

Compiler Testing via a Theory of Sound Optimisations in the C11/C++11 Memory Model

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Introduction

Testing sequential programs to hunt for compiler bugs is well established at this time. However, testing concurrency bugs still remains a hard problem. This is majorly due to ill understood specification of the memory consistency model, and lack of information on the various transformations that preserve concurrent program semantics. This work designs a strategy to reduce the complexity of finding concurrency bugs in C11/C++11 via testing sequential code. The source code trace is compared with that of the final end code trace. Previous theoretical work establishing soundness of various local transformations in concurrent execution is utilized to achieve this.

Example of Compiler optimisation

Consider the following example C code, where *th_1* and *th_2* are run by two different threads.

```
int g1 = 1; int g2 = 0;

void *th_1(void *p) {
    for (int l = 0; (l != 4); l++) {
        if (g1) return NULL;
        for (g2 = 0; (g2 >= 26); ++g2)
            ;
    }
}

void *th_2(void *p) {
    g2 = 42;
    printf("%d\n", g2);
}
```

The above code should print the value of *g2* to be 42.

However, the above code when compiled using gcc 4.7.0 with -O2 enabled on x86-64 machine, the result of printf is 0.

Compiler Testing via a Theory of Sound Optimisations in the C11/C++11 Memory Model

Example of Compiler optimisation

Consider the following example C code, where `th_1` and `th_2` are run by two different threads.

```
int g1 = 0, g2 = 0;  
void th_1(void*) {  
    int i; for (i = 0; i < 10; i++)  
        g1 = i * g1 * g1;  
}
```

The above code should print the value of `g2` to be 42. However, the above code when compiled using gcc 4.7.0 with `-O2` enabled on x86-64 machine, the result of `printf` is 0.

The reason why it should be 42 is that the value of `g2` is never changed in `th_1`. Notice that `g1` has 1, so the conditional will always return *NULL*. It is only `th_2` that writes to `g2`.

The above code is optimized using Loop invariant code motion in *th_1*. However, the code that results due to it in x86-64 format is as below:

```
th_1:
    movl  g1(%rip), %edx    # load g1 (1) into edx
    movl  g2(%rip), %eax    # load g2 (0) into eax
    testl %edx, %edx        # if g1 != 0
    jne   .L2               # jump to .L2
    movl  $0, g2(%rip)
    ret
.L2:
    movl  %eax, g2(%rip)    # store eax (0) into g2
    xorl  %eax, %eax        # return 0 (NULL)
    ret
```

Notice the last *movl* before return. Here the value of *g2* is restored to be 0. This is sound if the program was sequential, however, in a concurrent setting this is clearly unsafe.

Main idea of testing using traces: Another Example

Testing for such concurrency bugs is difficult. For this purpose, we note that the concurrency bugs are only among those actions which involve a shared memory. So reducing the source program to a set of actions performed on shared memory can first be done. This is followed by identifying the possible traces of these actions allowed by the program on its executions. The above code's problem can be observed by the following trace observed to be incorrect after optimization.

Init	g1	1	Init	g1	1
Init	g2	0	Init	g2	0
Load	g1	1	Load	g1	1
			Load	g2	0
			Store	g2	0

Compiler Testing via a Theory of Sound Optimisations in the C11/C++11 Memory Model

└ Main idea of testing using traces: Another Example

The memory model of C11 by this time was defined using traces / execution based semantics. It was more of utilizing this to do practical testing of C programs.

Testing for such concurrency bugs is difficult. For this purpose, we note that the concurrency bugs are only among those actions which involve a shared memory. So reducing the source program to a set of actions performed on shared memory can first be done. This is followed by identifying the possible traces of these actions allowed by the program on its executions. The above code's problem can be observed by the following trace observed to be incorrect after optimization.

Exec	g1: 1	Exec	g2: 1
Load	g1: 1	Exec	g2: 2
		Exec	g2: 3
		Exec	g2: 4

Overview of C11 memory model

To summarize the memory model, each shared memory access has a memory order. Each action has an access, memory order and thread id.

$\text{mem_ord}, \mu ::= \text{NA} \mid \text{SC} \mid \text{ACQ} \mid \text{REL} \mid \text{R/A} \mid \text{RLX}$

$\phi ::= \text{R}_\mu l v \mid \text{W}_\mu l v \mid \text{Lock } l \mid \text{Unlock } l \mid \text{Fence}_\mu \mid \text{RMW}_\mu l v_1 v_2$

$\text{actions} ::= aid, tid: \phi$

Useful terminology used for optimization

- Every concurrent program has various executions possible.
- These executions involve various shared memory *actions* that are done (even those due to multiple iterations of loop).
- A collection of these actions is defined to be an *opsem*.
- *opsem* also retains the syntactic order between actions belonging to same thread.
- All possible *opsems* for a program is called *opsemset*.

An example is as below;

`x = 1; y = 1; if (x == y){x = 42;}`
has, among others, the two opsems below:



Effect of an optimization

- The effect of an optimization is directly seen at the *opsem* level.
- For an *opsem*, an optimization has the effect of reordering, eliminating and introducing actions.

The following example showcases this:

```
for (i=0; i<2; i++) {  
    z = z + y + i;  
    x = y;  
}  
⇒  
t = y; x = t;  
for (i=0; i<2; i++) {  
    z = z + t + i;  
}
```

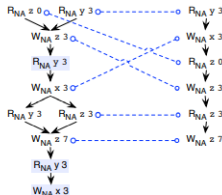


Figure 3: effect of loop invariant code motion (LIM) on an opsem

Soundness of Optimisations

- Every *opsem* represents an execution.
- The outcome of the execution can be characterized as the final values in memory and the final read values.
- These two are represented together as an *obs* or observable behavior.
- A pair *opsem*, *obs* represent a candidate execution.
- An optimization is sound if the set of *obs* of the transformed program is a subset of that of the source program .

Types of Optimizations considered

- Elimination - eg: Read-after-Write, Write-after-Write, etc.
- Reordering - eg: Read-Write, Read-Read, etc.
- Introduction - Read / Write.

Using above results for testing

Most bugs found in *gcc* were that where writes were introduced in the program. Some bugs were based on illegal reordering across atomic(SC) actions. The figure below showcases such a program

```
atomic_uint a; int32_t g1, g2;  
int main (int, char *[]) {  
    a.load () & a.load ();  
    g2 = g1 != 0;  
}
```

Trace analysis showcasing illegal reordering

gcc test version disallowed any reorderings across atomic actions. However, on trace analysis it was observed that the load of *g1* was moved above the two atomic loads to *a*.



Although in this case such a reordering does not result in any new outcome, introducing other concurrent threads running might result in some new behaviors.

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└ Trace analysis showcasing illegal reordering

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```
Thread 0: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 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2420 2421 2422 2423 2424 2425 2426 2427 2428 2429 2430 2431 2432 2433 2434 2435 2436 2437 2438 2439 2440 2441 2442 2443 2444 2445 2446 2447 2448 2449 2450 2451 2452 2453 2454 2455 2456 2457 2458 2459 2460 2461 2462 2463 2464 2465 2466 2467 2468 2469 2470 2471 2472 2473 2474 2475 2476 2477 2478 2479 2480 2481 2482 2483 2484 2485 2486 2487 2488 2489 2490 2491 2492 2493 2494 2495 2496 2497 2498 2499 2500 2501 2502 2503 2504 2505 2506 2507 2508 2509 2510 2511 2512 2513 2514 2515 2516 2517 2518 2519 2520 2521 2522 2523 2524 2525 2526 2527 2528 2529 2530 2531 2532 2533 2534 2535 2536 2537 2538 2539 2540 2541 2542 2543 2544 2545 2546 2547 2548 2549 2550 2551 2552 2553 2554 2555 2556 2557 2558 2559 2560 2561 2562 2563 2564 2565 2566 2567 2568 2569 2570 2571 2572 2573 2574 2575 2576 2577 2578 2579 2580 2581 2582 2583 2584 2585 2586 2587 2588 2589 2590 2591 2592 2593 2594 2595 2596 2597 2598 2599 2600 2601 2602 2603 2604 2605 2606 2607 2608 2609 2610 2611 2612 2613 2614 2615 2616 2617 2618 2619 2620 2621 2622 2623 2624 2625 2626 2627 2628 2629 2630 2631 2632 2633 2634 2635 2636 2637 2638 263
```


Yet another interesting transformation

The following program gives us an interesting view of "bug" caused by transformation

```
atomic_int a; uint16_t g;  
void func_1 () {  
    for (; a.load () <= 0; a.store (a.load () + 1))  
        for (; g; g--);  
}
```

On trace analysis, we note that a load to g has been replaced by a store to g .

ALoad	a	0	4	○-----○	ALoad	a	0	4
Load	g	0	2	○-----○ ?	Store	g	0	2
ALoad	a	0	4	○-----○	ALoad	a	0	4
AStore	a	0	4	○-----○	AStore	a	0	4
ALoad	a	1	4	○-----○	ALoad	a	1	4

Is it a bug?

The above situation was caused by the following transformation

$$\hat{\text{for}} \text{ } (; g ; g--) ; \quad \longrightarrow \quad \hat{\text{ }} \quad g = 0 ;$$

The source program itself would not change the value of g , leaving it to be the default value 0. In that sense, the transformation above does make sense, as a load is replaced by a redundant write to 0. However, whether such a transformation should be allowed or not is a debate. Note that the introduced write could lead to cache contention where there shouldn't be any, leading to performance dipping down.

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The above situation was caused by the following transformation

$$\text{for } i, p, q \in \mathbb{N} \quad \rightarrow \quad g \neq 0$$

The source program itself would not change the value of g , leaving it to be the default value 0. In that sense, the transformation above does make sense, as a load is replaced by a redundant write to 0. However, whether such a transformation should be allowed or not is a debate. Note that the introduced write could lead to cache contention where there shouldn't be any, leading to performance dipping down.

Its interesting that a transformation can in essence involve removing and inserting actions as an atomic step. Definitely, the class of transformations one can do is infinte. :o

Thank you

Questions?