The One Page Model Checker

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Abstract

We show how standard IPC mechanisms can be used with the fork() system call to perform explicit state model checking on all interleavings of a multithreaded application. We specifically show how to check for deadlock and race conditions in programs with two threads. Our techniques are easy to apply to other languages, and require only the most rudimentary parsing of the target language. Our fundamental system fits in one page of C code.

1 Introduction and Related Work

Debugging multithreaded applications is hard. Race conditions mean that failures may be nondeterministic. Deadlock can be hard to trace, because it involves behaviors from multiple concurrent threads. Tools to prove that a piece of code has no such behaviors can help find such errors, and instill confidence that the programs will work correctly when deployed.

Here we describe a method for measuring the behavior of multithreaded programs through all possible execution interleavings. Our work is straightforward and applicable to many different programming languages, although it also has some significant, fundamental limitations.

Several other techniques have been proposed which relate to model checking multithreaded applications. Visser et al[3] built an optimized system which implements the Java VM and can prove properties about multithreaded applications. Mercer and Jones[1] built an explicit state model checker designed around specific CPUs which verifies properties of compiled code.

In 1997, Savage et al[2] introduced a tool which enforces a locking discipline on resources to prevent nondeterministic behavior caused by OS scheduling. While not a model checker per se, this tool also aims to help programmers reduce the uncertainty associated with multithreaded applications.

2 System Overview

The principle behind our system is easy to understand. Given a program with two threads, we wish to search for particular conditions like deadlock among all
possible thread interleavings. For example, if the first thread executes \texttt{print(ab)} and the second executes \texttt{print(12)}, then at least the following behaviors are possible: the first thread could run to completion, followed by the second, producing the output string “ab12”, or the second could run to completion first, producing “12ab”. If the operating system chooses to switch between the threads while they’re running, the strings “a1b2”, “a12b”, or “1a2b” might also occur. Of course, if \texttt{print()} isn’t thread safe, the program might also exhibit other behaviors or crash entirely.

To test all possible interleavings, the model checker must have a way of trying different execution paths and must keep track of which paths have been explored. Our system’s simplicity and compactness comes from using the Unix-standard \texttt{fork()} system call, which forks a process at the point of the function call into two independent, identical processes. \texttt{fork()} can be called inside branching, looping or subroutine constructs, and both the original and newly created child processes will return to the following statement and continue as if nothing happened. This is different from most thread implementations, which must be called with a subroutine to execute in the new thread, after which the thread terminates.

\texttt{fork()} allows our model checker to be implemented much like a normal recursive depth-first search. In such a search, the program’s stack is used to implicitly keep track of the current progress through the state space being searched. In place of nested function calls, our implementation creates a child process at each branching point to explore the next level of the search. This can happen surprisingly quickly, due to efficient OS techniques like copy-on-write paging which allows efficient forking; our Athlon 64 3000+ running Debian GNU/Linux can perform over 7,000 \texttt{fork()} operations per second.

Since our model checker operates on programs with two threads, we carefully synchronize pairs of processes to implement the possible execution orders. We call this technique “the buddy system”, and a pair of cooperating threads “buddies”. Each pair of buddies maintains a data structure in shared memory containing semaphores, execution path and other elements required for IPC and coordination.

And since \texttt{fork()} creates processes, not threads, we implement threadlike behavior using shared memory. Threads do not get separate copies of program variables as processes do, so we create a structure in a shared memory segment where buddy processes keep all application variables.

\section*{2.1 Example}

We will expand the earlier example into separate statements to show how our technique works. Thread 0 executes \texttt{print(a); print(b)}, while thread 1 executes \texttt{print(1); print(2)}. First, we instrument our code by placing calls to a function \texttt{hook()} before each statement, then calling \texttt{done()} at the end of execution:

\begin{verbatim}
thread0() {
    hook(); print(a);
}
\end{verbatim}
hook(); print(b);
done();
}

thread1() {
    hook(); print(1);
    hook(); print(2);
    done();
}

The code is then compiled and linked with our model checking code. When it executes, \textit{fork}() is called to create a separate process for each thread, each of which executes into the first \textit{hook}(). There are only two possible ways in which the threads can execute their first statements; either \textit{thread}0 or \textit{thread}1 goes first. Each “thread” (really a process) thus forks into two processes, resulting in two parents and two children. The pair of parents become buddies, and the pair of children become buddies. The parent processes each wait for their children to terminate, much as a recursive function calls itself and waits for the recursive call to finish. The child process for thread 1 blocks using a semaphore, waiting for its buddy in thread 0 to execute a single statement. The buddy process does this by returning from the call to \textit{hook}(), which allows the first statement, \textit{print}(a), to execute. Then that process hits the next call to \textit{hook}() and signals to its buddy that it has finished executing a statement.

Now the process repeats; either thread0 can execute another statement, or thread1 can execute its first statement. Again, each buddy forks, with the parents waiting for the children to finish. The child process for thread 0 again goes first, returning to execute \textit{print}(b), then calling \textit{done}(), which signals to the buddy process that thread 0 has completed execution. With no remaining alternatives, thread 1 now runs to completion, giving a resulting output of “ab12”.

Once the grandchildren of the original two threads have each terminated, the children continue running. Since the grandchildren explored the case in which thread 0 executed another statement, the children explore what happens when thread 1 runs. Thread 1 returns from its hook and executes \textit{print}(1), then signals its buddy. Once again, the children have two alternatives, so they fork another pair of grandchildren. The thread 0 grandchild executes its second statement and terminates, allowing thread 1 to complete and producing the string “a1b2”. The children again execute a statement from thread 1, \textit{print}(2), after which thread 0 runs to completion, producing “a12b”. Now the original two threads can continue, executing \textit{print}(1) from thread 1, and forking another set of children, which fork grandchildren as before, producing the strings “1ab2”, “1a2b”, and “12ab”.

3
3 Code Instrumentation, Language Independence and Statement Atomicity

In order for our system to work properly, application code must be properly instrumented, by making calls to `hook()` before each program statement. These statements are assumed to execute atomically, which does not generally happen in current systems, but which can be assured using a technique we describe later in this section.

This instrumentation process is very simple, and works independently of language constructions like loops, function calls and branches. For example, we first implemented the example we gave in the last section as follows, essentially the same as we listed it before:

```c
if(child) {
    // thread 0
    hook(); printf('a');
    hook(); printf('b');
    done();
}
else {
    // thread 1
    hook(); printf('1');
    hook(); printf('2');
    done();
}
```

But later, we generalized it to work for arbitrary strings using a separate function and a loop:

```c
void str(char *s) {
    int i;
    for(i=0; s[i]; i++) {
        hook(); b->common.outstr[b->common.outidx++] = s[i];
    }
}
```

```
main() {
    ...
    if(child) {
        // thread 0
        str("ab");
        done();
    }
    else {
```

4
// thread 1
str("12");
done();
}
}

A naive, automated instrumentation tool might have added additional `hook()` calls as follows, but that would have merely added overhead to the model checking process:

```c
void str(char *s) {
    int i;
    hook(); for(i=0; s[i]; i++) {
        hook(); b->common.outstr[b->common.outidx++] = s[i];
    }
}
```

```c
main() {
    ...
    if(child) {
        // thread 0
        hook(); str("ab");
        done();
    } else {
        // thread 1
        hook(); str("12");
        done();
    }
}
```

While modifying program source code before model checking is generally deprecated, we feel our technique has several interesting features. First, adding calls to `hook()` before each program statement is easy to do automatically for reasonably written source code, even without constructing a formal parser for the target language. The implementor must simply avoid placing calls where they would cause syntax errors in the program, such as in between function declarations. Redundant calls to `hook()` add overhead, but don’t otherwise break our system. This makes our system straightforward to implement in a variety of languages, whereas traditional systems require significant adaptation to target languages in order to properly model their behavior.

Second, our instrumentation can be used to perform other tasks beside model checking, by changing the behavior of `hook()`. For instance, `hook()` could be modified to implement white box testing, in which test cases are constructed which together must execute all code branches.
Third, our instrumentation can be left in place to guarantee the statement-level atomicity assumed by our system. Generally speaking, modern CPUs offer only machine instruction level atomicity – the OS may interrupt a process between any two instructions and begin execution of a different process. Model checkers like Estes work on these machine instructions directly, but their results can only be applied to that particular compilation of the application on a particular CPU. This may prove to be the only way to prove useful thread safety and liveness properties about unmodified code on a particular CPU, and would tend to suggest that dealing with multithreaded applications in their original high-level language form doesn’t even make sense. On the other hand, if calls to `hook()` are left in place in distributed code, the function can be modified to essentially make each application statement into an individual critical section.

Admittedly, this adds a large amount of overhead to the code, since system calls to raise and lower a semaphore must be made for each program statement. But in modern high level scripting languages particularly, programs tend to have fewer statements, with powerful built-in commands having relatively high execution costs. Such languages may be particularly difficult to verify at the machine code level, since they run via large, complex interpreters. As a first approximation of the overhead our technique would add, we wrote a C program which forks into two processes, each of which loops 1,000,000 times. In the loop, each process grabs a semaphore, adds the current index to a variable, then releases the semaphore. The program performed the 4,000,000 semaphore operations in about 0.8 seconds on our Athlon64 3000+. We then ran a program in Perl which loops 2,000,000 times in a single process, likewise adding up the index values. It also took about 0.8 seconds, suggesting that efficient C-based hooks in the perl code to ensure statement-level atomicity might add only 50% overhead to such a program, and possibly less for a program using fewer, more costly operations than simple loops and additions.

4 Formal Definitions

Here we define terminology used in the algorithms described in the next sections.

- Assume there exist functions `hook()`, which is called before execution of each application thread program statement, and `done()`, which is called after the last statement in each thread. Application threads may include most usual language features, such as branching, looping and function calls (see section 3).

- We define the execution counter for a thread to be the number of times `hook()` has been called since the beginning of the thread’s execution. Intuitively, this is the number of statements executed in that thread, plus one.

- If $s_0$ is the value of the execution counter for thread 0 and $s_1$ is the corresponding counter for thread 1, the pair $(s_0, s_1)$ forms the combined execution counter for the two threads.
An execution trace is defined to be a string \( t \in \{0, 1\}^* \) which represents the order in which statements from the two threads were executed to reach a particular combined execution counter. In our earlier example, the execution trace 0011 corresponds to the output “ab12”.

Let \( V_0 \) and \( V_1 \) represent the vectors of shared variable values for threads 0 and 1 having an execution trace \( t \) and combined execution counter \( C \). The tuple \( I = (V_0, V_1, t, C) \) is a partial interleaving for the two threads (partial, since the threads may not yet have run to completion).

5 Search Algorithm

Our algorithm for performing a depth first search on all possible execution interleavings of two threads \( t_0 \) and \( t_1 \) is as follows:

- **Base case:** Let \( I \) be the initial partial interleaving for threads \( t_0, t_1 \), representing the program state at the first call to \( \text{hook}() \) in each thread, before any application statements have executed.

- **Recursion:** Given a partial interleaving \( I \) for threads \( t_0, t_1 \),
  - Run any user-supplied code for checking conditions.
  - If \( \text{done}() \) has been called in both threads, terminate the current thread and indicate successful program execution for a single complete interleaving.
  - If \( \text{done}() \) has been called in only one thread, allow the other thread to continue to completion.
  - Otherwise, fork both threads to create children \( t_0', t_1' \). Parents both wait for termination of the children. \( t_0' \) returns from \( \text{hook}() \), allowing a single statement to execute while \( t_1' \) blocks. Then the recursive step is performed again on \( t_0', t_1' \) with a new partial interleaving \( I' \). When \( t_0', t_1' \) have terminated, \( t_1 \) returns, executing a single statement, and then the recursive step is performed again for \( t_0, t_1 \) with new partial interleaving \( I'' \).

Omitting \#include statements and helper functions for setting up semaphores and shared memory, our C implementation of this algorithm fits in one printed page of code (80 columns by 65 lines).

6 Detecting Race Conditions and Pruning the Search Space

Note that in the above example, program output is entirely dependent on the order in which the OS schedules the two threads for execution. Such nondeterministic behavior is almost never intended, and usually represents a bug in the code.
Consequently, we provide a technique for verifying that threads behave the same regardless of the order in which they are executed. This technique also makes it easy to avoid unnecessary exploration of the space of possible interleaveings. Formally, we define a race condition as follows:

- Let $I = \langle V_0, V_1, t, C \rangle$ and $I' = \langle V'_0, V'_1, t', C' \rangle$ represent partial interleavings such that $C = C'$. That is, $I$ and $I'$ are partial interleavings which have reached the same execution counter in each thread but potentially through a different order of execution. $I$ and $I'$ form a race condition if $I \neq I'$.

To implement this technique, we maintain a shared table keyed on the combined execution counters explored while searching the state space. Each table entry records the partial interleaving at that combined execution counter. When a particular combined execution counter is reached via a different execution trace, the current partial interleaving is compared against the stored partial interleaving. If they differ, the two partial interleavings are displayed as examples of execution paths capable of producing differing behaviors. A program with no race conditions will of course display only the single possible outcome of program execution.

The second purpose of this table is to record which combined execution counters have been reached before. Since our algorithm performs a depth first search on the possible thread interleavings, the second occurrence of a combined execution counter can only occur once all the remaining interleavings from that point on have already been explored. Consequently, if a race condition does not occur at a particular explored partial interleaving, there is no need to explore it again since the two threads are in exactly the same state as they were the last time.

Although we have not yet been able to derive a formula for the complexity of our pruning algorithm, it is clear that this pruning technique is at least an order of magnitude improvement over an exhaustive search. We ran our algorithm on pairs of threads each executing 3 to 8 statements. Values represent the total number of calls to \texttt{hook()}, which roughly corresponds to the number of states explored.

| Technique      | 3  | 4  | 5  | 6  | 7  | 8  |
|----------------|----|----|----|----|----|----|
| Exhaustive     | 30 | 112| 420| 1584| 6006| 22876|
| Pruning        | 18 | 32 | 50 | 72 | 98 | 128|

This addition was surprisingly easy to add to our system; it required less than a page of code in changes.

## 7 Supporting IPC

Our implementation supports multiple semaphores which may be used by the user application for interprocess communication. This complicates our system, since a thread may block until the other thread releases a particular semaphore, and complicates the actual implementation even more, due to practical issues
regarding process cleanup, IPC and resource management. Here we give the algorithm for supporting an arbitrary number of application semaphores.

- Let the definition of a partial interleaving be extended to include a set of semaphores \( S = \{s_0..s_n\} \), which may be up or down.

- Let the function \( \text{down}(i) \) be a valid application statement (to be preceded by a call to \( \text{hook}() \)). \( \text{down}(i) \) causes the current thread to lower \( s_i \) if it is up, and do nothing otherwise.

- Let the function \( \text{up}(i) \) perform the complimentary operation, with the addition that if \( s_i \) is already up, the thread blocks until the other thread calls \( \text{down}(i) \). If the other thread is already blocking, report deadlock and terminate both threads.

- **Base case:** Let \( I \) be the initial partial interleaving for threads \( t_0, t_1 \), representing the program state at the first call to \( \text{hook}() \) in each thread, before any application statements have executed.

- **Recursion:** Given a partial interleaving \( I \) for threads \( t_0, t_1 \),
  - Run any user-supplied code for checking conditions.
  - If \( \text{done}() \) has been called in both threads, terminate the current thread and indicate successful program execution for a single complete interleaving.
  - If \( \text{done}() \) has been called in only one thread, allow the other thread to continue to completion. If the other thread is blocked, report an error, since the thread will block forever.
  - If a thread is blocked, allow the other thread to execute another statement.
  - Otherwise, fork both threads to create children \( t_0', t_1' \). Parents both wait for termination of the children. \( t_0' \) returns from \( \text{hook}() \), allowing a single statement to execute while \( t_1' \) blocks. Then the recursive step is performed again on \( t_0', t_1' \) with a new partial interleaving \( I' \). When \( t_0', t_1' \) have terminated, \( t_1 \) returns, executing a single statement, and then the recursive step is performed again for \( t_0, t_1 \) with new partial interleaving \( I'' \).

8 Limitations

In most thread implementations, threads share all global variables, but each has its own stack. Local variables are thus maintained independently from other threads. Our implementation presently provides no support for such variables, and assumes that all thread state can be monitored via the shared variables and execution counter. It would be easy to create a second structure associated with each buddy process for storing variables unique to each thread, and account for
that additional state information when checking for race conditions and pruning the state space.

As we described in section 3, our assumption that program statements are performed atomically is not at all guaranteed by real computers, unless our technique is employed at a machine code level. To achieve reported results in practice, statement-level atomicity would need to be enforced by the operating system, language interpreter, or by using a modified hook() as we described.

While using fork() to store program execution state makes our system very simple to implement, it imposes a significant amount of system overhead. The system resources for two processes, including two process table entries, are required for each level of depth in the search space, which corresponds to the number of statements executed by the combined threads. This makes even simple programs, like a pair of threads which each loops 1,000,000 times, impossible to verify with our system.

Finally, our current system is limited to programs with two threads. See section 10 for discussion on removing this limitation.

9 Implementation and Performance

As we showed in section 6, our pruning algorithm performs far better than an exhaustive search. Default (though modifiable) OS limitations on the number of available semaphore sets and our implementation’s inefficient use of single semaphore sets rather than multiple semaphores in multiple sets limits us to running applications which execute a total of about 22 steps. These it handles in under 0.1 seconds. The resulting maximum of 44 live processes imposes no noticeable memory consumption.

While our fundamental search algorithm can be implemented in about a page of code, our full system supporting application semaphores, race detection and pruning, and with helper functions, debugging code, and whitespace currently weighs in at 611 lines of C. The implementation requires 4 semaphores for each level of depth in the DFS, and requires $n^3$ storage in the DFS depth to maintain the table of partial interleavings complete with program execution paths. For our current depth limit of 22, this amounts to about 100k of memory.

10 Future Work

Our system is limited to programs with two threads. Since our system is modeled after the traditional recursive depth first search algorithm, there is a clear path for extending our algorithm to support any number of threads. Rather than pairs of parent processes spawning a single pair of children, each parent in a set of $n$ parent buddies would iteratively spawn $n-1$ children (waiting each time for the previous child to die). The $n$ $n$-member buddy sets (cliques?) would then be dispatched, exploring the paths in which each child executes its next statement. Instead of a maximum $2k$ live processes for a $k$-level DFS, up to $nk$
processes would exist.

Implementation, in our experience, might be time consuming, due to the inherent difficulty humans seem to have keeping track of multiprocess systems. However, with careful planning, and for programmers more experienced with multiprocess applications, this extension should not prove too difficult.

One feature that might be quite easy to add is the ability for parents to run without waiting for their children. Unchecked, this would act like a “fork bomb”, potentially swamping the system as the entire search tree unfolded at once. But with a limit on how many pairs of processes could run at once, our system would immediately be able to run on SMP systems with arbitrary numbers of processors, limited only by the size of the process table and the system memory.

At the other extreme, with only two processes running at once, it’s unnecessary to allocate each pair of buddies their own set of semaphores, as our first implementation does. With more careful use and management, we suspect that a single set would suffice, avoiding system limits on available semaphores. The state table also need not require so much storage; cryptographic hash functions can be used to reduce arbitrary amounts of data to a 128 bit digest which can be stored in place of the actual partial interleaving. An expected \(2^{64}\) entries would have to be made before any pair of entries would have the same digest, which is far more than any PC can store today.

As we described in section 3, our system should be easy to implement in a variety of languages, possibly just by using cross-language extensions to call our original C implementation. There are also other uses for `hook()` which we described but have not implemented.

11 Conclusion

We gave a straightforward technique for checking thread-related properties of programs with two threads. Our technique is general-purpose and language-independent, and may be particularly suited to modern high-level scripting languages due to the difficulty of machine-code level model checking for these languages and the overhead required to enforce the statement-level atomicity required by our system.

Our system performs much better than an exhaustive search of the state space, understands application semaphore use, and detects deadlock and race conditions. Furthermore, our implementation is quite compact; our exhaustive search algorithm fits in one printed page of C code, and our complete implementation fits in under ten.

References

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