Automatically Comparing Memory Consistency Models

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Context

In the specification of languages and architectures, a **memory consistency model** (MCM) defines what happens when threads access **shared memory locations**, and the extent to which different threads see consistent data. MCMs often take the form of a **set of axioms** that characterise which of a program's executions are allowed.

Multiprocessors (x86, ARM, Power), graphics processors (Nvidia, AMD), and high-level languages (C, C++, OpenCL) all define their own MCM.

Problem

Because MCMs take into account various optimisations employed by compilers and architectures, they are often **complex and counterintuitive**. This makes them challenging to design and to understand. Indeed, many bugs have been traced back to programmers, compiler-writers, and architects misunderstanding MCMs.

In particular,

- it is hard to assess the impact of a **proposed change** to an MCM's set of axioms,
- it is hard to ensure that a **compiler mapping** correctly implements its source language's MCM using its target language's MCM, and
- it is hard to ensure that a **compiler optimisation** is valid for a given MCM.

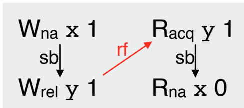
Our solution

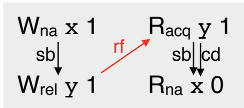
We use a constraint solver called **Alloy** to search for a program execution within the 'diff' between two given MCMs, gradually increasing the upper bound on execution size until one is found or time runs out. We then construct a litmus test that can only pass by taking this execution. (Getting Alloy to generate litmus tests directly is computationally infeasible.)

- If we give Alloy two variants of the same MCM, then any resultant litmus test is **minimal for distinguishing them**.
- If we give Alloy a source MCM, and a target MCM composed with a compiler mapping, then any resultant litmus test is a **minimal example of a bug in the mapping**.
- If we give Alloy the same MCM twice, the second copy composed with a compiler optimisation, then any resultant litmus test is a **minimal example of a bug in the optimisation**.

A thorny issue

How can we avoid constructing C++ litmus tests that are **racy** (and hence useless)? For example, these two executions are both disallowed by C++ ...





... and give rise (respectively) to similar-looking litmus tests...

```
x=1;          || r0=load(y,
store(y,1,    ||   ACQ);
  REL);       || r1=x;
```

```
x=1;          || r0=load(y,
store(y,1,    ||   ACQ);
  REL);       || if(r0) r1=x;
```

... but the left-hand test is racy! We avoid this problem by not generating executions like the top-left one in the first place. We achieve this by imposing an extra constraint, called **deadness**. (See our paper for more details.)

Results

- We compared **changes to the C++ MCM** proposed by Batty et al. (2016), Nienhuis et al. (2016), and Lahav et al. (2017) against the original C++ MCM. The distinguishing litmus tests that Alloy found automatically are **simpler than or the same as** those found manually by the respective authors.
- We checked some **compiler optimisations** against the C++ MCM, and found bugs that are **simpler than or the same as** those found manually by Vafeiadis et al. (2015).
- We checked **compiler mappings** from C++ to Power multiprocessors and from OpenCL to AMD graphics processors, and found bugs that are **simpler than or the same as** those found manually by Lahav et al. (2016) and by Wickerson et al. (2015).
- We used our technique to aid the development of a **refined MCM for Nvidia graphics processors** that supports an efficient mapping from OpenCL.

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