Replication of Concurrent Applications in a Shared Memory Multikernel

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(ABSTRACT)

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

William Shakespeare has profoundly affected the field of literature worldwide. In the United States there was a surge of Shakespearean literature starting in the 1960s, with the opening of the Montgomery Shakespearean festival and continuing into the present ...

Table 1.1: The Graduate School wants captions above the tables.

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2	2	4

Chapter 2

Popcorn Linux Background

2.1 Multikernel Boot

2.2 Inter-Kernel Messaging Layer

2.3 Popcorn Namespace

2.3.1 Replicated Execution

2.3.2 FT PID

2.4 Network Stack Replication

Chapter 3

Deterministic Execution

Deterministic execution provides a property that given the same input, a multithreaded program can always generate the same output. Such a system fits perfectly for our replication purpose. As long as the primary and secondary receive the same input, the replicated application will sure end up with the same state and generate the same output.

For multi-threaded programs, an observation is that as long as the threads don't communicate with each other, the execution is sure to be deterministic[**?**]. For example, in pthread based programs, all the inter-thread communications are synchronized by pthread primitives. By making the interleaving of sychronization primitives to be deterministic, the entire program is sure to be deterministic. With this observation, some runtime deterministic solutions actually enforce determinism by trapping pthread primitives[**?**][**?**][**?**]. This type of deterministic system is called "Weak Deterministic System". It assumes that the applications are data race free, and only guarantee the deterministic interleaving of thread synchronization primitives such as mutex locks and condition variables. Our implementation falls into this category, but unlike other runtime deterministic systems, our runtime does not directly trap pthread primitives, but provides two system calls for programmer to define a deterministic section. The runtime maintains a global execution order, according to this order, an execution token is passed among all the tasks deterministically. Only the task with the execution token can enter the deterministic area, and the token will be held on this task only if it leaves its deterministic area.

This chapter is structured as follows:

- Section 3.1 shows the basic algorithm and programming interface of the deterministic system.

- Section 3.2 explains the logical time imbalance problem of this algorithm and two solutions for two different cases.

```
 1  void producer() {
 2      while (running){
 3          item = generate_item();
 4          syscall(__NR_det_start);
 5          pthread_mutex_lock(mutex);
 6          syscall(__NR_det_end);
 7          putItem(queue, item);
 8          pthread_mutex_unlock(mutex);
 9      }
10  }
11
12  void consumer() {
13      while (running){
14          syscall(__NR_det_start);
15          pthread_mutex_lock(mutex);
16          syscall(__NR_det_end);
17          item = getItem(queue);
18          pthread_mutex_unlock(mutex);
19          consume_item(item);
20      }
21  }
```

Figure 3.1: An example use of the deterministic syscalls

3.1   Logical Time Based Deterministic Scheduling

Inspired by Kendo and Conversion, this scheduling policy maintains a logical time for each task inside the current Popcorn namespace. There is a "token" being passed among all the tasks in the namespace according to the logical time of each task. Our system provides following system calls for the applications to control the thread-interleaving:

- __det_start: When it is called, only the task holds the token can proceed. If the current thread is able to proceed, this thread will be marked as "in a deterministic section".

- __det_end: When it is called, the system will increase the current thread's logical time by 1, and marks it as "out of a deterministic section".

.

Figure 3.1 shows an example use of the system calls. Simply wrap pthread_mutex_lock with __det_start and __det_end will make the acquisition of the mutex to be deterministic.

If the logical time is updated but the one has the minimal logical time is sleeping in __det_start, the one whose updates the tick will wake the sleeping one up. As long as the

```
22  void __det_start()
23  {
24      if (token->token != current)
25          sleep(current);
26      current->ft_det_state = FT_DET_ACTIVE;
27  }
28  void __det_end()
29  {
30      current->ft_det_state = FT_DET_INACTIVE;
31      __update_tick(1);
32  }
33  void __det_tick(int tick)
34  {
35      __update_tick(tick);
36  }
37  void __update_tick(int tick)
38  {
39      current->tick += tick;
40      token->task = find_task_with_min_tick(ns);
41      if (is_waiting_for_toUponken(token->task))
42          wake_up(token->task);
43  }
```

Figure 3.2: Simplified implementation of deterministic system calls

replicated application updates logical time in a same way on both primary and secondary, they will sure end up with the same thread interleaving. Figure 3.2 shows a simplified version of this algorithm (some mutual exclusion points are omitted here).

To make an application to run in a deterministic way, one should put __det_start and __det_end around the synchronization primitives such as pthread_mutex_lock , so that the order of getting into critical sections is controlled under our deterministic scheduling.

3.1.1 Eliminate Deadlocks

With wrapping all the pthread_mutex_lock with our deterministic system calls, there is a potential risk of having deadlocks. Serializing all the lock acquisitions with our implementation basically means putting a giant global mutex lock around every lock acquisition. As shown in Figure 3.3, Thread 2 has a lower logical time and try to acquire the mutex(b), however mutex(b) is contended, as a result Thread 2 will call futex_wait and put the thread into sleep until mutex(b) is released by someone else. At this point, Thread 2 will never increase its logical time until mutex(b) is released. So Thread 1 will never goes through the __det_start,

Thread 1　　　　Thread 2

```
┌──   __det_start
├── mutex_lock(b)      │
├──   __det_end        ┼   __det_start
│                      ├── mutex_lock(b)
├── mutex_lock(a)  ┼     __det_end
│
└──   __det_start
├── mutex_lock(b)
├──   __det_end


├── mutex_lock(a)
```

Logical Time:5　　　Logical Time:3
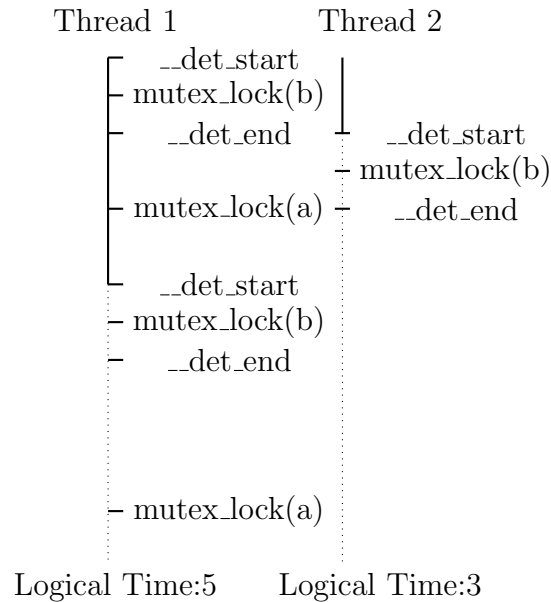
Figure 3.3: An example of deadlock

and it will never unlock mutex(b) which means Thread 2 will never be woken up.

Since we already know that a contented mutex will call futex_wait to wait for a unlock event, the solution to this deadlock problem is to temporary remove the thread in futex_wait out of the deterministic schedule, and add it back when it returns from futex_wait. In the example of Figure 3.3 Thread 1 will be able to proceed its __det_start and keep executing. In order to not to break the determinism, we guarantee the following:

- We guarantee that the waiting queue in futex_wait is strictly FIFO, which means the wakeup sequence will be the same as the sequence of getting into futex_wait. Since the latter one is ensured by our __det_start, with this hack to futex, the wake up sequence from futex_wait will be the same sequence determined by previous __det_start. This is implemented by fixing the priority of each futex object, so that the priority queue inside futex_wait can behave like a FIFO queue.

- We guarantee that when waking up from a futex_wait, the thread always waits for the token before returning to the user space. With this implemented, the timing (in terms of logical time) of getting out of a contended pthread_mutex_lock will be deterministic. This is implemented by adding a __det_start after the wake up point of futex_wait.
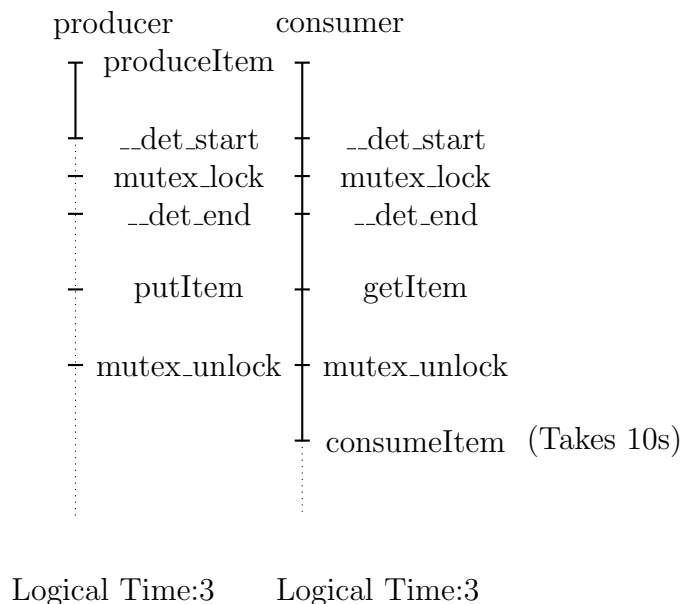
Figure 3.4: An example of logical time imbalance.

3.2   Balance the Logical Time

Only increasing the logical time by 1 at __det_end isn't enough. With an example we show how this could break the scalability and how to mitigate this problem. In Figure 3.4, we show a particular execution point of the producer-consumer model in the program snippet we presented in Figure 3.1, solid lines represents the path that is already executed. In this case, consumer reaches consumeItem with logical time 3 and has the token. Assume the real execution time of consumeItem is 10s, which means that when the consumer reaches __det_end, it would be at least 10s later, that is, the producer has to wait at __det_start for at least 10s. However we've already enforces the access order of the mutex, the execution out of the critical section should go in parallel since threads don't communicate at that point, in worst case, this kind of waiting will turn a parallel program into a serial program.

Generally, logical time imbalance can happen in two cases:

- A task is running for a long time (in user space).

- A task is sleeping for a long time (in kernel space).

In the upcoming sections we will discuss the solution of each of the cases.

3.2.1 Execution Time Profiling

When a task is running in a computational region (in user space) which might take a long time, the logical time of the task should increase along with the execution. In Kendo this is done by counting retired read instructions using performance counters to track to progress of a running task and increases its logical time accordingly. However it is hard to ensure that on the primary and the secondary the performance counter can have the same behaviour, as a result we have to find another way to track the progress of a running task.

Instead of deciding the logical time during the runtime, we discovered a way to settle the logical time during the compilation time. The basic idea is to collect the execution time of via a profile run, then compile the application with the data from the profile run. First, we introduce another system call to increase the logical time of a task:

- __det_tick: This system call comes with a parameter of an integer. When it is called, the logical time will be increased by value defined by the parameter.

This system call should be inserted in the program where the logical time needs to be increased. In order to automate this instrumentation process, based on LLVM, we implemented two compiler passes to do the profiling and instrumentation.

Profile Pass In order to get the execution time of a program, we make a profile pass to collect the execution time at the granularity of basic block. During the compilation time, this compiler pass will assign a unique number to each basic block, and inserts time profiling functions around every basic block beyond a certain threshold in terms of number of instructions. Figure 3.5 shows a basic block instrumented with the profile functions in LLVM-IR. In this basic block, bbprof_start (line 3) and bbprof_end (line 16) are inserted at the beginning and the end of this basic block.

The profile run is launched by our profile launcher, which will keep track of the execution time of the application, and compute the average execution time for each instrumented basic block upon the application exits. In the end, all the gathered information will be output to a file for future use.

Logical Time Pass After the program finished one profile run with the instrumentation of profile pass, we can launch our compiler again to generate the final executable. The logical time pass will take the profile data file as input. This time at the end of each basic block, a __det_tick will be inserted with the parameter of a scaled execution time of the current basic block. So that the logical time will be bumped at the end of each basic block according to the actual execution time of each basic block. Fi gure 3.6 shows an example of instrumented basic block in LLVM-IR. This is the same basic block as we showed in Figure 3.5. In this

```
1   if.end.23:                                          ; preds = %for.end
2     %38 = load i8*, i8** %CompressedData, align 8
3     %39 = call i32 (i32, ...) @bbprof_start(i32 249)
4     %40 = load %struct.outBuff*, %struct.outBuff** %fileData, align 8
5     %buf = getelementptr inbounds %struct.outBuff, %struct.outBuff* %40,
          i32 0, i32 0
6     %41 = load i8*, i8** %buf, align 8
7     %42 = load %struct.outBuff*, %struct.outBuff** %fileData, align 8
8     %bufSize24 = getelementptr inbounds %struct.outBuff, %struct.outBuff*
          %42, i32 0, i32 1
9     %43 = load i32, i32* %bufSize24, align 4
10    %44 = load i32, i32* @_ZL12BWTblockSize, align 4
11    %45 = load i32, i32* @_ZL9Verbosity, align 4
12    %call25 = call i32 @BZ2_bzBuffToBuffCompress(i8* %38, i32* %outSize,
          i8* %41, i32 %43, i32 %44, i32 %45, i32 30)
13    store i32 %call25, i32* %ret, align 4
14    %46 = load i32, i32* %ret, align 4
15    %cmp26 = icmp ne i32 %46, 0
16    %47 = call i32 (i32, ...) @bbprof_end(i32 249)
17    br i1 %cmp26, label %if.then.27, label %if.end.29
```

Figure 3.5: An instrumented basic block in pbzip2 with execution time profiling functions.

example, Line 9 is the end of the basic block, it comes with a __det_tick system call with a value 2895535, which is generated and normalized from a previous profile run. In this basic block, line 5 is the most time consuming part in the entire program (pbzip2), as a result this basic block needs a relatively large tick increment.

3.2.2   Tick Bumping for External Events

When a task is sleeping in the kernel, usually it is in a system call and waiting for some events to wake it up. Especially for system calls like epoll_wait, poll and accept and other I/O system calls, the arrival time of the event is non-deterministic, as a result, we cannot simply use __det_tick to increase the logical time with a predefined value from a profile run, because we have no idea how long the thread will be sleeping in the kernel.

Some deterministic systems simply remove the sleeping tasks out of the deterministic schedule and put them back after they are back to user space. This is not applicable in a replication system like ours, as previously stated, the wake up time of those system calls might be different from the primary and secondary replica. As a result we must not abandon those sleeping tasks, and have to maintain the consistent state of the logical time for those tasks.

In order to let the token passing keep going with those blocking system calls, we need a

```
 1    ( . . . . . )
 2    %bufSize24 = getelementptr inbounds %struct.outBuff, %struct.outBuff*
          %35, i32 0, i32 1
 3    %36 = load i32, i32* %bufSize24, align 4
 4    %37 = load i32, i32* @_ZL12BWTblockSize, align 4
 5    %38 = load i32, i32* @_ZL9Verbosity, align 4
 6    %call25 = call i32 @BZ2_bzBuffToBuffCompress(i8* %32, i32* %outSize,
          i8* %34, i32 %36, i32 %37, i32 %38, i32 30)
 7    store i32 %call25, i32* %ret, align 4
 8    %39 = load i32, i32* %ret, align 4
 9    %cmp26 = icmp ne i32 %39, 0
10    %40 = call i32 (...) @syscall(i32 321, i64 2895535)
11    br i1 %cmp26, label %if.then.27, label %if.end.29
```

Figure 3.6: An instrumented basic block in pbzip2 with dettick.
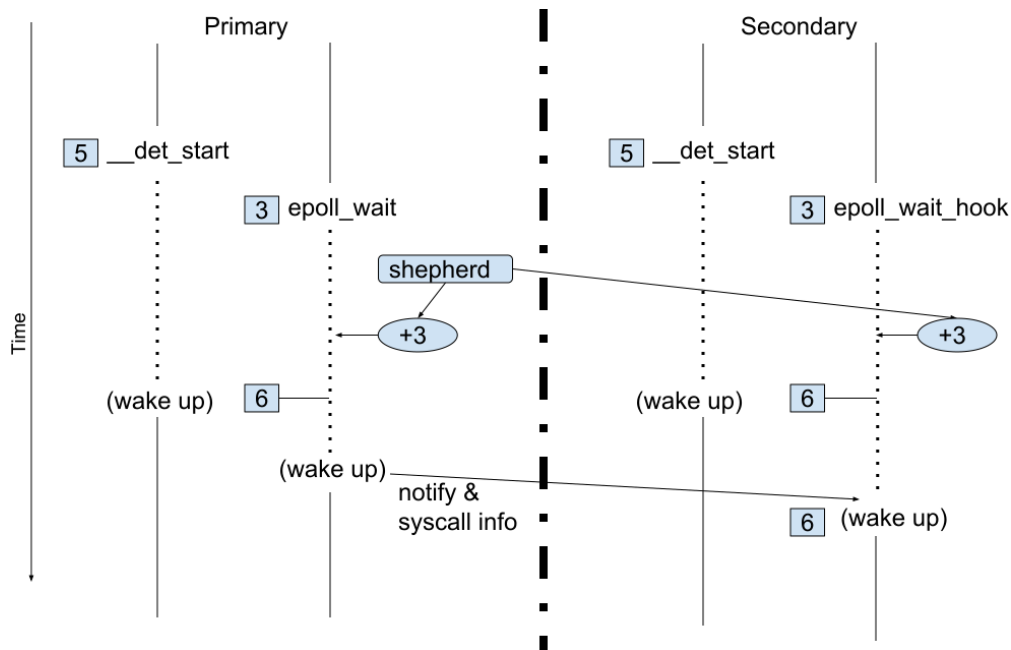

Figure 3.7: An example of tick bumping

way to keep bumping those thread's logical time while they are sleeping, a "Tick Shepherd" is implemented to dynamically bump the logical time of the threads that are sleeping in such system calls. The Tick Shepherd is a kernel thread which is mostly sleeping in the background, whenever the token is passed on to a thread that is sleeping on external events or a thread is going to sleep with the token, the shepherd will be woken up to increase the sleeping thread's logical time and send the increased value to the replica. In the meanwhile the corresponding system call on the replica will be blocked at the entry point, and bumps its logical time according to the information from the primary. Figure 3.8 shows the simplified version of Tick Shepherd, it only runs on the primary replica. The syscall on the secondary doesn't proceed until the primary returns from the syscall. In this way we can make sure that when both of the syscalls wake up from sleeping, all the replicas will end up with a consistent state, in terms of logical time. The Tick Shepherd will keep bumping sleeping tasks logical time until for a given period the state of all the tasks comes to a stable point, where nobody makes a single syscall. After that, it will go back to sleep again.

Figure 3.7 shows an example of how Tick Shepherd works in action. In this example, tick shepherd detects the token is on a thread sleeping in epoll_wait, so it bumps its tick by 3 and sends this info to the secondary so that the token can leave this thread. And after the primary returns from epoll_wait, it sends a message to the secondary, so that the corresponding thread can start to execute its epoll_wait and uses the output from the primary as its own output. In order to be efficient, we only let Tick Shepherd to bump the system calls that for sure will be called for deterministic times, the current implementation covers all the major I/O related system calls.

3.3 Related Work

Deterministic systems have been studied for a long time. From the implementation perspective view, they can be categorized into 4 different genres: language level, runtime level, OS level and architectural level.

Clik++ [?] is an parallel extension to C++ which makes creating parallel program easier. This extension provides a property that can indicate threads to be executed in a serial way, so that the determinism can be ensured. Grace [?] is also a C++ extension that adds a fork-join parallel schema to C++, it enforces the determinism of the execution with its underlying language runtime. Both of them are very limited to a specific parallel programming model, and existing applications need to be rewritten to achieve determinism.

Kendo[?], Parrot[?] and Dthreads[?] provide runtime substitutions for pthread library. By making pthread synchronizations to be deterministic, any race-free pthread-based application can be executed in a deterministic way. They are easy to be applied onto existing applications. However they are limited to pthread only applications. Although Melchior can only make pthread to run deterministically in an automatically way, a developer is al-

```
44  while (!kthread_should_stop()) {
45    if (ns->task_count == 0 ||
46      ns->wait_count == 0) {
47      sleep(); // Sleep until some task wakes it up
48      continue;
49    }
50    token = ns->token;
51    tick = token->task->ft_det_tick;
52    udelay(20); // delay for a small duration
53    token2 = ns->token;
54    tick2 = token2->task->ft_det_tick;
55    // Which means the token hasn't been changed during the delay,
56    // It's time to bump the tick
57    if (token == token2 && tick2 == tick) {
58      if (!is_waiting_for_token(token->task) &&
59        (is_concerned_syscall(token->task->current_syscall)) {
60          if (ns->wait_count != 0 &&
61            token->task->bumped == 0) {
62              bump_task = token->task;
63              id_syscall = token->task->id_syscall;
64              bump = ns->last_tick + 1;
65              previous_bump = token->task->ft_det_tick;
66              token->task->ft_det_tick = ns->last_tick + 1;
67              update_token(ns);
68              send_bump(bump_task, id_syscall, previous_bump, bump);
69              continue;
70          }
71      }
72    }
73  }
```

Figure 3.8: Simplified implementation of Tick Shepherd

ways free to use the runtime system calls to hand tune any type of parallel applications to make them deterministic. Among these three, Kendo uses the same deterministic scheduling policy as Melchior. However it relies on hardware counters to keep track of the program's progress in runtime, given the fact that hardware counters could be non-deterministic[?], we doubt the determinism of Kendo in some cases. DMP[?] provides an OS layer to make any program running on top of it deterministic, which is applicable for all kinds of parallel programming models. However DMP's overhead is too high due to massive trapping to shared memory accesses. We synchronization provided by the programming model, this could be unnecessary.

In [?], an architectural solution is proposed. It's a hardware layer between the CPU core and memory hierarchy, the goal is to track all the memory access and does versioning on the memory operations. By doing deterministic submission to the memory hierarchy, it ensures the determinism of the parallel execution. Although it's a promising solution which is totally transparent to the upper layer, it's not usable out of box in recent years.

Chapter 4

Schedule Replication

In chapter 3 we described using a deterministic system to ensure the applications on the primary and secondary replica can have the same thread interleaving. The major advantage of the deterministic system is that we can minimize the communication between the replicas. However the downside is that we need to precisely adjust the logical time to maintain decent parallelism for multithreaded applications. We showed various solutions to balance the logical time because we need to keep the execution to be fast and deterministic. If all the burdens come from being deterministic, can we break the determinism once for all but still keep the replicas to be synchronized? The answer is yes.

In this chapter we are going to describe Schedule Replication for replicated applications. In this algorithm, we break the determinism entirely and use messages to synchronize every single synchronization primitives between the primary and replica. For an application that has massive number of synchronization primitives, this approach might introduce overheads from the communication, Figure 4.1 shows the relation between two different algorithms. Fortunately, our system is for inter-kernel replication, and Popcorn Linux provides a messaging layer with negatable latency. As a result having massive massages between replicas won't put too much overhead to the replication.

Figure 4.1: Trade off between two algorithms

4.1 Execute-Log-Replay

Before we get into the detail of this algorithm, let's revisit some important properties that are provided by the deterministic system.

- Serialization of deterministic areas. (The code region between detstart and detend).

- Same total order of getting into deterministic areas on primary and secondary.

The first property is guaranteed by the fact that the logical time won't change during the execution of a deterministic area, and the second property is guaranteed by increasing the logical time in a same way on both primary and replica. As long as these two properties are guaranteed, the thread interleaving on both primary and secondary are sure to be the same (also for tick bump). In our Schedule Replication mode, we guarantee these two properties with the following approaches:

- Serialize deterministic areas with a global mutex on both primary and secondary.

- Log the sequence of getting into deterministic areas on the primary and replay it on the secondary.

Here we still use __det_start and __det_end to wrap around a code section that needs to be synchronized with the replica. Figure **??** shows a simplified version of __det_start and __det_end in Schedule Replication.

Figure **??** shows an example of how Schedule Replication works in action.

4.2 Related Work

```
74  void __det_start ()
75  {
76      if (is_secondary (current))
77          wait_for_sync (current->seq,
78              ns->seq, current->ft_pid);
79      lock (ns->global_mutex);
80      current->ft_det_state = FT_DET_ACTIVE;
81  }
82  void __det_end ()
83  {
84      if (is_primary (current))
85          send_sync (current->seq,
86              ns->seq, current->ft_pid);
87      current->seq++;
88      ns->seq++;
89      current->ft_det_state = FT_DET_INACTIVE;
90      unlock (ns->global_mutex);
91  }
```

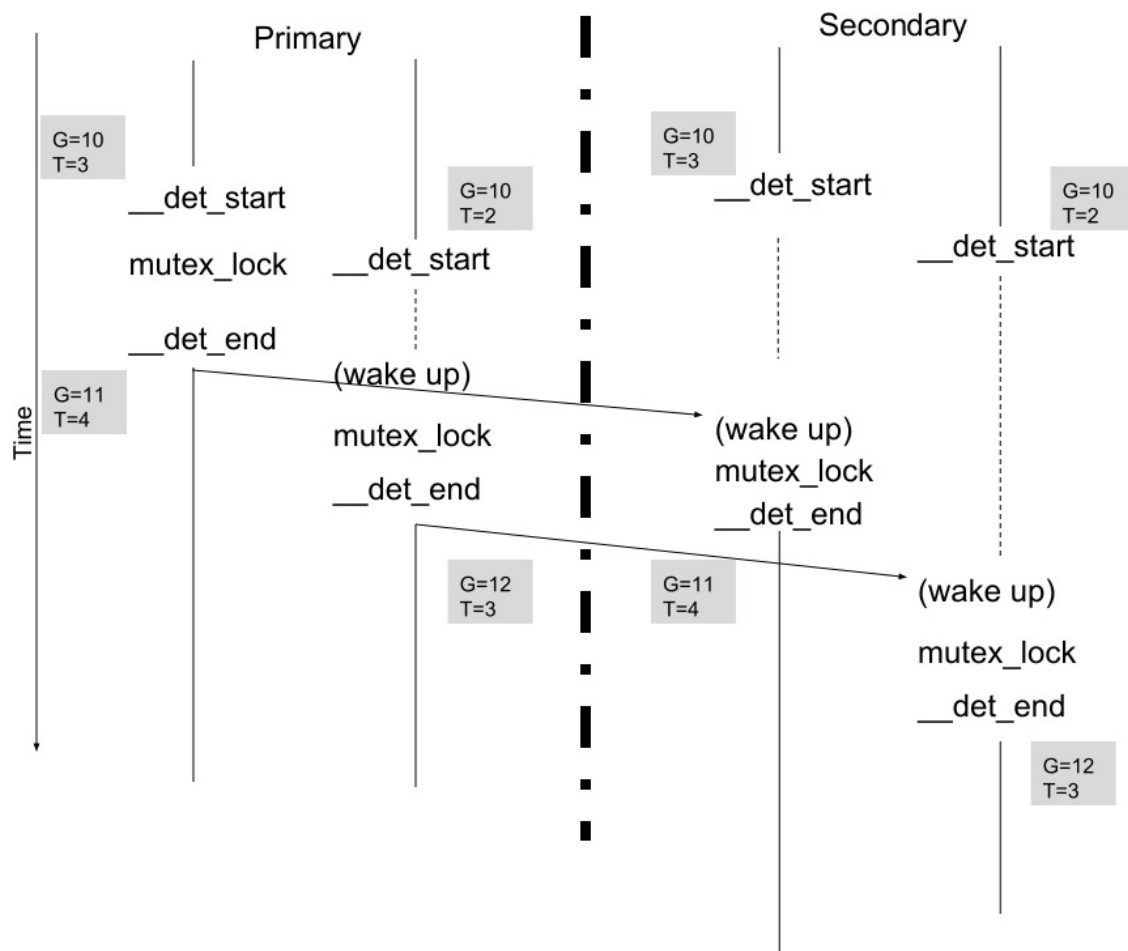Figure 4.2: Simplified implementation of system calls for schedule replication

Figure 4.3: An example of Schedule Replication

Chapter 5

Additional Runtime Support

In this chapter we will address some remaining issues of the replication system.

5.1 Syscall Synchronization

During the execution of an application, for most of the system calls, given the same external input, the application on both primary and secondary can produce the same result, however there are still some system calls that are intrinsically non-deterministic, which will lead to divergence of the execution on all the replicas. As a result we have to synchronize the output of them to ensure the consistent final output of the applications on both sides.

Disabling vDSO vDSO(virtual dynamic shared object) is a mechanism that allows a system call to be done in user space, instead of having context switch to the kernel space. This is done by having a shared memory section between the user space and the kernel. When the system call is initiated, the corresponding function in the vDSO library is called instead of trapping into the kernel, then the library will fetch the result from this shared memory area and return. This boosts the performance for some "read only" system calls (like gettimeofday/time). However, in our case, if the system call doesn't go into the kernel space, we cannot track and synchronize them. Also, in order to synchronize the system call data we have to get into the kernel space anyway to send inter-kernel messages. So vDSO in our context becomes a burden to the implementation. As a result in our system we have to disable vDSO.

In the following subsections we will describe each synchronized system call in detail.

```
1  struct pollfd {
2      int    fd;          /* file descriptor */
3      short  events;      /* requested events */
4      short  revents;     /* returned events */
5  };
```

Figure 5.1: pollfd data structure

5.1.1 gettimeofday/time

gettimeofday and time are used for getting the current timestamp. Since the primary and secondary can not always have the same execution progress, the timing of calling gettimeofday/time might be different. For those applications that the output is time related, those system calls will cause output divergence. For gettimeofday/time, the primary simply copies the result to the secondary, when secondary executes the corresponding gettimeofday/time, it directly uses the output from the primary and bypasses it's original path.

5.1.2 poll

poll is used for waiting on a set of file descriptors for I/O. A programmer can register a set of file descriptors to poll along with the type of events that is related to those file descriptors. poll takes an array of pollfd struct as shown in Figure 5.1. When it is called, it waits until one or more registered file descriptors become ready with registered events.

poll notification mechanism relies on the Linux VFS subsystem. However, as described in previous chapter, on the secondary kernel the replicated TCP/IP stack will bypass the original execution path for accept/read/write on sockets, in other words, the VFS subsystem is partially bypassed. As a result, poll will not be woken up properly on the secondary even when the event already arrives, which leads to a different output other than the primary.

5.2 Override Pthread Library

5.3 STDIO and STDERR

5.4 Synchronization Exclusion

Chapter 6

Evaluation

6.1 Correctness Evaluation

6.1.1 Racey Benchmarks

6.2 PBZip2

6.2.1 Overhead Profiling

6.2.2 Results

6.3 Mongoose Webserver

6.3.1 Overhead Profiling

6.3.2 Results

6.4 Nginx Webserver

6.4.1 Overhead Profiling

6.4.2 Results

6.5 Redis Database Server

6.5.1 Overhead Profiling

6.5.2 Results

Chapter 7

Conclusion

7.1 Contributions

7.2 Future Work

7.2.1 Pre-Lock Synchronization

7.3 Further Evaluation

Chapter 8

Bibliography