Dynamische Programmanalysen für nebenläufige Programme - Data Race Prediction mit TSan V2

Seminararbeit

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1 Introduction

Nowadays concurrent programs are very common in order to make use of 'hyper-threading and multi-core architectures'[1, p. 14]. 'Due to the highly non-deterministic behavior of concurrent programs' [2, p. 1] data races may arise but can also be hard to find, as they also 'may only arise under a specific schedule' [2, p. 1]. This seminar work shows the motivation and background for the data prediction tool ThreadSanitizer (TSan) V2, which differentiates itself from the first version by utilizing happens-before methods instead of the lockset method. Afterwards the concepts of the FastTrack [3] algorithm will be shown as TSan uses a slightly modified version of the FastTrack algorithm. Examples showing the limits of FastTrack and TSan follow, as they are both incomplete and thus do not find every data race. In the following the same notation as in [2] will be used for traces and events.

2 Motivation and Examples

As stated in the introduction concurrent programs are commonly used and are inherently prone to data races. The problem with data races is that they can cause undefined behavior and crashes while also being hard to reproduce. This makes data races hard to find and they might not always be apparent. This chapter will show a few examples from [4] but rewritten in the programming language C++. The following example shows a program, which exhibits a data race (see chapter 3):

```
#include "pthread.h"

int var1;
pthread_mutex_t var2;

void *Thread1(void *x) {
    // w(x)1
    var1++;
    // acq(y)2
    pthread_mutex_lock(&var2);
    // rel(y)3
    pthread_mutex_unlock(&var2);
    return NULL;
}

void *Thread2(void *x) {
    // acq(y)4
    pthread_mutex_lock(&var2);
    // w(x)5
    var1--;
    // rel(y)6
    pthread_mutex_unlock(&var2);
    return NULL;
}

int main() {
    pthread_t t[2];
    pthread_create(&t[0], NULL, Thread1, NULL);
    pthread_create(&t[1], NULL, Thread2, NULL);
    pthread_join(t[0], NULL);
    pthread_join(t[1], NULL);
}
```

Listing 1: Program containing conflicting events

Generally the corresponding event in the resulting trace is seen above each operation as a comment in the code. For example acquiring and releasing a lock is accomplished by the `pthread_mutex_lock()`- and the `pthread_mutex_unlock()`-method, which is used in line 10, where a lock on the variable `var2` is acquired. The corresponding event in the trace would be $1\#acq(y)_2$ which is indicated by the method name and the comment above in line 9. The method name shows which thread the event is from and the comment specifies the event. The following trace can be generated for the program 1:

	1#	2#
1.	w(x)	
2.	acq(y)	
3.	rel(y)	
4.		acq(y)
5.		w(x)
6.		rel(y)

Table 1: Possible trace of listing 1

In the trace 1 the events $1\#w(x)_1$ and $2\#w(x)_5$ do not appear right next to each other which might indicate that these two events are not part of a data race. By rerunning the program 1 eventually the following trace can be obtained:

	1#	2#
4.		acq(y)
5.		w(x)
1.	w(x)	
6.		rel(y)
2.	acq(y)	
3.	rel(y)	

Table 2: Trace 1 reordered

The trace 2 shows the two events $1\#w(x)_1$ and $2\#w(x)_5$ are now right next to each other and hence they are part of a data race. This only became apparent after reordering the original trace 1 which shows that data races may be hard to detect in some cases so tools are needed to detect them.

3 Background

3.1 Dynamic Data Race Prediction

Race prediction can be done static or dynamic. Static race prediction uses static analysis, meaning it tries to find data races before running the code. For more details on static race prediction see [5].
Dynamic data race prediction tools run a program and then try to find data races by reordering the obtained trace. The method of reordering traces to try to predict data races is called dynamic data race prediction, see [4, p. 2], and will be discussed in this work.
The approach of finding all possible reorderings is used in exhaustive predictive methods. Since modern programs may utilize multiple threads each executing large blocks of code, finding all possible reorderings might not always be feasible. Therefore effective predictive methods are employed which compromise *completeness* and *soundness* for better coverage. FastTrack and TSan are examples for dynamic data race prediction using effective predictive methods.
Sulzmann and Stadtmüller [2, p. 2] define completeness and soundness as follows:

> Sound means that races reported by the algorithm can be observed via some appropriate reordering of the trace. If unsound, we refer to wrongly a classified race as a *false positive*. Complete means that all valid reorderings that exhibit some race can be predicted by the algorithm. If incomplete, we refer to any not reported race as a *false negative*.

3.2 Happens-Before Relation and Data Race

As stated in [4, p. 4], the happens-before relation is used to partially order the events in a system. The happens-before relation is defined as a strict partial order so the ordering is transitive but irreflexive.
Events can either be ordered and therefore a happens-before relation can be established between them, or they can not be ordered in which case both events 'are said to be *concurrent*' [6, p. 2]. Further two events '[...] *conflict* if they both access (read or write) the same variable, and at least one of the operations is a write. Using this terminology, a trace has a race condition if it has two concurrent conflicting accesses.' [3, p. 2]. An example of a data race can be seen in the trace 2.
In FastTrack and TSan Lamport's happens-before relation [6], referred to as HB relation, is used. The HB relation additionally to the above imposes the program order condition and critical section order condition. The program order condition defines that two events e and f belonging to the same thread, with e appearing before f in the trace, then $e <^{HB} f$ applies. $<^{HB}$ denotes the HB ordering relation. The critical section order condition imposes that for two acquire and release events $acq(y)$ and $rel(y)$, with $rel(y)$ appearing before $acq(y)$ in the trace, then $rel(y) <^{HB} acq(y)$ applies [4, p. 4].

3.3 Vector-Clock

As stated by Cormac [3, p. 1]:

> Typically, the happens-before relation is represented using vector clocks (VCs) [...]. Vector clocks are expensive, however, because they record information about each thread in a system. Thus, if the target program has n threads, then each VC requires O(n) storage space and each VC operation requires O(n) time. Motivated in part by the performance limitations of vector clocks, a variety of alternative imprecise race detectors have been developed, which may provide better coverage but can report false alarms on race-free programs.

notation of VC, inc, sync...

3.4 Epoch

4 FastTrack + TSan

```c
#include <pthread.h>

int var;

void *Thread1(void *x) {
    // w(x)1
    var++;
    return NULL;
}

void *Thread2(void *x) {
    // w(x)2
    var--;
    // w(x)3
    // this write will not be reported as part of a data race
    var++;
    return NULL;
}

int main() {
    pthread_t t[2];
    pthread_create(&t[0], NULL, Thread1, NULL);
    pthread_create(&t[1], NULL, Thread2, NULL);
    pthread_join(t[0], NULL);
    pthread_join(t[1], NULL);
}
```

Listing 2: Program demonstrating the incompleteness of TSan

As seen in [7] Lamport's happens-before relation is also unsound. Because FastTrack and TSan both use the HB relation they might produce false positives as a result. The following program 3 shows an example in which TSan produces a false negative:

```c
#include <pthread.h>

int var1;
int var2;

void *Thread1(void *x) {
    // r(x)1
    // w(y)2
    var2 = var1 + 5;
    return NULL;
}

```

```c
void *Thread2(void *x) {
    // r(y)3
    if (var2 == 5)
        // w(x)4
        var1 = 10;
    else
        while (true);
    return NULL;
}

int main() {
    pthread_t t[2];
    pthread_create(&t[0], NULL, Thread1, NULL);
    pthread_create(&t[1], NULL, Thread2, NULL);
    pthread_join(t[0], NULL);
    pthread_join(t[1], NULL);
}
```

Listing 3: Program demonstrating the unsoundness of TSan

The program 3 may produce the following trace 3:

	1#	2#
1.	r(x)	
2.	w(y)	
3.		r(y)
4.		w(x)

Table 3: Possible trace of listing 3

5 Conclusion

List of Literature

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