Record-Replay Debugging for the SCOOP Concurrency Model

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Abstract
To support developers in writing reliable and efficient concurrent programs, novel concurrent programming abstractions have been proposed in recent years. Programming with such abstractions requires new analysis tools because the execution semantics often differs considerably from established models. We present a record-replay technique for programs written in SCOOP, an object-oriented programming model for concurrency. The resulting tool enables developers to reproduce the nondeterministic execution of a concurrent program, a necessary prerequisite for debugging and testing.

1 Introduction
Avoiding concurrency-specific errors such as data races and deadlocks is still the responsibility of developers in most languages that provide synchronization through concurrency libraries. To avoid the problems of the library approach, a number of languages have been proposed that fully integrate synchronization mechanisms. SCOOP (Simple Concurrent Object-Oriented Programming) [6,10], an object-oriented programming model for concurrency, is one of them.

The main idea of SCOOP is to simplify the writing of correct concurrent programs, by allowing developers to use familiar concepts from object-oriented programming, but protecting them from common concurrency errors such as data races. Empirical evidence supports the claim that SCOOP indeed simplifies reasoning about concurrent programs as opposed to more established models [8].

The complex interactions between concurrent components make it difficult to analyze the behavior of typical concurrent programs. Effective use of a programming model therefore requires tools to help developers analyze and improve programs. Static analysis of models, e.g., [2,7,11,15], can establish some degree of functional correctness. However, they fail to explain why a particular execution does not terminate. Once a problem has been identified, it may be difficult to reproduce it because the problem might manifest itself only under some particular interleavings. Worse, the act of debugging itself might make it go away because of changes in the interleaving caused by the observation instructions. The term Heisenbug is sometimes used to denote this phenomenon. Addressing these issues requires adapting record-replay techniques to the context of concurrent, non-deterministic execution. Section 2 surveys existing tools that address this goal. They are not appropriate, however, for the semantics of SCOOP.

We present a SCOOP adaptation of Choi and Srinivasan’s [3] record-replay technique for Java threads. The resulting tool has been integrated into the EVE [4] development environment, which we extended with support for SCOOP. We found that the SCOOP model provides abstractions that can be leveraged by the technique: SCOOP’s synchronization mechanism provides abstractions which are coarse-grained enough to limit state space explosion and thus keep execution records small.
This article is structured as follows. Section 2 provides an overview of related work. Section 3 gives an overview of the SCOOP model. Section 4 presents the adapted record-replay technique. Section 5 concludes with an outlook on future work.

2 Related Work

The main problem of debugging concurrent programs is to make concurrent executions repeatable; a number of approaches to address this problem have emerged. The approach of Pan and Linton [12] logs all data read from shared memory locations. To replay, it simulates the events from the log. While this approach has the advantage of allowing immediate reverse execution of a program (backstepping), its main drawback is the prohibitively large amount of data generated during execution, as acknowledged by [12].

Most approaches have, as a consequence, focused on recording only the order of events, not the data; in a second step this information is used to replay the execution. The predominant approaches can be classified according to the type of information recorded: either only coarse-grained information such as object accesses and synchronization events [5, 14] or every shared-memory access [9]. LeBlanc and Mellor-Crummey [5] describe a method termed Instant Replay that records the order of accesses to shared objects during a monitoring phase by assigning version numbers to objects and recording for each process which object versions have been accessed. Through this recording of object accesses, it can be ensured during replay that processes access objects of the same version numbers as during monitoring, thus reproducing the execution and the object values. Tai et al. [14] consider programs where all shared objects are protected by synchronization mechanisms. They record the order of the synchronization operations. During replay, the execution can thus be recreated under the assumption that a program is free of data races. Netzer [9] proposes monitoring every shared-memory access so that data race-freedom no longer needs to be assumed. The technique is optimized with regard to the amount of information needed to reproduce an execution; it performs a transitive reduction of the dependencies between shared-memory accesses and only records the optimal ordering, thus significantly reducing the size of the trace log. A drawback of the approach consists, however, in the large amount of runtime overhead, as pointed out by [13].

Bacon and Goldstein [1] present a hardware-assisted scheme for deterministic replay. In contrast to the software-based methods, the scheme succeeds in avoiding the complications of the probe effect. Xu et al. [16] develop this approach further using a variant of the transitive reduction [9] to minimize log size.

Instead of relying on a log of application events, as the previously discussed approaches usually do, Russinovich and Cogswell [13] recreate program executions by logging thread switches caused by the system scheduler. They modify the operating system to generate a log that can recreate the thread switches upon replay. Choi and Srinivasan [3] further improve this approach by logging logical thread schedules representing equivalence classes of physical thread schedules with respect to the ordering of shared-memory access events. Our approach for record-replay is based on logical thread schedules and adapts the idea in the context of SCOOP.

3 Background

This section gives an overview of SCOOP. The starting idea of SCOOP is that every object is associated for its lifetime with a processor, called its handler. A processor is an autonomous thread of control capable of executing actions on objects. An object’s class describes the possible actions as features. A processor can be a CPU, but it can also be implemented in software, for
example as a process or as a thread; any mechanism that can execute instructions sequentially is suitable as a processor.

A variable $x$ belonging to a processor can point to an object with the same handler (non-separate object), or to an object on another processor (separate object). In the first case, a feature call $x.f$ is non-separate: the handler of $x$ executes the feature synchronously. In this context, $x$ is called the target of the feature call. In the second case, the feature call is separate: the handler of $x$, i.e., the supplier, executes the call asynchronously on behalf of the requester, i.e., the client. The possibility of asynchronous calls is the main source of concurrent execution. The asynchronous nature of separate feature calls implies a distinction between a feature call and a feature application: the client logs the call with the supplier (feature call) and moves on; only at some later time will the supplier actually execute the body (feature application).

The producer-consumer problem serves as a simple illustration of these ideas. A root class defines the entities producer, consumer, and buffer. Assume that each object is handled by its own processor. One can then simplify the discussion using a single name to refer both to the object and its handler. For example, one can use “producer” to refer both to the producer object and its handler.

```
producer: separate PRODUCER
consumer: separate CONSUMER
buffer: separate BUFFER [INTEGER]
```

The keyword separate specifies that the referenced objects may be handled by a processor different from the current one. A creation instruction on a separate entity such as producer will create an object on another processor; by default the instruction also creates that processor.

Both the producer and the consumer access an unbounded buffer in feature calls such as buffer.put ($n$) and buffer.item. To ensure exclusive access, the consumer must lock the buffer before accessing it. Such locking requirements of a feature must be expressed in the formal argument list: any target of separate type within the feature must occur as a formal argument; this ensures that the arguments’ handlers are locked for the duration of the feature execution, thus preventing data races. Such targets are called controlled. For instance, in consume, buffer is a formal argument; the consumer has exclusive access to the buffer while executing consume.

Condition synchronization relies on preconditions (after the require keyword) to express wait conditions. Any precondition of the form $x$ some condition makes the execution of the feature wait until the condition is true. For example, the precondition of consume delays the execution until the buffer is not empty. As the buffer is unbounded, the corresponding producer feature does not need a wait condition.

```
consume (buffer: separate BUFFER [INTEGER])
    —— Consume an item from the buffer.
    require not (buffer.count = 0)
    local
        consumed_item: INTEGER
    do
        consumed_item := buffer.item
    end
```

The runtime system ensures that the result of the call buffer.item is properly assigned to the entity consumed_item using a mechanism called wait by necessity: while the consumer usually
does not have to wait for an asynchronous call to finish, it will do so if it needs the result.

The SCOOP concepts require runtime support. The following description is abstract; actual implementations may differ. Each processor maintains a request queue of requests resulting from feature calls on other processors. A non-separate feature call can be processed right away without going through the request queue; the processor creates a non-separate feature request for itself and processes it right away using its call stack. The rest of this discussion applies to separate feature calls, such as the call on the buffer performed on behalf of the consumer. When the client executes such a feature call, it enqueues a separate feature request to the request queue of the supplier’s handler. The supplier will process the feature requests in the order of queuing.

Whenever a processor is ready to let go of the obtained locks, i.e., at the end of its current feature application, it issues an unlock request to each locked processor. Each locked processor will unlock itself as soon as it processed all previous feature requests. In the example, the producer issues an unlock request to the buffer after it issued a feature request for put.

The runtime system includes a scheduler, which serves as an arbiter between processors. When a processor is ready to process a feature request in its request queue, it will only be able to proceed after the request is satisfiable. In a synchronization step, the processor tries to obtain the locks on the arguments’ handlers in a way that the precondition holds. For this purpose, the processor sends a locking request to the scheduler, which stores the request in a queue and schedules satisfiable requests for application. Once the scheduler satisfies the request, the processor starts an execution step.

4 Record-replay

This section presents a record-replay technique for SCOOP programs. The technique is an adaptation of Choi and Srinivasan’s approach, developed for Java multithreading. Their notion of logical thread schedules helps keep the size of the log file small. Section 4.1 presents the SCOOP-adaptation of logical thread schedules, called logical processor schedules. Section 4.2 and Section 4.3 show how the SCOOP runtime records and replays them.

4.1 Logical Processor Schedules

As demonstrated in Section 2, a number of effective approaches to the problem of deterministic replay of multithreaded programs exist. For executions on uniprocessor systems, the approach of Russinovich and Cogswell has been shown to outperform techniques that try to record how threads interact. They propose to log thread scheduler information and to enforce the same schedule when a run is replayed. This approach also works well in our case. To minimize the overhead from capturing physical processor schedules – the equivalent of physical thread schedules in the case of SCOOP – we adapt the notion of logical thread schedules from Choi and Srinivasan. This section describes this adaptation.

Consider a share market application with investors, markets, issuers, and shares. The markets and the investors are handled by different processors. Listing 1 shows the class for the investors. Each investor has a feature to buy a share. To execute it, the investor must wait for the lock on the market and for the precondition to be satisfied.

Listing 1: Investor class

```java
class INVESTOR feature
  id: INTEGER
```
buy (market: separate MARKET; issuer_id: INTEGER)
   —— Buy a share of the issuer on the market.
require
   market.can_buy (id, issuer_id)
do
   market.buy (id, issuer_id)
end
end

The following feature initiates a transaction that involves two investors and one market with shares from two issuers:

do_transaction (first_investor; second_investor: separate INVESTOR; baseIssuer_id: INTEGER)
   —— Make the two investors buy two shares from two consecutive issuers on the market.
local
   nextIssuer_id: INTEGER
   do
      first_investor.buy (market, baseIssuer_id)
      nextIssuer_id := baseIssuer_id + 1
      second_investor.buy (market, nextIssuer_id)
   end

Figure 1 depicts a number of possible physical processor schedules for this example. The difference between schedules a and b is that in a, the application sets the local variable nextIssuer_id after the first investor buys its share from the market, whereas in b the variable is set before this event. In schedule c, the second investor buys its share before the first investor does. Schedules a and b give rise to the same behavior on the market, whereas schedule c causes the transaction to be reversed: the second investors gets to buy its share first. The reason is that changes in the update of local variables do not influence shared objects, whereas the order of critical events does. In SCOOP, the only critical events occur in the synchronization step, i.e., when the scheduler approves a locking request. We regard two physical processor schedules as equivalent if they have the same order of locking requests. A logical processor schedule denotes an equivalence class of physical processor schedules, i.e., physical processor schedules where the scheduler approves the locking requests in the same order. Section 4.2 describes the implementation of logical processor schedules.

4.2 Recording Logical Processor Schedules

A logical processor schedule consists of one interval list per processor. An interval list is a sequence of intervals that keeps track of a processor’s approved locking requests. The scheduler uses a global counter with value counter_g to number the approved locking requests. An interval [l, u] is defined by a lower global counter value l and an upper global counter value u, such that the locking requests with numbers in [l, u] belong to the same processor and no locking request with a number in an adjacent interval belongs to the same processor.

Once the recorder is activated, the scheduler executes Algorithm 1. To detect when a new interval should start, the scheduler maintains for each processor a local counter with value counter_l and a local counter base with value base_l. The local counter base of a processor p
stores the value of the global counter at the point where the scheduler started recording an interval for \( p \). The local counter counts \( p \)'s locking requests that got approved from the moment where the scheduler started recording the interval for \( p \). Processor \( p \)'s current interval is then given as \([\text{base}_{i}[p] + 1, \text{base}_{i}[p] + \text{counter}_{i}[p]]\).

Whenever the scheduler approves a locking request \( r \) of a processor \( p \), it goes through the following checks. If \( p \)'s local counter is undefined, then \( p \) does not have an interval yet, and thus \( r \) belongs to a new interval for \( p \). Hence, the scheduler starts recording a new interval for \( p \).

If \( p \)'s local counter is defined and \( \text{counter}_{\text{global}} \neq \text{base}_{\text{local}} + \text{counter}_{\text{local}} \), then the scheduler would have approved locking requests of any other processor \( q \) since it started recording \( p \)'s interval, then the scheduler would have incremented the global counter, but not \( p \)'s local counter. Thus the equation would not hold. Hence, the scheduler did not approve locking request of other processors and thus \( r \) belongs to \( p \)'s current interval.

If \( p \)'s local counter is defined and \( \text{counter}_{\text{global}} \neq \text{base}_{\text{local}} + \text{counter}_{\text{local}} \), then the scheduler
Algorithm 1: Record

upon event (Initialize) do // The program starts.
  counter_g := 0; // The global counter.
  forall the p ∈ processors do
    counter_l[p] := undef; // The local counters.
    base_l[p] := undef; // The local counter bases.
    intervals[p] := (); // The interval lists.
end

upon event (Approved | p) do // The scheduler approved p’s request.
  if counter_l[p] = undef then
    base_l[p] := counter_g;
    counter_l[p] := 1;
    counter_g := counter_g + 1;
  else if counter_l[p] ≠ undef ∧ counter_g = base_l[p] + counter_l[p] then
    counter_l[p] := counter_l[p] + 1;
    counter_g := counter_g + 1;
  else if counter_l[p] ≠ undef ∧ counter_g ≠ base_l[p] + counter_l[p] then
    intervals[p] := intervals[p] • [base_l[p] + 1, base_l[p] + counter_l[p]];
    base_l[p] := counter_g;
    counter_l[p] := 1;
    counter_g := counter_g + 1;
end

upon event (Terminate) do // The program terminates.
  forall the p ∈ processors do
    if counter_l[p] ≠ undef then
      intervals[p] := intervals[p] • [base_l[p] + 1, base_l[p] + counter_l[p]];
      write (p, intervals[p]);
  end
end

is currently recording an interval for p, and r belongs to a new interval. This can be seen as follows. If the scheduler would not have approved locking requests of any other processor q, since it started recording p’s current interval, then only p would have incremented the global counter and its local counter. Thus the equation would hold. Hence, the scheduler must have approved one or more locking requests of other processors and thus r belongs a new interval on p. In this case, the scheduler finishes p’s current interval and adds r to a new interval.

At the end of the program execution, the scheduler checks for each processor whether there is any pending interval, in which case it adds the interval to the respective interval list.

Consider again the market example. Assume the investor class has an additional feature buy_alternative, which allows an investor to buy a share if possible; if it is not possible, a backup share is bought. For this reason, each investor has a backup market and an identifier of a backup issuer.
buy_alternative (market: separate MARKET; issuer_id: INTEGER)
--- Try to buy a share of the issuer on the market.
--- If this fails, buy some backup share on the backup market.

do
  if market.can_buy (id, issuer_id) then
    market.buy (id, issuer_id)
  else
    buy (backup_market, backupIssuer_id)
  end
end

Consider the setup in Figure 2. Assume that a new transaction asks each investor to buy at
least one share of the software company by calling buy and then buy_alternative. The schedule
in Figure 3 leads to a deadlock because the two investors hold a lock on one market while trying
to lock the other market; however, not all possible schedules exhibit the problem. The proposed
technique produces the following logical processor schedule: application: [1, 1], first investor:
[2, 2] • [6, 6], second investor: [4, 4] • [8, 8], Zurich market: [3, 3] • [7, 7], and New York market:
[5, 5] • [9, 9]. Section 4.3 shows how to replay this logical processor schedule to reproduce the
deadlock.

4.3 Replaying Logical Processor Schedules

To replay a logical processor schedule, the scheduler once again uses a global counter counter_g;
this time the global counter represents the number of the locking request that the scheduler
wants to approve next. To replay, the scheduler executes Algorithm 2.

To begin, the scheduler gets ready to approve the first locking request. Whenever the
scheduler is about to approve a locking request l of a processor p, the scheduler first checks
whether l is next. To do so, the scheduler consults p’s interval list and checks whether it
contains an interval with counter_g. If the interval list contains such an interval, then the
scheduler approves the locking request and gets ready to approve the next locking request, i.e.,
it increments the global counter. If the interval list does not contain such an interval then the
scheduler tries another locking request.

To replay the logical processor schedule from Section 4.2, the scheduler initializes the global
counter to 1. As soon as the application sends a locking request, the scheduler approves and
increments the global counter to 2. The first two calls on the investors cause them to each send
a locking request. The scheduler lets the first investor proceed and sets the global counter to
3. The second investor must wait because its interval list does not contain the current global
Figure 3: A physical processor schedule of the market example in detail. The numbers next to the scheduler lifeline indicate the approved locking requests.

counter value. The first investor calls the Zurich market, whose locking request the scheduler approves right away. Now the global counter is at 4, and the scheduler lets the second investor and the New York market proceed. As a consequence, the global counter reaches 6. In the meantime, the application performed two more calls to the investors. In sequence, the scheduler approves the locking requests of the first investor, the Zurich market, the second investor, and the New York market. The deadlock is guaranteed.
Algorithm 2: Replay

upon event (Initialize) do // The program starts.
    counter\₉ := 1; // The global counter.
    forall the p \in processors do
        intervals[p] := read (p); // The interval lists.
    end

upon event (Check \mid p) do // The scheduler checks on p’s request.
    if \exists \[l, u\] \in intervals[p]: l \leq \text{counter} \₉ \leq u then
        \text{counter} \₉ := \text{counter} \₉ + 1;
        trigger (Ok ); // The request is next.
    else
        trigger (NotOk ); // The request is not next.
    end

5 Conclusion

While the SCOOP model protects developers from introducing data races, its run-time system is complex; this makes errors such as deadlock hard to analyze without the ability to reproduce them. We introduced a record-replay technique to record and reproduce the execution of SCOOP programs. The technique uses the idea of logical thread schedules [3] to abstract from non-critical events. The simplicity of the SCOOP model helped to apply this technique: the approvals of locking request are the only relevant critical events.

The ability to replay executions using logical processor schedules is an important component to test SCOOP programs. In future work, schedules may be generated in order to drive programs systematically through different orders.

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