



1-1-2011

Litmus Tests for Comparing Memory Consistency Models: How Long Do They Need to Be?

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Sela Mador-Haim, Rajeev Alur, and Milo Martin, "Litmus Tests for Comparing Memory Consistency Models: How Long Do They Need to Be?", . January 2011.

University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-11-04.

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Abstract

Even though the general problem of comparing two memory models is infeasible, in this paper we show that checking the equivalence of two memory models becomes feasible when we consider a more restricted class of memory models. We define a class of memory models that is expressive enough to include most known hardware memory models, and we establish a bound of two threads and no more than six memory access instructions for contrasting litmus tests in this class of models. Thus, we can compare memory models in this class by checking a small number of litmus tests. We build a tool for comparing memory models based on this theorem and use the tool to explore and map the space of this class of models.

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Litmus Tests for Comparing Memory Consistency Models: How Long Do They Need to Be?*

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ABSTRACT

Even though the general problem of comparing two memory models is infeasible, in this paper we show that checking the equivalence of two memory models becomes feasible when we consider a more restricted class of memory models. We define a class of memory models that is expressive enough to include most known hardware memory models, and we establish a bound of two threads and no more than six memory access instructions for contrasting litmus tests in this class of models. Thus, we can compare memory models in this class by checking a small number of litmus tests. We build a tool for comparing memory models based on this theorem and use the tool to explore and map the space of this class of models.

1. INTRODUCTION

Well-defined memory consistency models are important for reasoning about the correctness of hardware, parallel software, and compiler optimizations. Developing and understanding formal specifications of hardware memory models is a challenge due to the subtle differences in allowed reorderings. Architecture manuals include litmus tests that can be used to differentiate between memory models, but do not guarantee the completeness of those litmus tests.

Recent work [11] showed memory consistency models can be contrasted by systematically enumerating litmus tests of a bounded length. This technique, however, is not sufficient to prove the equivalence of two models. Conventional wisdom is that contrasting litmus tests are typically short, but a bound for litmus tests has not been established so far. Without restricting our class of memory models, there is no bound for the size of contrasting litmus tests. For example, for any bound k , we can define two models that behaves differently only for one specific test of size $k+1$. Therefore, we need to consider a more restricted class of memory models.

This paper defines a class of memory models which is limited to show a bound, yet expressive enough to contain most hardware memory models, including Sun’s SPARC [15], Intel’s x86 [8] and Alpha [13]. This class of memory models is defined using a must-not-reorder function that specifies which instructions in the program cannot be reordered. For a given must-not-reorder function, we specify all possible orders between memory operations using a “happens-before”

partial order. We prove that for this class of models, short litmus tests consisting of two threads and up to three memory access instructions (reads and writes) in each thread are sufficient to contrast any two models in this class. Furthermore, we show that the number of non-memory-access operations is also bounded and depends on the choice of predicates in the must-not-order function.

In addition to bounding the size of contrasting litmus tests, we reduce the number of litmus tests further by considering instantiations of seven different templates, which are sufficient for contrasting all memory models in this class. This way, we reduce the number of litmus tests necessary for equivalence checking of two memory models by several orders of magnitude over naive enumeration.

Finally, we use this equivalence checking technique to explore this class of memory models. We select a set of predicates that specifies the commonly used properties of memory models including different reordering choices for memory access instructions, full fences, and data dependencies. We show that for this class of memory models, consisting of 90 different models, there are eight pairs of equivalent models and identify nine litmus tests that are sufficient for differentiating all memory models in this class.

The main contributions of this paper are:

A theorem that bounds the size of contrasting litmus tests, which justifies the conventional wisdom regarding the size of litmus tests.

A tool for comparing memory models, which works in a reasonable time (seconds) and can show the equivalence between memory models based on the theorem we proved.

Results of exploration of the space of memory models in our class of models, using our tool, showing how different choices in the specification affect the models and which models are equivalent.

2. SPECIFYING MEMORY MODELS

This section defines the class of memory models studied in this paper. We start with a general definition of memory models as a set of allowed program executions. We provide a definition for an expressive but limited class of memory models, describe the predicates used for defining the models, and show how different known memory models are defined in our framework.

2.1 Program Executions

A *parallel program* P is a set of concurrently executed threads, where each *thread* is a sequence of instructions. In the context of memory models, we classify instructions

*The authors acknowledge the support of NSF grants CCF-0905464 and CCF-0644197, and of the Gigascale Systems Research Center, one of six research centers funded under the Focus Center Research Program (FCRP), a Semiconductor Research Corporation entity.

into two groups: memory access instructions, which are instructions that read and write to memory, and non-memory access instructions, which include any other instruction including memory fences, arithmetic operations and branches.

Memory consistency models define the possible behaviors of a parallel program and constrain the values each read may observe. A general way to define a memory model is as a set of allowed *program executions*. Informally, a program execution specifies the sequence of instructions that were executed in each thread, annotated with the actual values for all the involved registers.

In each step, a program executes an instruction with concrete values for all of the involved registers. An instance of instruction i , annotated with the values for all the involved registers, is called an *instruction execution*.

A thread may exhibit many different executions, because an execution usually depends on the other threads. A *thread execution*, α_t is a sequence of instruction executions in the order they are executed in thread t . In case an instruction is executed more than once (due to a loop), there can be several instruction executions that correspond to the same instruction, so loops are unrolled.

As an example for thread executions, suppose a thread t reads from memory to registers $r1$ and $r2$, computes the result of $r1 + r2$, stores it to $r3$, and finally writes $r3$ to memory. An execution α_t of that thread could have any value for $r1$ and $r2$, but each write would always be the sum of $r1$ and $r2$.

The order of two instruction executions x and y with respect to a given thread execution α_t is called *program order*. We use the notation $x < y$ when x precedes y in α_t . A *program execution*, α_P , associates a thread execution with each thread in a program P . A memory model M is defined as a set of allowed program executions. For two memory models, M_1 and M_2 , we say that $M_1 \subseteq M_2$ if and only if for every program execution α_P , $\alpha_P \in M_1$ implies $\alpha_P \in M_2$. If $M_1 \subseteq M_2$ and $M_2 \subseteq M_1$, the two models are equivalent.

2.2 The Class of Memory Models

The general problem of comparing two memory models, in which each memory model is defined as a set of allowed program executions, is infeasible. The size of contrasting litmus tests is generally unbounded. Our approach is to consider a class of memory models that is limited enough to bound the size of contrasting litmus tests yet expressive enough to include most existing hardware memory models.

The class of memory models we consider is a class of relaxed memory models that allow reorderings of local instructions. The order in which memory access operations (read and write) are performed does not have to be the same as their program order, and the types of instructions that can and cannot be reordered vary between different memory models. We allow a thread to read its own writes early, but do not allow read other thread's writes early [1]. Thus, this class of memory models is expressive enough to include most hardware memory models, including Sequential Consistency (SC) [9], Sun's SPARC [15] and Intel's x86 [8], but not non-store-atomic models like PowerPC [3].

These memory models are defined using a *must-not-reorder* function $F(x, y) \rightarrow \{True, False\}$. Intuitively, if $F(x, y)$ is true, the instructions x and y cannot be reordered and must be executed in program order. Based on the choice of F , we define which program executions are allowed, using

two relations between instruction executions in a program execution α_P : A *read-from map* \mapsto , mapping reads to the writes they are reading from, and an *happens-before* order \Rightarrow , which represents the global order of execution of instructions in the program.

Given a program execution α_P and a local order function F , a relation \mapsto is a read-from relation between instruction executions in α_P , if:

If $x \mapsto y$, then x is a write, y is a read, and the value read by y is same as the value written by x .

If $x \mapsto y$ and $z \mapsto y$, then $x = z$ (only one write is mapped to each read)

If x is a read and there is no write y such that $y \mapsto x$, then x reads the initial value

If $x > y$, then $x \not\mapsto y$ (cannot read from a future write in the same thread)

Given a program execution α_P , a local order function F and a read-from map \mapsto , a happens before relation \Rightarrow is a partial order between instruction executions in α_P with the following properties:

Program order If $F(x, y)$ and $y > x$ then $x \Rightarrow y$

Write-write If x and y are both writes to the same address, then either $x \Rightarrow y$ or $y \Rightarrow x$

Write-read If $x \mapsto y$ and x and y are from different threads, then $x \Rightarrow y$

Read-Write If x is a read and y is a write to the same address such that $y \not\mapsto x$, and there is no write z such that $z \mapsto x$ and $y \Rightarrow z$, then $x \Rightarrow y$.

Ignore local If $x > y$ then $x \not\Rightarrow y$

A program execution α_P is allowed in F , if there for some read-from relation \mapsto for α_P there is a happens-before relation \Rightarrow which is acyclic.

2.3 Must-not-reorder Function Predicates

The must-not-reorder function F we use in our class of models is a quantifier-free positive boolean function, constructed from a set of predicates D on instruction executions. Predicates are either unary or binary, and are defined for a program execution α_P and instruction executions x, y in α_P . For example, some commonly used predicates are:

- $Read(x)$, $Write(x)$, $Fence(x)$ - the instruction is a read, a write or a fence
- $DataDep(x, y)$, $ControlDep(x, y)$ - data and control dependence
- $SameAddr(x, y)$ - both x and y access the same address

Our analysis of memory models is not restricted to a specific D . However, we require that all predicates preserve some symmetry, such that a read can be permuted with any other read (and a write by any other write) under this symmetry. As an example, the set of predicates listed here preserve value, address and register symmetries, so any two reads $Read\ X \rightarrow r1$ and $Read\ Y \rightarrow r2$ can be permuted.

2.4 Memory Model Examples

Using the must-not-order function, we can define different hardware models. For example, SC do not allow any reordering and therefore specified using $F_{SC} = False$.

IBM370's memory model allows reordering writes after reads, except reads to the same address. $F_{IBM370}(x, y) = (Write(x) \wedge Read(y) \wedge SameAddr(x, y)) \vee (Write(x) \wedge Write(y) \vee Read(x) \vee Fence(x) \vee Fence(y))$

SPARC's TSO allows reordering writes after reads, including reads to the same address. In case a write is ordered

Test A

T1	T2
Write X ← 1	Write Y ← 2
Fence	Read Y → r2
Read Y → r1	Read X → r3
Outcome: r1 = 0; r2 = 2; r3 = 0	

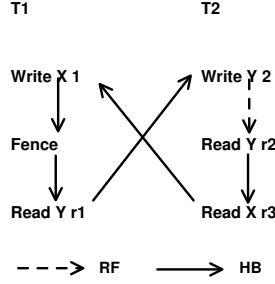


Figure 1: A Litmus test for TSO

after a read to the same address, there is an effect of load forwarding, where a load observes local writes before they become visible to other threads. As seen in Figure 1, the \Rightarrow relation does not include write-read edges between writes and reads in the same thread. There is no happens-before edge from Write Y ← 2 to Read Y → r2 and thus \Rightarrow is acyclic. $F_{TSO}(x, y) = (Write(x) \wedge Write(y)) \vee Read(x) \vee Fence(x) \vee Fence(y)$.

Finally, SPARC's RMO allows reordering everything except fences, dependent instructions and read/write instructions after a write to the same address. $F_{RMO}(x, y) = (Write(y) \wedge SameAddr(x, y)) \vee Fence(x) \vee Fence(y) \vee DataDep(x, y) \vee ControlDep(x, y)$.

3. SMALL LITMUS TEST THEOREM

Given two memory model specifications, we want to find whether they are equal or different. We show that for the family of memory models defined in Section 2.2, we only need litmus tests with a bounded size. We find the bound for these tests in terms of the number of memory accesses in the test and number of threads.

THEOREM 1. *For every two memory models, M_1 and M_2 , that are defined via a must-not-reorder function, if $M_2 \not\subseteq M_1$, then there is a test P and an execution α_P with two threads and up to six memory access operations, such that $\alpha_P \notin M_1$, $\alpha_P \in M_2$.*

3.1 Conflict Cycle

Given two memory models M_1 and M_2 , if $M_2 \not\subseteq M_1$, there is a test P and execution α_P such that $\alpha_P \in M_2$ and $\alpha_P \notin M_1$. In this case, there is a read-from map \mapsto and an happens-before relation \Rightarrow_2 for α_P and M_2 , such that \Rightarrow_2 is acyclic, and for every read-from map (including \mapsto) and \Rightarrow_1 for α_P and M_1 , \Rightarrow_1 is cyclic.

Given \Rightarrow_1 , an happens-before relation for M_1, α_P, \mapsto , let C be the set of instruction executions in the smallest cycle in \Rightarrow . We construct the following execution, $\alpha_{P'}$, based on the instructions in C :

1. If $x \in C$ then $x \in \alpha_{P'}$.
2. If x is a write, y is a read and $x \mapsto y$, the value read by y in $\alpha_{P'}$ is the value written by x .
3. If x is a read, y is a write and $x \mapsto y$, the value read by x in $\alpha_{P'}$ is the initial value.
4. If x, y are write instructions and $x \mapsto y$, we add a new read instruction z at the end of the thread of x , reading the value written by y .

LEMMA 1. $\alpha_{P'}$ is in M_2 but not in M_1

Proof: \Rightarrow_2 , the happens-before relation for M_2 is acyclic, and therefore the instructions in C do not form a cycle in \Rightarrow_2 . There are two instructions $x, y \in C$, such that $x \mapsto_1 y$, $x \not\mapsto_2 y$ and there is no other instruction before x connected to any instruction after y in the graph of \Rightarrow_2 (there is no bypass edge). We call this edge between x and y a *critical edge*. The only source of difference between \Rightarrow_1 and \Rightarrow_2 is the difference in the local order function, and therefore x and y belong to the same thread.

The only edges $\alpha_{P'}$ adds to C are due to the added read operations. These operations have incoming edges but no outgoing edges and therefore can not form a cycle. Hence, $\alpha_{P'}$ has an acyclic happens-before relation in M_2 .

For any happens-before relation $\Rightarrow_{P'}$ for $\alpha_{P'}$ and M_1 and any x, y in C , if $x \mapsto_1 y$ is a program order edge, then $x \Rightarrow_{P'} y$ as well, because the local order function stay the same. If x is a write and y is a read, then $x \Rightarrow_{P'} y$ because y still reads the value written by x . If x is a read and y is a write, then $x \Rightarrow_{P'} y$ because x reads the initial value and all writes precede it. If x and y are both writes, $x \Rightarrow_{P'} y$ as well, because the added read in x 's thread sees the value of y , which is possible only if y precedes x . All the edges in the cycle of \Rightarrow_1 are preserved in $\Rightarrow_{P'}$, and therefore it is cyclic.

3.2 Constructing Minimal Test

A *segment* is a sequence of instructions, connected by program-order edges, that starts with a memory access operation (read or write), ends with a memory access, and has no other memory access in between them. We can classify the segments according to the type of memory accesses: read-read, read-write, write-read, and write-write.

A segment that contains a critical edge is a critical segment. We can now show that for each type of critical segment, we can construct a litmus test with only two threads and up to six memory access operations, as illustrated in the diagrams in Figure 2:

Case 1 The critical segment is read-write. Use this segment at thread T_1 . Add an identical segment for T_2 , changing the address of the read to match the write in T_1 , and the write to match the read in T_1 . Total number of memory access operations: four.

Case 2 The critical segment is a write-write. Use this segment for thread T_1 , duplicate it for thread T_2 , switching addresses. Add a read at the end of T_1 , reading the value of the first write in T_2 , and a read at the end of T_2 , reading the value of the first write in T_1 . Total number of memory access operations: six.

Case 3 The critical segment is a read-read. Because there are no inter-thread read-read edges in \Rightarrow , there *must* be either a write-write segment or both a write-read segment $W1, \dots, R1$ and a read-write segment $R2, \dots, W2$ in the cycle. In the later case, according to the symmetry requirement in Section 2.3, there is a symmetric segment $R2', \dots, W2'$ such that $R2' = R1$. Therefore, we merge both segments into a write-write segment: $W1, \dots, R1, \dots, W2'$. Use the read-read segment for thread T_1 and the write-write segment for thread T_2 . Total number of memory access operations: four to five.

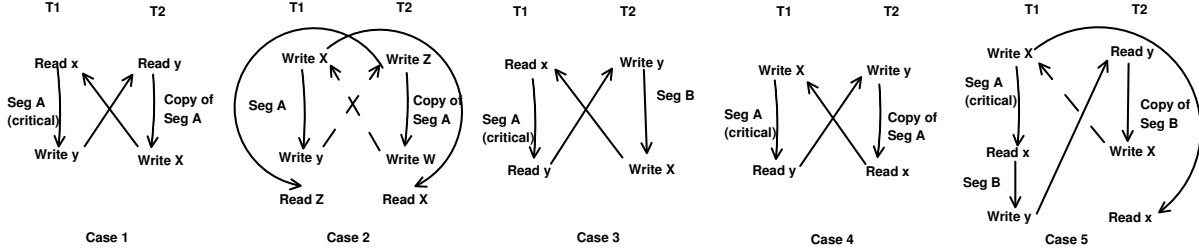


Figure 2: Litmus test templates by critical segment

Case 4 The critical segment is a write-read to different addresses. Use this segment as T_1 , duplicate it for T_2 , change the read in T_2 to match the address of the write in T_1 and vice versa. Each read gets the initial value. Total number of memory access operations: four.

Case 5 Like Case 4, but write and read are both to the same address. If there is a segment with a write and then a read to the same address, there cannot be a memory-access read-write edge involving this read because according to our definition of a minimal cycle, the read should receive the initial value, which is impossible in this case. So we conclude there is another read-read or read-write segment in the same thread.

1. If there is a read-read segment to two different addresses, merge it after the critical segment (combined segment have 3 operations), and continue as in Case 4. Total number of memory access operations: six.
2. If there is a read-write segment, merge it after the critical segment, resulting in a write-write segment. Copy the read-write segment to T_2 , connect the end of T_1 with T_2 using a write-read edge, and connect the end of T_2 with the beginning of T_1 (adding a read at the end of T_2 as previously discussed). Total number of memory access operations: six.

3.3 Local Segments

Theorem 1 bounds the number of threads and the number of memory access operations (reads and writes) required in a litmus test. However, additional instructions such as fences, arithmetic operations or branches affect the dependency relations between memory access instructions and therefore may be required. The required number of non-memory access instructions depends on the specific choice of predicates in D .

For example, consider a hypothetical model with n special fence instructions f_1, \dots, f_n and the predicate $special(x, y)$ which is true if either: (1) x is a memory access instruction and $y = f_1$, (2) $x = f_n$ and y is a memory access. Or, (3) $x = f_i$ and $y = f_{i+1}$. Consider $F_1(x, y) = SameAddr(x, y) \vee special(x, y)$ and $F_2(x, y) = SameAddr(x, y)$. Any litmus test contrasting F_1 and F_2 should include a local segment of $n + 2$ instructions such as $Read X, f_1, \dots, f_n, Write y$. Therefore, the minimal number of non-memory access instructions in a local segment depends on the choice of predicates and the instruction set.

The length of local segments is bounded by the number of equivalence classes of instructions according to our choice

of predicates. Given a set of predicates D , two instructions x and y are equivalent with respect to D , $x =_D y$ if for every predicate $d \in D$ and every instruction z , $d(x, z) = d(y, z)$ and $d(z, x) = d(z, y)$. Consider the memory model with a must-not-order function F_1 , and a segment i_1, \dots, i_n in a minimal conflict cycle for this model. Because it is a segment in a cycle, for every two adjacent instructions i_j, i_{j+1} , $F_1(i_j, i_{j+1})$ is true. Suppose two instructions in the segment are equivalent $i_j =_D i_k$ ($1 < j < k < n$), then $F_1(i_j, i_{k+1})$ is also true and therefore we can reduce the segment to $i_1, \dots, i_j, i_{k+1}, \dots, i_n$, in contradiction to the minimality of the cycles. We conclude that a local segment cannot contain two equivalent non-memory-access instructions, and therefore its length is bounded by the number of equivalence classes for these instructions.

3.4 Reducing the Number of Litmus Tests

A consequence of the proof of Theorem 1 in Section 3.2 is that not only we can bound the size of the litmus tests to two threads and six instructions, we can further reduce the number of litmus tests by exploring the cases described in the proof of Theorem 1. There are five different cases listed in the proof, and two of the cases (Case 3 and Case 5) are split into two sub-cases, which amounts to a total of seven templates. We can therefore compare memory models by instantiating these seven templates with all possible local segments.

Two segments s_1, s_2 are equivalent with respect to D if they are of the same length and for every pair of instructions in s_1 , every predicate in D would have the same value as for a pair of instructions in the same position in s_2 . Corollary 1 gives a bound for the number of tests as a function of the number of distinct segments of each type.

COROLLARY 1. *Suppose the number of distinct local segments of each type given by N_{WW} , N_{WR} , N_{RW} , and N_{RR} . The total number of required tests is given by $N_{RW} + N_{WW} + N_{RR}(N_{WW} + N_{WR} \times N_{RW}) + N_{WR}(1 + N_{RR} + N_{RW})$*

As discussed in Section 3.3, it is sufficient to know the set of predicates to bound the number of local segments. For example, suppose the predicates are: $Read(x)$, $Write(x)$, $Fence(x)$, $SameAddr(x, y)$ and $DataDep(x, y)$. For read-write segments, we need to consider segments with only independent read and write, with dependent read and write, and a segment with a fence between the read and the write. For each of these three cases, we need to consider read and write to the same address and to different addresses, so $N_{RW} = 6$ and similarly $N_{RR} = 6$. For write-read and write write segments we do not need to consider dependencies (writes

Test L1

T1	T2
Write $X \leftarrow 1$	Read $Y \rightarrow r1$
Write $Y \leftarrow 1$	Fence
	Read $X \rightarrow r2$

Outcome:
 $r1 = 1; r2 = 0$
 Test L3

T1	T2
Write $X \leftarrow 1$	Read $Y \rightarrow r1$
Fence	Read $X \rightarrow r2$
Write $Y \leftarrow 2$	

Outcome:
 $r1 = 2; r2 = 0$
 Test L5

T1	T2
Read $X \rightarrow r1$	Read $Y \rightarrow r2$
Write $Y \leftarrow 1$	Write $X \leftarrow 1$

Outcome:
 $r1 = 1; r2 = 1$
 Test L7

T1	T2
Write $X \leftarrow 1$	Write $Y \leftarrow 1$
Read $X \rightarrow r1$	Read $Y \rightarrow r3$
Read $Y \leftarrow r1$	Read $X \rightarrow r2$

Outcome:
 $r1 = 0; r2 = 0$
 Test L9

T1	T2
Write $X \leftarrow 1$	Read $Y \rightarrow r2$
Read $X \rightarrow r1$	$t2 = r2 - r2 + 2$
$t1 = r1 - r1 + 1$	Write $X \rightarrow t2$
Write $Y \leftarrow [t1]$	Read $X \rightarrow r3$

Outcome:
 $r1 = 1; r2 = 1; r3 = 1$

Figure 3: Contrasting litmus tests

do not generate dependencies), so $N_{WR} = N_{WW} = 4$. According to Corollary 1, we need a total of 230 tests to contrast memory models expressible with these predicates. Similarly, without data dependencies, we need 124 tests.

A naive enumeration of all tests within the bounds of Theorem 1 results in approximately million tests even without dependencies. Earlier work [11] describes optimizations that reduce the number of tests to several thousands. This paper improves upon earlier work by more than an order of magnitude.

4. EXPERIMENTAL RESULTS

4.1 Implementation

We implemented a tool for contrasting memory model specifications via systematic exploration of litmus tests. We use the method described in Section 3.4 to reduce the number of tests according to the set of predicates used in the specification. The memory models are specified using a must-not-reorder function and the axioms in Section 2.2. We use the SAT solver mini-sat [7] to test if a litmus test is admissible for a given memory model.

4.2 Exploring the Space of Memory Models

Using this tool, we performed an exhaustive exploration of all memory models that are expressible using the framework described in Section 2.2, with the predicates: $Read(x)$, $Write(x)$, $Fence(x)$, $SameAddr(x, y)$ and $DataDep(x, y)$. This set of predicates is sufficient to describe most common properties of memory models,

Test L2

T1	T2
Write $X \leftarrow 1$	Read $X \rightarrow r1$
Write $X \leftarrow 2$	Read $X \rightarrow r2$

Outcome:
 $r1 = 2; r2 = 0$
 Test L4

T1	T2
Write $X \leftarrow 1$	Read $Y \rightarrow r1$
Fence	$t1 = r1 - r1 + X$
Write $Y \leftarrow 2$	Read $[t1] \rightarrow r2$

Outcome:
 $r1 = 2; r2 = 0$
 Test L6

T1	T2
Read $X \rightarrow r1$	Read $Y \rightarrow r2$
$t1 = r1 - r1 + 1$	$t2 = r2 - r2 + 1$
Write $Y \leftarrow t1$	Write $X \leftarrow t2$

Outcome:
 $r1 = 1; r2 = 1$
 Test L8

T1	T2
Write $X \leftarrow 1$	Write $Y \leftarrow 1$
Read $X \rightarrow r1$	Read $Y \rightarrow r3$
$t1 = r1 - r1 + Y$	$t2 = r3 - r3 + X$
Read $[t1] \rightarrow r2$	Read $[t2] \rightarrow r4$

Outcome:
 $r1 = 1; r2 = 0; r3 = 1; r4 = 0$

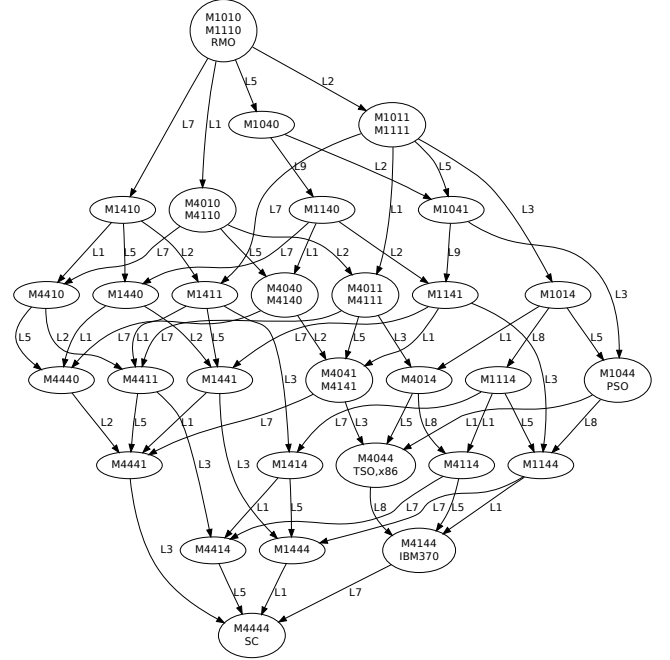


Figure 4: Relation between explored models (without data dependencies)

including data dependencies. Models expressible in this framework include IBM370, Intel’s x86 Sparc’s TSO, PSO and variants of RMO and Alpha (for a complete specification of RMO and Alpha, we need to add control dependencies, which were not implemented but are supported by our framework). As discussed in Section 3.4, it is sufficient to check 230 litmus tests to contrast all models when using the above set of predicates.

Based in the selected predicates, there are five possible choices for each of the four pairs of memory operations (write-write, write-read, read-write and read-read). The options to allow reordering are:

0. Always
1. Accesses to different addresses
2. There are no data dependencies
3. Different addresses and no data dependencies
4. Never

Some of the above options can be eliminated for some of the instruction pairs. Reordering read-write and write-write with the same address can violate single-thread consistency and therefore we do not consider them. Additionally, there is no need to consider dependencies for write-read and write-write. After eliminating these cases, there are two available choices for write-write, there choices for write-read and read-write and all five choices are available for read-read, which result in 90 possible memory models.

Using our tool, we compared these 90 models with each other. The tool tested whether each model is equivalent or strictly stronger than the other models, and which litmus tests can be used to contrast each pair of models. The comparison of each pair of models was done in a few seconds, and a pairwise comparison of all 90 models completed in 20 minutes.

Out of the 90 different models, eight pairs of models are equivalent. All equivalent pairs of models are models that

differ only with the choice of whether to allow reordering of writes with later reads to the same address. Furthermore, a set of nine different litmus tests is sufficient to contrast any two non-equivalent memory models in this space. Figure 3 shows the set of nine litmus tests. The relationships between the explored models is shown in Figure 4. The direction of the arrows is from weaker to stronger models, and the labels on the edges are the litmus tests that distinguish between the models. Due to space considerations, the graph in Figure 4 does not include models with data dependencies.

A further analysis of this minimal set of litmus tests shows that tests L1 to L7 in Figure 3 correspond directly to the choices in model enumeration. For example, test L5 checks if a read can be reordered after an independent write to a different address, and test L6 checks if a read can be reordered after a dependent write to the same address (ignoring data dependencies). The assignment $t1 = r1 - r1 + 1$ is a standard trick for generating data dependencies between $r1$ and the write that uses $t1$. One exception in the case of reordering writes after later reads to the same address. As shown in Case 5 of the proof of Theorem 1, when the critical segment is a write-read segment to the same address, we need either a read-read or a write-read segment following it to close a cycle. This leads to litmus tests L8 and L9 in Figure 3. Test L8 is used in models where reads to a different address cannot be reordered. By adding dependencies between the reads, it can also be used for models that do not allow reordering dependent reads. Similarly, Test L9 is used for models that do not allow reordering reads with later writes. However, in models that allow reordering both read-write and dependent read-read, neither Test L8 nor Test L9 can be used. Thus, write-read reordering to the same address cannot be detected. These models are the eight pairs of equivalent models found by our experiments.

5. RELATED WORK

There has been a considerable amount of work on defining frameworks for specifying memory consistency models [1, 2, 4, 5, 12, 14, 16]. The concept of happens-before partial order between events was introduced by Lamport [10] and then by Adve [2] in the context of memory consistency models. Burckhardt and Musuvathi [6] provide a definition for SPRAC’s TSO using a happens-before relation. Alglave et al. [4] define a framework for specifying hardware memory consistency models using a happens-before relation. Our class of memory models is similar to the one described by Alglave et al. Mador-Haim et al. [11] describes a technique for contrasting memory models via automatic generation of litmus tests up to a certain bound, but they do not identify a bound for those litmus tests.

6. CONCLUSIONS

In this paper we showed that even though the general problem of comparing two memory model specifications is infeasible, checking the equivalence of two memory models becomes feasible when we consider a more restricted class of memory models. We defined a class that is limited yet expressive enough to include most known hardware memory models, and we established a bound of two threads and six memory accesses for contrasting litmus tests in this class of models. Thus, we can compare memory models in this class by testing a small number of litmus tests.

Furthermore, we analyzed a subset of this class that includes most common memory model features, including instruction reordering, fences and data dependencies, and showed that a set of nine litmus tests is sufficient to contrast models in this subset.

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