *POPL '09*, pages 29–40, 2009.
- [2] M. Abadi, A. Birrell, T. Harris, and M. Isard. Semantics of transactional memory and automatic mutual exclusion. In *POPL '08*, pages 63–74, 2008.
- [3] E. Allen, D. Chase, J. Hallett, V. Luchangco, J.-W. Maessen, S. Ryu, G. L. S. Jr., and S. Tobin-Hochstadt. The Fortress language specification, version 1.0. Technical report, Sun Microsystems, Inc., Mar. 2008.
- [4] T. Bergan, O. Anderson, J. Devietti, L. Ceze, and D. Grossman. CoreDet: a compiler and runtime system for deterministic multithreaded execution. In *ASPLOS '10*, pages 53–64, 2010.
- [5] R. D. Blumofe, C. F. Joerg, B. C. Kuszmaul, C. E. Leiserson, K. H. Randall, and Y. Zhou. Cilk: An efficient multithreaded runtime system. In *PPoPP '95*, pages 207–216, 1995.
- [6] S. Cherem, T. Chilimbi, and S. Gulwani. Inferring locks for atomic sections. In *PLDI '08*, pages 304–315, 2008.
- [7] P. Danturi, M. Nesterenko, and S. Tixeuil. Self-stabilizing philosophers with generic conflicts. *ACM Transactions on Autonomous and Adaptive Systems*, 4(1):1–20, 2009.
- [8] D. Dice, O. Shalev, and N. Shavit. Transactional locking ii. In *20th International Symposium on Distributed Computing (DISC 2006)*, pages 194–208, 2006.
- [9] E. W. Dijkstra. Two starvation free solutions to a general exclusion problem. EWD 625.
- [10] E. W. Dijkstra. Cooperating sequential processes. In F. Genuys, editor, *Programming Languages: NATO Advanced Study Institute*, pages 43–112. Academic Press, 1968.
- [11] A. B. Downey. *The Little Book of Semaphores*. Green Tea Press, 2nd edition, 2008.
- [12] M. Emmi, J. S. Fischer, R. Jhala, and R. Majumdar. Lock allocation. In *POPL '07*, pages 291–296, 2007.
- [13] R. S. Engelschall. Gnu Pth—the GNU portable threads. June 2006. URL <http://www.gnu.org/software/pth>.
- [14] K. P. Eswaran, J. N. Gray, R. A. Lorie, and I. L. Traiger. The notions of consistency and predicate locks in a database system. *Communications of the ACM*, 19(11):624–633, 1976.
- [15] P. Felber, C. Fetzer, and T. Riegel. Dynamic performance tuning of word-based software transactional memory. In *PPoPP '08*, pages 237–246, 2008.
- [16] J. Fischer, R. Majumdar, and T. Millstein. Tasks: language support for event-driven programming. In *PEPM '07*, pages 134–143, 2007.
- [17] M. Frigo, C. E. Leiserson, and K. H. Randall. The implementation of the Cilk-5 multithreaded language. In *PLDI '98*, volume 33, pages 212–223, May 1998.
- [18] A. R. Gingras. Dining philosophers revisited. *SIGCSE Bulletin*, 22(3):21–ff., 1990.
- [19] J. Gosling, B. Joy, G. Steele, and G. Bracha. *The Java™ Language Specification (3rd Edition)*. Addison-Wesley Professional, 2005.
- [20] A. Gustafsson. Threads without the pain. *Queue*, 3(9):34–41, 2005.
- [21] T. Harris and K. Fraser. Language support for lightweight transactions. In *OOPSLA '03*, pages 388–402, 2003.
- [22] T. Harris, S. Marlow, S. Peyton Jones, and M. Herlihy. Composable memory transactions. In *PPoPP '05*, pages 48–60, 2005.
- [23] B. Hindman and D. Grossman. Atomicity via source-to-source translation. In *2006 Workshop on Memory System Performance and Correctness (MSPC '06)*, pages 82–91, 2006.
- [24] C. A. R. Hoare. Monitors: an operating system structuring concept. *Communications of the ACM*, 17(10):549–557, 1974.
- [25] C. A. R. Hoare. *Communicating Sequential Processes*. Prentice-Hall, 1985.
- [26] C. A. R. Hoare. *Toward a Theory of Parallel Programming*, volume 9 of *A.P.I.C. Studies in Data Processing*, pages 61–71. Academic Press, 1972.
- [27] R. Ierusalimschy, L. H. de Figueiredo, and W. Celes. *Lua 5.1 Reference Manual*. Lua.org, 2006.
- [28] M. Isard and A. Birrell. Automatic mutual exclusion. In *11th USENIX Workshop on Hot Topics in Operating Systems (HotOS XI)*, pages 1–6, 2007.
- [29] T. H. Khilan Gudka, Susan Eisenbach. “Hello World!”: Lock inference in the presence of large libraries. Technical report, Imperial College London, July 2010.



## Code Excerpts

```
#include "ants.hpp"

void* ant (void* args) {
    OCM_THREAD(&args);

    point * arg = (point *) args;
    int x = arg->x;
    int y = arg->y;
    ocm::ocmFree(arg);

    int health = STARTING_HEALTH;

    while (1) {
        yield;

        if ( board->getCount(FOOD) == 0 ) break;

        // Decide how to move (to food, or random)
        point foodHere = findFood(x,y);
        int dx = foodHere.x - x;
        int dy = foodHere.y - y;

        if ( dx == 0 && dy == 0 ) {
            dx = rand() % 3 - 1;
            dy = rand() % 3 - 1;
        }

        if( board->traversable(x+dx,y+dy) ) {
            // move
            board->set(x,y,EMPTY);
            x += dx;
            y += dy;
            if ( board->get(x,y) == FOOD )
                // eat
                health += FOOD_HEALTH;
            board->set(x,y,ANT);
        }

        yield;
        usleep(ANT_DELAY);

        health -= DECAY_RATE;
        if ( health <= 0 ) {
            // Not enough food.
            board->set(x,y,DEAD_ANT);
            break;
        }
    }

    return NULL;
}
```

```
point findFood(size_t x, size_t y) {
    point looking = {x,y};

    // Check neighboring points for food
    for (size_t i = x-1; i <= x+1; ++i)
        for (size_t j = y-1; j <= y+1; ++j)
            if ( board->get(i, j) == FOOD ) {
                looking.x = i;
                looking.y = j;
                return looking;
            }

    return looking;
}

// Repeatedly prints the current state of the grid.
void* printLoop(void * args) {
    OCM_THREAD(&args);

    while(board->getCount(FOOD) > 0) {
        board->print();
        yield;
        usleep(PRINT_DELAY);
        yield;
    }

    return NULL;
}

void addAnts(ocm::thread_t* &antThreads) {
    point* p;
    int i = 0;
    while ( i < NUM_ANTS ) {
        p = (point *) ocm::ocmMalloc(sizeof(point));
        p->x = rand() % GRID_SIZE;
        p->y = rand() % GRID_SIZE;

        if (board->get(p->x,p->y) == EMPTY) {
            board->set(p->x,p->y,ANT);
            ocm::thread_create(&antThreads[i], NULL, ant, p);
            ++i;
        } else
            // Grid was occupied; try again
            ocm::ocmFree(p);
    }

    return;
}
```

```

void addFood() {
    size_t x,y;
    int foodCount = NUM_FOOD;

    while(foodCount > 0) {
        x = rand() % GRID_SIZE;
        y = rand() % GRID_SIZE;
        if (board->get(x,y) == EMPTY) {
            board->set(x,y,FOOD);
            --foodCount;
        }
    }

    return;
}

int main(int argc, const char * argv[]) {
    OCM_START(NUM_ANTS+1);

    board = new Grid(GRID_SIZE,GRID_SIZE);
    addFood();
    board->print();

    ocm::thread_t* antThreads = new ocm::thread_t[NUM_ANTS];
    ocm::thread_t printThread;
    addAnts(antThreads);

    usleep(ANT_DELAY);

    ocm::thread_create(&printThread, NULL, printLoop, NULL);

    for (int i = 0; i < NUM_ANTS; ++i) {
        ocm::thread_join(antThreads[i], NULL);
    }

    ocm::thread_join(printThread,NULL);

    yield;

    board->print();

    delete[] antThreads;
    delete board;

    OCM_EXIT();

    return 0;
}

```