diy7 is a tool suite for testing shared memory models. We provide several tools, litmus7 (Part I) and klitmus7 (Sec. 5) for running tests, diy7 generators (Part II) for producing tests from concise specifications, and herd7 (Part III) for simulating memory models. In Part IV we describe a few concrete experiments, illustrating frequent usage patterns of diy7 generators and of litmus7.

The software is written in Objective Caml\(^1\), and released as sources. The web site of diy7 is \url{http://diy.inria.fr/}; authors can be contacted at diy-devel@inria.fr. This software is released under the terms of the CeCILL-B Free Software License Agreement.

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Part I

Running tests with litmus7

Traditionally, a *litmus test* is a small parallel program designed to exercise the memory model of a parallel, shared-memory, computer. Given a litmus test in assembler (X86, Power or ARM) litmus7 runs the test.

Using litmus7 thus requires a parallel machine, which must additionally feature gcc and the pthreads library. Our tool litmus7 has some limitations especially as regards recognised instructions. Nevertheless, litmus7 should accept all tests produced by the companion test generators (see Part II) and has been successfully used on Linux, MacOS, AIX and Android.

1 A tour of litmus7

1.1 A simple run

Consider the following (rather classical, store buffering) SB.litmus litmus test for X86:

```
X86 SB
"Fre PodWR Fre PodWR"
{x=0; y=0; }
PO | P1 ;
MOV [x],$1 | MOV [y],$1 ;
MOV EAX,[y] | MOV EAX,[x] ;
locations [x;y]
exists (0:EAX=0 /\ 1:EAX=0)
```

A litmus test source has three main sections:

1. The initial state defines the initial values of registers and memory locations. Initialisation to zero may be omitted.
2. The code section defines the code to be run concurrently — above there are two threads. Yes we know, our X86 assembler syntax is a mistake.
3. The final condition applies to the final values of registers and memory locations.

Run the test by:

```
% litmus7 SB.litmus

%%%%%%%%%%%%%%%%%%%%%%%%
% Results for SB.litmus %
%%%%%%%%%%%%%%%%%%%%%%%%
X86 SB
"Fre PodWR Fre PodWR"
{x=0; y=0; }
PO | P1 ;
MOV [x],$1 | MOV [y],$1 ;
MOV EAX,[y] | MOV EAX,[x] ;
exists (0:EAX=0 /\ 1:EAX=0)
Generated assembler
#START _litmus_P1
```
movl $1,(%r10)
movl (%r9),%eax

#START _litmus_P0
movl $1,(%r9)
movl (%r10),%eax

Test SB Allowed
Histogram (4 states)
40    >0:EAX=0; 1:EAX=0;
499923: >0:EAX=1; 1:EAX=0;
500009: >0:EAX=0; 1:EAX=1;
28    : >0:EAX=1; 1:EAX=1;
Ok

Witnesses
Positive: 40, Negative: 999960
Condition exists (0:EAX=0 \ 1:EAX=0) is validated
Hash=7dbd6b8e6dd4abc2ef3d48b0376fb2e3
Observation SB Sometimes 40 999960
Time SB 0.44

The litmus test is first reminded, followed by actual assembler — the machine is a 64 bits one, in-line address references disappeared, registers may change, and assembler syntax is now more familiar. The test has run one million times, producing one million final states, or outcomes for the registers EAX of threads P0 and P1. The test run validates the condition, with 40 positive witnesses.

1.2 Cross compilation

With option -o <name.tar>, litmus7 does not run the test. Instead, it produces a tar archive that contains the C sources for the test.

Consider SB-PPC.litmus, a Power version of the previous test:

PPC SB-PPC
"Fre PodWR Fre PodWR"
{
0:r2=x; 0:r4=y;
1:r2=y; 1:r4=x;
}
P0   | P1
li r1,1 | li r1,1
stw r1,0(r2) | stw r1,0(r2);
lwz r3,0(r4) | lwz r3,0(r4);
exists (0:r3=0 \ 1:r3=0)

Our target machine (ppc) runs MacOS, which we specify with the -os option:

% litmus7 -o /tmp/a.tar -os mac SB-PPC.litmus
% scp /tmp/a.tar ppc:/tmp

Then, on the remote machine ppc:

ppc% mkdir SB & cd SB
ppc% tar xf /tmp/a.tar
ppc% ls
comp.sh Makefile outs.c outs.h README.txt run.sh SB-PPC.c show.awk utils.c utils.h

Test is compiled by the shell script comp.sh (or by (Gnu) make, at user’s choice) and run by the shell script run.sh:

ppc% sh comp.sh
ppc% sh run.sh

... Test SB-PPC Allowed
Histogram (3 states)
1784 *>0:r3=0; 1:r3=0;
498564:>0:r3=1; 1:r3=0;
499652:>0:r3=0; 1:r3=1;
Ok

Witnesses
Positive: 1784, Negative: 998216
Condition exists (0:r3=0 /\ 1:r3=0) is validated
Hash=4edecf6abc507611612efaec1c4a9bc
Observation SB-PPC Sometimes 1784 998216
Time SB-PPC 0.55

As we see, the condition validates also on Power. Notice that compilation produces an executable file, SB-PPC.exe, which can be run directly, for a less verbose output.

1.3 Running several tests at once

Consider the additional test STFW-PPC.litmus:

```
PPC STFW-PPC
"Rfi PodRR Fre Rfi PodRR Fre"
{
  0:r2=x; 0:r5=y;
  1:r2=y; 1:r5=x;
}
P0 | P1;
li r1,1 | li r1,1;
stw r1,0(r2) | stw r1,0(r2);
lwz r3,0(r2) | lwz r3,0(r2);
lwz r4,0(r5) | lwz r4,0(r5);
exists
(0:r3=1 /\ 0:r4=0 /\ 1:r3=1 /\ 1:r4=0)
```

To compile the two tests together, we can give two file names as arguments to litmus:

```
$ litmus7 -o /tmp/a.tar -os mac SB-PPC.litmus STFW-PPC.litmus
```

Or, more conveniently, list the litmus sources in a file whose name starts with @:

```
$ cat @ppc
SB-PPC.litmus
STFW-PPC.litmus
$ litmus7 -o /tmp/a.tar -os mac @ppc
```
To run the test on the remote ppc machine, the same sequence of commands as in the one test case applies:

```plaintext
ppc% tar xf /tmp/a.tar && make && sh run.sh
...
```

Test SB-PPC Allowed
Histogram (3 states)
1765  *>0:r3=0; 1:r3=0;
498741:>>0:r3=1; 1:r3=0;
499494:>>0:r3=0; 1:r3=1;
Ok

Witnesses
Positive: 1765, Negative: 998235
Condition exists (0:r3=0 /\ 1:r3=0) is validated
Hash=4edecf6abc507611612efaec1c4a9bc
Observation SB-PPC Sometimes 1765 998235
Time SB-PPC 0.57
...

Test STFW-PPC Allowed
Histogram (4 states)
480  *>0:r3=1; 0:r4=0; 1:r3=1; 1:r4=0;
499560:>>0:r3=1; 0:r4=1; 1:r3=1; 1:r4=0;
499827:>>0:r3=1; 0:r4=0; 1:r3=1; 1:r4=1;
133  :>0:r3=1; 0:r4=1; 1:r3=1; 1:r4=1;
Ok

Witnesses
Positive: 480, Negative: 999520
Condition exists (0:r3=1 /\ 0:r4=0 /\ 1:r3=1 /\ 1:r4=0) is validated
Hash=92b2c3f6332309325000656d0632131e
Observation STFW-PPC Sometimes 480 999520
Time STFW-PPC 0.56
...

Now, the output of `run.sh` shows the result of two tests.

## 2 Controlling test parameters

Users can control some of testing conditions. Those impact efficiency and outcome variability.

Sometimes one looks for a particular outcome — for instance, one may seek to get the outcome `0:r3=1; 1:r3=1;` that is missing in the previous experiment for test SB-PPC. To that aim, varying test conditions may help.

### 2.1 Architecture of tests

Consider a test `a.litmus` designed to run on `t` threads `P_0, \ldots, P_{t-1}`. The structure of the executable `a.exe` that performs the experiment is as follows:

- So as to benefit from parallelism, we run `n = \max(1, a/t)` (integer division) tests concurrently on a machine where `a` logical processors are available.
- Each of these (identical) tests consists in repeating `r` times the following sequence:
– Fork \( t \) (POSIX) threads \( T_0, \ldots, T_{t-1} \) for executing \( P_0, \ldots, P_{t-1} \). Which thread executes which code is either fixed, or changing, controlled by the launch mode. In our experience, the launch mode has marginal impact.

In cache mode the \( T_k \) threads are re-used. As a consequence, \( t \) threads only are forked.

– Each thread \( T_k \) executes a loop of size \( s \). Loop iteration number \( i \) executes the code of \( P_k \) (in fixed mode) and saves the final contents of its observed registers in some arrays indexed by \( i \). Furthermore, still for iteration \( i \), memory location \( x \) is in fact an array cell.

How this array cell is accessed depends upon the memory mode. In direct mode the array cell is accessed directly as \( x[i] \); as a result, cells are accessed sequentially and false sharing effects are likely. In indirect mode the array cell is accessed by the means of a shuffled array of pointers; as a result we observed a much greater variability of outcomes. Additionally, the increment of the main loop (of size \( s \)) can be set to a value or stride different from the default of one. Running a test several times with changing the stride value also proved quite effective in favouring outcome variability.

If the random preload mode is enabled, a preliminary loop of size \( s \) reads a random subset of the memory locations accessed by \( P_k \). Preload have a noticeable effect and teh random preload mode is enabled by default. Starting from version 5.0, we provide a more precise control over preloading memory locations — See Sec. 3.2.

The iterations performed by the different threads \( T_k \) may be unsynchronised, exactly synchronised by a pthread based barrier, or approximately synchronised by specific code. Absence of synchronisation may be interesting when \( t \) exceeds \( a \). As a matter of fact, in this situation, any kind of synchronisation leads to prohibitive variability of outcomes. However, for a large value of parameter \( s \) and small \( t \) we have observed spontaneous concurrent execution of some iterations amongst many. Pthread based barriers are exact but they are slow and in fact offers poor synchronisation for short code sequences. The approximate synchronisation is thus the preferred technique.

Starting from version 5.0, we provide a slightly altered user synchronisation mode: userfence, which alters user mode by executing memory fences to speedup write propagation. The new mode features overall better synchronisation, yielding dramatic improvements on some examples. However, outcome variability may suffer from this more accurate synchronisation, hence user mode remains the default.

More importantly, we provide an additional exact, timebase synchronisation technique: test threads will first synchronise using polling synchronisation barrier code, agree on a target timebase\(^2\) value and then loop reading the timebase until it exceeds the target value. This technique yields very good synchronisation and allows fine synchronisation tuning by assigning different starting delays to different threads — see Sec. 3.1. As ARM does not provide timebase counters, notice that “timebase” synchronisation for ARM silently degrades to synchronisation by the means of the polling synchronisation barrier.

– Wait for the \( t \) threads to terminate and collect outcomes in some histogram like structure.

- Wait for the \( n \) tests to terminate and sum their histograms.

Hence, running \texttt{a.exe} produces \( n \times r \times s \) outcomes. Parameters \( n, a, r \) and \( s \) can first be set directly while invoking \texttt{a.exe}, using the appropriate command line options. For instance, assuming \( t = 2 \), \texttt{./a.exe -a 201 -r 10k -s 1} and \texttt{./a.exe -n 1 -r 1 -s 1M} will both produce one million outcomes, but the latter is probably more efficient. If our machine has 8 cores, \texttt{./a.exe -a 8 -r 1 -s 1M} will yield 4 millions outcomes, in a time that we hope not to exceed too much the one experienced with \texttt{./a.exe -n 1}. Also observe that the memory allocated is roughly proportional to \( n \times s \), while the number of \( T_k \) threads created will be \( t \times n \times r \) (\( t \times n \) in cache mode). The \texttt{run.sh} shell script transmits its command line to all the executable (\texttt{.exe}) files it invokes, thereby providing a convenient means to control testing condition for

\(^2\)Power and x86-based systems provide a user accessible timebase counter that should provide consistent times to all cores and processors.
several tests. Satisfactory test parameters are found by experimenting and the control of executable files by command line options is designed for that purpose.

Once satisfactory parameters are found, it is a nuisance to repeat them for every experiment. Thus, parameters \( a \), \( r \) and \( s \) can also be set while invoking litmus, with the same command line options. In fact those settings command he default values of .exe files controls. Additionally, the synchronisation technique for iterations, the memory mode, and several others compile time parameters can be selected by appropriate litmus7 command line options. Finally, users can record frequently used parameters in configuration files.

### 2.2 Affinity

We view affinity as a scheduler property that binds a (software, POSIX) thread to a given (hardware) logical processor. In the most simple situation a logical processor is a core. However in the presence of hyper-threading (x86) or simultaneous multi threading (SMT, Power) a given core can host several logical processors.

#### 2.2.1 Introduction to affinity

In our experience, binding the threads of test programs to selected logical processors yields significant speedups and, more importantly, greater outcome variety. We illustrate the issue by the means of an example.

We consider the test \( \text{ppc-iriw-lwsync.litmus} \):

```plaintext
PPC ppc-iriw-lwsync
{
0:r2=x; 1:r2=x; 1:r4=y;
2:r4=y; 3:r2=x; 3:r4=y;
}

P0 | P1 | P2 | P3
li r1,1 | lwz r1,0(r2) | li r1,1 | lwz r1,0(r4) ;
stw r1,0(r2) | lwsync | stw r1,0(r4) | lwsync ;
| lwz r3,0(r4) | | lwz r3,0(r2) ;
exists (1:r1=1 \( \land \) 1:r3=0 \( \land \) 3:r1=1 \( \land \) 3:r3=0)
```

The test consists of four threads. There are two writers (P0 and P2) that write the value one into two different locations (x and y), and two readers that read the contents of x and y in different orders — P1 reads x first, while P3 reads y first. The load instructions \text{lwz} in reader threads are separated by a lightweight barrier instruction \text{lwsync}. The final condition \text{exists (1:r1=1} \( \land \) 1:r3=0 \( \land \) 3:r1=1 \( \land \) 3:r3=0) characterises the situation where the reader threads see the writes by P0 and P2 in opposite order. The corresponding outcome 1:r1=1; 1:r3=0; 3:r1=1; 3:r3=0; is the only non-sequential consistent (non-SC, see Part II) possible outcome. By any reasonable memory model for Power, one expects the condition to validate, \emph{i.e.} the non-SC outcome to show up.

The tested machine \text{vargas} is a Power 6 featuring 32 cores (\emph{i.e.} 64 logical processors, since SMT is enabled) and running AIX in 64 bits mode. So as not to disturb other users, we run only one instance of the test, thus specifying four available processors. The litmus7 tool is absent on \text{vargas}. All these conditions command the following invocation of litmus7, performed on our local machine:

```bash
$ litmus7 -r 1000 -s 1000 -a 4 -os aix -ws w64 ppc-iriw-lwsync.litmus -o ppc.tar
$ scp ppc.tar vargas:/var/tmp
```

On \text{vargas} we unpack the archive and compile the test:

```
vargas% tar xf /var/tmp/ppc.tar && sh comp.sh
```

Then we run the test:
vargas% ./ppc-iriw-lwsync.exe
Test ppc-iriw-lwsync Allowed
Histogram (15 states)
163674:>1:r1=0; 1:r3=0; 3:r1=0; 3:r3=0;
34045 :>1:r1=1; 1:r3=0; 3:r1=0; 3:r3=0;
40283 :>1:r1=0; 1:r3=1; 3:r1=0; 3:r3=0;
95079 :>1:r1=1; 1:r3=1; 3:r1=0; 3:r3=0;
33848 :>1:r1=0; 1:r3=0; 3:r1=1; 3:r3=0;
72201 :>1:r1=0; 1:r3=1; 3:r1=1; 3:r3=0;
43031 :>1:r1=0; 1:r3=0; 3:r1=0; 3:r3=1;
95079 :>1:r1=1; 1:r3=0; 3:r1=0; 3:r3=0;
32452 :>1:r1=0; 1:r3=0; 3:r1=0; 3:r3=0;
73052 :>1:r1=1; 1:r3=0; 3:r1=0; 3:r3=1;
1 :>1:r1=1; 1:r3=0; 3:r1=0; 3:r3=1;
42482 :>1:r1=0; 1:r3=0; 3:r1=0; 3:r3=1;
90470 :>1:r1=1; 1:r3=0; 3:r1=0; 3:r3=1;
30306 :>1:r1=0; 1:r3=0; 3:r1=0; 3:r3=1;
43239 :>1:r1=0; 1:r3=0; 3:r1=0; 3:r3=1;
205837:>1:r1=1; 1:r3=0; 3:r1=0; 3:r3=1;
No

Witnesses
Positive: 0, Negative: 1000000
Condition exists (1:r1=1 \ 1:r3=0 \ 3:r1=1 \ 3:r3=0) is NOT validated
Hash=4fbfaafa51f6784d699e9bdaf5ba047d
Observation ppc-iriw-lwsync Never 0 1000000
Time ppc-iriw-lwsync 1.32

The non-SC outcome does not show up.

Altering parameters may yield this outcome. In particular, we may try using all the available logical processors with option -a 64. Affinity control offers an alternative, which is enabled at compilation time with litmus7 option -affinity:

$ litmus7 ... -affinity incr1 ppc-iriw-lwsync.litmus -o ppc.tar
$ scp ppc.tar vargas:/var/tmp

Option -affinity takes one argument (incr1 above) that specifies the increment used while allocating logical processors to test threads. Here, the (POSIX) threads created by the test (named $T_0$, $T_1$, $T_2$ and $T_3$ in Sec. 2.1) will get bound to logical processors 0, 1, 2, and 3, respectively.

Namely, by default, the logical processors are ordered as the sequence 0,1,...,A−1 — where A is the number of available logical processors, which is inferred by the test executable\(^3\). Furthermore, logical processors are allocated to threads by applying the affinity increment while scanning the logical processor sequence. Observe that since the launch mode is changing (the default) threads $T_k$ correspond to different test threads $P_i$ at each run. The unpack compile and run sequence on vargas now yields the non-SC outcome, better outcome variety and a lower running time:

vargas% tar xf /var/tmp/ppc.tar && make
vargas% ./ppc-iriw-lwsync.exe
Test ppc-iriw-lwsync Allowed
Histogram (16 states)
180600:>1:r1=0; 1:r3=0; 3:r1=0; 3:r3=0;

\(^3\)Parameter $A$ is not to be confused with $a$ of section 2.1. The former serves to compute logical threads while the latter governs the number of tests that run simultaneously. However parameters $a$ will be set to $A$ when affinity control is enabled and when $a$ value is 0.
<table>
<thead>
<tr>
<th>Case</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive: 9, Negative: 999991</td>
<td>Condition exists ((1:r1=1 \land 1:r3=0 \land 3:r1=1 \land 3:r3=0)) is validated</td>
</tr>
<tr>
<td>Hash</td>
<td>4fbfaafa51f6f784d699e9bda5ba047d</td>
</tr>
<tr>
<td>Observation</td>
<td>ppc-iriw-lwsync Sometimes 9 999991</td>
</tr>
<tr>
<td>Time</td>
<td>ppc-iriw-lwsync 0.68</td>
</tr>
</tbody>
</table>

One may change the affinity increment with the command line option \(-i\) of executable files. For instance, one binds the test threads to logical processors 0, 2, 4 and 6 as follows:

```
vargas% ./ppc-iriw-lwsync.exe -i 2
Test ppc-iriw-lwsync Allowed
```

<table>
<thead>
<tr>
<th>Case</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive: 0, Negative: 1000000</td>
<td>Condition exists ((1:r1=1 \land 1:r3=0 \land 3:r1=1 \land 3:r3=0)) is NOT validated</td>
</tr>
<tr>
<td>Hash</td>
<td>4fbfaafa51f6f784d699e9bda5ba047d</td>
</tr>
<tr>
<td>Observation</td>
<td>ppc-iriw-lwsync Never 0 1000000</td>
</tr>
<tr>
<td>Time</td>
<td>ppc-iriw-lwsync 0.92</td>
</tr>
</tbody>
</table>
One observes that the non-SC outcome does not show up with the new affinity setting.

One may also bind test thread to logical processors randomly with executable option +ra.

vargas% ./ppc-iriw-lwsync.exe +ra
Test ppc-iriw-lwsync Allowed
Histogram (15 states)
...
No

Witnesses
Positive: 0, Negative: 1000000
Condition exists (1:r1=1 \ 1:r3=0 \ 3:r1=1 \ 3:r3=0) is NOT validated
Hash=4fbfaafa51f6784d699e9bdaf5ba047d
Observation ppc-iriw-lwsync Never 0 1000000
Time ppc-iriw-lwsync 1.85

As we see, the condition does not validate either with random affinity. As a matter of fact, logical processors are taken at random in the sequence 0, 1, ..., 63; while the successful run with -i 1 took them in the sequence 0, 1, 2, 3. One can limit the sequence of logical processor with option -p, which takes a sequence of logical processor numbers as argument:

vargas% ./ppc-iriw-lwsync.exe +ra -p 0,1,2,3
Test ppc-iriw-lwsync Allowed
Histogram (16 states)
...
8 *>1:r1=1; 1:r3=0; 3:r1=1; 3:r3=0;
...
Ok

Witnesses
Positive: 8, Negative: 999992
Condition exists (1:r1=1 \ 1:r3=0 \ 3:r1=1 \ 3:r3=0) is validated
Hash=4fbfaafa51f6784d699e9bdaf5ba047d
Observation ppc-iriw-lwsync Sometimes 8 999992
Time ppc-iriw-lwsync 0.70

The condition now validates.

2.2.2 Study of affinity

As illustrated by the previous example, both the running time and the outcomes of a test are sensitive to affinity settings. We measured running time for increasing values of the affinity increment from 0 (which disables affinity control) to 20, producing the following figure:
As regards outcome variety, we get all of the 16 possible outcomes only for an affinity increment of 1.

The differences in running times can be explained by reference to the mapping of logical processors to hardware. The machine **vargas** consists in four MCM’s (Multi-Chip-Module), each MCM consists in four “chips”, each chip consists in two cores, and each core may support two logical processors. As far as we know, by querying **vargas** with the AIX commands **lsattr**, **bindprocessor** and **llstat**, the MCM’s hold the logical processors 0–15, 16–31, 32–47 and 48–63, each chip holds the logical processors $4k$, $4k+1$, $4k+2$, $4k+3$ and each core holds the logical processors $2k$, $2k + 1$.

The measure of running times for varying increments reveals two noticeable slowdowns: from an increment of 1 to an increment of 2 and from 5 to 6. The gap between 1 and 2 reveals the benefits of SMT for our testing application. An increment of 1 yields both the greatest outcome variety and the minimal running time. The other gap may perhaps be explained by reference to MCM’s: for a value of 5 the tests runs on the logical processors 0, 5, 10, 15, all belonging to the same MCM; while the next affinity increment of 6 results in running the test on two different MCM (0, 6, 12 on the one hand and 18 on the other).

As a conclusion, affinity control provides users with a certain level of control over thread placement, which is likely to yield faster tests when threads are constrained to run on logical processors that are “close” one to another. The best results are obtained when SMT is effectively enforced. However, affinity control is no panacea, and the memory system may be stressed by other means, such as, for instance, allocating important chunks of memory (option `-s`).

### 2.2.3 Advanced control

For specific experiments, the technique of allocating logical processors sequentially by following a fixed increment may be too rigid. **l7** offers a finer control on affinity by allowing users to supply the logical processors sequence. Notice that most users will probably not need this advanced feature.

Anyhow, so as to confirm that testing **ppc-iriw-lwsync** benefits from not crossing chip boundaries, one may wish to confine its four threads to logical processors 16 to 19, that is to the first chip of the second MCM. This can be done by overriding the default logical processors sequence by an user supplied one given as an argument to command-line option `-p`:

```
vargas% ./ppc-iriw-lwsync.exe -p 16,17,18,19 -i 1
Test ppc-iriw-lwsync Allowed
Histogram (16 states)
```


Witnesses
Positive: 3, Negative: 999997
Condition exists (1:r1=1 \ / 1:r3=0 \ / 3:r1=1 \ / 3:r3=0) is validated
Hash=4fbfafaaf51f6784d699e9bda55a047d
Observation ppc-iriw-lwsync Sometimes 3 999997
Time ppc-iriw-lwsync 0.63

Thus we get results similar to the previous experiment on logical processors 0 to 3 (option -i 1 alone).

We may also run four simultaneous instances (-n 4, parameter n of section 2.1) of the test on the four available MCM’s:

vargas% ./ppc-iriw-lwsync.exe -p 0,1,2,3,16,17,18,19,32,33,34,35,48,49,50,51 -n 4 -i 1
Test ppc-iriw-lwsync Allowed
Histogram (16 states)
...
57 *>1:r1=1; 1:r3=0; 3:r1=1; 3:r3=0;
...
Ok

Witnesses
Positive: 57, Negative: 3999943
Condition exists (1:r1=1 \ / 1:r3=0 \ / 3:r1=1 \ / 3:r3=0) is validated
Hash=4fbfafaaf51f6784d699e9bda55a047d
Observation ppc-iriw-lwsync Sometimes 57 3999943
Time ppc-iriw-lwsync 0.75

Observe that, for a negligible penalty in running time, the number of non-SC outcomes increases significantly.

By contrast, binding threads of a given instance of the test to different MCM’s results in poor running time and no non-SC outcome.

vargas% ./ppc-iriw-lwsync.exe -p 0,1,2,3,16,17,18,19,32,33,34,35,48,49,50,51 -n 4 -i 4
Test ppc-iriw-lwsync Allowed
Histogram (15 states)
...

Witnesses
In the experiment above, the increment is 4, hence the logical processors allocated to the first instance of the test are 0, 16, 32, 48, of which indices in the logical processors sequence are 0, 4, 8, 12, respectively. The next allocated index in the sequence is \( 12 + 4 = 16 \). However, the sequence has 16 items. Wrapping around yields index 0 which happens to be the same as the starting index. Then, so as to allocate fresh processors, the starting index is incremented by one, resulting in allocating processors 1, 17, 33, 49 (indices 1, 5, 9, 13) to the second instance — see section 2.3 for the full story. Similarly, the third and fourth instances will get processors 2, 18, 34, 50 and 3, 19, 35, 51, respectively. Attentive readers may have noticed that the same experiment can be performed with option -i 16 and no -p option.

Finally, users should probably be aware that at least some versions of Linux for x86 feature a less obvious mapping of logical processors to hardware. On a bi-processor, dual-core, 2-ways hyper-threading, Linux, AMD64 machine, we have checked that logical processors residing on the same core are \( k \) and \( k + 4 \), where \( k \) is an arbitrary core number ranging from 0 to 3. As a result, a proper choice for favouring effective hyper-threading on such a machine is -i 4 (or -p 0, 4, 1, 5, 2, 6, 3, 7 -i 1). More worthwhile noticing, perhaps, the straightforward choice -i 1 disfavours effective hyper-threading...

## 2.2.4 Custom control

Most tests run by litmus7 are produced by the litmus test generators described in Part II. Those tests include meta-information that may direct affinity control. For instance we generate one test with the diyone7 tool, see Sec. 6.2. More specifically we generate \texttt{IRIW+lwsyncs} for Power (\texttt{ppc-iriw-lwsync} in the previous section) as follows:

% diyone7 -arch PPC -name IRIW+lwsyncs Rfe LwSyncdRR Fre Rfe LwSyncdRR Fre

We get the new source file \texttt{IRIW+lwsyncs.litmus}:

```plaintext
PPC IRIW+lwsyncs
"Rfe LwSyncdRR Fre Rfe LwSyncdRR Fre"
Prefetch=0:x=T,1:x=F,1:y=T,2:y=F,3:y=F,3:x=T
Com=Rf Fr Rf Fr
Orig=Rfe LwSyncdRR Fre Rfe LwSyncdRR Fre
{
  0:r2=x;
  1:r2=x; 1:r4=y;
  2:r2=y;
  3:r2=y; 3:r4=x;
}
```

The relevant meta-information is the “Com” line that describes how test threads are related — for instance, thread 0 stores a value to memory that is read by thread 1, written “Rf” (see Part II for more details). Custom affinity control will tend to run threads related by “Rf” on “close” logical processors, where we can for instance consider that close logical processors belong to the same physical core (SMT for Power).

This minimal logical processor topology is described by two litmus7 command-line option: -smt \(<n>\) that specifies \(n\)-way SMT; and -smt_mode \(\text{seq}|\text{end}\) that specifies how logical processors from the same core are numbered. For a 8-cores 4-ways SMT power7 machine we invoke litmus7 as follows:
Notice that memory mode is direct and that the number of available logical processors is unspecified, resulting in running one instance of the test. More importantly, notice that affinity control is enabled `-affinity custom`, additionally specifying custom affinity mode.

We then upload the archive `a.tar` to our Power7 machine, unpack, compile and run the test:

```
power7% tar xmf a.tar
power7% make ...
power7% ./IRIW+lwsyncs.exe -v
```

```
IRIW+lwsyncs: n=1, r=1000, s=1000, +rm, +ca, p=’0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21 thread allocation:
[23,22,3,2] {5,5,0,0}
```

Option `-v` instructs the executable to show settings of the test harness: we see that one instance of the test is run (n=1), size parameters are reminded (r=1000, s=1000) and shuffling of indirect memory mode is performed (+rm). Affinity settings are also given: mode is custom (+ca) and the logical processor sequence inferred is given (-p 0,1,...,31). Additionally, the allocation of test threads to logical processors is given, as [...] as well as the allocation of test threads to physical cores, as {...}.

Here is the run output proper:

```
Test IRIW+lwsyncs Allowed
Histogram (15 states)
2700 :>1:r1=0; 1:r3=0; 3:r1=0; 3:r3=0;
142  :>1:r1=1; 1:r3=0; 3:r1=0; 3:r3=0;
37110 :>1:r1=0; 1:r3=1; 3:r1=0; 3:r3=0;
181257:>1:r1=1; 1:r3=1; 3:r1=0; 3:r3=0;
78   :>1:r1=0; 1:r3=0; 3:r1=1; 3:r3=0;
15   *:>1:r1=1; 1:r3=0; 3:r1=1; 3:r3=0;
103459:>1:r1=0; 1:r3=1; 3:r1=1; 3:r3=0;
149486:>1:r1=1; 1:r3=1; 3:r1=1; 3:r3=0;
30820 :>1:r1=0; 1:r3=0; 3:r1=0; 3:r3=1;
9837  :>1:r1=1; 1:r3=0; 3:r1=1; 3:r3=1;
2399  :>1:r1=0; 1:r3=1; 3:r1=0; 3:r3=1;
204629:>1:r1=0; 1:r3=0; 3:r1=1; 3:r3=1;
214700:>1:r1=1; 1:r3=0; 3:r1=1; 3:r3=1;
5186  :>1:r1=0; 1:r3=1; 3:r1=1; 3:r3=1;
58182 :>1:r1=1; 1:r3=1; 3:r1=1; 3:r3=1;
Ok

Witnesses: 15, Negative: 999985
Condition exists (1:r1=1 /\ 1:r3=0 /\ 3:r1=1 /\ 3:r3=0) is validated
Hash=836eb3085132d3cb06973469a08098df
Com=Rf Fr Rf Fr
Orig=Rfe LwSyncdRR Fre Rfe LwSyncdRR Fre
Affinity=[2, 3] [0, 1] ; (1,2) (3,0)
Observation IRIW+lwsyncs Sometimes 15 999985
Time IRIW+lwsyncs 0.70
```

As we see, the test validates. Namely we observe the non-SC behaviour of IRIW in spite of the presence of two lwsync barriers. We may also notice, in the executable output some meta-information related to
affinity: it reads that threads 2 and 3 on the one hand and threads 0 and 1 on the other are considered “close” (i.e. will run on the same physical core); while threads 1 and 2 on the one hand and threads 3 and 0 on the other are considered “far” (i.e. will run on different cores).

Custom affinity can be disabled by enabling another affinity mode. For instance with `-i 0` we specify an affinity increment of zero. That is, affinity control is disabled altogether:

```
power7% ./IRIW+lwsyncs.exe -i 0 -v
./IRIW+lwsyncs.exe -i 0 -v
IRIW+lwsyncs: n=1, r=1000, s=1000, +rm, i=0, p='0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21
Test IRIW+lwsyncs Allowed
Histogram (15 states)
...
No
```

Witnesses
Positive: 0, Negative: 1000000
Condition exists \((1:r1=1 \land 1:r3=0 \land 3:r1=1 \land 3:r3=0)\) is NOT validated
Hash=836eb3085132d3cb06973469a08098df
Com=Rf Fr Rf Fr
Orig=Rfe LwSyncdRR Fre Rfe LwSyncdRR Fre
Observation IRIW+lwsyncs Never 0 1000000
Time IRIW+lwsyncs 0.90

As we see, the test does not validate under those conditions.

Notice that section 18 describes a complete experiment on affinity control.

### 2.3 Controlling executable files

**Test conditions** Any executable file produced by litmus7 accepts the following command line options.

- **-v** Be verbose, can be repeated to increase verbosity. Specifying `-v` is a convenient way to look at the default of options.

- **-q** Be quiet.

- **-a <n>** Run maximal number of tests concurrently for \(n\) available logical processors — parameter \(a\) in Sec. 2.1. Notice that if affinity control is enabled (see below), `-a 0` will set parameter \(a\) to the number of logical processors effectively available.

- **-n <n>** Run \(n\) tests concurrently — parameter \(n\) in Sec. 2.1.

- **-r <n>** Perform \(n\) runs — parameter \(r\) in Sec. 2.1.

- **-fr <f>** Multiply \(r\) by \(f\) (\(f\) is a floating point number).

- **-s <n>** Size of a run — parameter \(s\) in Sec. 2.1.

- **-fs <f>** Multiply \(s\) by \(f\).

- **-f <f>** Multiply \(s\) by \(f\) and divide \(r\) by \(f\).

Notice that options `-s` and `-r` accept a generalised syntax for their integer argument: when suffixed by \(k\) (resp. \(M\)) the integer gets multiplied by \(10^3\) (resp. \(10^6\)).

The following options are accepted only for tests compiled in indirect memory mode (see Sec. 2.1):

- **-rm** Do not shuffle pointer arrays, resulting a behaviour similar do direct mode, without recompilation.
+rm Shuffle pointer arrays, provided for regularity.

The following option is accepted only for tests compiled with a specified stride value (see Sec. 2.1).

-st <n> Change stride to <n>. The default stride is specified at compile time by litmus7 option -stride. A value of zero or less is replaced by the number of threads in the test.

The following option is accepted when enabled at compile time:

-l <n> Insert the assembly code of each thread in a loop of size <n>.

**Affinity** If affinity control has been enabled at compilation time (for instance, by supplying option -affinity incr1 to litmus7), the executable file produced by litmus7 accepts the following command line options.

-p <ns> Logical processors sequence. The sequence <ns> is a comma separated list of integers, The default sequence is inferred by the executable as 0,1,...,A−1, where A is the number of logical processors featured by the tested machine; or is a sequence specified at compile time with litmus7 option -p.

-i <n> Increment for allocating logical processors to threads. Default is specified at compile time by litmus7 option -affinity incr<n>. Notice that -i 0 disable affinity and that .exe files reject the -i option when affinity control has not been enabled at compile time.

+ra Perform random allocation of affinity at each test round.

+ca Perform custom affinity.

Notice that when custom affinity is not available, would it be that the test source lacked meta-information or that logical processor topology was not specified at compile-time, then +ca behaves as +ra.

Logical processors are allocated test instance by test instance (parameter n of Sec. 2.1) and then thread by thread, scanning the logical processor sequence left-to-right by steps of the given increment. More precisely, assume a logical processor sequence P = p0,p1,...,pA−1 and an increment i. The first processor allocated is p0, then p1, then p2i, etc, Indices in the sequence P are reduced modulo A so as to wrap around. The starting index of the allocation sequence (initially 0) is recorded, and coincidence with the index of the next processor to be allocated is checked. When coincidence occurs, a new index is computed, as the previous starting index plus one, which also becomes the new starting index. Allocation then proceeds from this new starting index. That way, all the processors in the sequence will get allocated to different threads naturally, provided of course that less than A threads are scheduled to run. See Sec. 2.2.3 for an example with A = 16 and i = 4.

### 3 Advanced control of test parameters

#### 3.1 Timebase synchronisation mode

Timebase synchronisation of the testing loop iterations (see Sec. 2.1) is selected by litmus7 command line option -barrier timebase. In that mode, test threads will first synchronise using polling synchronisation barrier code, agree on a target timebase value and then loop reading the timebase until it exceeds the target value. Some tests demonstrate that timebase synchronisation is more precise than user synchronisation (-barrier user and default).

For instance, consider the x86 test 6SB, a 6-thread analog of the SB test:

```
x86 6SB
"Fre PodWR Fre PodWR Fre PodWR Fre PodWR Fre PodWR Fre PodWR Fre PodWR"
{}
P0 | P1 | P2 | P3 | P4 | P5
```
MOV \([x],\$1 \) | MOV \([y],\$1 \) | MOV \([z],\$1 \) | MOV \([a],\$1 \) | MOV \([b],\$1 \) | MOV \([c],\$1 \) ;
MOV EAX,\([y]\) | MOV EAX,\([z]\) | MOV EAX,\([a]\) | MOV EAX,\([b]\) | MOV EAX,\([c]\) | MOV EAX,\([x]\) ;
exists
\((0:EAX=0 \land 1:EAX=0 \land 2:EAX=0 \land 3:EAX=0 \land 4:EAX=0 \land 5:EAX=0)\)

As for \(SB\), the final condition of \(6.SB\) identifies executions where each thread loads the initial value 0 of a location that is written into by another thread.

Thread 0
Thread 1
Thread 2
Thread 3
Thread 4
Thread 5

\[ \begin{align*}
\text{a: } & Wx=1 & \text{c: } & Wy=1 & \text{e: } & Wz=1 & \text{g: } & Wa=1 & \text{i: } & Wb=1 & \text{k: } & Wc=1 \\
\text{b: } & Ry=0 & \text{d: } & Rz=0 & \text{f: } & Ra=0 & \text{h: } & Rb=0 & \text{j: } & Rc=0 & \text{l: } & Rx=0
\end{align*} \]

We first compile the test in user synchronisation mode, saving \texttt{litmus7} output files into the directory \(R\):

\%
mkdir -p R
\%
litmus7 -barrier user -vb true -o R 6.SB.litmus
\%
cd R
\%
make

The additional command line option \(-vb\ true\) activates the printing of some timing information on synchronisations.

We then directly run the test executable \(6.SB.exe\):

\%
./6.SB.exe
Test 6.SB Allowed
Histogram (62 states)
7569 :>0:EAX=1; 1:EAX=0; 2:EAX=0; 3:EAX=0; 4:EAX=0; 5:EAX=0;
8672 :>0:EAX=0; 1:EAX=1; 2:EAX=0; 3:EAX=0; 4:EAX=0; 5:EAX=0;
... 326 :>0:EAX=1; 1:EAX=0; 2:EAX=1; 3:EAX=1; 4:EAX=1; 5:EAX=1;
907 :>0:EAX=0; 1:EAX=1; 2:EAX=1; 3:EAX=1; 4:EAX=1; 5:EAX=1;
No

Witnesses
Positive: 0, Negative: 1000000
Condition exists \((0:EAX=0 \land 1:EAX=0 \land 2:EAX=0 \land 3:EAX=0 \land 4:EAX=0 \land 5:EAX=0)\) is NOT validated
Hash=107f1303932972b3abace3ee4027408e
Observation 6.SB Never 0 1000000
Time 6.SB 0.85

The targeted outcome — reading zero in the \(EAX\) registers of the \(6\) threads — is not observed. We can observe synchronisation times for all tests runs with the executable command line option \(+vb\):

\%
./6.SB.exe +vb
99999: 162768 420978 564546 -894 669468
99998: -93 3 81 -174 -651

19
We see five columns of numbers that list, for each test run, the starting delays of $P_1$, $P_2$ etc. with respect to $P_0$, expressed in timebase ticks. Obviously, synchronisation is rather loose, there are always two threads whose starting delays differ of about 1000 ticks.

We now compile the same test in timebase synchronisation mode, saving litmus7 output files into the pre-existing directory RT:

```
% mkdir -p RT
% litmus7 -barrier timebase -vb true -o RT 6.SB.litmus
% cd RT
% make
```

And we run the test directly (option -vb disable the printing of any synchronisation timing information):

```
% ./6.SB.exe -vb
Test 6.SB Allowed
Histogram (64 states)
60922  *>0:EAX=0; 1:EAX=0; 2:EAX=0; 3:EAX=0; 4:EAX=0; 5:EAX=0;
38299 :>0:EAX=1; 1:EAX=0; 2:EAX=0; 3:EAX=0; 4:EAX=0; 5:EAX=0;
...
598  :>0:EAX=0; 1:EAX=1; 2:EAX=1; 3:EAX=1; 4:EAX=1; 5:EAX=1;
142  :>0:EAX=1; 1:EAX=1; 2:EAX=1; 3:EAX=1; 4:EAX=1; 5:EAX=1;
Ok
```

Witnesses
Positive: 60922, Negative: 939078
Condition exists ($0:EAX=0 \land 1:EAX=0 \land 2:EAX=0 \land 3:EAX=0 \land 4:EAX=0 \land 5:EAX=0$) is validated
Hash=107f1303932972b3abace3ee4027408e
Observation 6.SB Sometimes 60922 939078
Time 6.SB 1.62

We now see that the test validates. Moreover all of the 64 possible outcomes are observed.

Timebase synchronisation works as follows: at every iteration,

1. one of the threads reads timebase $T$;
2. all threads synchronise by the means of a polling synchronisation barrier;
3. each thread computes $T_i = T + \delta_i$, where $\delta_i$ is the timebase delay, a thread specific constant;
4. each thread loops, reading the timebase until the read value exceeds $T_i$.

By default the timebase delay $\delta_i$ is $2^{11} = 2048$ for all threads.

The precision of timebase synchronisation can be illustrated by enabling the printing of all synchronisation timings:

```
% ./6.SB.exe +vb
...
...
For each test iteration and each thread, two numbers are shown (1) the last timebase value read by and (2) (in brackets [...]) how many iterations of loop 4. were performed. Additionally a star “*” indicates the occurrence of the targeted outcome. Here, we see that a nearly perfect synchronisation can be achieved (cf. line 99982: above).

Once timebase synchronisation have been selected (litmus7 option -barrier timebase), test executable behaviour can be altered by the following two command line options:

- **ta** <n> Change the timebase delay $\delta_i$ of all threads.
- **tb** <0:n;1:n;...> Change the timebase delay $\delta_i$ of individual threads.

The litmus7 command line option **-vb** true (verbose barrier) governs the printing of synchronisation timings. It comes handy when choosing values for the **-ta** and **-tb** options. When set, the executable show synchronisation timings for outcomes that validate the test final condition. This default behaviour can be altered with the following two command line options:

- **vb** Do not show synchronisation timings.
- **+vb** Show synchronisation timings for all outcomes.

Synchronisation timings are expressed in timebase ticks. The format depends on the synchronisation mode (litmus7 option -barrier). This section just gave two examples for user mode (timings are show as differences from thread $P_0$); and for timebase mode (timings are shown as differences from a commonly agreed by all thread timebase value). Notice that, when affinity control is enabled, the running logical processors of threads are also shown.

### 3.2 Advanced prefetch control

Supplying the tags custom, static, static1 or static2 to litmus7 command line option -preload commands the insertion of cache prefetch or flush instructions before every test instance.

In custom mode the execution of such cache management instruction is under total user control, the other, “static”, modes offer less control to the user, for the sake of not altering test code proper.

#### 3.2.1 Custom prefetch

Custom prefetch mode offers complete control over cache management instructions. Users enable this mode by supplying the command line option -preload custom to litmus7. For instance one may compile the x86 test **6.SB.litmus** as follows:

```bash
% mkdir -p R
% litmus7 -mem indirect -preload custom -o R 6.SB.litmus
% cd R
% make
```

Notice the test is compiled in indirect memory mode, in order to reduce false sharing effects.

The executable **6.SB.exe** accepts two new command line options: -prf and -pra. Those options takes arguments that describe cache management instructions. The option **-pra** takes one letter that stands for a cache management instruction as we here describe:

<table>
<thead>
<tr>
<th>Letter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>do nothing</td>
</tr>
<tr>
<td>F</td>
<td>cache flush</td>
</tr>
<tr>
<td>T</td>
<td>cache touch</td>
</tr>
<tr>
<td>W</td>
<td>cache touch for a write</td>
</tr>
</tbody>
</table>

All those cache management instructions are not provided by all architectures, in case some instruction is missing, the letters behave as follows:

- **F**: do nothing, **T**: do nothing, **W**: behave as **T**.

With **-pra X** the commanded action applies to all threads and all variables, for instance:
will perform a run where every test thread touches the test locations that it refers to (i.e. X and Y for Thread 0, Y and Z for Thread 1, etc.) before executing test code proper. Although one may achieve interesting results by using this -pra option, the more selective -prf option should prove more useful. The -prf option takes a comma separated list of cache management directives. A cache management directive is n:loc=X, where n is a thread number, loc is a program variable, and X is a cache management control letter. For instance, -prf 0:y=T instructs thread 0 to touch location y. More generally, having each thread of the test 6.SB to touch the memory location it reads with its second instruction would favor reading the initial value of these locations, and thus validating the final condition of the test “(0:EAX=0 \(\land\) 1:EAX=0 \(\land\) 2:EAX=0 \(\land\) 3:EAX=0 \(\land\) 4:EAX=0 \(\land\) 5:EAX=0)”. Notice that those locations can be found by looking at the test code or at the diagram of the target execution. Let us have a try:

```
% ./6.SB.exe -pra T
```

The -prf option takes a comma separated list of cache management directives. A cache management directive is n:loc=X, where n is a thread number, loc is a program variable, and X is a cache management control letter. For instance, -prf 0:y=T instructs thread 0 to touch location y. More generally, having each thread of the test 6.SB to touch the memory location it reads with its second instruction would favor reading the initial value of these locations, and thus validating the final condition of the test “(0:EAX=0 \(\land\) 1:EAX=0 \(\land\) 2:EAX=0 \(\land\) 3:EAX=0 \(\land\) 4:EAX=0 \(\land\) 5:EAX=0)”. Notice that those locations can be found by looking at the test code or at the diagram of the target execution. Let us have a try:

```
% ./6.SB.exe -prf 0:y=T,1:z=T,2:a=T,3:b=T,4:c=T,5:x=T
Test 6.SB Allowed
Histogram (63 states)
10 *0:EAX=0; 1:EAX=0; 2:EAX=0; 3:EAX=0; 4:EAX=0; 5:EAX=0;
...
Witnesses
Positive: 10, Negative: 999990
...
Prefetch=0:y=T,1:z=T,2:a=T,3:b=T,4:c=T,5:x=T
...
As can be seen, the final condition is validated. Also notice that the prefetch directives used during the run are reminded. If given several times, -prf options cumulate, the rightmost directives taking precedence in case of ambiguity. As a consequence, one may achieve the same prefetching effect as above with:

```
% ./6.SB.exe -prf 0:y=T -prf 1:z=T -prf 2:a=T -prf 3:b=T -prf 4:c=T -prf 5:x=T
```

3.2.2 Prefetch metadata

The source code of tests may include prefetch directives as metadata prefixed with “Prefetch=” in particular, the generators of the diy7 suite (see Part II) produce such metadata. For instance in the case of the 6.SB test (generated source 6.SB+Prefetch.litmus), this metadata reads:

```
```

That is, each thread flushes the location it stores to and touches each location it reads from. Notice that each thread starts with a memory location access (here a store) and ends with another (here a load). The idea simply is to accelerate the exit access (with a cache touch) while delaying the entry access (with a cache flush).

When prefetch metadata is available, it acts as the default of prefetch directives:

```
% litmus7 -mem indirect -preload custom -o R 6.SB+Prefetch.litmus
% cd R
% make
```

Then we run the test by:

```
% ./6.SB+Prefetch.exe
Test 6.SB Allowed
Histogram (63 states)
674 *0:EAX=0; 1:EAX=0; 2:EAX=0; 3:EAX=0; 4:EAX=0; 5:EAX=0;
```
Witnesses
Positive: 674, Negative: 999326


One may notice that the prefetch directives from the source file medata found its way to the test executable.

As with any kind of metadata, one can change the prefetch metadata by editing the litmus source file, or better by using the -hints command line option. The -hints command line option takes a filename as argument. This file is a mapping that associates new metadata to test names. As an example, we reverse diy7 scheme for cache management directives: accelerating entry accesses and delaying exit accesses:

% cat map.txt
% litmus7 -mem indirect -preload custom -hints map.txt -o R 6.SB.litmus
% cd R
% make
% ./6.SB.exe
Test 6.SB Allowed
Histogram (63 states)
24  *>0:EAX=0; 1:EAX=0; 2:EAX=0; 3:EAX=0; 4:EAX=0; 5:EAX=0;


As we see above, the final condition validates. It does so in spite of the apparently unfavourable cache management directives.

We can experiment further without recompilation, by using the -pra and -prf command line options of the test executable. Those are parsed left-to-right, so that we can (1) cancel any default cache management directive with -pra I and (2) enable cache touch for the stores:

Test 6.SB Allowed

Witnesses
Positive: 0, Negative: 1000000


As we see, the final condition does not validate.

By contrast, flushing or touching the locations that the threads load permit to repetitively achieve validation:

chi% ./6.SB.exe -pra I -prf 0:y=F -prf 1:z=F -prf 2:a=F -prf 3:b=F -prf 4:c=F -prf 5:x=F
Test 6.SB Allowed
Histogram (63 states)
211  *>0:EAX=0; 1:EAX=0; 2:EAX=0; 3:EAX=0; 4:EAX=0; 5:EAX=0;

Test 6.SB Allowed
Histogram (63 states)
10  *>0:EAX=0; 1:EAX=0; 2:EAX=0; 3:EAX=0; 4:EAX=0; 5:EAX=0;
As a conclusion, interpreting the impact of cache management directives is not easy. However, custom preload mode (litmus command line option `-preload custom`) and test executable options `-pra` and `-prf` allow experimentation on specific tests.

3.2.3 “Static” prefetch control

Custom prefetch mode comes handy when one wants to tailor cache management directives for a particular test. In practice, we run batches of tests using source metadata for prefetch directives. In such a setting, the code that interprets the prefetch directives is useless, as we do not use the `-prf` option of the test executables. As this code get executed before each test thread code, it may impact test results. It is desirable to suppress this code from test executables, still performing cache management instructions. To that aim, litmus7 provides some “static” preload modes, enabled with command line options `-preload static`, `-preload static1` and `-preload static2`.

In the former mode `-preload static` and without any further user intervention, each test thread executes the cache management instructions commanded by the `Prefetch` metadata:

```bash
% mkdir -p S
% litmus7 -mem indirect -preload static -o R 6.SB+Prefetch.litmus
% make -C S
% S/6.SB+Prefetch.exe
Test 6.SB Allowed
Histogram (63 states)
804 *>0:EAX=0; 1:EAX=0; 2:EAX=0; 3:EAX=0; 4:EAX=0; 5:EAX=0;
...
Observation 804 999196
...
```

As we can see above, the effect of the cache management instructions looks more favorable than in custom preload mode.

Users still have a limited control on the execution of cache management instructions: produced executable accept a new `-prs <n>` option, which take a positive or null integer as argument. Then, each test thread executes the cache management instructions commanded by source metadata with probability $1/n$, the special value $n = 0$ disabling prefetch altogether. The default for the `-prs` options is “1” (always execute the cache management instructions). Let us try:

```bash
% S/6.SB+Prefetch.exe -prs 0 | grep Observation
Observation 6.SB Never 0 1000000
% S/6.SB+Prefetch.exe -prs 1 | grep Observation
Observation 6.SB Sometimes 901 999099
% S/6.SB+Prefetch.exe -prs 2 | grep Observation
Observation 6.SB Sometimes 29 999971
% S/6.SB+Prefetch.exe -prs 3 | grep Observation
Observation 6.SB Sometimes 16 999984
```

In those experiments we show the “Observation” field of litmus7 output: this field gives the count of outcomes that validate the final condition, followed by the count of outcomes that do not validate the final condition. The above counts confirm that cache management instructions favor validation.

The remaining preload modes `static1` and `static2` are similar, except that they produce executable files that do not accept the `-prs` option. Furthermore, in the former mode `-preload static1` cache management instructions are always executed, while in the latter mode `-preload static2` cache management instructions are executed with probability $1/2$. Those modes thus act as pure static mode (litmus7 option `-preload static`), with runtime options `-prs 1` and `-prs 2` respectively. Moreover, as the test scaffold includes no code to interpret the `-prs <n>` switch, the test code is less perturbed. In practice and for the 6.SB example, there is little difference:
4 Usage of litmus7

Arguments

litmus7 takes file names as command line arguments. Those files are either a single litmus test, when having extension .litmus, or a list of file names, when prefixed by @. Of course, the file names in @files can themselves be @files.

Options

There are many command line options. We describe the more useful ones:

General behaviour

-\texttt{-version} Show version number and exit.
-\texttt{-libdir} Show installation directory and exit.
-\texttt{-v} Be verbose, can be repeated to increase verbosity.
-\texttt{-mach <name>} Read configuration file \texttt{name.cfg}. See the next section for the syntax of configuration files.
-\texttt{-o <dest>} Save C-source of test files into \texttt{<dest>} instead of running them. If argument \texttt{<dest>} is an archive (extension .tar) or a compressed archive (extension .tgz), litmus7 builds an archive: this is the “cross compilation feature” demonstrated in Sec. 1.2. Otherwise, \texttt{<dest>} is interpreted as the name of an existing directory and tests are saved in it.
-\texttt{-driver (shell|C|XCode)} Choose the driver that will run the tests. In the “shell” (and default) mode, each test will be compiled into an executable. A dedicated shell script \texttt{run.sh} will launch the test executables. In the “C” mode, one executable \texttt{run.exe} is produced, which will launch the tests. Finally, the \texttt{XCode} mode is for inclusion of the tests into a dedicated iOS App, which we do not distribute at the moment.
-\texttt{-crossrun \langle(user@)?host(:port)?|adb|qemu\rangle} When the shell driver is used (-\texttt{driver shell} above), the first two possible arguments instruct the \texttt{run.sh} script to run individual tests on a remote machine. The remote host can be contacted by the means of \texttt{ssh} or the Android Debug Bridge.

\texttt{ssh user} is a login name on the the remote host, \texttt{<host>} is the name of the remote host, and \texttt{port} is a port-number which can be omitted when standard (22).

\texttt{adb} Tests will be run in the remote directory /\texttt{data/tmp}.

This option may be useful when the tested machine has little disk space or a crippled installation. Default is disabled — \textit{i.e.} run tests on the machine where the \texttt{run.sh} script runs.
The argument `qemu` instruct the shell script to use the `qemu` emulator. The `QEMU` environment variable must be defined to the emulator path before running the `run.sh` script, as in (sh syntax):

```
QEMU=qemu sh run.sh
```

- `index <@name>` Save the source names of compiled files in index file `@name`.
- `hexa` Hexadecimal output, default is decimal.

**Test conditions**  The following options set the default values of the options of the executable files produced:

- `-a <n>` Run maximal number of tests concurrently for `n` available logical processors — set default value for `-a` of Sec. 2.3. Default is special and will command running exactly one test instance. When affinity control is enabled, the value 0 has the special meaning of having executables to set the number of available logical processors according to how many are actually present.

- `-limit <bool>` Do not process tests with more than `n` threads, where `n` is the number of available cores defined above. Default is `true`. Does not apply when option `-a` is absent.

- `-r <n>` Perform `n` runs — set default value for option `-r` of Sec. 2.3. The option accepts generalised syntax for integers and default is 10.

- `-s <n>` Size of a run — set default value for option `-s` of Sec. 2.3. The option accepts generalised syntax for integers and default is 100000 (or 100k).

The following additional options control the various modes described in Sec. 2.1, and more. Those cannot be changed without running litmus7 again:

- `barrier (user|userfence|pthread|none|timebase)` Set synchronisation mode, default `user`. Synchronisation modes are described in Sec. 2.1

- `launch (changing|fixed)` Set launch mode, default `changing`.

- `mem (indirect|direct)` Set memory mode, default `indirect`. It is possible to instruct executables compiled in indirect mode to behave almost as if compiled in direct mode, see Sec. 2.3.

- `stride (none|adapt|<n>)` Specify a stride value of `<n>` — set default value for option `-st` of Sec. 2.3. See Sec. 2.1 for details on the stride parameter. The default is `none` — i.e. tests have no `-st` option. The special tag `adapt` sets the default stride to be the number of threads in test.

- `st <n>` Alias for `-stride <n>`.

- `para (self|shell)` Perform several tests concurrently, either by forking POSIX threads (as described in Sec. 2.1), or by forking Unix processes. Only applies for cross compilation. Default is `self`.

- `alloc (dynamic|static|before)` Set memory allocation mode. In “dynamic” and “before” modes, the memory used by test threads is allocated with `malloc` — in “before” mode, memory is allocated before forking test instances. In “static” mode, the memory is pre-allocated as static arrays. In that latter case, the size of allocated arrays depend upon compile time defined parameters: the number of available logical processors (see option `-a <n>`) and the size of a run (see option `-s <n>`). It remains possible to change those those at execution time, provided the resulting memory size does not exceed the compile time value. Default is `dynamic`.

- `preload (no|random|custom|static|static1|static2)` Specify preload mode (see Sec. 2.1), default is `random`. Starting from version 5.0 we provide additional “custom” and “static” modes for a finer control of prefetching and flushing of some memory locations by some threads. See Sec 3.2.

---

4 For backward compatibility, `<n>` being negative or zero is equivalent to `none`. 26
-safer (no|all|write) Specify safer mode, default is write. When instructed to do so, executable files perform some consistency checks. Those are intended both for debugging and for dynamically checking some assumptions on POSIX threads that we rely upon. More specifically the test harness checks for the stabilisation of memory locations after a test round in the “all” and “write” mode, while the initial values of memory locations are checked in “all” mode.

-speedcheck (no|some|all) Quick condition check mode, default is “no”. In mode “some”, test executable will stop as soon as its condition is settled. In mode “all”, the run.sh script will additionally not run the test if invoked once more later.

The following option commands affinity control:

-**affinity** (none|incr<n>|random|custom) Enable (of disable with tag none) affinity control, specifying default affinity mode of executables. Default is none, i.e. executables do not include affinity control code. The various tags are interpreted as follows:

1. incr<n>: integer <n> is the increment for allocating logical processors to threads — see Sec. 2.2. Notice that with -affinity incr0 the produced code features affinity control, which executable files do not exercise by default.
2. random: executables perform random allocation of test threads to logical processors.
3. custom: executables perform custom allocation of test threads to logical processors.

Notice that the default for executables can be overridden using options -i, +ra and +ca of Sec. 2.3.

-i <n> Alias for -affinity incr<n>.

Notice that affinity control is not implemented for MacOs.

The following options are significant when affinity control is enabled. Otherwise they are silent no-ops.

-p <ns> Specify the sequence of logical processors. The notation <ns> stands for a comma separated list of integers. Set default value for option -p of Sec. 2.3. Default for this -p option will let executable files compute the logical processor sequence themselves.

-force_affinit <bool> Code that sets affinity will spin until all specified cores (as given with option -avail <n>) processors are up. This option is necessary on devices that let core sleep when the computing load is low. Default is false.

Custom affinity control (see Sec. 2.2.4) is enabled, first by enabling affinity control (e.g. with -affinity ...), and then by specifying a logical processor topology with options -smt and -smt_mode.

-smt <n> Specify that logical processors are close by groups of n, default is 1.

-smt_mode (none|seq|end) Specify how “close” logical processors are numbered, default is none. In mode “end”, logical processors of the same core are numbered as c, c + Ac etc. where c is a physical core number and Ac is the number of physical cores available. In mode “seq”, logical processors of the same core are numbered in sequence.

Notice that custom affinity works only for those tests that include the proper meta-information. Otherwise, custom affinity silently degrades to random affinity.

Finally, a few miscellaneous options are documented:

-l <n> Insert the assembly code of each thread in test in a loop of size <n>. Accepts generalised integer syntax, disabled by default. Sets default value for option -l of Sec. 2.3.

This feature may prove useful for measuring running times that are not too much perturbed by the test harness, in combination with options -s 1 -r 1.
-vb <bool> Disable/enable the printing of synchronisation timings, default is false.

This feature may prove useful for analysing the synchronisation behaviour of a specific test, see Sec. 3.1.

-ccopts <flags> Set gcc compilation flags (defaults: X86="-fomit-frame-pointer -O2", PPC/ARM="-02").

-gcc <name> Change the name of C compiler, default gcc.

-linkopt <flags> Set gcc linking flags. (default: void).

-gas <bool> Emit Gnu as extensions (default Linux/Mac=true, AIX=false)

Target architecture description Litmus compilation chain may slightly vary depending on the following parameters:

-os (linux|mac|aix) Set target operating system. This parameter mostly impacts some of gcc options. Default linux.

-ws (w32|w64) Set word size. This option first selects gcc 32 or 64 bits mode, by providing it with the appropriate option (-m32 or -m64 on linux, -maix32 or -maix64 on AIX). It also slightly impacts code generation in the corner case where memory locations hold other memory locations. Default is a bit contrived: it acts as w32 as regards code generation, while it provides no 32/64 bits mode selection option to gcc.

Change input Some items in the source of tests can be changed at the very last moment. The new items are defined in mapping files whose names are arguments to the appropriate command line options. Mapping files simply are lists of pairs, with one line starting with a test name, and the rest of line defining the changed item. The changed item may also contains several lines: in that case it should be included in double quotes "".

-names <file> Run litmus7 only on tests whose names are listed in <file>.

-excl <file> Do not run litmus7 on tests whose names are listed in <file>.

-rename <file> Change test names.

-kinds <file> Change test kinds. This amounts to changing the quantifier of final conditions, with kind Allow being exists, kind Forbid being ~exists and kind Require being forall.

-conds <file> Change the final condition of tests.

-hints <file> Change meta-data, or hints. Hints command advanced features such as custom affinity (option -affinity custom and Sec. 2.2.4) and prefetch control (option -preload custom and Sec. 3.2).

Observe that the rename mapping is applied first. As a result kind or condition change must refer to new names. For instance, we can highlight that a X86 machine is not sequentially consistent by first renaming SB into SB+SC, and then changing the final condition. The new condition expresses that the first instruction (a store) of one of the threads must come first:

```
rename.txt                     cond.txt

SB  SB+SC                     SB+SC "forall (0:EAX=1 \/: 1:EAX=1)"
```

Then, we run litmus:
% litmus7 -mach x86 -rename rename.txt -conds cond.txt SB.litmus

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Results for SB.litmus %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
X86 SB+SC
"Fre PodWR Fre PodWR"

{x=0; y=0;}

PO | P1
MOV [x],$1 | MOV [y],$1
MOV EAX,[y] | MOV EAX,[x]

forall (0:EAX=1 \ 1:EAX=1)

Generated assembler
#START _litmus_P1
  movl $1,(%r8,%rdx)
  movl (%rdx),%eax
#START _litmus_P0
  movl $1,(%rdx)
  movl (%r8,%rdx),%eax

Test SB+SC Required
Histogram (4 states)
39954 >0:EAX=0; 1:EAX=0; 3979407:>0:EAX=1; 1:EAX=0;
3980444:>0:EAX=0; 1:EAX=1; 195 :>0:EAX=1; 1:EAX=1;
No

Witnesses
Positive: 7960046, Negative: 39954
Condition forall (0:EAX=1 \ 1:EAX=1) is NOT validated
Hash=7dbd6b8e6dd4abc2ef3d48b0376fb2e3
Observation SB+SC Sometimes 7960046 39954
Time SB+SC 0.48

One sees that the test name and final condition have changed.

Miscellaneous

-sleep <n> Insert a delay of n seconds between each individual test run.

-exit <bool> Exit status of each individual test executable reflects the final condition success or failure, default false (test exit status always is success in absence of errors).

Configuration files

The syntax of configuration files is minimal: lines “key = arg” are interpreted as setting the value of parameter key to arg. Each parameter has a corresponding option, usually -key, except for single-letter options:

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5.1 Compiling and running a kernel litmus test

Kernel tests are normally written in C, augmented with specific kernel macros. As an example, here is SB+onces.litmus, the kernel version of the store buffering litmus test:

```
C SB+onces

P0(volatile int* y, volatile int* x) {
    int r0;
    WRITE_ONCE(*x, 1);
    r0 = READ_ONCE(*y);
}

P1(volatile int* y, volatile int* x) {
    int r0;
    WRITE_ONCE(*y, 1);
    r0 = READ_ONCE(*x);
}

exists (0:r0=0 \ 1:r0=0)
```
As can be seen above, C litmus tests are formatted differently from assembler tests: the code of threads is presented as functions, not as columns of instructions. One may also notice that the test uses the kernel macros `WRITE_ONCE` (guaranteed memory write) and `READ_ONCE` (guaranteed memory read).

The tool `klitmus7` offers only the cross compilation mode: i.e., `klitmus7` translates the tests to some C files, plus `Makefile` and run script (`run.sh`).

```bash
% klitmus7 -o X.tar SB+onces.litmus
```

The above command outputs the archive `X.tar`.

Then, users compile the contents of the archive on the target machine, which need not be the machine where `klitmus7` has run.

```bash
% mkdir -p X && cd X && tar xmf ../X.tar
% make
make -C /lib/modules/3.13.0-108-generic/build/ M=/tmp/X modules
make[1]: Entering directory `/usr/src/linux-headers-3.13.0-108-generic'
  CC [M] /tmp/X/litmus000.o
  Building modules, stage 2.
  MODPOST 1 modules
  CC /tmp/X/litmus000.mod.o
  LD [M] /tmp/X/litmus000.ko
make[1]: Leaving directory `/usr/src/linux-headers-3.13.0-108-generic'
```

Notice that the final compilation relies on kernel headers being installed.

One then run the test. This step must be performed with root privileges, and requires the `insmod` and `rmmod` commands to be installed. We get:

```bash
% sudo sh run.sh
Fri Aug 18 16:37:43 CEST 2017
Compilation command: klitmus7 -o X.tar SB+onces.litmus
OPT=
uname -r=3.13.0-108-generic
Test SB+onces Allowed
Histogram (4 states)
184992 *>0:r0=0; 1:r0=0;
909016 :>0:r0=1; 1:r0=0;
858961 :>0:r0=0; 1:r0=1;
47031 :>0:r0=1; 1:r0=1;
Ok
Witnesses
Positive: 184992, Negative: 1815008
Condition exists (0:r0=0 /\ 1:r0=0) is validated
Hash=2487db0f8d32ae7ec0eacf5d0e301d7
Observation SB+onces Sometimes 184992 1815008
Time SB+onces 0.18
```

Output is similar to `litmus7` output. One sees that the store buffer idiom is also observed in kernel mode.

In this simple example, we compile and run one single test. However, usual practice is, as it is for `litmus7`, to compile and run several tests at once. One achieve this naturally, by supplying several source files as command line arguments to `klitmus7`, or by using index files, see Sec 4.
5.2 Runtime control of kernel modules

The value of some test parameters (see Sec. 2) can be set differently from defaults. This change is performed by the means of a key value interface.\(^5\) For instance, one sets the number of threads devoted to the test, the size of a run and the number of runs by using keywords `avail`, `size` and `nruns`, respectively:

\[
\% \texttt{sudo sh run.sh avail=2 size=100 nruns=1}
\]

Mon Aug 21 11:04:12 CEST 2017

Compilation command: `klitmus7 -o /tmp/X.tar SB+onces.litmus
OPT=avail=2 size=100 nruns=1
uname -r=3.13.0-108-generic

Test SB+onces Allowed
Histogram (3 states)
12  *>0:r0=0; 1:r0=0;
48  :>0:r0=1; 1:r0=0;
40  :>0:r0=0; 1:r0=1;
0k

Witnesses
Positive: 12, Negative: 88
Condition exists \((0:r0=0 \land 1:r0=0)\) is validated
Hash=2487db0f8d3aeb7ec0eacdf5d0e301d7
Observation SB+onces Sometimes 12 88
Time SB+onces 0.00

Mon Aug 21 11:04:12 CEST 2017

The kernel modules produced by `klitmus7` can be controlled by using the following keys = `<int>` settings. The default values of those parameters are set at compile time, by the means of command line options passed to `klitmus7`, see below.

`size` Size of a run.

`nruns` Number of runs.

`ninst` Number of test instances run. When the value of this parameter is zero (usual case) it is unused (see `avail` below).

Otherwise, `ninst` instance of each test is run. However, if the total number of threads used by a given test exceeds the number of online logical processors of the machine, the test is not run.

`avail` Number of threads devoted to testing. This parameter is active when `ninst` is zero.

If this parameter is zero (or exceeds the number of online logical processors) then it is changed to the number of online logical processors of the machine. Finally, `avail` divided by the number of threads in test are run. Since this is euclidean division the resulting number of instances can be zero. In that case, the test is not run.

`stride` Stride for scanning locations arrays — see Sec. 2.1. If this parameter is zero, it is silently changed to one.

`affincr` Affinity control. Any value strictly greater than zero is an affinity increment (see section 2.2.1). A value of zero means no affinity control. A strictly negative value commands random affinity control.

---

\(^5\)This interface is the one provided for configuring kernel modules at load time.
It is important to notice that the values of keywords are integers in a strict sense. Namely, the generalized syntax of integer (such as 10k, 1M etc.) is not accepted. Moreover, except in the affinity case, where negative values are accepted, only positive (or null) values are accepted.

5.3 Usage of klitmus7

Given that klitmus7 purpose is running kernel litmus tests, klitmus7 accepts tests written (1) in C or (2) in LISA, an experimental generic assembler language.

As regards options klitmus7 accepts a restricted subset of the options accepted by litmus7, plus a few specific options.

General behaviour

-version Show version number and exit.
-libdir Show installation directory and exit.
-v Be verbose, can be repeated to increase verbosity.
-o <dest> Save C-source of test files into <dest>. Argument <dest> can be an archive (extension .tar), a compressed archive (extension .tgz), or an existing directory. This option is mandatory for klitmus7, while it is optional for litmus7.
-hexa Hexadecimal output, default is decimal.
-pad <n> Sets the padding for C litmus filenames, default 3. Namely, klitmus7 dumps the code for tests into files that are named systematically litmus<i>.c, where i is an index number formatted with "%0<n>i" (zero left padding, with minimal size of <n>). As a result, by default, file names are litmus000.c, litmus001.c, litmus002.c, ...

Test conditions Most of these options set the default values of the parameters described above.

-a <n> Run maximal number of tests concurrently for n available logical processors — set default value for parameter avail. Default is 0. As a result, the runtime parameter avail will default to the number of online logical processors.
-limit <bool> Do not process tests with more than n threads, where n is the number of available logical processors specified above. Default is true. Does not apply when option -a is absent.
-r <n> Perform n runs — set default value of the parameter nrings. The option accepts generalised syntax for integers and default is 10.
-s <n> Size of a run — set default value for parameter size. The option accepts generalised syntax for integers and default is 100000 (or 100k).
-st (adapt|<n>) Set stride value, default is 1. Set default value of parameter stride. In case the command line argument is adapt, the parameter default value will be the number of threads in test.

-affinity (none|incr<n>|random) Enable (of disable with tag none) affinity control, specifying default value of parameter affincr; with tag none yielding a default value of 0, tag incr<n> yielding a default value of <n>, and tag random yielding a default value of -1. Default is none, i.e., modules do not perform affinity control, although they include code do so — this is a significant difference with litmus7 default). The various tags are interpreted as follows:

1. incr<n>: integer <n> is the increment for allocating logical processors to threads — see Sec. 2.2.

Setting -affinity incr0 is special and defined as equivalent to -affinity none.
2. random modules perform random allocation of test threads to logical processors.

-<n> Alias for -affinity incr<n>.

-barrier (userfence|tb) Set synchronisation mode. Default is userfence. One may notice that this option offers less variety than the corresponding litmus7 option (see Sec. 2.1, experience having proved to us that those two setting are the most useful ones.

Change input

-names <file> Run litmus7 only on tests whose names are listed in <file>.

-excl <file> Do not run litmus7 on tests whose names are listed in <file>.

-rename <file> Change test names.

-rcu (yes|no|only) Accept or not tests that contains RCU (read-copy-update) primitives, which can be quite long to run. Default is no. The tags have the following meaning:

1. yes: Accept RCU tests.
2. no: Reject RCU tests (silently).
3. only: Accept RCU tests and reject others.

-expedited <bool> translate teh RCU primitive synchronize_rcu to synchronize_expedited (which may be much faster). Default is true.

Miscellaneous option

-ccopt <string> Additional option for the C compiler.
Part II
Generating tests

6 Preamble

We wrote diy7 as part of our empirical approach to studying relaxed memory models: developing in tandem testing tools and models of multiprocessor behaviour. In this tutorial, we attempt an independent tool presentation. Readers interested by the companion formalism are invited to refer to our CAV 2010 publication [1].

The distribution includes additional test generators: diyone7 for generating one test and diycross7 for generating simple variations on one test.

6.1 Relaxation of Sequential Consistency

Relaxation is one of the key concepts behind simple analysis of weak memory models. We define a candidate relaxation by reference to the most natural model of parallel execution in shared memory: Sequential Consistency (SC), as defined by L. Lamport [3]. A parallel program running on a sequentially consistent machine behaves as an interleaving of its sequential threads.

Consider once more the example SB.litmus:

X86 SB
"Fre PodWR Fre PodWR"
{x=0; y=0; }
P0 | P1 ;
MOV [y],$1 | MOV [x],$1 ; #(a)Wy1 | (c)Wx1
MOV EAX,[x] | MOV EAX,[y] ; #(b)Rx0 | (d)Ry0
exists (0:EAX=0 \(\land\) 1:EAX=0)

To focus on interaction through shared memory, let us consider memory accesses, or memory events. A memory event will hold a direction (write, written W, or read, written R), a memory location (written x, y) a value and a unique label. In any run of the simple example above, four memory events occur: two writes (c) Wx1 and (a) Wy1 and two reads (b) Rx0 with a certain value \(v_1\) and (d) Ry0 with a certain value \(v_2\).

If the program’s behaviour is modelled by the interleaving of its events, the first event must be a write of value 1 to location x or y and at least one of the loads must see a 1. Thus, a SC machine would exhibit only three possible outcomes for this test:

- Allowed: 0:EAX=0 \(\land\) 1:EAX=1
- Allowed: 0:EAX=1 \(\land\) 1:EAX=0
- Allowed: 0:EAX=1 \(\land\) 1:EAX=1

However, running (see Sec. 1.1) this test on a x86 machine yields an additional result:

- Allowed: 0:EAX=0 \(\land\) 1:EAX=0

And indeed, x86 allows each write-read pair on both processors to be reordered [2]: thus the write-read pair in program order is relaxed on each of these architectures. We cannot use SC as an accurate memory model for modern architectures. Instead we analyse memory models as relaxing the ordering constraints of the SC memory model.
6.2 Introduction to candidate relaxations

Consider again our classical example, from a SC perspective. We briefly argued that the outcome “0:EAX = 0 ∧ 1:EAX = 0” is forbidden by SC. We now present a more complete reasoning:

- From the condition on outcome, we get the values in read events: (b) Rx0 and (d) Ry0.
- Because of these values, (b) Rx0 must precede the write (c) Wx1 in the final interleaving of SC. Similarly, (d) Ry0 must precede the write (a) Wy1. This we note (b) \( \rightarrow_{fr} (c) \) and (d) \( \rightarrow_{fr} (a) \).
- Because of sequential execution order on one single processor (a.k.a. program order), (a) Wy1 must precede (b) Rx0 (first processor); while (c) Wx1 must precede (d) Ry0 (second processor). This we note (a) \( \rightarrow_{po} (b) \) and (c) \( \rightarrow_{po} (d) \).

We synthesise the four constraints above as the following graph:

Constraint arrows or global arrows are shown in brown colour. As the graph contains a cycle of brown arrows, the events cannot be ordered. Hence the execution presented is not allowed by SC.

The key idea of diy7 resides in producing programs from similar cycles. To that aim, the edges in cycles must convey additional information:

- For \( \rightarrow_{po} \) edges, we consider whether the locations of the events on both sides of the edge are the same or not (’s’ or ‘d’); and the direction of these events (W or R). For instance the two \( \rightarrow_{po} \) edges in the example are PodWR. (program order edge between a write and a read whose locations are different).
- For \( \rightarrow_{fr} \) edges, we consider whether the processor of the events on both sides of the edge are the same or not (’i’ for internal, or ’e’ for external). For instance the two \( \rightarrow_{fr} \) edges in the example are Fre.

So far so good, but our x86 machine produced the outcome 0:EAX=0 ∧ 1:EAX=0. The Intel Memory Ordering White Paper [2] specifies: “Loads may be reordered with older stores to different locations”, which we rephrase as: PodWR is relaxed. Considering Fre to be safe, we have the graph:
And the brown sub-graph becomes acyclic.

We shall see later why we choose to relax PodWR and not Fre. At the moment, we observe that we can assume PodWR to be relaxed and Fre not to be (i.e. to be safe) and test our assumptions, by producing and running more litmus tests. The diy7 suite precisely provides tools for this approach.

As a first example, SB.litmus can be created as follows:

```
% diyone7 -arch X86 -name SB Fre PodWR Fre PodWR
```

As a second example, we can produce several similar tests as follows:

```
% diy7 -arch X86 -safe Fre -relax PodWR -name SB
Generator produced 2 tests
Relaxations tested: {PodWR}
```

diy7 produces two litmus tests, SB000.litmus and SB001.litmus, plus one index file @all. One of the litmus tests generated is the same as above, while the new test is:

```
% cat SB001.litmus
X86 SB001
"Fre PodWR Fre PodWR Fre PodWR"
Cycle=Fre PodWR Fre PodWR Fre PodWR
Relax=PodWR
Safe=Fre
{ }
```

```
% cat @all
# diy -arch X86 -safe Fre -relax PodWR -name SB
# Revision: 3333
SB000.litmus
SB001.litmus
```

diy7 first generates cycles from the candidate relaxations given as arguments, up to a limited size, and then generates litmus tests from these cycles.

### 6.3 More candidate relaxations

We assume the memory to be coherent. Coherence implies that, in a given execution, the writes to a given location are performed by following a sequence, or coherence order, and that all processors see the same sequence.
In diy7, the coherence orders are specified indirectly. For instance, the candidate relaxation \( W_{se} \) (resp. \( W_{si} \)) specifies two writes, performed by different processors (resp. the same processor), to the same location \( \ell \), the first write preceding the second in the coherence order of \( \ell \). The condition of the produced test then selects the specified coherence orders. Consider for instance:

```
% diyone7 -arch X86 -name x86-2+2W Wse PodWW Wse PodWW
```

The cycle that reveals a violation of the SC memory model is:

(a) \( W_{y2} \)
(b) \( W_{x1} \)
(c) \( W_{x2} \)
(d) \( W_{y1} \)

PodWW

So the coherence order is 0 (initial store, not depicted), 1, 2 for both locations \( x \) and \( y \). While the produced test is:

```
X86 x86-2+2W
"Wse PodWW Wse PodWW"
Prefetch=0:x=F,0:y=W,1:y=F,1:x=W
Com=Ws Ws
Orig=Wse PodWW Wse PodWW
{
    P0 | P1 ;
    MOV [x],$2 | MOV [y],$2 ;
    MOV [y],$1 | MOV [x],$1 ;
existence (x=2 \( / \) y=2)
```

By the coherence hypothesis, checking the final value of locations suffices to characterise those two coherence orders, as expressed by the final condition of \texttt{x86-2+2W}:

```
existence (x=2 \( / \) y=2)
```

See Sec. 10 for alternative means to identify coherence orders.

Candidate relaxations \( R_{fe} \) and \( R_{fi} \) relate writes to reads that load their value. We are now equipped to generate the famous \texttt{iriw} test (independent reads of independent writes):

```
% diyone7 -arch X86 Rfe PodRR Fre Rfe PodRR Fre -name iriw
```

We generate its internal variation (\textit{i.e.} where all \( R_{fe} \) are replaced by \( R_{fi} \)) as easily:

```
% diyone7 -arch X86 Rfi PodRR Fre Rfi PodRR Fre -name iriw-internal
```

We get the cycles of Fig. 1, and the litmus tests of Fig. 2.

Candidate relaxations given as arguments really are a “concise specification”. As an example, we get \texttt{iriw} for Power, simply by changing \texttt{-arch X86} into \texttt{-arch PPC}.

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Figure 1: Cycles for iriw and iriw-internal

Figure 2: Litmus tests iriw and iriw-internal

X86 iriw
"Rfe PodRR Fre Rfe PodRR Fre"

\begin{verbatim}
{ }
P0 | P1 | P2 | P3 ;
MOV EAX,[y] | MOV [x],$1 | MOV EAX,[x] | MOV [y],$1 ;
MOV EBX,[x] | MOV EBX,[y] | ;
exists (0:EAX=1 \& 0:EBX=0 \& 2:EAX=1 \& 2:EBX=0)
\end{verbatim}

X86 iriw-internal
"Rfi PodRR Fre Rfi PodRR Fre"

\begin{verbatim}
{ }
P0 | P1 ;
MOV [x],$1 | MOV [y],$1 ;
MOV EAX,[x] | MOV EAX,[y] ;
MOV EBX,[y] | MOV EBX,[x] ;
extists (0:EAX=1 \& 0:EBX=0 \& 1:EAX=1 \& 1:EBX=0)
\end{verbatim}
% diyone7 -arch PPC Rfe PodRR Fre Rfe PodRR Fre
PPC A
"Rfe PodRR Fre Rfe PodRR Fre"
{
0:r2=y; 0:r4=x;
1:r2=x;
2:r2=x; 2:r4=y;
3:r2=y;
}
P0 | P1 | P2 | P3;
lwz r1,0(r2) | li r1,1 | lwz r1,0(r2) | li r1,1;
lwz r3,0(r4) | stw r1,0(r2) | lwz r3,0(r4) | stw r1,0(r2);
exists (0:r1=1 ∧ 0:r3=0 ∧ 2:r1=1 ∧ 2:r3=0)

Also notice that without the -name option, diyone7 writes its result to standard output.

6.4 Summary of simple candidate relaxations

We summarise the candidate relaxations available on all architectures.

6.4.1 Communication candidate relaxations

We call communication candidate relaxations the relations between two events communicating through memory, though they could belong to the same processor. Thus, these events operate on the same memory location.

<table>
<thead>
<tr>
<th>diy7 syntax</th>
<th>Source</th>
<th>Target</th>
<th>Processor</th>
<th>Additional property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rfi</td>
<td>W</td>
<td>R</td>
<td>Same</td>
<td>Target reads its value from source</td>
</tr>
<tr>
<td>Rfe</td>
<td>W</td>
<td>R</td>
<td>Different</td>
<td>Target reads its value from source</td>
</tr>
<tr>
<td>Wsi</td>
<td>W</td>
<td>W</td>
<td>Same</td>
<td>Source precedes target in coherence order</td>
</tr>
<tr>
<td>Wse</td>
<td>W</td>
<td>W</td>
<td>Different</td>
<td>Source precedes target in coherence order</td>
</tr>
<tr>
<td>Fri</td>
<td>R</td>
<td>W</td>
<td>Same</td>
<td>Source reads a value from a write that precedes target in coherence order</td>
</tr>
<tr>
<td>Fre</td>
<td>R</td>
<td>W</td>
<td>Different</td>
<td>Source reads a value from a write that precedes target in coherence order</td>
</tr>
</tbody>
</table>

6.4.2 Program order candidate relaxations

We call program order candidate relaxations each relation between two events in the program order. These events are on the same processor, since they are in program order. As regards code output, diy7 interprets a program order candidate relaxation by generating two memory instructions (load or store) following one another.

Program order candidate relaxations have the following syntax:

\[ \text{Po(s|d)(R|W)(R|W)} \]

where:

- \( s \) (resp. \( d \)) indicates that the two events are to the same (resp. different) location(s);
- \( R \) (resp. \( W \)) indicates an event to be a read (resp. a write);

In practice, we have:
It is to be noticed that PosWR, PosWW and PosRW are similar to Rfi, Wsi and Fri, respectively. More precisely, diy7 is unable to consider a PosWR (or PosWW, or PosRW) candidate relaxation as not being also a Rfi (or Wsi, or Fri) candidate relaxation. However, litmus tests conditions may be more informative in the case of Rfi and Fri.

### 6.4.3 Fence candidate relaxations

Relaxed architectures provide specific instructions, namely barriers or fences, to enforce order of memory accesses. In diy7 the presence of a fence instruction is specified with fence candidate relaxations, similar to program order candidate relaxations, except that a fence instruction is inserted. Hence we have FencedsRR, FenceddRR, etc. The inserted fence is the strongest fence provided by the architecture — that is, `mfence` for x86 and `sync` for Power.

Fences can also be specified by using specific names. More precisely, we have MFence for x86; while on Power we have Sync, LwSync, Eieio and Isync. Hence, to yield two reads to different locations and separated by the lightweight Power barrier `lwsync`, we specify LwSyncdRR. On ARM we have DMB, DSB and ISB.

### 7 Testing candidate relaxations with diy7

The tool diy7 can probably be used in various, creative, ways; but the tool first stems from our technique for testing relaxed memory models. The `-safe` and `-relax` options are crucial here. We describe our technique by the means of an example: X86-TSO.

#### 7.1 Principle

Before engaging in testing it is important to categorise candidate relaxations as safe or relaxed. This can be done by interpretation of vendor’s documentation. For instance, the iriw test of Sec. 6.3 is the example 7.7 of [2] “Stores Are Seen in a Consistent Order by Other Processors”, with a Forbid specification. Hence we deduce that Fre, Rfe and PodRR are safe. Then, from test iriw-internal of Sec. 6.3, which is Intel’s test 7.5 “Intra-Processor Forwarding Is Allowed” with an allow specification, we deduce that Rfi is relaxed. Namely, the cycle of iriw-internal is “Fre Rfi PodRR Fre Rfi PodRR”. Therefore, the only possibility is for Rfi to be relaxed.

Overall, we deduce:

- Candidate relaxations PosWR (Rfi) and PodWR are relaxed
- The remaining candidate relaxations PosRR, PodRR, PosWW (Wsi), PodWW, PosRW (Fri), Fre and Wse are safe. Fence relaxations FencedsWR and FenceddWR are also safe and worth testing.

Of course these remain assumptions to be tested. To do so, we perform one series of tests per relaxed candidate relaxation, and one series of tests for confirming safe candidate relaxations as much as possible. Let $S$ be all safe candidate relaxations.
• Let \( r \) be a relaxed candidate relaxation. We produce tests for confirming \( r \) being relaxed by \texttt{diy -relax \( r \) -safe \( S \)}. We run these tests with \texttt{litmus7}. If one of the tests yields \texttt{Ok}, then \( r \) is confirmed to be relaxed, provided the experiments on \( S \) below do not fail.

• For confirming the safe set, we produce tests by \texttt{diy -safe \( S \)}. We run these tests as much as possible and expect never to see \texttt{Ok}.

Namely, \texttt{diy7} builds cycles as follows:

• \texttt{diy -relax \( r \) -safe \( S \)} build cycles with at least one \( r \) taking other candidate relaxations from \( S \).

• \texttt{diy -safe \( S \)} build cycles from the candidate relaxations in \( S \).

For the purpose of confirming relaxed candidate relaxations, \( S \) can be replaced by a subset.

### 7.2 Testing x86

Repeating command line options is painful and error prone. Besides, configuration parameters may get lost. Thus, we regroup those in configuration files that simply list the options to be passed to \texttt{diy7}, one option per line. For instance here is the configuration file for testing the safe relaxations of x86, \texttt{x86-safe.conf}.

```
#safe x86 conf file
-arch X86
#Generate tests on four processors or less
-nprocs 4
#From cycles of size at most six
-size 6
#With names safe000, safe0001,...
-name safe
#List of safe relaxations
-safe PosR* PodR* PodWW PosWW Rfe Wse Fre FencesWR FencedWR
```

Observe that the syntax of candidate relaxations allows one shortcut: the wildcard \( * \) stands for \( W \) and \( R \). Thus \( PodR\* \) gets expanded to the two candidate relaxations \( PodRW \) and \( PodRR \).

We get safe tests by issuing the following command, preferably in a specific directory, say \texttt{safe}.

```bash
% diy7 -conf x86-safe.conf
Generator produced 38 tests
Relaxations tested: {}
```

Here are the configuration files for confirming that \( Rfi \) and \( PodWR \) are relaxed, \texttt{x86-rfi.conf} and \texttt{x86-podwr.conf}.

```
#rfi x86 conf file
-arch X86
-nprocs 4
-size 6
-name rfi
-safe PosR* PodR* PodWW PosWW Rfe Wse Fre FencesWR FencedWR
-relax Rfi
```

```
#podwr x86 conf file
-arch X86
-nprocs 4
-size 6
-name podwr
-safe Fre
-relax PodWR
```

Notice that we used the complete safe list in \texttt{x86-rfi.conf} and a reduced list in \texttt{x86-podwr.conf}. Tests are to be generated in specific directories.
% cd rfi
% diy7 -conf x86-rfi.conf
Generator produced 11 tests
Relaxations tested: {Rfi}
% cd ../podwr
% diy7 -conf x86-podwr.conf
Generator produced 2 tests
Relaxations tested: {PodWR}
% cd ..

Now, let us run all tests at once, with the parameters of machine saumur (4 physical cores with hyper-threading):

% litmus7 -mach saumur rfi/@all > rfi/saumur.rfi.00
% litmus7 -mach saumur podwr/@all > podwr/saumur.podwr.00
% litmus7 -mach saumur safe/@all > safe/saumur.safe.00

If your machine has 2 cores only, try litmus -a 2 -limit true...

We now look for the tests that have validated their condition in the result files of litmus7. A simple tool, readRelax7, does the job:

% readRelax7 rfi/saumur.rfi.00 podwr/saumur.podwr.00 safe/saumur.safe.00

** Relaxation summary **

{Rfi} With {Rfe, Fre, Wse, PodRW, PodRR} {Rfe, Fre, PodRR}
{Fre, Wse, PodWW, PodRR} {Fre, PosWW, PodRR, MFencedWR}
{Fre, PodWW, PodRR, MFencedWR} {Fre, PodRR} {Fre, PodRR, MFencedWR}
{PodWR} With {Fre}

The tool readRelax7 first lists the result of all tests (which is omitted above), and then dumps a summary of the relaxations it found. The sets of the candidate relaxations that need to be safe for the tests to indeed reveal a relaxed candidate relaxation are also given. Here, Rfi and PodWR are confirmed to be relaxed, while no candidate relaxation in the safe set is found to be relaxed. Had it been the case, a line {} With {...} would have occurred in the relaxation summary. The safe tests need to be run a lot of times, to increase our confidence in the safe set.

8 Additional relaxations

We introduce some additional candidate relaxations that are specific to the Power architecture. We shall not detail here our experiments on Power machines. See our experience report http://diy.inria.fr/phat/ for more details.

8.1 Intra-processor dependencies

In a very relaxed architecture such as Power, *intra-processor dependencies* becomes significant. Roughly, intra-processor dependencies fall into two categories:

Data dependencies occur when a memory access instruction reads a register whose contents depends upon a previous (in program order) load. In diy7 we specify such a dependency as:

\[ Dp(s|d)(R|W) \]
where, as usual, s (resp. d) indicates that the source and target events are to the same (resp. different)
location(s); and R (resp. W) indicates that the target event is a read (resp. a write). As a matter of
fact, we do not need to specify the direction of the source event, since it always is a read.

Finally, one may control the nature of the dependency: address dependency (DpAddr(s|d)(R|W)) or
data dependency (DpData(s|d)W).

**Control dependencies** occur when the execution of a memory access is conditioned by the contents of a
previous load. Their syntax is similar to the one of Dp relaxations, with a Ctrl tag:

\[
\text{Ctrl}(s|d)(R|W)
\]

This default syntax expands to control dependencies as guaranteed by the Power documentation. For
read to write, conditioning execution is enough (expanded syntax, DpCtrl(s|d)W). But for read to
read, an extra instruction, isync, is needed (expanded syntax DpCtrlIsync(s|d)R, see below). The
syntax DpCtrl(s|d)R also exists, it expresses the conditional execution of a load instruction and does
*not* create ordering.

ARM has similar candidate relaxations, Isync being replaced by ISB.

In the produced code, diy7 expresses a data dependency by a *false dependency* (or *dummy dependency*)
that operates on the address of the target memory access. For instance:

% diyone7 DpDw Rfe DpDw Rfe
PPC A
"DpAddrDw Rfe DpAddrDw Rfe"
{
0:r2=y; 0:r5=x;
1:r2=x; 1:r5=y;
}
P0 | P1 ;
1wz r1,0(r2) | 1wz r1,0(r2) ;
xor r3,r1,r1 | xor r3,r1,r1 ;
li r4,1 | li r4,1 ;
stwx r4,r3,r5 | stwx r4,r3,r5 ;
exists (0:r1=1 /\ 1:r1=1)

On P0, the effective address of the indexed store stwx r4,r3,r5 depends on the contents of the index
register r3, which itself depends on the contents of r1. The dependency is a “false” one, since the contents
of r3 always is zero, regardless of the contents of r1. One may observe that DpDw is changed into DpAddrDw
in the comment field of the test. As a matter of fact, DpDw is a macro for the address dependency DpAddrW.
We could have specified data dependency instead:

% diyone7 DpDataDw Rfe DpAddrDw Rfe
PPC A
"DpDataDw Rfe DpAddrDw Rfe"
{
0:r2=y; 0:r4=x;
1:r2=x; 1:r5=y;
}
P0 | P1 ;
1wz r1,0(r2) | 1wz r1,0(r2) ;
xor r3,r1,r1 | xor r3,r1,r1 ;
addi r3,r3,1 | li r4,1 ;
st w r3,0(r4) | stwx r4,r3,r5 ;
On $P_0$, the value stored by the last (store) instruction $\text{stw} \ r3,0(r4)$ is now computed from the value read by the first (load) instruction $\text{lwz} \ r1,0(r2)$. Again, this is a “false” dependency.

A control dependency is implemented by the means of an useless compare and branch sequence, plus the $\text{isync}$ instruction when the target event is a load. For instance

% diyone7 CtrlIdR Fre SyncdWW Rfe
PPC A
"DpCtrlIsyncdR Fre SyncdWW Rfe"
{
0:r2=y; 0:r4=x;
1:r2=x; 1:r4=y;
}

Also notice that CtrlIdR is interpreted as DpCtrlIsyncR in the comment field of the test.

Of course, in all cases, we assume that “false” dependencies are not “optimised out” by the assembler or the hardware.

### 8.2 Composite relaxations and cumulativity

Users may specify a small sequence of single candidate relaxations as behaving as a single candidate relaxation to diy7. The syntax is:

$$[r_1, r_2, \ldots]$$

The main usage of the feature is to specify *cumulativity candidate relaxations*, that is, the sequence of Rfe and of a fence candidate relaxation (A-cumulativity), the sequence of a fence candidate relaxation and of Rfe (B-cumulativity), or both (AB-cumulativity).

Cumulativity candidate relaxations are best expressed by the following syntactical shortcuts: let $r$ be a fence candidate relaxation, then $A Cr$ stands for $[\text{Rfe}, r]$, $BCr$ stands for $[r, \text{Rfe}]$, while $ABCr$ stands for $[\text{Rfe}, r, \text{Rfe}]$.

Hence, a simple way to generate iriw-like (see Sec. 6.3) litmus tests with $\text{lwsync}$ is as follows:

% diy7 -name iriw-lwsync -nprocs 8 -size 8 -relax ACLwSyncdRR -safe Fre
Generator produced 3 tests
Relaxations tested: $\{\text{ACLwSyncdRR}\}$

where we have for instance:

% cat iriw-lwsync001.litmus
PPC iriw-lwsync001
"Fre Rfe LwSyncdRR Fre Rfe LwSyncdRR Fre Rfe LwSyncdRR"  
Cycle=Fre Rfe LwSyncdRR Fre Rfe LwSyncdRR Fre Rfe LwSyncdRR Fre Rfe LwSyncdRR
Relax=ACLwSyncdRR
Safe=Fre
{
  0:r2=z; 0:r4=x; 1:r2=x;
  2:r2=x; 2:r4=y; 3:r2=y;
  4:r2=y; 4:r4=z; 5:r2=z;
}

P0 | P1 | P2 | P3 | P4 | P5 ;
lwz r1,0(r2) | li r1,1 | lwz r1,0(r2) | li r1,1 | lwz r1,0(r2) | li r1,1 ;
lwync | stw r1,0(r2) | lwync | stw r1,0(r2) | lwync | stw r1,0(r2) ;
lwz r3,0(r4) | | lwz r3,0(r4) | | lwz r3,0(r4) | ;
exists (0:r1=1 /\ 0:r3=0 /\ 2:r1=1 /\ 2:r3=0 /\ 4:r1=1 /\ 4:r3=0)

8.3 Detour candidate relaxations

Detours combine a Pos candidate relaxation and a sequence of two external communication candidate relaxations. More precisely detours are some constrained Pos candidate relaxations: the source and target events must be related by a sequence of two communication candidate relaxations, whose target and source are a common event whose processor is new.

<table>
<thead>
<tr>
<th>diy7 syntax</th>
<th>Source</th>
<th>Target</th>
<th>Detour</th>
</tr>
</thead>
<tbody>
<tr>
<td>DetourR</td>
<td>R</td>
<td>R</td>
<td>Fre; Rfe</td>
</tr>
<tr>
<td>DetourW</td>
<td>W</td>
<td>R</td>
<td>Wse; Rfe</td>
</tr>
<tr>
<td>DetourRW</td>
<td>R</td>
<td>W</td>
<td>Fre; Wse</td>
</tr>
<tr>
<td>DetourWW</td>
<td>W</td>
<td>W</td>
<td>Wse; Wse</td>
</tr>
</tbody>
</table>

DetourRR and DetourWR are accepted as synonyms for DetourR and DetourW respectively. Graphically, we have:

```
DetourR

a: Rx=0
   po
   rf
b: Rx=1

DetourW

c: Wx=1
   co
   rf
a: Wx=1
   po

DetourRW

b: Wx=2
   co
   co
a: Rx=0
   po

DetourWW

c: Wx=2
   co
   co
a: Wx=1
   po

b: Wx=3
```

Finally notice that “internal” detours need no special treatment as they can be expressed by the sequences “Fri; Rfi”, “Wsi;Rfi”, etc.
9 Test variations with diycross7

The tool diycross7 has an interface similar to diyone7, except it accepts list of candidate relaxations where diyone7 accepts single candidate relaxations. The new tool produces the test resulting by “cross producing” the lists. For instance, one can generate all variations on the IRIW test (see Sec. 6.3) that involve data dependencies and the lightweight barrier lwsync as follows:

```
% diycross7 -arch PPC -name IRIW Rfe DpdR,LwSyncdRR Fre Rfe DpdR,LwSyncdRR Fre
Generator produced 3 tests
% ls
@all IRIW+addrs.litmus IRIW+lwsync+addr.litmus IRIW+lwsyncs.litmus
```

diycross7 outputs the index file @all that lists the test source files, and three tests, with names we believe to be self-explanatory:

```
% cat IRIW+lwsync+addr.litmus
PPC IRIW+lwsync+addr
"Rfe LwSyncdRR Fre Rfe DpAddrdR Fre"
Cycle=Rfe LwSyncdRR Fre Rfe DpAddrdR Fre
{
  0:r2=y;
  1:r2=x; 1:r4=x;
  2:r2=x;
  3:r2=x; 3:r5=y;
}
```

Users may use the special keywords allRR, allRW, allWR and allWW to specify the set of all existing program order candidate relaxations between the specified “R” or “W”. For instance, we get the complete variations on IRIW by:

```
% diycross7 -arch PPC -name IRIW Rfe allRR Fre Rfe allRR Fre
Generator produced 28 tests
% ls
@all
IRIW.litmus
IRIW+addr+po.litmus
IRIW+lwsync+addr.litmus
...
IRIW+isyncs.litmus
```

10 Identifying coherence orders with observers

We first produce the “four writes” test 2+2W for Power:

```
% diyone7 -name 2+2W -arch PPC PodWW Wse PodWW Wse
% cat 2+2W.litmus
PPC 2+2W
"PodWW Wse PodWW Wse"
```


Test 2+2W is the Power version of the x86 test x86-2+2W of Sec. 6.3. In that section, we argued that the final condition exists (x=2 \(\land\) y=2) suffices to identify the coherence orders 0, 1, 2 for locations x and y. As a consequence, a positive final condition reveals the occurrence of the specified cycle: Wse PodWW Wse PodWW.

### 10.1 Simple observers

Observers provide an alternative, perhaps more intuitive, means to identify coherence orders: an observer simply is an additional thread that performs several loads from the same location in sequence. Here, loading value 1 and then value 2 from location x identifies the coherence order 0, 1, 2. The command line switch -obs force commands the production of observers (test 2+2WObs):

```bash
% diyone7 -name 2+2WObs -obs force -obstype straight -arch PPC PodWW Wse PodWW Wse
% cat 2+2WObs.litmus

PPC 2+2WObs
"PodWW Wse PodWW Wse"

{ 0:r2=x; 1:r2=y; 2:r2=x; 2:r4=y; 3:r2=y; 3:r4=x; }

P0  |  P1  |
li r1,2  |  li r1,2  
stw r1,0(r2) | stw r1,0(r2) |
li r3,1  |  li r3,1  
stw r3,0(r4) | stw r3,0(r4) |

exists (0:r1=1 \(\land\) 0:r3=2 \(\land\) 1:r1=1 \(\land\) 1:r3=2)
```

Thread P0 observes location x, while thread P1 observes location y. With respect to 2+2W, final condition has changed, the direct observation of the final contents of locations x and y being replaced by two successive observations of the contents of x and y.

It should first be noticed that the reasoning above assumes that having the same thread to read 1 from say x and then 2 implies that 1 takes place before 2 in the coherence order of x. This may not be the case in general — although it holds for Power. Moreover, running 2+2W and 2+2WObs yields contrasted results. While a positive conclusion is immediate for 2+2W, we were not able to reach a similar conclusion for 2+2WObs. As a matter of fact, 2+2WObs yielding Ok stems from the still-to-be-observed coincidence of several events: both observers threads must run at the right pace to observe the change from 1 to 2, while the cycle must indeed occur.

### 10.2 More observers

#### 10.2.1 Fences and loops in observers

A simple observer consisting of loads performed in sequence is a straight observer. We define two additional sorts of observers: fenced observers, where loads are separated by the strongest fence available, and loop observers, which poll on location contents change. Those are selected by the homonymous tags given as arguments to the command line switch -obstype. For instance, we get the test 2+2WObsFenced by:

```bash
% diyone7 -name 2+2WObsFenced -obs force -obstype fenced -arch PPC PodWW Wse PodWW Wse
% cat 2+2WObsFenced.litmus
```

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10.2.2 Local observers

With local observers, coherence order is observed by the test threads. This implies changing the tests, and some care must be exercised when interpreting results.

The idea is as follows: when two threads are connected by a Wse candidate relaxation, meaning that the first thread ends by writing \( v \) to some location \( \ell \) and that the second thread starts by writing \( v+1 \) to the same location \( \ell \), we add an observing read of location \( \ell \) at the end of the first thread. Then, reading \( v+1 \) means that the write by the first thread precedes the write by the second thread in \( \ell \) coherence order. More concretely, we instruct \texttt{diy7} generators to emit such local observers with option \texttt{-obs local}:

```plaintext
% diyone7 -name 2+2WLocal -obs local -obstype straight -arch PPC PodWW Wse PodWW Wse
% cat 2+2WLocal.litmus
PPC 2+2WLocal
"PodWW Wse PodWW Wse"
{
0:r2=x; 0:r4=y;
1:r2=y; 1:r4=x;
}

P0 | P1 ;
li r1,2 | li r1,2 ;
stw r1,0(r2) | li r1,2 ;
li r3,1 | li r3,1 ;
stw r3,0(r4) | li r3,1 ;

exists (0:r5=2 \( / \) 1:r5=2)
```

With respect to 2+2W, final condition has changed, the direct observation of the final contents of locations \( y \) and \( x \) being replaced local observation of \( y \) by thread 0 and local observation of \( x \) by thread 1.

Based for instance on the test execution witness, whose only SC-violation cycle is the same as as for 2+2W.
one may argue that tests $2+2W$ and $2+2W_{\text{Local}}$ are equivalent, in the sense that both are allowed or both are forbidden by a model or machine.

Local observers can also be fenced or looping. For instance, one produces $2+2W_{\text{LocalFenced}}$, the fenced local observer version of $2+2W$ as follows:

```plaintext
% diyone7 -name 2+2WLocalFenced -obs local -obstype fenced -arch PPC PodWW Wse PodWW Wse
% cat 2+2WLocalFenced.litmus
PPC 2+2WLocalFenced
"PodWW Wse PodWW Wse"
{
0:r2=x; 0:r4=y;
1:r2=y; 1:r4=x;
}
    P0 | P1 ;
li r1,2 | li r1,2 ;
stw r1,0(r2) | stw r1,0(r2);
    li r3,1 | li r3,1 ;
stw r3,0(r4) | stw r3,0(r4);
sync | sync ;
li r6,200 | li r6,200 ;
exists
(0:r5=2 \&\& 1:r5=2)
```

While one produces $2+2W_{\text{LocalLoop}}$, the looping local observer version of $2+2W$ as follows:

```plaintext
% diyone7 -name 2+2WLocalLoop -obs local -obstype loop -arch PPC PodWW Wse PodWW Wse
% cat 2+2WLocalLoop.litmus
PPC 2+2WLocalLoop
"PodWW Wse PodWW Wse"
{
0:r2=x; 0:r4=y;
1:r2=y; 1:r4=x;
}
    P0 | P1 ;
li r1,2 | li r1,2 ;
stw r1,0(r2) | stw r1,0(r2);
    li r3,1 | li r3,1 ;
stw r3,0(r4) | stw r3,0(r4);
li r6,200 | li r6,200 ;
L00: | L02: ;
In the code above, observing loads are attempted at most 200 times or until a value different from 1 is read.

### 10.2.3 Performance of observers

As an indication of the performance of the various sorts of observers, the following table summarises a litmus7 experiment performed on an 8-core 4-way SMT Power7 machine machine.

<table>
<thead>
<tr>
<th></th>
<th>2+2W</th>
<th>2+2Wobs</th>
<th>2+2WobsFenced</th>
<th>2+2WobsLoop</th>
<th>2+2WLocal</th>
<th>2+2WLocalFenced</th>
<th>2+2WLo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>2.2M/160M</td>
<td>0/80M</td>
<td>326/80M</td>
<td>25k/80M</td>
<td>2/160M</td>
<td>34k/160M</td>
<td>111</td>
</tr>
</tbody>
</table>

The row “Positive” shows the number of observed positive outcomes/total number of outcomes produced. For instance, in the case of 2+2W, we observed the positive outcome \( x=2 \land y=2 \) more than 2 million times out of a total of 160 million outcomes. As a conclusion, all techniques achieve decent results, except straight observers.

### 10.3 Three stores or more

In test 2+2W the coherence orders sequence two writes. If there are three writes or more to the same location, it is no longer possible to identify a coherence order by observing the final contents of the memory location involved. In other words, observers are mandatory.

The argument to the -obs switch commands the production of observers. It can take four values:

- **accept**: Produce observers when absolutely needed. More precisely, given memory location \( x \), no equality on \( x \) appears in the final condition for zero or one write to \( x \), one such appears for two writes, and observers are produced for three writes or more.
- **avoid**: Never produce observers, i.e. fail when there are three writes to the same location.
- **force**: Produce observers for two writes or more.
- **local**: Always produce local observers.

With diyone7, one easily build a three writes test as for instance the following W5:

```bash
% diyone7 -obs accept -obstype fenced -arch PPC -name W5 Wse Wse PodWW Wse PodWW
% cat W5.litmus
PPC W5
"Wse Wse PodWW Wse PodWW"
{ 0:r2=y; 1:r2=y; 1:r4=x; 2:r2=x; 2:r4=y; 3:r2=y; }
P0 | P1 | P2 | P3 |
|   | li r1,3 | li r1,2 | li r1,2 |
| sync | stw r1,0(r2) | stw r1,0(r2) | stw r1,0(r2) |
| li r3,1 | li r3,1 | |
| sync | stw r3,0(r4) | stw r3,0(r4) | |
| li r4,0(r2) | | |
exists (x=2 \land 0:r1=1 \land 0:r3=2 \land 0:r4=3)
```

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As apparent from the code above, we have a fenced observer thread on \( y \) (P0), while the final state of \( x \) is observed directly (\( x=2 \)). The command line switch \(-\text{obs force}\) would yield two observers, while \(-\text{obs avoid}\) would lead to failure.

With command line switch \(-\text{obs local}\) we get three local observations of coherence, which suffice to reconstruct the complete coherence orders:

\%
\texttt{diyone7 -obs local -obstype fenced -arch PPC -name W5Local Wse Wse PodWW Wse PodWW}
\texttt{chi\% cat W5Local.litmus}
PPC W5Local
"Wse Wse PodWW Wse PodWW"
{
0:r2=x; 0:r4=y;
1:r2=y; 1:r4=x;
2:r2=x;
} 
\texttt{P0 | P1 | P2 ;}
li r1,3 | li r1,2 | li r1,2 ;
stw r1,0(r2) | stw r1,0(r2) | stw r1,0(r2) ;
li r3,1 | li r3,1 | sync ;
stw r3,0(r4) | stw r3,0(r4) | lwz r3,0(r2) ;
sync | sync | |
; 
1wz r5,0(r4) | 1wz r5,0(r4) | 
exists (0:r5=2 \&\& 1:r5=2 \&\& 2:r3=3)
\%

11 Command usage

The \texttt{diy7} suite consists in four main tools:

\texttt{diyone7} generates one litmus test from the specification of a violation of the sequential consistency memory model as a cycle — see Sec. 6.2.

\texttt{diycross7} generates variations of \texttt{diyone7} style tests — see Sec. 9.

\texttt{diy7} generates several tests, aimed at confirming that candidate relaxations are relaxed or safe—see Sec. 7.

\texttt{readRelax7} Extract relevant information from the results of tests—see Sec. 7.2.

11.1 A note on test names

We have designed a simple naming scheme for tests. A normalised test name decomposes first as a family name, and second as a description of program-order (or internal) candidate relaxations.

11.1.1 Family names

Cycles (and thus tests) are first grouped by families. Family names describe test structure, based upon external communication candidates relaxations. More specifically, external communication candidates relaxations suffice to settle the directions (\( W \) or \( R \)) of first and last events of threads, considering the case when those two events are the same. For instance, consider the cycle “PodWW Rfe PodRR Frc”: there are two threads in the corresponding test (as there are two external communication candidate relaxations), one thread starts and ends with a write (written \( WW \)), while the other thread starts and ends with a read (written \( RR \)). The family name is thus \( WW+RR \), (or \( RR+WW \), but we choose the former). For reference, a normalised family name is the minimal amongst the representations of a given cycle, following the lexical order derived from the order \( W < WW < RR < RW < WR < R \).
The most common families have nicknames, which are defined by this document. For instance, consider the test whose cycle is “PodWR Fre PodWR Fre”. The family name is WR+WR, as this is a two-thread test, both threads starting with a write and ending with a read. The nickname for this family is, as we already know, SB (store-buffering). Here is the list of nicknames and family names for two thread tests:

<table>
<thead>
<tr>
<th>2+2W</th>
<th>WR+WR</th>
<th>PodWW Wse PodWW Wse</th>
</tr>
</thead>
<tbody>
<tr>
<td>LB</td>
<td>RW+RW</td>
<td>PodRW Rfe PodRW Rfe</td>
</tr>
<tr>
<td>MP</td>
<td>WR+RW</td>
<td>PodWW Rfe PodRR Fre</td>
</tr>
<tr>
<td>R</td>
<td>WR+RW</td>
<td>PodWW Wse PodWR Fre</td>
</tr>
<tr>
<td>S</td>
<td>WR+RW</td>
<td>PodWW Rfe PodRW Wse</td>
</tr>
<tr>
<td>SB</td>
<td>WR+RW</td>
<td>PodWR Fre PodWR Fre</td>
</tr>
</tbody>
</table>

Isolated writes (and reads) originate from the combinations of communication relaxations, for instance [Fre,Rfe]. They appear as “W” (and “R”) in family names. For instance, “Rfe PodRR Fre Rfe PodRR Fre” contains two such isolated writes, its name is thus WR+RR and its nickname is, as we know, IRIW (Independent reads of independent writes). The test “Rfe PodRW Rfe PodRR Fre” contains one isolated write, as apparent from this diagram:

```
  a: Wx=1  b: Rx=1  d: Ry=1
  po  rf  po
  f   rf
  c: Wy=1

WRC
```

The family name is thus WR+RW+RR and the nickname is WRC (Write to Read Causality).

### 11.1.2 Descriptive names for variants

Every family has a prototype, homonymous test where every thread code consists in one (for W or R) or two memory accesses to different locations (for WW, WR etc.). For instance, the MP test is derived from the cycle “PodWW Rfe PodRR Fre”. Variants are described by tags that illustrates the various program-order relaxations: they appear after the family name, still with “+” as a separation. For instance the test derived from “LwSyncdWW Rfe DpAddrdR Fre” is named MP+lwsync+addr.

When all threads have the same tag tag, the test name is abbreviated as Family+tags. For instance, the test MP+lwsync+lwsync (“LwSyncdWW Rfe LwSyncdRR Fre”) is in fact MP+lwsync. Additionally, the tag pos (all po’s) is omitted, in order to yield family names for the prototype tests — cf. MP whose name would have been MP+pos otherwise.

For the sake of terseness, tags do not describe program-order relaxations completely. For instance both DpAddrdR and DpAddrdW (address dependency to read and write, respectively) have the same tag, addr. It does not harm for simple tests, as the missing direction can be inferred from the family name. Consider for instance MP+lwsync+addr and LB+lwsync+addr.

---

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The naming scheme extends to cycles with consecutive program-order relaxations, by separating tags with “-” when they follow one another: for instance “LwSyncdWW Rfe DpAddrdR PodRR Fre” is named MP+lwsync+addr-po. Unfortunately, the current naming scheme falls short in supplying non-ambiguous names to all tests. For instance, “LwSyncdWW Rfe DpAddrdW PodWR Fre” is also named MP+lwsync+addr-po. In that situation tools will either fail or silently add a numeric suffix, depending on the boolean -addnum option.

As a result, we get the two tests: MP+lwsync+addr-po and MP+lwsync+addr-po001.

Future versions of diy7 may solve this issue in a more satisfying manner. At the moment, users are advised not to rely too much on the automatic naming scheme. Users may name tests in a non-ambiguous fashion by (1) specifying an explicit family name (-name name) and (2) selecting the numeric scheme (-num true):

Future versions of diy7 may solve this issue in a more satisfying manner. At the moment, users are advised not to rely too much on the automatic naming scheme. Users may name tests in a non-ambiguous fashion by (1) specifying an explicit family name (-name name) and (2) selecting the numeric scheme (-num true):

The diycross7 generator outputs the same tests as above, with names **MP+X000** and **MP+X001**.

### 11.2 Common options

All test generators accept the following documented command-line options:

- **-v** Be verbose, repeat to increase verbosity.
- **-version** Show version number and exit.

---

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-arch (X86|PPC|ARM|AArch64|LISA|C) Set architecture. Default is PPC.

-o <dest> Redirect output to <dest>. This option applies when tools generate a set of tests and an index file @all, i.e. in all situations except for diyone7 simplest operating mode.

If argument <dest> is an archive (extension .tar) or a compressed archive (extension .tgz), the tool builds an archive. Otherwise, <dest> is interpreted as the name of an existing directory. Default is ".", that is tool output goes into the current directory.

-obs (accept|avoid|force|local) Management of observers, default is avoid. See Sec. 10.3.

-obstype (fenced|loop|straight) Style of observers, default is fenced. See Sec. 10.2.

-cond (cycle|uni|observe) Control final condition of tests, default is cycle. In mode cycle, the final condition identifies executions that correspond to the generating cycle. In mode unicond, the final condition identifies executions that are valid w.r.t. the uniproc model (see Sec. 13.2). In mode observe there is no final condition: the litmus7 and herd7 tools will simply list the final values of locations.

-oneloc Do not reject tests that acts on unique location. Notice that conditions on such tests usually are not significant and should probably be edited by hand. See also options -cond unicond and -cond observe above.

-optcond Optimise conditions by disregarding the values of loads that are neither the target of Rf, nor the source of Fr. This is the default.

-nooptcond Do not optimise conditions.

-optcoherence Optimise conditions assuming that the tested system (at least) follows the uniproc model (see Sec. 13.2).

-nooptcoherence Do not optimise conditions assuming that the tested system (at least) follows the uniproc model. This is the default.

-neg <bool> Negate final condition, default is false.

-c <bool> Avoid equivalent cycles. Default is true. Setting -c true is intended for debug.

The naming of tests is controlled by the following options:

-name <name> Use name for naming tests, the exact consequences depend on the generator. By default the generator has no name available.

-num <bool> Use numeric names, i.e. from a base name <base> the generator will name tests as <base>000, <base>001 etc. The default depends upon the generator.

-addnum <bool> If true, when faced with tests whose name <name> has already been given, use names <name>001, <name>002, etc. Otherwise fail in the same situation. The default depends upon the generator.

-fmt <n> Size of numerical suffixes, default is 3.

11.3 Usage of diyone7

The tool diyone7 has two operating modes. The selected mode depends on the presence of command-line arguments.

In the first operating mode, diyone7 takes a non-empty list of candidate relaxations as arguments and outputs a litmus test. Note that diyone7 may fail to produce the test, with a message that briefly details the failure.
Test a [Rfe Rfe PodRR] failed:
Impossible direction PodRR Rfe

In this mode, -name <name> sets the name of the test to <name> and output it into file <name>.litmus. If absent, the test name is A and output goes to standard output.

Otherwise, i.e. when there are no command-line arguments, diyone7 reads the standard input and generates the tests described by the lines it reads. Each line starts with a test name name, followed by “:”, followed by a list of candidate relaxations RS. Then, diyone7 acts as if invoked as diyone opts -name name RS.

The tool diyone7 accepts the following documented option:

-norm Normalise tests and give them normalised names. In the first operating mode (when a cycle is explicitly given) the test will be named with a family name and a descriptive name. In the second operating mode, numeric names are used, base being either given explicitly (with option -name <base>) or being a normalised family name.

11.4 Usage of diycross7

diycross7 produces several tests by “cross producing” lists of candidate relaxations given as arguments, see Sec 9. diycross7 also produces an index file @all that lists all produced litmus source files.

If option -name <name> is given, it sets the family name of generated tests, otherwise standard family names are used (cf. Sec. 11.1). By default descriptive names are used (i.e. -num false) and diycross7 will fail if two different tests have the same name (i.e. -addnum false):

% diycross7 PodWW Rfe [DpAddrdR,PodRR],[DpAddrdW,PodWR] Fre
Fatal error: Duplicate name MP+po+addr-po

Should this happen users can resort either to numeric names,

%diycross7 -num true PodWW Rfe [DpAddrdR,PodRR],[DpAddrdW,PodWR] Fre
Generator produced 2 tests
con% ls
@all MP000.litmus MP001.litmus

or to disambiguating numeric suffixes.

%diycross7 -addnum true PodWW Rfe [DpAddrdR,PodRR],[DpAddrdW,PodWR] Fre
Generator produced 2 tests
con% ls
@all MP+po+addr-po001.litmus MP+po+addr-po.litmus

11.5 Usage of diy7

As diycross7, diy7 produce several files, hence naming issues are critical. By default, diy7 uses family names and the numeric naming scheme (-num true). Users can specify a family name family for all tests with -name family, or attempt using the descriptive names of Sec 11.1 with -num false. Moreover, diy7 produces an index file @all that lists the file names of all tests produced.

The tool diy7 also accepts the following, additional, documented options.

-conf <file> Read configuration file <file>. A configuration file consists in a list of options, one option per line. Lines introduced by # are comments and are thus ignored.

-size <n> Set the maximal size of cycles. Default is 6.

-exact Produce cycles of size exactly <n>, in place of size up to <n>.
-nprocs \(<n>\) Reject tests with more than \(<n>\) threads. Default is 4.

-eprocs Produce tests with exactly \(<n>\) threads, where \(<n>\) is set above.

-ins \(<n>\) Reject tests as soon as the code of one thread originates from \(<n>\) edges or more. Default is 4.

-relax \(<relax-list>\) Set relax list. Default is empty. The syntax of \(<relax-list>\) is a comma (or space) separated list of candidate relaxations.

-mix \(<bool>\) Mix the elements of the relax list (see below), default \textit{false}.

-maxrelax \(<n>\) In mix mode, upper bound on the number of different candidate relaxations tested together. Default is 100

-safe \(<relax-list>\) Set safe list. Default is empty.

-mode \(\text{critical|sc|free|uni}\) Control generation of cycles, default \textit{sc}. Those tags command the activation of some constraints over cycle generation, see below.

-cumul \(<bool>\) Permit implicit cumulativity, \textit{i.e.} authorise building up the sequence Rfe followed by a fence, or the reverse. Default is \textit{true}.

The relax and safe lists command the generation of cycles as follows:

1. When the relax list is empty, cycles are built from the candidate relaxations of the safe list.
2. When the relax list is of size 1, cycles are built from its single element \(r\) and from the elements of the safe list. Additionally, the cycle produced contains \(r\) at least once.
3. When the relax list is of size \(n\), with \(n > 1\), the behaviour of \textit{diy7} depends on the mix mode:
   (a) By default (-mix \textit{false}), \textit{diy7} generates \(n\) independent sets of cycles, each set being built with one relaxation from the relax list and all the relaxations in the safe list. In other words, \textit{diy7} on a relax list of size \(n\) behaves similarly to \(n\) runs of \textit{diy7} on each candidate relaxation in the list.
   (b) Otherwise (-mix \textit{true}), \textit{diy7} generates cycles that contains at least one element from the relax list, including some cycles that contain different relaxations from the relax list. The cycles will contain at most \(m\) different elements from the relax list, where \(m\) is specified with option “-maxrelax \(m\)”.

Generally speaking, \textit{diy7} generates “some” cycles and does not generate “all” cycles (up to a certain size \textit{e.g.}). In (default) \textit{sc} mode, \textit{diy7} performs some optimisation, most of which we leave unspecified. As an exception to this non-specification, \textit{diy7} in \textit{sc} (default) mode is guaranteed not to generate redundant elementary communication relaxation in the following sense: let us call \textit{Com} the union of \(Ws\), \(Rf\) and \(Fr\) (the \textit{el}i specification is irrelevant here). \(Ws\) being transitive and by definition of \(Fr\), one easily shows that the transitive closure \textit{Com+} of \textit{Com} is the union of \textit{Com} plus \([Ws,Rf]\) (\(Ws\) followed by \(Rf\)) plus \([Fr,Rf]\).

As a consequence, maximal subsequences of communication relaxations in \textit{diy7} cycles are limited to single relaxations (\textit{i.e.} \(Ws\), \(Rf\) and \(Fr\)) and to the above mentioned two sequences (\textit{i.e.} \([Ws,Rf]\) and \([Fr,Rf]\)). For instance, \([Ws,Ws]\) and \([Fr,Ws]\) should never appear in \textit{diy7} generated cycles. However, such subsequences can be generated on an individual basis with \textit{diyone7}, see the example of \(W5\) in Sec 10.3.

In critical mode (-mode \textit{critical}), cycles are strictly specified as follows:

1. Communication candidate relaxations sequences are limited to \(Rf,Fr,Ws,[Ws,Rf]\) and \([Fr,Rf]\), as in \textit{sc} mode.
2. No two internal\textsuperscript{7} candidate relaxations follow one another.

\textsuperscript{7}That is, the source and target accesses are by the same processor.
3. If the option -cumul false is specified, diy7 will not construct the sequence of Rfe followed by a fence (or B-cumulativity) candidate relaxation or of a fence (or A-cumulativity) candidate relaxation followed by Rfe.

4. Cycles that access one single memory location are rejected.

5. None of the rules above applies to the internal sequences of composite candidate relaxations. For instance, if [Rfi,PodRR] is given as a candidate relaxation, the sequence “Rfi,PodRR” appears in cycles.

The cycles described above are the critical cycles of [5].

In free mode (-mode free), cycles are strictly specified as follows:

1. Communication candidate relaxations sequences are limited to Rf,Fr,Ws,[Ws,Rf] and [Fr,Rf]. However, arbitrary sequences of communication candidates are accepted when they are internal and external or external and internal.

2. Cycles that access one single memory location are rejected.

Finally, the uni mode enforces the following constraints on cycles:

1. Sequences of communication candidate relaxations are restricted in the same manner as for free mode (see above).

2. Sequences of Po candidate relaxation are rejected.

11.6 Usage of readRelax7

readRelax7 is a simple tool to extract relevant information out of litmus7 run logs of tests produced by the diy7 generator. For a given run of a given litmus test, the relevant information is:

- Whether the test yielded Ok or not,
- An optional candidate relaxation, which is the one given as argument to diy7 option -relax at test build time, or none.
- The safe list relevant to the given test, i.e. the safe candidate relaxations that appear in the tested cycle.

See Sec. 7.2 for an example.

The tool readRelax7 takes file names as arguments. If no argument is present, it reads a list of file names on standard input, one name per line.

12 Additional tools: extracting cycles and classification

When non-standard family names or numeric names are used, it proves convenient to rename tests with the standard naming scheme. We provide two tools to do so: mcycle7 that extracts cycles from litmus source files and classify7 that normalises and renames cycles.

For instance, one can use diy7 to generate all simple, critical, tests up to three threads for X86 with the following configuration file X.conf

```
-arch X86
-name X
-nprocs 3
-size 6
-safe Pod**,Fre,Rfe,Wse
-mode critical
```
Cycles are extracted with mcycle7, which takes the index file @all as argument:

% mcycle7 @all
X000: Wse PodWR Fre PodWR Fre PodWW
X001: Rfe PodRR Fre PodWR Fre PodWW
X002: Wse PodWR Fre PodWW
X003: Wse PodWW Wse PodWR Fre PodWW
X004: Rfe PodRW Wse PodWR Fre PodWW
X005: Rfe PodRR Fre PodWW
X006: Wse PodWW Rfe PodRR Fre PodWW
X007: Rfe PodRW Rfe PodRR Fre PodWW
X008: Wse Rfe PodRR Fre PodWW
X009: Wse PodWW Wse PodWW
...

The output of mcycle7 can be piped into classify7 for family classification:

% mcycle7 @all | classify7 -arch X86
2+2W
  X009 -> 2+2W : PodWW Wse PodWW Wse
3.2W
  X010 -> 3.2W : PodWW Wse PodWW Wse PodWW Wse
3.LB
  X020 -> 3.LB : PodRW Rfe PodRW Rfe PodRW Rfe
3.SB
  X016 -> 3.SB : PodWR Fre PodWR Fre PodWR Fre
ISA2
  X007 -> ISA2 : PodWW Rfe PodRW Rfe PodRR Fre
LB
  X019 -> LB : PodRW Rfe PodRW Rfe
MP
  X005 -> MP : PodWW Rfe PodRR Fre
...

Notice that classify7 accepts the arch option, as it needs to parse cycles.

Finally, one can normalise tests, using normalised names by piping mcycle7 output into diyone7 with options -norm -num false:

% mkdir src
% mcycle7 @all | diyone7 -arch X86 -norm -num false -o src
Generator produced 23 tests
% ls src
2+2W.litmus @all R.litmus WRC.litmus WRW+WR.litmus Z6.2.litmus
3.2W.litmus ISA2.litmus RWC.litmus WRR+2W.litmus WWC.litmus Z6.3.litmus
3.LB.litmus LB.litmus SB.litmus WRW+2W.litmus Z6.0.litmus Z6.4.litmus
3.SB.litmus MP.litmus S.litmus W+RWC.litmus Z6.1.litmus Z6.5.litmus
Alternatively, one may instruct classify7 to produce output for diyone7. In that case one should pass option -diyone to classify7 so as to instruct it to produce output that is parsable by diyone7:

% rm -rf src && mkdir src
% mcycles7 @all | classify7 -arch X86 -diyone | diyone7 -arch X86 -o src
Generator produced 23 tests
% ls src
2+2W.litmus @all R.litmus WRC.litmus WRW+WR.litmus Z6.2.litmus
3.2W.litmus ISA2.litmus RWC.litmus WR+2W.litmus WWC.litmus Z6.3.litmus
3.LB.litmus LB.litmus SB.litmus WR+2W.litmus Z6.0.litmus Z6.4.litmus
3.SB.litmus MP.litmus S.litmus W+RWC.litmus Z6.1.litmus Z6.5.litmus

12.1 Usage of mcycle7

The tool mcycle7 has no options and takes litmus source files or index files as arguments. It outputs a list of lines to standard output. Each line starts with a test name, suffixed by “;”, then the cycle of the named test. Notice that this format is the input format to diyone7 in its second operating mode — see Sec. 11.3.

It is important to notice that, for mcycle7 to extract cycles, those must be present as meta-information in source files. In practice, this means that mcycle7 operates normally on sources produced by diyone7, diycross7 and diy7. Moreover only one instance of a given cycle will be output.

12.2 Usage of classify7

The tool classify7 reads its standard input, interpreting it as a list of cycles in the output format of mcycle7. It normalises and classifies those cycles. The tool classify7 accepts the following documented options:

-arch (X86|PPC|ARM) Set architecture. Default is PPC. ARM support is experimental.

-u Instruct classify7 to fail when two tests have the same normalised name. Otherwise classify7 will output one line per test, regardless of duplicate names.

-diyone Output a normalised list of names and cycles, which is legal input for diyone7.
Part III
Simulating memory models with herd7

The tool herd7 is a memory model simulator. Users may write simple, single events, axiomatic models of their own and run litmus tests on top of their model. The herd7 distribution already includes some models.

The authors of herd7 are Jade Alglave and Luc Maranget.

13 Writing simple models

This section introduces cat, our language for describing memory models. The cat language is a domain specific language for writing and executing memory models. From the language perspective, cat is loosely inspired by OCaml. That is, it is a functional language, with similar syntax and constructs. The basic values of cat are sets of events, which include memory events but also additional events such as fence events, and relations over events.

13.1 Sequential consistency

The simulator herd7 accepts models written in text files. For instance here is sc.cat, the definition of the sequentially consistent (SC) model in the partial-order style:

```
SC

include "fences.cat"
include "cos.cat"

(* Atomic *)
empty rmw & (fre;coe) as atom

(* Sequential consistency *)
acyclic po | fr | rf | co as sc
```

The model above illustrates some features of model definitions:

1. A model file starts with a tag (here SC), which can also be a string (in double quotes) in case the tag includes special characters or spaces.

2. Pre-defined bindings. Here po (program order) and rf (read from) are pre-defined. The remaining two communication relations (co and fr) are computed by the included file cos.cat, which we describe later — See Sec. 13.4. For simplicity, we may as well assume that co and fr are pre-defined.

3. The computation of new relations from other relations, and their binding to a name with the let construct. Here, a new relation com is the union “|” of the three pre-defined communication relations.

4. The performance of some checks. Here the relation “po | com” (i.e. the union of program order po and of communication relations) is required to be acyclic. Checks can be given names by suffixing them with “as name”. This last feature will be used in Sec. 14.2

One can then run some litmus test, for instance SB (for Store Buffering, see also Sec. 1.1), on top of the SC model:

```
% herd7 -model ./sc.cat SB.litmus
Test SB Allowed
States 3
```
The output of herd7 mainly consists in the list of final states that are allowed by the simulated model. Additional output relates to the test condition. One sees that the test condition does not validate on top of SC, as “No” appears just after the list of final states and as there is no “Positive” witness. Namely, the condition “exists (0:EAX=0 /\ 1:EAX=0)” reflects a non-SC behaviour, see Sec. 13.1.

The simulator herd7 works by generating all candidate executions of a given test. By “candidate execution” we mean a choice of events, program order _po_, of the read-from relation _rf_ and of final writes to memory (last write to a given location). In the case of the SB example, we get the following four executions:

Indeed, there is no choice for the program order _po_, as there are no conditional jumps in this example; and no choice for the final writes either, as there is only one store per location, which must be co-after the initial stores (pictured as small red dots). Then, there are two read events from locations _x_ and _y_ respectively, which take their values either from the initial stores or from the stores in program. As a result, there are four possible executions. The model _sc.cat_ gets executed on each of the four candidate executions. The three first executions are accepted and the last one is rejected, as it presents a cycle in _po_ \_fr_. On the following diagram, the cycle is obvious:

---

8Alternatively, we may adopt the simpler view that a candidate execution includes a choice of all communication relations.
13.2 Total Store Order (TSO)

However, the non-SC execution shows up on x86 machines, whose memory model is TSO. As TSO relaxes the write-to-read order, we attempt to write a TSO model `tso-00.cat`, by simply removing write-to-read pairs from the acyclicity check:

"A first attempt for TSO"

```
include "cos.cat"

(* Communication relations that order events*)
let com-tso = rf | co | fr

(* Program order that orders events *)
let po-tso = po & (W*W | R*M)

(* TSO global-happens-before *)
let ghb = po-tso | com-tso
acyclic ghb as tso
show ghb
```

This model illustrates several features of model definitions:

- New predefined sets: W, R and M, which are the sets of read events, write events and of memory events, respectively.
- The cartesian product operator “*” that returns the cartesian product of two event sets as a relation.
- The intersection operator “&” that operates on sets and relations.

As a result, the effect of the declaration `let po-tso = po & (W*W | R*M)` is to define `po-tso` as the program order on memory events minus write-to-read pairs.

We run SB on top of the tentative TSO model:
The non-SC behaviour is now accepted, as write-to-read po-pairs do not participate to the acyclicity check any more. In effect, this allows the last execution above, as ghb (i.e. po-tso | com-tso) is acyclic.

However, our model tso-00.cat is flawed: it is still too strict, forbidding some behaviours that the TSO model should accept. Consider the test SB+rfi-pos, which is test STFW-PPC for X86 from Sec. 1.3 with a normalised name (see Sec. 11.1). This test targets the following execution:
Namely the test condition \textit{exists} \(0:EAX=1 \land 0:EBX=0 \land 1:EAX=1 \lor 1:EBX=0\) specifies that Thread 0 writes 1 into location \(x\), reads the value 1 from the location \(x\) (possibly by store forwarding) and then reads the value 0 from the location \(y\); while Thread 1 writes 1 into \(y\), reads 1 from \(y\) and then reads 0 from \(x\). Hence, this test derives from the previous \textbf{SB} by adding loads in the middle, those loads being satisfied from local stores. As can be seen by running the test on top of the \texttt{tso-00.cat} model, the target execution is forbidden:

\begin{verbatim}
% herd7 -model tso-00.cat SB+rfi-pos.litmus
Test SB+rfi-pos Allowed
States 15
0:EAX=0; 0:EBX=0; 1:EAX=0; 1:EBX=0;
...
0:EAX=1; 0:EBX=1; 1:EAX=1; 1:EBX=1;
No Witnesses
Positive: 0 Negative: 15
...
\end{verbatim}

However, running the test with \texttt{litmus} demonstrates that the behaviour is observed on some X86 machine:
% arch
x86_64
% litmus7 -mach x86 SB+rfi-pos.litmus
...
Test SB+rfi-pos Allowed
Histogram (4 states)
11589 *>0:EAX=1; 0:EBX=0; 1:EAX=1; 1:EBX=0;
3993715:0:EAX=1; 0:EBX=1; 1:EAX=1; 1:EBX=0;
3994308:0:EAX=1; 0:EBX=0; 1:EAX=1; 1:EBX=1;
388  :0:EAX=1; 0:EBX=1; 1:EAX=1; 1:EBX=1;
Ok
Witnesses
Positive: 11589, Negative: 7988411
Condition exists (0:EAX=1 \ 0:EBX=0 \ 1:EAX=1 \ 1:EBX=0) is validated ...

As a conclusion, our tentative TSO model is too strong. The following diagram pictures its ghb relation:
One easily sees that ghb is cyclic, whereas it should not. Namely, the internal read-from relation rfi does not create global order in the TSO model. Hence, rfi is not included in ghb. We rephrase our tentative TSO model, resulting into the new model tso-01.cat:

"A second attempt for TSO"

include "cos.cat"

>(* Communication relations that order events*)
let com-tso = rfe | co | fr

>(* Program order that orders events *)
let po-tso = po & (W*W | R*M)

>(* TSP global-happens-before *)
let ghb = po-tso | com-tso
acyclic ghb
show ghb

As can be observed above rfi (internal read-from) is no longer included in ghb. However, rfe (external read-from) still is. Notice that rfe and rfi are pre-defined.

As intended, this new tentative TSO model allows the behaviour of test SB+rfi-pos:

% herd7 -model tso-01.cat SB+rfi-pos.litmus
Test SB+rfi-pos Allowed
States 16
...
0:EAX=1; 0:EBX=1; 1:EAX=1; 1:EBX=0;
...
Ok
Witnesses
Positive: 1 Negative: 15
...

And indeed, the global-happens-before relation is no-longer cyclic:
We are not done yet, as our model is too weak in two aspects. First, it has no semantics for fences. As a result the test $SB+mfences$ is allowed, whereas it should be forbidden, as this is the very purpose of the fence $mfence$. 
One easily solves this issue by first defining the \texttt{mfence} that relates events with a \texttt{MFENCE} event \texttt{po-in-between} them; and then by adding \texttt{mfence} to the definition of \texttt{po-tso}:

\begin{verbatim}
let mfence = po & (\_ * MFENCE) ; po
let po-tso = po & (W*W | R*M) | mfence
\end{verbatim}

Notice how the relation \texttt{mfence} is defined from two pre-defined sets: \texttt{\_} the universal set of all events and \texttt{MFENCE} the set of fence events generated by the X86 \texttt{mfence} instruction. An alternative, more precise definition, is possible:

\begin{verbatim}
let mem-to-mfence = po & M * MFENCE
let mfence-to-mem = po & MFENCE * M
let mfence = mem-to-mfence; mfence-to-mem
\end{verbatim}

This alternative definition of \texttt{mfence}, although yielding a smaller relation, is equivalent to the original one for our purpose of checking ghb acyclicity.

But the resulting model is still too weak, as it allows some behaviours that any model must reject for the sake of single thread correctness. The following test \texttt{CoRWR} illustrates the issue:

X86 CoRWR
{ }
\begin{verbatim}
P0;
MOV EAX,[x];
MOV [x],$1;
MOV EBX,[x];
extists (0:EAX=1 \or 0:EBX=0)
\end{verbatim}

The test final condition targets the following execution candidate:
The TSO check "acyclic po-tso|com-tso" does not suffice to reject two absurd behaviours pictured in the execution diagram above: (1) the read \(a\) is allowed to read from the \(po\)-after write \(b\), as \(rfi\) is not included in \(com-tso\); and (2) the read \(c\) is allowed to read the initial value of location \(x\) although the initial write \(d\) is \(co\)-before the write \(b\), since \(po \& (W \ast R)\) is not in \(po-tso\).

For any model, we rule out those very untimely behaviours by the so-called UNIPROC check that states that executions projected on events that access one variable only are SC. In practice, having defined \(po-loc\) as \(po\) restricted to events that touch the same address (i.e. as \(po \& loc\)), we further require the acyclicity of the relation \(po-loc|fr|rf|co\). In the TSO case, the UNIPROC check can be somehow simplified by considering only the cycles in \(po-loc|fr|rf|co\) that are not already rejected by the main check of the model. This amounts to design specific checks for the two relations that are not global in TSO: \(rfi\) and \(po \& (W*R)\). Doing so, we finally produce a correct model for TSO tso-02.cat:

"A third attempt for TSO"

```
include "cos.cat"

(* Uniproc check specialized for TSO *)
irreflexive po-loc & (R*W); rfi as uniprocRW
irreflexive po-loc & (W*R); fri as uniprocWR

(* Communication relations that order events*)
let com-tso = rfe | co | fr

(* Program order that orders events *)
let mfence = po & (_ * MFENCE) ; po
let po-tso = po & (W*W | R*M) | mfence

(* TSP global-happens-before *)
let ghb = po-tso | com-tso
show mfence,ghb
acyclic ghb as tso
```

This last model illustrates another feature of \texttt{cat}: herd7 may also performs irreflexivity checks with the keyword “irreflexive”.

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13.3 Sequential consistency, total order definition

We now illustrate another style of model. We consider the original definition of sequential consistency [3]. An execution is SC when there exists a total order \( S \) on events such that:

1. \( S \) includes the program order \( po \);
2. and read events read from the most recent write events in the past, i.e. a read \( r \) from location \( x \) reads the value stored by the \( S \)-maximal write amongst those writes to location \( x \) that are \( S \) smaller than \( r \).

So we could just generate all total orders amongst memory events, and filter those “scheduling order candidates” according to the two rules above.

Things are a bit more complex in \texttt{herd7}, due to the presence of initial and final writes. Up to now we have ignored initial and final writes, we are now going to integrate them explicitly.

Initial writes are write events that initialise the memory locations. Initial writes are not generated by the instructions of the test. Instead, they are created by \texttt{herd7} machinery, and are available from model text as the set \( IW \).

Final writes may be generated by program instructions, and, when such, they must be ordered by \( S \). A final write is a write to a phantom read performed once program execution is over. The constraint on final writes originates from \texttt{herd7} technique to enumerate execution candidates: actual execution candidates also include a choice of final writes for the locations that are observed in the test final condition\(^9\). As test outcome (i.e. the final values of observed locations) is settled before executing the model, it is important not to accept executions that yield a different outcome. Doing so may validate outcomes that should be rejected. In practice, the final write \( w_f \) to location \( x \) must follow all other writes to \( x \) in \( S \). Considering that the set of final writes is available to \texttt{cat} models as the pre-defined set \( FW \), the constraint on final writes can be expressed as a relation:

\[
\text{let preSC = loc \& (W \setminus FW) \* FW}
\]

Where \( loc \) is a predefined relation that relates all events that access the same location.

By contrast with final writes, initial writes are not generated by program instructions, and it is possible not to order them completely. In particular, it is not useful to order initial writes to different locations, nor the initial write to location \( x \) with any access to location \( y \). Notice that we could include initial writes in \( S \) as we did for final writes. Not doing so will improve efficiency.

Finally, the order \( S \) is not just any order on memory events (predefined set \( M \), which includes initial and final writes writes), it is a topological order of the program events (implemented as the set \( M\setminus IW \)) that extends the pre-order \( \text{preSC} \). We can generate all such topological orders with the \texttt{cat} primitive \texttt{linearisations}:

\[
\text{let allS = linearisations(M\setminus IW,preSC)}
\]

The call \texttt{linearisation(E,r)}, where \( E \) is a set of events and \( r \) is a relation on events, returns the set of all total orders defined on \( S \) that extend \( r \). Notice that if \( r \) is cyclic, the empty set is returned.

We now need to iterate over the set \( allS \). We do so with the \texttt{with} construct:

\[
\text{with S from allS}
\]

It is important to notice that the construct above extends the current execution candidate (i.e. a choice of events, plus a choice of two relations \( po \) and \( rf \)) with a candidate order \( S \). In other words, the scope of the iteration is the remainder of the model text. Once model execution terminates for a choice of \( S \) (some element of \( allS \)), model execution restarts just after the \texttt{with} construct, with variable \( S \) bound to the next choice picked in \( allS \).

As a first consistency check, we check that \( S \) includes the program order:

\[
\text{empty po \setminus S as PoCons}
\]

\(^9\)Doing so permits pruning executions that are irrelevant to the test final condition, see \texttt{herd7} option \texttt{-speedcheck}
Notice that, to check for inclusion, we test the emptiness of relation difference (operator “\”).

It remains to check that the $rf$ relation of the execution candidate is the same as the one defined by condition 2. To that aim, we complement $S$ with the constraint over initial writes that must precede all events to their location:

\[
\text{let } S = S \mid \text{loc} \land \text{IW} \ast (M \setminus \text{IW})
\]

Observe that $S$ is no longer a total order. However, it is still a total order when restricted to events that access a given location, which is all that matters for condition 2 to give a value to all reads. As regards our SC model, we define $rf-S$ the read-from relation induced by $S$ as follows:

\[
\text{let } WRS = \text{W} \ast \text{R} \land S \land \text{loc} (* \text{Writes from the past, same location} *)
\]

\[
\text{let } rf-S = WRS \setminus (S;WRS) (* \text{Most recent amongst them} *)
\]

The definition is a two-step process: we first define a relation $WRS$ from writes to reads (to the same location) that follow them in $S$. Observe that, by complementing $S$ with initial writes, we achieve that for any read $r$ there exists at least a write $w$ such that $(w, r) \in WRS$. It then remains to filter out non-maximal writes in $WRS$ as we do in the definition of $rf-S$, by the means of the difference operator “\". We then check the equality of $rf$ (pre-defined as part of the candidate execution) and of $rf-S$ by double inclusion:

\[
\text{empty } rf \setminus rf-S \text{ as RfCons}
\]

\[
\text{empty } rf-S \setminus rf \text{ as RfCons}
\]

As an exemple, he show six attempts of po compatible $S$ orders for the non-SC outcome of the test $SB$ in figure 3. Observe that all attempts fail as $rf$ and $rf-S$ are different in all diagrams.

We also show all successfull SC scheduling in figure 4.

For reference we provide our complete model lamport.cat

"SC, L. Lamport style"

\[
(* \text{writes to location x precede final write to location x} *)
\]

\[
\text{let } \text{preSC} = \text{loc} \land (\text{W} \setminus \text{FW}) \ast \text{FW}
\]

\[
(* \text{Compute the set of total orders that extend preSC on program events} *)
\]

\[
\text{let } \text{allS} = \text{linearisations}(M \setminus \text{IW}, \text{preSC})
\]

\[
(* \text{For all such orders} *)
\]

\[
\text{with } S \text{ from allS}
\]

\[
\text{let } \text{PO} = \text{po}
\]

\[
\text{let } \text{POminusS} = \text{PO}\setminus S
\]

\[
(* \text{Check compatibility with po} *)
\]

\[
\text{empty } \text{po} \setminus S \text{ as ScPo}
\]

\[
(* \text{Add initial writes} *)
\]

\[
\text{let } S = S \mid \text{loc} \land (\text{IW} \ast (M \setminus \text{IW}))
\]

\[
(* \text{Define most recent write in the past} *)
\]

\[
\text{let } WRS = \text{W} \ast \text{R} \land S \land \text{loc} (* \text{Writes from the past, same location} *)
\]

\[
\text{let } rf-S = WRS \setminus (S;WRS) (* \text{Most recent amongst them} *)
\]

\[
(* \text{Check equality with rf} *)
\]
Figure 3: Failed attempts of SC scheduling orders $S$. 

\[ \begin{align*} 
ix: & W_x = 0 \\
iy: & W_y = 0 \\
a: & W_x = 1 \\
b: & R_y = 0 \\
c: & W_y = 1 \\
d: & R_x = 0 \\
\end{align*} \]
Figure 4: SC executions of test SB.
empty rf \ rf-S as RfCons
empty rf-S \ rf as RfCons

13.4 Computing coherence orders

All the models seen so far include the file *cos.cat* that define “coherence relations”, written co. This section describes the file *cos.cat*. It can be skipped in first reading, as users may find sufficient to include the file.

For a given location \( x \) the coherence order is a total order on the write events to location \( x \). The coherence relation \( co \) is the union of those total orders for all locations. In this section, we show how to compute all possible coherence orders for a candidate execution. We seize the opportunity to introduce advanced features of the cat language, such as functions and pattern matching over sets.

Possible coherence orders for a given location \( x \) are not totally arbitrary in two aspects:

1. The write events to location \( x \) include the initial write event to location \( x \). The initial write to \( x \) must come first in any coherence order for \( x \).
2. One of the writes to \( x \) performed by the test (may) have been declared to be final by herd machinery prior to model execution. In that case, the final write to \( x \) must come last in any coherence order for \( x \).

See Sec. 13.3 for details on initial and final writes.

We can express the two conditions above for all locations of the program as a relation co0:

\[
\text{let co0 = loc & (IW*(W\IW)|(W\FW)*FW)}
\]

Where the pre-defined sets \( IW \) and \( FW \) are the sets of all initial and final writes respectively.

Then, assuming that \( W_x \) is the set of all writes to location \( x \), one can compute the set of all possible coherence orders for \( x \) with the linearisations primitive as \( \text{linearisations}(W_x, co0) \). In practice, we define a function that takes the set \( W_x \) as an argument:

\[
\text{let makeCoX(Wx) = linearisations(Wx, co0)}
\]

The linearisations primitive is introduced in Sec. 13.3. It returns all topological sorts of the events of the set \( W_x \) that are compatible with the relation co0.

In fact, we want to compute the set of all possible co relations, i.e. all the unions of all the possible coherence orders for all locations \( x \). To that end we use another cat primitive: partition(S), which takes a set of events as argument and returns a set of set of events \( T = \{S_1, \ldots, S_n\} \), where each \( S_i \) is the set of all events in \( S \) that act on location \( L_i \), and, of course \( S \) is the union \( \bigcup_{i=1}^{n} S_i \). Hence we shall compute the set of all \( W_x \) sets as \( \text{partition}(W) \), where \( W \) is the pre-defined set of all writes (including initial writes).

For combining the effect of the partition and linearisations primitives, we first define a map function that, given a set \( S = \{e_1, \ldots, e_n\} \) and a function \( f \), returns the set \( \{f(e_1), \ldots, f(e_n)\} \):

\[
\begin{align*}
\text{let map f} & = \\
& \text{let rec do_map S = match S with} \\
& \quad | \{\} \rightarrow \{\} \\
& \quad | e ++ S \rightarrow f e ++ do_map S \\
& \text{end in} \\
& \text{do_map}
\end{align*}
\]

The map function is written in curried style. That is one calls it as \( \text{map f S} \), parsed as \( (\text{map f}) S \). More precisely, the left-most function call \( (\text{map f}) \) returns a function. Here it returns \( \text{do_map} \) with free variable \( f \) being bound to the argument \( f \). The definition of map illustrate several new features:

1. The empty set constant “\( \{\} \)”, and the set addition operator \( e ++ S \) that returns the set \( S \) augmented with element \( e \).
2. Recursive function definitions. The function do_map is recursive as it calls itself.

3. Pattern matching on sets. This construct, similar to OCaml pattern matching on lists, discriminates between empty (\{\} \rightarrow e_0) and non-empty (\{ e ++ es \rightarrow e_1\}) sets. In the second case of a non-empty set, the expression \(e_1\) is evaluated in a context extended with two bindings: a binding from the variable \(e\) to an arbitrary element of the matched set, and a binding from the variable \(es\) to the matched set minus the arbitrary element.

Then, we generate the set of all possible coherence orders for all locations \(x\) as follows:

```ocaml
let allCoX = map makeCoX (partition(W))
```

Notice that allCoX is a set of sets of relations, each element being the set of all possible coherence orders for a specific \(x\).

We still need to generate all possible co relations, that is all unions of the possible coherence orders for all locations \(x\). It can be done by another cat function: cross, which takes a set of sets \(S = \{S_1, S_2, \ldots, S_n\}\) as argument and returns all possible unions built by picking elements from each of the \(S_i\):

\[
\{ e_1 \cup e_2 \cup \cdots \cup e_n \mid e_1 \in S_1, e_2 \in S_2, \ldots, e_n \in S_n \}
\]

One may notice that if \(S\) is empty, then cross should return one relation exactly: the empty relation, i.e. the neutral element of the union operator. This choice for cross(\(\emptyset\)) is natural when we define cross inductively:

\[
cross(S_1 ++ S) = \bigcup_{e_1 \in S_1, t \in \cross(S)} \{e_1 \cup t\}
\]

In the definition above, we simply build \(\cross(S_1 ++ S)\) by building the set of all unions of one relation \(e_1\) picked in \(S_1\) and of one relation \(t\) picked in \(\cross(S)\).

So as to write cross, we first define a classical fold function over sets: given a set \(S = \{e_1, e_2, \ldots, e_n\}\), an initial value \(y_0\) and a function \(f\) that takes a pair \((e, y)\) as argument, fold computes:

\[
f(e_{i_1}, f(e_{i_2}, \ldots, f(e_{i_n}, y_0)))
\]

where \(i_1, i_2, \ldots, i_n\) defines a permutation of the indices \(1, 2, \ldots, n\).

```ocaml
let fold f =
  let rec fold_rec (es,y) = match es with
  | {} -> y
  | e ++ es -> fold_rec (es,f (e,y))
  end in
  fold_rec
```

The function fold is written in the same curried style as map. Notice that the inner function fold_rec takes one argument. However this argument is a pair. As a gentle example of fold usage, we could have defined map as:

```ocaml
let map f = fun S -> fold (fun (e,y) -> f e ++ y) (S,\{\})
```

This example also introduce “anonymous” functions.

As a more involved example of fold usage, we write the function cross.

```ocaml
let rec cross S = match S with
 | {} -> \{ 0 \} (* 0 is the empty relation *)
 | S1 ++ S ->
  let ts = cross S in
  fold
  (fun (e1,r) -> map (fun t -> e1 \| t) ts \| r)
  (S1,\{\})
end
```
The function \texttt{cross} is a recursive function over a set (of sets). Its code follows the inductive definition given above.

Finally, we generate all possible \texttt{co} relations by:

\begin{verbatim}
let allCo = cross allCoX
\end{verbatim}

The file \texttt{cos.cat} goes on by iterating over \texttt{allCo} using the \texttt{with x from s} construct:

\begin{verbatim}
with co from allCo
\end{verbatim}

See Sec. 13.3 for details on this construct.

Once \texttt{co} has been defined, one defines \texttt{fr} and internal and external variations:

\begin{verbatim}
(* From now, co is a coherence relation *)
let coi = co & int
let coe = co & ext

(* Compute fr *)
let fr = rf^-1 ; co
let fri = fr & int
let fre = fr & ext
\end{verbatim}

The pre-defined relation \texttt{ext} (resp. \texttt{int}) relates events generated by different (resp. the same) threads.

\section{Producing pictures of executions}

The simulator \texttt{herd7} can be instructed to produce pictures of executions. Those pictures are instrumental in understanding and debugging models. It is important to understand that \texttt{herd7} does not produce pictures by default. To get pictures one must instruct \texttt{herd7} to produce pictures of some executions with the \texttt{-show} option. This option accepts specific keywords, its default being “\texttt{none}”, instructing \texttt{herd7} not to produce any picture.

A frequently used keyword is “\texttt{prop}” that means “show the executions that validate the proposition in the final condition”. Namely, the final condition in litmus test is a quantified boolean proposition as for instance “\texttt{exists (0:EAX=0 \land 1:EAX=0)}” at the end of test \texttt{SB}.

But this is not enough, users also have to specify what to do with the picture: save it in file in the DOT format of the \texttt{graphviz} graph visualization software, or display the image, or both. One instructs \texttt{herd7} to save images with the \texttt{-o dirname} option, where \texttt{dirname} is the name of a directory, which must exists. Then, when processing the file \texttt{name.litmus}, \texttt{herd7} will create a file \texttt{name.dot} into the directory \texttt{dirname}.

For displaying images, one uses the \texttt{-gv} option.

As an example, so as to display the image of the non-SC behaviour of \texttt{SB}, one should invoke \texttt{herd7} as:

\begin{verbatim}
% herd7 -model tso-02.cat -show prop -gv SB.litmus
\end{verbatim}

As a result, users should see a window popping and displaying this image:

\footnote{This option requires the Postscript visualiser \texttt{gv}.}
Notice that we got the PNG version of this image as follows:

```
% herd7 -model tso-02.cat -show prop -o /tmp SB.litmus
% dot -Tpng /tmp/SB.dot -o SB+CLUSTER.png
```

That is, we applied the dot tool from the graphviz package, using the appropriate option to produce a PNG image.
One may observe that there are ghb arrows in the diagram. This results from the \texttt{show ghb} instruction at the end of the model file \texttt{tso-02.cat}.

### 14.1 Graph modes

The image above much differs from the one in Sec. 13.2 that describes the same execution and that is reproduced in Fig. 5.

In effect, \texttt{herd7} can produce three styles of pictures, \texttt{dot} clustered pictures, \texttt{dot} free pictures, and \texttt{neato} pictures with explicit placement of the events of one thread as a column. The style is commanded by the \texttt{-graph} option that accepts three possible arguments: \texttt{cluster} (default), \texttt{free} and \texttt{columns}. The following pictures show the effect of graph styles on the \textbf{SB} example:
Notice that we used another option, `-squished true`, that much reduces the information displayed in nodes. Also notice that the first two pictures are formatted by `dot`, while the rightmost picture is formatted by `neato`.

One may also observe that the "-graph columns" picture does not look exactly like Fig. 5. For instance the `ghb` arrows are thicker in the figure. There are many parameters to control `neato` (and `dot`), many of which are accessible to `herd7` users by the means of appropriate options. We do not intend to describe them all. However, users can reproduce the style of the diagram of this manual using yet another feature of `herd7`: configuration files that contains settings for `herd7` options and that are loaded with the `-conf name` option. In this manual we mostly used the `doc.cfg` configuration file. As this file is present in `herd7` distribution, users can use the diagram style of this manual:

```
% herd7 -conf doc.cfg ...
```

### 14.2 Showing forbidden executions

Images are produced or displayed once the model has been executed. As a consequence, forbidden executions won’t appear by default. Consider for instance the test `SB+mfences`, where the `mfence` instruction is used to forbid `SB` non-SC execution. Runing `herd7` as

```
% herd7 -model tso-02.cat -conf doc.cfg -show prop -gv SB+mfences.litmus
```

will produce no picture, as the TSO model forbids the target execution of `SB+mfences`. 

To get a picture, we can run SB+mfences on top of the minimal model, a pre-defined model that allows all executions:

```
% herd7 -model minimal -conf doc.cfg -show prop -gv SB+mfences.litmus
```

And we get the picture:

It is worth mentioning again that although the minimal model allows all executions, the final condition selects the displayed picture, as we have specified the `-show prop` option.

The picture above shows `mfence` arrows, as all fence relations are displayed by the minimal model. However, it does not show the `ghb` relation, as the minimal model knows nothing of it. To display `ghb` we could write another model file that would be just as `tso-02.cat`, with checks erased. The simulator `herd7` provides a simpler technique: one can instruct `herd7` to ignore either all checks (`-through invalid`), or a selection of checks (`-skipchecks name1,...,nameN`). Thus, either of the following two commands will produce the picture we wish:

```
% herd7 -through invalid -model tso-02.cat -conf doc.cfg -show prop -gv SB+mfences.litmus

% herd7 -skipcheck tso -model tso-02.cat -conf doc.cfg -show prop -gv SB+mfences.litmus
```
Notice that `mfence` and `ghb` are displayed because of the instruction “show mfence ghb” (fence relation are not shown by default); while `-skipcheck tso` works because the `tso-02.cat` model names its main check with “as tso”.

The image above is barely readable. For such graphs with many relations, the `cluster` and `free` modes are worth a try. The commands:

```
% herd7 -skipcheck tso -model tso-02.cat -conf doc.cfg -show prop -graph cluster -gv SB+mfences.litmus
% herd7 -skipcheck tso -model tso-02.cat -conf doc.cfg -show prop -graph free -gv SB+mfences.litmus
```

will produce the images:
Namely, command line options are scanned left-to-right, so that most of the settings of doc.cfg are kept\textsuperscript{11} (for instance thick ghb arrows), while the graph mode is overriden.

## 15 Model definitions

We describe our cat language for defining models. The syntax of the language is given in BNF-like notation. Terminal symbols are set in typewriter font (like this). Non-terminal symbols are set in italic font (like that). An unformatted vertical bar \ldots | \ldots denotes alternative. Square brackets \[\ldots\] denote optional components. Curly brackets \{\ldots\} denotes zero, one or several repetitions of the enclosed components. Parentheses \(\ldots\) denote grouping.

Model source files may contain comments of the OCaml type (\(*\ldots\*\), can be nested), or line comments starting with “//” and running until end of line.

### 15.1 Overview

The cat language is much inspired by OCaml, featuring immutable bindings, first-class functions, pattern matching, etc. However, cat is a domain specific language, with important differences from OCaml.

1. Base values are specialised, they are sets of events and relations over events. There are also tags, akin to C enumerations or OCaml “constant” constructors and first class functions. Moreover, events can be extracted from sets and pair of events (element of relations) from relations.

\textsuperscript{11}The setting of showthread is also changed, by the omitted -showthread true command line option
There are two structured values: tuples of values and sets of values. Once should notice that primitive set of events and structured set of events are not the same thing. In fact, the language prevents the construction of structured set of events. Similarly, there are no structured sets of elements of relations, there are only relations.

2. There is a distinction between expressions that evaluate to some value, and instructions that are executed for their effect.

A model, or cat program is a sequence of instructions. At startup, pre-defined identifiers are bound to event sets and relations over events. Those pre-defined identifiers describe a candidate execution (in the sense of the memory model). Executing the model means allowing or forbidding that candidate execution.

### 15.2 Identifiers

\[
\begin{align*}
\text{letter} & ::= \text{a...z | A...Z} \\
\text{digit} & ::= 0...9 \\
\text{id} & ::= \text{letter} \{\text{letter} | \text{digit} | \_ | . | -}\end{align*}
\]

Identifiers are rather standard: they are a sequence of letters, digits, “_” (the underscore character), “.” (the dot character) and “-” (the minus character), starting with a letter. Using the minus character inside identifiers may look a bit surprising. We did so as to allow identifiers such as \text{po-loc}.

At startup, pre-defined identifiers are bound to event sets and to relations between events.

Those pre-defined identifiers first describe the events of the candidate execution as various sets, as described by the first table of figure 6. Specific fence event sets depends on the test architecture, their name is always uppercase and derive from the mnemonic of the instruction that generates them. The second table of figure 6 shows a (non-exhaustive) list.

Other pre-defined identifiers are relations. Most of those are the program order \text{po} and its refinements:
<table>
<thead>
<tr>
<th>identifier</th>
<th>name</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>po</td>
<td>program order</td>
<td>instruction order lifted to events</td>
</tr>
<tr>
<td>addr</td>
<td>address dependency</td>
<td>the address of the second event depends on the value loaded by the first (read) event</td>
</tr>
<tr>
<td>data</td>
<td>data dependency</td>
<td>the value stored by the second (write) event depends on the value loaded by the first (read) event</td>
</tr>
<tr>
<td>ctrl</td>
<td>control dependency</td>
<td>the second event is in a branch controled by the value loaded by the commfirst (read) event</td>
</tr>
<tr>
<td>rmw</td>
<td>read-exclusive</td>
<td>relate the read and write events emitted by matching successful load-reserve store conditional instructions.</td>
</tr>
</tbody>
</table>

Finally, a few pre-defined relations describe the execution candidate structure and write-to-read communication:

<table>
<thead>
<tr>
<th>identifier</th>
<th>name</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>id</td>
<td>identity</td>
<td>relates each event to itself</td>
</tr>
<tr>
<td>loc</td>
<td>same location</td>
<td>events that touch the same address</td>
</tr>
<tr>
<td>ext</td>
<td>external</td>
<td>events from different threads</td>
</tr>
<tr>
<td>int</td>
<td>internal</td>
<td>events from the same thread</td>
</tr>
<tr>
<td>rf</td>
<td>read-from</td>
<td>links a write $w$ to a read $r$ taking its value from $w$</td>
</tr>
</tbody>
</table>

Some additional relations are defined by library files written in the cat language, see Sec. 15.7.
15.3 Expressions

Expressions are evaluated by herd7, yielding a value.

\[
\begin{align*}
expr &::= 0 \\
& \mid \text{id} \\
& \mid \text{tag} \\
& \mid ( ) | ( expr , expr \{ \text{, } expr \} ) \\
& \mid \{ \} | \{ expr \{ \text{, } expr \} \} \\
& \mid expr \ast | expr + | expr ? | expr ^{-1} \\
& \mid \sim expr \\
& \mid [ expr ] \\
& \mid expr | expr \text{ } \ast expr | expr \text{ ; } expr | expr \text{ } \text{\textbackslash } expr | expr \& expr | expr \ast expr \\
& \mid expr expr \\
& \mid \text{fun pat } \rightarrow expr \\
& \mid \text{let } [\text{rec} ] \text{ binding } \{ \text{and binding} \} \text{ in } expr \\
& \mid \text{match expr with clauses end} \\
& \mid ( expr ) | \text{begin } expr \text{ end} \\
& \mid \text{instructions } id [\text{taglist}] \\
\end{align*}
\]

\[
\begin{align*}
tag &::= \text{'id} \\
taglist &::= tag, taglist \\
pat &::= id | ( ) | ( id \{ \text{, id} \} ) \\
binding &::= \text{valbinding } | \text{funbinding} \\
valbinding &::= id = expr \\
funbinding &::= id pat = expr \\
\end{align*}
\]

clauses ::= tagclauses | setclauses \\
tagclauses ::= [\text{\textbar\textbar} ] tag \rightarrow expr [\text{\textbar\textbar} tag \rightarrow expr] [\text{\textbar\textbar} \rightarrow expr] \\
setclauses ::= [\text{\textbar\textbar} ] \{ \} \rightarrow expr [\text{\textbar\textbar} id \ast id \rightarrow expr]

Simple expressions

Simple expressions are the empty relation (keyword 0), identifiers id and tags tag. Identifiers are bound to values, either before the execution (see pre-defined identifiers in Sec. 15.2), or by the model itself. Tags are constants similar to C enum values or OCaml constant constructors. Tags must be declared with the enum instruction. We go back to enum and tags in Sec. 15.4 and ??.

Tuples

Tuples include a constant, the empty tuple ( ), and constructed tuples \(( expr_1 , expr_1 , \ldots , expr_n )\), with \( n \geq 2 \). In other words there is no tuple of size one. Syntax \(( expr )\) denotes grouping and has the same value as expr.

Explicit sets of values

Explicit sets are written as the comma separated list of their elements between curly braces: \{ expr_1 , expr_1 , \ldots , expr_n \}, with \( n \geq 0 \). Sets are homogenous, in the sense that sets hold elements of the same type.
In case the values $expr_k$ are events, the result will be a primitive event set. In case they are elements of relations, the result will be a relation (and not a set of event pairs).

The empty set $\{\}$ is the empty set of events and the empty relation.

**Operator expressions**

Most operators are overloaded and apply to event sets, relations and explicit sets. However, by nature, some operators apply to relations only (as sequence and transitive closure below) or to sets only (as the cartesian product). Additionally, an event in a context where an event set is expected will be promoted to a singleton event set. The situation of an elementary relation in a relation context is similar.

The transitive and reflexive-transitive closure of an expression are performed by the postfix operators $+$ and $\ast$. The postfix operator $^-1$ performs relation inversion. The construct $expr$ (option) evaluates to the union of $expr$ value and of the identity relation. Notice that postfix operators operate on relations only.

There is one prefix operator $\sim$ that performs relation and set complement.

Finally, there is one last unary operator: $[expr]$ that evaluate $expr$ to an event set and returns the identity relation over this set.

Infix operators are $|$ (union), $++$ (set addition), $;$ (sequence), $\&$ (intersection), $\setminus$ (set difference), and $\ast$ (cartesian product). Infix operators are listed in order of increasing precedence, while postfix and prefix operators bind tighter than infix operators. All infix operators are right-associative, except set difference which is left-associative, and cartesian product which is non-associative.

The union, intersection and difference operators apply to relations and all kinds of sets. The cartesian product takes two event sets as arguments and returns a relation.

The addition operator $expr_1 ++ expr_2$ operates on sets: the value of $expr_2$ must be a set of values (or an event, or an element of relation) $S$ and the operator returns the set $S$ augmented with the value of $expr_1$ (or a new event set, or a new relation). By exception, the arguments to the addition operator can also be an elementary relation and realation. It then yields a relation.

For the record, given two relations $r_1$ and $r_2$, the sequence $r_1 ; r_2$ is defined as $\{(x, y) \mid \exists z, (x, z) \in r_1 \land (z, y) \in r_2\}$.

**Function calls**

Functions calls are written $expr_1 expr_2$. That is, functions are of arity one and the application operator is left implicit. Notice that function application binds tighter than all binary operators and looser that postfix operators. Furthermore the implicit application operator is left-associative.

The **cat** language has call-by-value semantics. That is, the effective parameter $expr_2$ is evaluated before being bound to the function formal parameter(s).

N-ary functions can be encoded either using tuples as arguments or by currying (i.e., as functions that return functions). Considering binary functions, in the former case, a function call is written $expr_1 ( expr_2 , expr_3 )$; while in the latter case, a function call is written $expr_1 \ updownarrow expr_2 \ updownarrow expr_3$ (which by left-associativity, is to be understood as $( expr_1 \ updownarrow expr_2 ) \ updownarrow expr_3$). The two forms of function call are not interchangeable, using one or the other depends on the definition of the function.

**Functions**

Functions are first class values, as reflected by the anonymous function construct **fun** $pat \rightarrow expr$. A function takes one argument only.

In the case where this argument is a tuple, it may be destructured by the means of a tuple pattern. That is $pat$ above is $(id_1, \ldots, id_n)$. For instance here is a function that takes a tuple of relations (or sets) as argument and return their symmetric difference:

```
fun (a,b) -> (a\b)|(|b\a)
```
Functions have the usual static scoping semantics: variables that appear free in function bodies (expr above) are bound to the value of such free variable at function creation time. As a result one may also write the symmetric difference function as follows:

\[
\text{fun } a \to \text{fun } b \to (a \setminus b) \cup (b \setminus a)
\]

Local bindings

The local binding construct \texttt{let [rec]bindings in expr} binds the names defined by \texttt{bindings} for evaluating the expression \texttt{expr}. Both non-recursive and recursive bindings are allowed. The function binding \texttt{id pat = expr} is syntactic sugar for \texttt{id = fun pat -> expr}.

The construct

\[
\text{let pat}_1 = \text{expr}_1 \text{ and } \ldots \text{ and pat}_n = \text{expr}_n \text{ in } \text{expr}
\]
evaluates \texttt{expr}_1, \ldots, \texttt{expr}_n, and binds the names in the patterns \texttt{pat}_1, \ldots, \texttt{pat}_n to the resulting values. The bindings for \texttt{pat=expr} are as follows: if \texttt{pat} is \texttt{( )}, then \texttt{expr} must evaluate to the empty tuple; if \texttt{pat} is \texttt{id} or \texttt{( id )}, then \texttt{id} is bound to the value of \texttt{expr}; if \texttt{pat} is a proper tuple pattern \texttt{(id}_1, \ldots, \texttt{id}_n\texttt{)} with \texttt{n} \geq 2, then \texttt{expr} must evaluate to a tuple value of size \texttt{n} \texttt{(v}_1, \ldots, \texttt{v}_n\texttt{)} and the names \texttt{id}_1, \ldots, \texttt{id}_n are bound to the values \texttt{v}_1, \ldots, \texttt{v}_n. By exception, in the case \texttt{n} = 2, the expression \texttt{expr} may evaluate to an elementary relation. If so, the value behaves as a tuple of arity two.

The construct

\[
\text{let rec pat}_1 = \text{expr}_1 \text{ and } \ldots \text{ and pat}_n = \text{expr}_n \text{ in } \text{expr}
\]
computes the least fixpoint of the equations \texttt{pat}_1 = \texttt{expr}_1, \ldots, \texttt{pat}_n = \texttt{expr}_n. It then binds the names in the patterns \texttt{pat}_1, \ldots, \texttt{pat}_n to the resulting values. The least fixpoint computation applies to set and relation values, (using inclusion for ordering); and to functions (using the usual definition ordering).

Pattern matching over tags

The syntax for pattern matching over tags is:

\[
\text{match expr with } \text{tag}_1 \to \text{expr}_1 \mid \cdots \mid \text{tag}_n \to \text{expr}_n \mid _\to \text{expr}_d \text{ end}
\]
The value of the match expression is computed as follow: first evaluate \texttt{expr} to some value \texttt{v}, which must be a tag \texttt{t}. Then \texttt{v} is compared with the tags \texttt{tag}_1, \ldots, \texttt{tag}_n, in that order. If some tag pattern \texttt{tag}_i equals \texttt{t}, then the value of the match is the value of the corresponding expression \texttt{expr}_i. Otherwise, the value of the match is the value of the default expression \texttt{expr}_d. As the default clause \texttt{_ -> expr}_d is optional, the match construct may fail.

Pattern matching over sets

The syntax for pattern matching over sets is:

\[
\text{match expr with } \{ \} \to \text{expr}_1 \mid id_1 ++ id_2 \to \text{expr}_2 \text{ end}
\]
The value of the match expression is computed as follow: first evaluate \texttt{expr} to some value \texttt{v}, which must be a set of values. If \texttt{v} is the empty set, that the value of the match is the value of the corresponding expression \texttt{expr}_1. Otherwise, \texttt{v} is a non-empty set, then let \texttt{v}_e be some element in \texttt{v} and \texttt{v}_r be the set \texttt{v} minus the element \texttt{v}_e. The value of the match is the value of \texttt{expr}_2 in a context where \texttt{id}_1 is bound to \texttt{v}_e and \texttt{id}_2 is bound to \texttt{v}_r.

The construct also also applies to primitive event sets and relations. If the matched expression is non-empty, then the bound element is an event and an element of relation, respectively. One easily rebuilds an event set (or a relation) for instance by using the singleton construct as \{ \texttt{id}_1 \}.
Parenthesised expressions

The expression \(( expr \)\) has the same value as \( expr \). Notice that a parenthesised expression can also be written as \( \text{begin} expr \text{ end} \).

15.4 Instructions

Instructions are executed for their effect. There are three kinds of effects: adding new bindings, checking a condition, and specifying relations that are shown in pictures.

\[
\text{instruction} ::= \text{let } [\text{rec}] \text{ binding } \{\text{and binding}\} \\
                 | \text{[flag]} \text{ check } expr \ [\text{as } id] \\
                 | \text{enum } id = [\ | \tag \{\ | \tag\} \\
                 | \text{procedure } id \text{ pat } = \{\text{instruction}\} \text{ end} \\
                 | \text{call } id \text{ expr } [\text{as } id] \\
                 | \text{show } expr \ [\text{as } id] \\
                 | \text{show } id \{, id\} \\
                 | \text{unshow } id \{, id\} \\
                 | \text{forall } id \text{ in } expr \text{ do } \{\text{instruction}\} \text{ end} \\
                 | \text{with } id \text{ from } expr \\
                 | \text{include}\text{string}
\]

\[
\text{check} ::= \text{checkname} | ~ \text{checkname}
\]

\[
\text{checkname} ::= \text{acyclic} | \text{irreflexive} | \text{empty}
\]

Bindings

The \text{let} and \text{let rec} constructs bind value names for the rest of model execution. See the subsection on bindings in Section 15.3 for additional information on the syntax and semantics of bindings.

Recursive definitions computes fixpoints of relations. For instance, the following fragment computes the transitive closure of all communication relations:

\[
\text{let com = rf | co | fr} \\
\text{let rec complus = com | (complus ; complus)}
\]

Notice that the instruction \text{let complus = (rf|co|fr)+} is equivalent. Notice that herd7 assumes that recursive definitions are well-formed, i.e. that they yield an increasing functional. The result of ill-formed definitions is undefined.

Although herd7 features recursive functions, those cannot be used to compute a transitive closure, due to the lack of some construct say to test relation equality. Nevertheless, one can write a generic transitive closure function by using a local recursive binding:

\[
\text{let tr}(r) = \text{let rec } t = r \ | \ (t ; t) \text{ in } t
\]

Again, notice that the instruction \text{let tr } (r) = r+ is equivalent.

Thanks to pattern matching constructs, recursive functions are useful to compute over sets (and tags). For instance here is the definition of a function \text{power} that compute power sets:

\[
\text{let rec power } S = \text{match } S \text{ with} \\
| | \{\} -> \{\{\}\} \\
| | e ++ S -> \\
\hspace{1cm} \text{let rec add_e } RR = \text{match } RR \text{ with} \\
| | \{\} -> \{}
\]

89
\begin{align*}
\ll R \oplus RR & \rightarrow R \oplus (e \oplus R) \oplus add_e \, RR \\
\text{end in} & \\
\text{add}_e \, (\text{power} \, S)
\end{align*}

Checks

The construct

\begin{align*}
\text{check expr}
\end{align*}

evaluates expr and applies the check check. There are six checks: the three basic acyclicity (keyword acyclic), irreflexivity (keyword irreflexive) and emptyness (keyword empty); and their negations. If the check succeeds, execution goes on. Otherwise, execution stops.

The performance of a check can optionally be named by appending as id after it. The feature permits not to perform some checks at user’s will, thanks to the -skipchecks id command line option.

A check can also be flagged, by prefixing it with the flag keyword. Flagged checks must be named with the as construct. Failed flagged checks do not stop execution. Instead successful flagged checks are recorded under their name, for herd7 machinery to handle flagged executions later. Flagged checks are useful for models that define conditions over executions that impact the semantics of the whole program. This is typically the case of data races. Let us assume that some relation race has been defined, such that an non-empty race relation in some execution would make the whole program undefined. We would then write:

\begin{align*}
\text{flag } \neg\text{empty race as undefined}
\end{align*}

Then, herd7 will indicate in its output that some execution have been flagged as undefined.

Procedure definition and call

Procedures are similar to functions except that they have no results: the body of a procedure is a list of instructions and the procedure will be called for the effect of executing those instructions. Intended usage of procedures is to define checks that are executed later. However, the body of a procedure may consist in any kind of instructions. Notice that procedure calls can be named with the as keyword. The intention is to control the performance of procedure calls from the command line, exactly as for checks (see above).

As an example of procedure, one may define the following uniproc procedure with no arguments:

\begin{align*}
\text{procedure uniproc()} = \\
& \text{let com} = \text{fr} \mid \text{rf} \mid \text{co} \text{ in} \\
& \text{acyclic com} \mid \text{po} \\
\text{end}
\end{align*}

Then one can perform the acyclicity check (see previous section) by executing the instruction:

\begin{align*}
\text{call uniproc()}
\end{align*}

As a result the execution will stop if the acyclicity check fails, or continue otherwise.

Procedures are lexically scoped as functions are. Additionally, the bindings performed during the execution of a procedure call are discarded when the procedure returns, all other effects performed (namely flags and shows) are retained.
Show (and unshow) directives

The constructs:

\[ \text{show \{ , id \} and unshow \{ , id \}} \]

take (non-empty, comma separated) lists of identifiers as arguments. The show construct adds the present values of identifiers for being shown in pictures. The unshow construct removes the identifiers from shown relations.

The more sophisticated construct

\[ \text{show expr as id} \]

evaluates expr to a relation, which will be shown in pictures with label id. Hence show id can be viewed as a shorthand for show id as id

Iteration over sets

The forall iteration construct permits the iteration of checks (in fact of any kind of instructions) over a set. Syntax is:

\[
\text{forall id in expr do instructions end}
\]

The expression expr must evaluate to a set S. Then, the list of instructions instructions is executed for all bindings of the name id to some element of S. In practice, as failed checks stop execution, this amounts to check the conjunction of the checks performed by instructions for all the elements of S. Similarly to procedure calls, the bindings performed during the execution of an iteration are discarded at iteration ends, all other effects performed are retained.

Candidate execution extension

This construct permits the extension of the current candidate execution by one binding. Syntax is with id from expr. The expression expr is evaluated to a set S. Then the remainder of the model is executed for each choice of element e in S in a context extended by a binding of the name id to e. An example of the construct usage is described in Sec. 13.3.

Model inclusion

The construct include "filename " is interpreted as the inclusion of the model contained in the file whose name is given as an argument to the include instruction. In practice the list of instructions defined by the included model file are executed. The string argument is delimited by double quotes " " , which, of course, are not part of the filename. Files are searched according to herd7 rules — see Sec. 16.4.

Bell extensions

Users can attain more genericity in their models by defining a bell file, as an addendum, or rather preamble, to a cat file.
Enumerations

The `enum` construct defines a set of enumerated values or tags. Syntax is

```plaintext
enum id = tag_1 | · · · | tag_n
```

The construct has two main effects. It first defines the tags `tag_1, . . . , tag_n`. Notice that tags do not exist before being defined, that is evaluating the expression `tag` is an error without a prior `enum` that defines the tag `tag`. Tags are typed in the sense that they belong to the tag type `id` and that tags from different types cannot be members of the same set. The second effect of the construct is to define a set of tags `id` as the set of all tags listed in the construct. That is, the `enum` construct performs the binding of `id` to `{tag_1, . . . , tag_n}`.

Scopes are a special case of enumeration: the construct `enum scopes` must be used to define hierarchical models such as Nvidia GPUs.

An `enum scopes` declaration must be paired with two functions `narrower` and `wider` that implement the hierarchy amongst scopes. For example:

```plaintext
enum scopes = 'discography || 'I || 'II || 'III || 'IV

let narrower(t) = match t with
  || 'discography -> {'I, 'II, 'III, 'IV}
end

let wider(t) = match t with
  || 'I -> 'discography
  || 'II -> 'discography
  || 'III -> 'discography
  || 'IV -> 'discography
end
```

Here we define five scopes, where the first one, `discography`, is wider than all the other ones.

Instructions

The predefined sets of events `W`, `R`, `RMW`, `F`, and `B` can be annotated with user-defined tags (see Sec. 15.4).

The constructs:

```plaintext
instructions
id
[taglist]
```

take the identifier of a pre-defined set and a possibly empty, square bracketed list of tags.

The primitive `tag2instrs` yields, given a tag `t`, the set of instructions bearing the annotation `t` that was previously declared in an enumeration type.

The primitive `tag2scope` yields, given a tag `t`, the relation between instructions TODO

15.5 Models

```plaintext
model ::= model-comment instruction
model-comment ::= id | string
```

A model is a list of instruction preceded by a small comment, which can be either a name that follows herd7 conventions for identifiers, or a string enclosed in double quotes “"".""
Models operate on candidate executions (see Sec. 15.2), instructions are executed in sequence, until one instruction stops, or until the end of the instruction list. In that latter case, the model accepts the execution. The accepted execution is then passed over to the rest of herd engine, in order to collect final states of locations and to display pictures.

15.6 Primitives

TODO:

15.7 Library

Standard library

The standard library is a cat file stdlib.cat which all models include by default. It defines a a few convenient relations that are thus available to all models.

<table>
<thead>
<tr>
<th>identifier</th>
<th>name</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>po-loc</td>
<td>po</td>
<td>restricted to the same address, namely po ∩ loc</td>
</tr>
<tr>
<td>rfe</td>
<td>external</td>
<td>read-from by different threads, namely rf ∩ ext</td>
</tr>
<tr>
<td>rfi</td>
<td>internal</td>
<td>read-from by the same thread, namely rf ∩ int</td>
</tr>
</tbody>
</table>

Coherence orders

For most models, a complete list of communication relations would also include co and fr. Those can be defined by including the file cos.cat (see Sec. 13.4).

<table>
<thead>
<tr>
<th>identifier</th>
<th>name</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>co</td>
<td>coherence</td>
<td>total order over writes to the same address</td>
</tr>
<tr>
<td>fr</td>
<td>from-read</td>
<td>links a read r to a write w’ co-after the write w from which r takes its value</td>
</tr>
<tr>
<td>coi, fri</td>
<td>internal</td>
<td>communications</td>
</tr>
<tr>
<td>coe, fre</td>
<td>external</td>
<td>communications</td>
</tr>
</tbody>
</table>

Notice that the internal and external sub-relations of co and fr are also defined.

Fences

Fence relations denote the presence of a specific fence (or barrier) in-between two events. Those can be defined by including architecture specific files.

<table>
<thead>
<tr>
<th>file</th>
<th>relations</th>
</tr>
</thead>
<tbody>
<tr>
<td>x86fences.cat</td>
<td>mfence, sfence, lfence</td>
</tr>
<tr>
<td>ppfences.cat</td>
<td>sync, lwsync, eleio, isync, ctrlisync</td>
</tr>
<tr>
<td>armfences.cat</td>
<td>dsb, dmb, dsb.st, dmb.st, isb, ctrlisb</td>
</tr>
<tr>
<td>mipsfences.cat</td>
<td>sync</td>
</tr>
<tr>
<td>aarch64fences.cat</td>
<td>...</td>
</tr>
</tbody>
</table>

In other words, models for, say, ARM machines should include the following instruction:

```
include "armfences.cat"
```
Notice that for the Power (PPC) (resp. ARM) architecture, an additional relation ctrlisync (resp. ctrlisb) is defined. The relation ctrlisync reads control +isync. It means that the branch to the instruction that generates the second event additionnaly contains a isync fence preceeding that instruction. For reference, here is a possible definition of ctrlisync:

\[
\text{let ctrlisync } = \text{ctrl & (\_ * ISYNC)}; \text{ po}
\]

One may define all fence relations by including the file fences.cat. As a result, fence relations that are relevant to the architecture of the test being simulated are properly defined, while irrelevant fence relations are the empty relation. This feature proves convenient for writing generic models that apply to several concrete architectures.

16 Usage of herd7

16.1 Arguments

The command herd7 handles its arguments like litmus7. That is, herd7 interprets its argument as file names. Those files are either a single litmus test when having extension .litmus, or a list of file names when prefixed by @.

16.2 Options

There are many command line options. We describe the more useful ones:

General behaviour

- **version** Show version number and exit.
- **-libdir** Show installation directory and exit.
- **-v** Be verbose, can be repeated to increase verbosity.
- **-q** Be quiet, suppress any diagnostic message.
- **-conf <name>** Read configuration file name. Configuration files have a very simple syntax: a line “opt arg” has the same effect as the command-line option “-opt arg”.
- **-o <dest>** Output files into directory <dest>. Notice that <dest> must exist. At the moment herd7 may output one .dot file per processed test: the file for test base.litmus is named base.dot. By default herd7 does not generate .dot files.
- **-suffix <suf>** Change the name of .dot files into basesuf.dot. Useful when several .dot files derive from the same test. Default is the empty string (no suffix).
- **-gv** Fork the gv Postscript viewer to display execution diagrams.
- **-evince** Fork the evince document viewer to display execution diagrams. This option provides an alternative to the gv viewer.
- **-dumpes <bool>** Dump generated event structures and exit. Default is false. Event structures will be dumped in a .dot file whose name is determined as usual — See options -o and -suffix above. Optionally the event structures can be displayed with the -gv option.
- **-unroll <int>** The setting -unroll n performs backwards jumps n times. This is a workaround for one of herd7 main limitation: herd7 does not really handle loops. Default is 2.
- **-hexa <bool>** Print numbers in hexadecimal. Default is false (numbers are printed in decimal).
Engine control  The main purpose of herd7 is to run tests on top of memory models. For a given test, herd7 performs a three stage process:

1. Generate candidate executions.
2. For each candidate execution, run the model. The model may reject or accept the execution.
3. For each candidate execution that the model accepts, record observed locations and, if so instructed, a diagram of the execution.

We now describe options that control those three stages.

-model (cav12|minimal|uniproc|<filename>.cat) Select model, this option accept one tag or one file name with extension .cat. Tags instruct herd7 to select an internal model, while file names are read for a model definition. Documented model tags are:

• cav12, the model of [4] (Power);
• minimal, the minimal model that allows all executions;
• uniproc, the uniproc model that checks single-thread correctness.

In fact, herd7 accepts potentially infinitely many models, as models can given in text files in an adhoc language described in Sec. 15. The herd7 distribution includes several such models: herd.cat, minimal.cat, uniproc.cat and x86tso.cat are text file versions of the homonymous internal models, but may produce pictures that show different relations. Model files are searched according to the same rules as configuration files. Some architectures have a default model: arm.cat model for ARM, ppc.cat model for PPC, x86tso.cat for X86, and mips-ps0.cat for MIPS.

-through (all|invalid|none) Let additional executions reach the final stage of herd7 engine. This option permits users to generate pictures of forbidden executions, which are otherwise rejected at an early stage of herd7 engine — see Sec. 14.2. Namely, the default “none” let only valid (according to the active model) executions through. The behaviour of this option differs between internal and text file models:

• For internal models: the tag all let all executions go through; while the tag invalid will reject executions that violate uniproc, while letting other forbidden execution go through.
• Text file models: the tags all and invalid let all executions go through. For such models, a more precise control over executions that reach herd7 final phase can be achieved with the option -skipcheck — see next option.

Default is none.

-skipchecks <name1,...,name_n> This option applies to text file models. It instructs herd7 to ignore the outcomes of the given checks. For the option to operate, checks must be named in the model file with the as name construct – see Sec. 15.4. Notice that the arguments to -skipcheck options cumulate. That is, “-skipcheck name1 -skipcheck name2” acts like “-skipcheck name1,name2”.

-strictskip <bool> Setting this option (-strictskip true), will change the behaviour of the previous option -skipcheck: it will let executions go through when the skipped checks yield false and the unskipped checks yield true. This option comes handy when one want to observe the executions that fail one (or several) checks while passing others. Default is false.

-optace <bool> Optimise the axiomatic candidate execution stage. When enabled by -optace true, herd7 does not generate candidate executions that fail the uniproc test. The default is “true” for internal models (except the minimal model), and “false” for text file models. Notice that -model uniproc.cat and -model minimal.cat -optace true should yield identical results, the second being faster. Setting -optace true can lower the execution time significantly, but one should pay attention not to design models that forget the uniproc condition.
-show (prop|neg|all|cond|wit|none) Select execution diagrams for picture display and generation. Execution diagrams are shown according to the final condition of test. The final condition is a quantified boolean proposition \( \exists p \), \( \neg \exists p \), or \( \forall p \). The semantics of recognised tags is as follows:

- **prop** Picture executions for which \( p \) is true.
- **neg** Picture executions for which \( p \) is false.
- **all** Picture all executions.
- **cond** Picture executions that validate the condition, i.e. \( p \) is true for \( \exists \) and \( \forall \), and false for \( \neg \exists \).
- **wit** Picture “interesting” executions, i.e. \( p \) is true for \( \exists \) and \( \neg \exists \), and false for \( \forall \).
- **none** Picture no execution.

Default is **none**.

-initwrites <bool> Represent init writes as plain write events, default is false except for specifically tagged generic models — see “Model options” in Sec. 15.5.

**Discard some observations** Those options intentionally omit some of the final states that herd7 would normally generate.

-speedcheck (false|true|fast) When enabled by -speedcheck true or -speedcheck fast, attempt to settle the test condition. That is, herd7 will generate a subset of executions (those named “interesting” above) in place of all executions. With setting -speedcheck fast, herd7 will additionally stop as soon as a condition \( \exists p \) is validated, and as soon as a condition \( \neg \exists p \) or \( \forall p \) is invalidated. Default is false.

-nshow <int> Stop once <int> pictures have been collected. Default is to collect all (specified, see option -show) pictures.

**Control dot pictures** These options control the content of DOT images.

We first describe options that act at the general level.

-graph (cluster|free|columns) Select main mode for graphs. See Sec. 14.1. The default is cluster.

-dotmode (plain|fig) The setting -dotmode fig produces output that includes the proper escape sequence for translating .dot files to .fig files (e.g. with dot -Tfig...). Default is plain.

-dotcom (dot|neato|circo) Select the command that formats graphs displayed by the -gv option. The default is dot for the cluster and free graph modes, and neato for the columns graph mode.

-showevents (all|mem|noregs) Control which events are pictured:

- all Picture all events.
- mem Picture memory events.
- noregs Picture all events except register events, i.e. memory, fences and branch events.

Default is noregs.

-showinitwrites <bool> Show initial write events (when existing, see option -initwrites) in pictures. Default is true.

-mono <bool> The setting -mono true commands monochrome pictures. This option acts upon default color selection. Thus, it has no effect on colors given explicitly with the -edgeattr option.
-scale <float> Global scale factor for graphs in columns mode. Default is 1.0.

-xscale <float> Global scale factor for graphs in columns mode, x direction. Default is 1.0.

yscale <float> Global scale factor for graphs in columns mode, y direction. Default is 1.0.

-showthread <bool> Show thread numbers in figures. In cluster mode where the events of a thread are clustered, thread cluster have a label. In free mode po edges are suffixed by a thread number. In columns mode, columns have a header node that shows the thread number. Default is true.

-texmacros <bool> Use latex commands in some text of pictures. If activated (showthread true), thread numbers are shown as \myth{n}. Assembler instructions are locations in nodes are argument to an \asm command. It user responsibility to define those commands in their \LaTeX documents that include the pictures. Possible definitions are \newcommand{\myth}[1]{Thread~#1} and \newcommand{\asm}[1]{\texttt{#1}}. Default is false.

A few options control picture legends.

-showlegend <bool> Add a legend to pictures. By default legends show the test name and a comment from the executed model. This comment is the first item of model syntax — see Sec 15.5. Default is true.

-showkind <bool> Show test kind in legend. The kind derive from the quantifier of test final condition, kind Allow being exists, kind Forbid being ~exists, and kind Require being forall. Default is false.

-shortlegend <bool> Limit legend to test name. Default is false.

A few options control what is shown in nodes and on their sizes, i.e. on how events are pictured.

-squished <bool> The setting -squished true drastically limits the information displayed in graph nodes. This is usually what is wanted in modes free and columns. Default is false.

-fixedsize <bool> This setting is meaningfull in columns graph mode and for squished nodes. When set by -fixedsize true it forces node width to be 65% of the space between columns. This may sometime yield a nice edge routing. Default is false.

-extrachars <float> This setting is meaningful in columns graph mode and for squished nodes. When the size of nodes is not fixed (i.e. -fixedsize false and default), herd7 computes the width of nodes by counting caracters in node labels and scaling the result by the font size. The setting -extrachars v commands adding the value v before scaling. Negative values are of course accepted. Default is 0.0.

-showobserved <bool> Highlight observed memory read events with stars “*”. A memory read is observed when the value it reads is stored in a register that appears in final states. Default is false.

-brackets <bool> Show brackets around locations. Default is false.

Then we list options that offer some control on which edges are shown. We recall that the main controls over the shown and unshown edges are the show and unshow directives in model definitions — see Sec. 15.4. However, some edges can be controled only with options (or configuration files) and the -unshow option proves convenient.

-showpo <bool> Show program order (po) edges. Default is true. Default is false.

-showinitrf <bool> Show read-from edges from initial state. Default is false.

-showfinalrf <bool> Show read-from edges to the final state, i.e show the last store to locations. Default is false. i.e show the last store to locations. Defaut is false.

-showfr <bool> Show from-read edges. Default is true.
-doshow <name_1,...,name_n> Do show edges labelled with name_1,...,name_n. This setting applies when names are bound in model definition.

-unshow <name_1,...,name_n> Do not show edges labelled with name_1,...,name_n. This setting applies at the very last moment and thus cancels any show directive in model definition and any -doshow command line option.

Other options offer some control over some of the attributes defined in Graphviz software documentation. Notice that the controlled attributes are omitted from DOT files when no setting is present. For instance in the absence of a -spline <tag> option, herd7 will generate no definition for the splines attribute thus resorting to DOT tools defaults. Most of the following options accept the none argument that restores their default behaviour.

-splines (spline|true|line|false|polyline|ortho|curved|none) Define the value of the splines attribute. Tags are replicated in output files as the value of the attribute, except for none.

-margin <float|none> Specifies the margin attribute of graphs.

-pad <float|none> Specifies the pad attribute of graphs.

-sep <string|none> Specifies the sep attribute of graphs. Notice that the argument is an arbitray string, so as to allow DOT general syntax for this attribute.

-fontname <string|none> Specifies the graph fontname attribute.

-fontsize <int|none> Specifies the fontsize attribute of all text in the graph.

-edgefontsizedelta <int> option -edgefontsizedelta m sets the fontsize attributes of edges to n + m, where n is the argument to the -fontsize option. Default is 0. This option has no effect if fontsize is unset.

-penwidth <float|none> Specifies the penwidth attribute of edges.

-arrowsize <float|none> Specifies the arrowsize attribute of edges.

-edgeattr <label,attribute,value> Give value value to attribute attribute of all edges labelled label. This powerful option permits alternative styles for edges. For instance, the ghb edges of the diagrams of this document are thick purple (blueviolet) arrows thanks to the settings: -edgeattr ghb,color,blueviolet -edgeattr ghb,penwidth,3.0 -edgeattr ghb,arrowsize,1.2. Notice that the settings performed by the -edgeattr option override other settings. This option has no default.

Change input Those options are the same as the ones of litmus7 — see Sec. 4.

-names <file> Run herd7 only on tests whose names are listed in <file>.

-rename <file> Change test names.

-kinds <file> Change test kinds. This amounts to changing the quantifier of final conditions, with kind Allow being exists, kind Forbid being ~exists and kind Require being forall.

-conds <file> Change the final condition of tests. This is by far the most useful of these options: in combination with option -show prop it permits a fine grain selection of execution pictures.
16.3 Configuration files

The syntax of configuration files is minimal: lines “key arg” are interpreted as setting the value of parameter key to arg. Each parameter has a corresponding option, usually -key, except for the single letter option -v whose parameter is verbose.

As command line option are processed left-to-right, settings from a configuration file (option -conf) can be overridden by a later command line option. Configuration files will be used mostly for controlling pictures. Some configuration files are present in the distribution. As an example, here is the configuration file apoil.cfg, which can be used to display images in free mode.

```
#Main graph mode
graph free
#Show memory events only
showevents memory
#Minimal information in nodes
squished true
#Do not show a legend at all
showlegend false
```

The configuration above is commented with line comments that startups with “#”. The above configuration file comes handy to eye-proof model output, even for relatively complex tests, such as IRIW+lwsyncs and IRIW+syncs:

```
% herd7 -conf apoil.cfg -show prop -doshow prop -gv IRIW+lwsyncs.litmus
% herd7 -through invalid -conf apoil.cfg -show prop -doshow prop -gv IRIW+syncs.litmus
```

In the command lines above, -show prop instructs herd7 to produce images of the executions that validate the final test condition, while -doshow prop instructs herd7 to display the relation named “prop”. In spite of the unfortunate name clashes, those are not to be confused...

We run the two tests on top of the default Power model that computes, amongst others, a prop relation. The model rejects executions with a cyclic prop. One can then see that the relation prop is acyclic for IRIW+lwsyncs and cyclic for IRIW+syncs:

99
Notice that we used the option `--through-invalid` in the case of `IRIW+syncs` as we would otherwise have no image.

### 16.4 File searching

Configuration and model files are searched first in the current directory; then in any directory specified by setting the shell environment variable `HERDDIR`; and then in herd installation directory, which is defined while compiling `herd7`.
Part IV
Some examples

In the following experiment reports we describe both how we generate tests and how we run them on various machines under various conditions.

17 Running several tests at once, changing critical parameters

In this section we describe an experiment on changing the stride (cf Sec. 2.1). This usage pattern applies to many situations, where a series of test is compiled once and run many times under changing conditions.

We assume a directory **tst-x86**, that contains a series of litmus tests and an index file @all. Those tests where produced by the diy7 tool (see Sec. 7). They are two thread tests that exercise various relaxed behaviour of x86 machines. More specifically, diy7 is run as “diy -conf X.conf”, where X.conf is the following configuration file

```
-arch X86
-name X
-safe Rfe,Fre,Wse,PodR*,PodWW,MFencedWR
-relax PodWR,[Rfi,PodRR]
-mix true
-mode critical
-size 5
-nprocs 2
```

As described in Sec. 11.5, diy7 will generate all critical cycles of size at most 5, built from the given lists of candidate relaxations, spanning other two threads, and including at least one occurrence of PodWR, [Rfi,PodRR] or both. In effect, as x86 machines follow the TSO model that relaxes write to read pairs, all produced tests should a priori validate.

We test some x86-64 machine, using the following x86-64.cfg litmus7 configuration file:

```
#Machine/OS specification
os = linux
word = w64
#Test parameters
size_of_test = 1000
number_of_run = 10
memory = direct
stride = 1
```

The number of available logical processors is unspecified, it thus defaults to 1, leading to running one instance of the test only (cf parameter a in Sec. 2.1)

We invoke litmus7 as follows, where run is a pre-existing empty directory:

```
% litmus7 -mach x86-64 -o run tst-x86/@all
```

The directory run now contains C-source files for the tests, as well as some additional files:

```
% ls run
comp.sh outs.c README.txt utils.c X000.c X002.c X004.c X006.c
```

One notices a short README.txt file, two scripts to compile (comp.sh) and run the tests (run.sh), and a Makefile. We use the latter to build test executables:
% cd run
% make -j 8
gcc -Wall -std=gnu99 -fomit-frame-pointer -O2 -m64 -pthread -c outs.c
gcc -Wall -std=gnu99 -fomit-frame-pointer -O2 -m64 -pthread -c utils.c
gcc -Wall -std=gnu99 -fomit-frame-pointer -O2 -m64 -pthread -S X000.c
... 
gcc -Wall -std=gnu99 -fomit-frame-pointer -O2 -m64 -pthread -o X005.exe outs.o utils.o X005.s
gcc -Wall -std=gnu99 -fomit-frame-pointer -O2 -m64 -pthread -o X006.exe outs.o utils.o X006.s
rm X005.s X004.s X006.s X000.s X001.s X002.s X003.s

This builds the seven tests X000.exe to X006.exe. The size parameters (size_of_test = 1000 and number_of_run = 10) are rather small, leading to fast tests:

% ./X000.exe
Test X000 Allowed
Histogram (2 states)
5000 :>0:EAX=1; 0:EBX=1; 1:EAX=1; 1:EBX=0;
5000 :>0:EAX=1; 0:EBX=0; 1:EAX=1; 1:EBX=1;
No
... 
Condition exists (0:EAX=1 \ 0:EBX=0 \ 1:EAX=1 \ 1:EBX=0) is NOT validated
...
Observation X000 Never 0 10000
Time X000 0.01

However, the test fails, in the sense that the relaxed outcome targeted by X000.exe is not observed, as can be seen quite easily from the “Observation Never…” line above.

To observe the relaxed outcome, it happens it suffices to change the stride value to 2:

% ./X000.exe -st 2
Test X000 Allowed
Histogram (3 states)
21 *:>0:EAX=1; 0:EBX=0; 1:EAX=1; 1:EBX=0;
4996 :>0:EAX=1; 0:EBX=1; 1:EAX=1; 1:EBX=0;
4983 :>0:EAX=1; 0:EBX=0; 1:EAX=1; 1:EBX=1;
Ok
... 
Condition exists (0:EAX=1 \ 0:EBX=0 \ 1:EAX=1 \ 1:EBX=0) is validated
...
Observation X000 Sometimes 21 9979
Time X000 0.00

We easily perform a more complete experiment with the stride changing from 1 to 8, by running the run.sh script, which transmits its command line options to all test executables:

% for i in $(seq 1 8)
  > do
  > sh run.sh -st $i > X.$i
  > done

Run logs are thus saved into files X.01 to X.08. The following table summarises the results:
For every test and stride value cells show how many times the targeted relaxed outcome was observed/total number of outcomes. One sees that even stride value performs better — noticeably 2, 6 and 8. Moreover variation of the stride parameters permits the observation of the relaxed outcomes targeted by all tests.

We can perform another, similar, experiment changing the $s$ (size_of_test) and $r$ (number_of_run) parameters. Notice that the respective default values of $s$ and $r$ are 1000 and 10, as specified in the x86-64.cfg configuration file. We now try the following settings:

```
% sh run.sh -a 16 -s 10 -r 10000 > Y.01
% sh run.sh -a 16 -s 100 -r 1000 > Y.02
% sh run.sh -a 16 -s 1000 -r 100 > Y.03
% sh run.sh -a 16 -s 10000 -r 10 > Y.04
% sh run.sh -a 16 -s 100000 -r 1 > Y.05
```

The additional -a 16 command line option informs test executable to use 16 logical processors, hence running 8 instances of the “X” tests concurrently, as those tests all are two thread tests. This technique of flooding the tested machine obviously yields better resource usage and, according to our experience, favours outcome variability.

The following table summarises the results:

<table>
<thead>
<tr>
<th></th>
<th>Y.01</th>
<th>Y.02</th>
<th>Y.03</th>
<th>Y.04</th>
<th>Y.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>X000</td>
<td>2.3k/800k</td>
<td>602/800k</td>
<td>465/800k</td>
<td>551/800k</td>
<td>297/800k</td>
</tr>
<tr>
<td>X001</td>
<td>2.9k/800k</td>
<td>632/800k</td>
<td>774/800k</td>
<td>667/800k</td>
<td>315/800k</td>
</tr>
<tr>
<td>X002</td>
<td>633/800k</td>
<td>55/800k</td>
<td>5/800k</td>
<td>7/800k</td>
<td>0/800k</td>
</tr>
<tr>
<td>X003</td>
<td>1.2k/800k</td>
<td>182/800k</td>
<td>152/800k</td>
<td>390/800k</td>
<td>57/800k</td>
</tr>
<tr>
<td>X004</td>
<td>2.4k/800k</td>
<td>974/800k</td>
<td>1.5k/800k</td>
<td>2.4k/800k</td>
<td>1.6k/800k</td>
</tr>
<tr>
<td>X005</td>
<td>239/800k</td>
<td>21/800k</td>
<td>8/800k</td>
<td>0/800k</td>
<td>1/800k</td>
</tr>
<tr>
<td>X006</td>
<td>912/800k</td>
<td>129/800k</td>
<td>102/800k</td>
<td>143/800k</td>
<td>14/800k</td>
</tr>
</tbody>
</table>

Again, we observe all targeted relaxed outcomes. In fact, x86 relaxations are relatively easy to observe on our 16 logical core machine.

Another test statistic of interest is efficiency, that is the number of targeted outcomes observed per second:

<table>
<thead>
<tr>
<th></th>
<th>Y.01</th>
<th>Y.02</th>
<th>Y.03</th>
<th>Y.04</th>
<th>Y.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>X000</td>
<td>285</td>
<td>2.2k</td>
<td>6.6k</td>
<td>9.2k</td>
<td>4.2k</td>
</tr>
<tr>
<td>X001</td>
<td>366</td>
<td>2.4k</td>
<td>13k</td>
<td>11k</td>
<td>5.2k</td>
</tr>
<tr>
<td>X002</td>
<td>78</td>
<td>212</td>
<td>71</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>X003</td>
<td>150</td>
<td>650</td>
<td>2.5k</td>
<td>7.8k</td>
<td>950</td>
</tr>
<tr>
<td>X004</td>
<td>288</td>
<td>3.7k</td>
<td>25k</td>
<td>59k</td>
<td>32k</td>
</tr>
<tr>
<td>X005</td>
<td>28</td>
<td>72</td>
<td>114</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>X006</td>
<td>118</td>
<td>461</td>
<td>1.7k</td>
<td>2.9k</td>
<td>280</td>
</tr>
</tbody>
</table>

As we can see, although the setting -s 10 -r 10000 yields the most relaxed outcomes, it may not be considered as the most efficient. Moreover, we see that tests X002 and X005 look more challenging than others.

Finally, it may be interesting to classify the “X” tests:
In this section we describe how to produce the C sources of tests on a machine, while running the tests on another. We also describe a sophisticated affinity experiment.

We assume a directory `tst-ppc`, that contains a series of litmus tests and an index file `@all`. Those tests where produced by the `diycross` tool. They illustrate variations of the classical IRIW test. More specifically, the IRIW variations are produced as follows (see also Sec. 9):

```%
% mkdir tst-ppc
% diycross7 -name IRIW -o tst-ppc Rfe PodRR,DpAddrdR,LwSyncdRR,EieiodRR,SyncdRR Fre Rfe PodRR,DpAddrdR,Lw
Generator produced 15 tests
%
```

We target a Power7 machine described by the configuration file `power7.cfg`:

```#
#Machine/OS specification
os = linux
word = w64
smt = 4
smt_mode = seq
#Test parameters
size_of_test = 1000
number_of_run = 10
avail = 0
memory = direct
stride = 1
affinity = incr0
```

One may notice the SMT (*Simultaneous Multi-Threading*) specification: 4-ways SMT (`smt=4`), logical processors pertaining to the same core being numbered in sequence (`smt_mode = seq`) — that is, logical processors from the first core are 0, 1, 2 and 3; logical processors from the second core are 4, 5, 6 and 7; etc. The SMT specification is necessary to enable custom affinity mode (see Sec. 2.2.4).

One may also notice the specification of 0 available logical processors (`avail=0`). As affinity support is enabled (`affinity=incr0`), test executables will find themselves the number of logical processors available on the target machine.

We compile tests to C-sources packed in archive `a.tar` and upload the archive to the target power7 machine as follows:

```%
% litmus7 -mach power7 -o a.tar tst-ppc/@all
% scp a.tar power7:
```

Then, on `power7` we unpack the archive and produce executable tests as follows:
As a starter, we can check the effect of available logical processor detection and custom affinity control (option +ca) by passing the command line option -v to one test executable, for instance IRIW.exe:

```
-power7% ./IRIW.exe -v +ca
./IRIW.exe -v +ca
IRIW: n=8, r=10, s=1000, st=1, +ca, p='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
thread allocation:
[23,22,3,2] {5,5,0,0}
[7,6,15,14] {1,1,3,3}
[11,10,5,4] {2,2,1,1}
[21,20,27,26] {5,5,6,6}
[9,8,25,24] {2,2,6,6}
[31,30,13,12] {7,7,3,3}
[19,18,29,28] {4,4,7,7}
[1,0,17,16] {0,0,4,4}
...```

We see that our machine `power7` features 32 logical processors numbered from 0 to 31 (cf p=... above) and will thus run n=8 concurrent instances of the 4 thread IRIW test. Additionally allocation of threads to logical processors is shown: here, the four threads of the test are partitioned into two groups, which are scheduled to run on different cores. For example, threads 0 and 1 of the first instance of the test will run on logical processors 23 and 22 (core 5); while threads 2 and 3 will run on logical processors 3 and 2 (core 0).

Our experiment consists in running all tests with affinity increment (see Sec. 2.2.1) being from 0 and then 1 to 8 (option -i i), as well as in random and custom affinity mode (options +ra and +ca):

```
-power7% for i in $(seq 0 8)
  do
  sh run.sh -i $i > Z.0$i
  done
-power7% sh run.sh +ra > Z.0R
-power7% sh run.sh +ca > Z.0C
```

The following table summarises the results, with X meaning that the targeted relaxed outcome is observed:
On sees that all possible relaxed outcomes shows up with proper affinity control. More precisely, setting the affinity increment to 2 or resorting to custom affinity result in the same effect: the first two threads of the test run on one core, while the last two threads of the test run on a different core. As demonstrated by the experiment, this allocation of test threads to cores suffices to favour relaxed outcomes for all tests except for IRIW+syncs, where the sync fences forbid them.

## 19 Cross running, testing low-end devices

Together litmus7 options `-gcc` and `-linkopt` permit using a C cross compiler. For instance, assume that litmus7 runs on machine A and that crossgcc, a cross compiler for machine C, is available on machine B. Then, the following sequence of commands can be used to test machine C:

```bash
A% litmus7 -gcc crossgcc -linkopt -static -o C-files.tar ...
A% scp C-files.tar B:

B% tar xf C-files.tar
B% make
B% tar cf /tmp/C-compiled.tar .
B% scp /tmp/C-compiled.tar C:

C% tar xf C-compiled.tar
C% sh run.sh
```

Alternatively, using option `-crossrun C`, one can avoid copying the archive C-compiled.tar to machine C:

```bash
A% litmus7 -crossrun C -gcc crossgcc -linkopt -static -o C-files.tar ...
A% scp C-files.tar B:

B% tar xf C-files.tar
B% make
B% sh run.sh
```

More specifically, option `-crossrun C` instructs the run.sh script to upload executables individually to machine C, just before running them. Notice that executables are removed from C once run.

We illustrate the crossrun feature by testing LB variations on an ARM-based Tegra3 (4 cores) tablet. Test LB (load-buffering) exercises the following “causality” loop:

<table>
<thead>
<tr>
<th></th>
<th>Z.00</th>
<th>Z.01</th>
<th>Z.02</th>
<th>Z.03</th>
<th>Z.04</th>
<th>Z.05</th>
<th>Z.06</th>
<th>Z.07</th>
<th>Z.08</th>
<th>Z.0C</th>
<th>Z.0R</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRIW</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>IRIW+addr+po</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+addr</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+eieio+addr</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+eieio+po</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+eieios</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+lwsync+addr</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+lwsync+eieio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+lwsync+po</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+lwsyncs</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+sync+addr</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
<td>X</td>
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<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+sync+eieio</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+sync+lwsync</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+sync+po</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRIW+syncs</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

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That is, thread 0 reads the values stored to location x by thread 1, thread 1 reads the values stored to location y by thread 0, and both threads read “before” they write.

We shall consider tests with varying interpretations of “before”: the write may simply follow the read in program order (po in test names), may depend on the read (data and addr), or they may be some fence in-between (isb and dmb). We first generate tests tst-arm with diycross7:

% mkdir tst-arm
diycross7 -arch ARM -name LB -o tst-arm PodRW,DpDatadW,DpCtrldW,ISBdRW,DMBdRW Rfe PodRW,DpDatadW,DpCtrdW Generator produced 15 tests

We use the following, tegra3.cfg, configuration file:

```
#Tegra 3
size_of_test = 5k
number_of_run = 200
avail = 4
memory = direct
#Cross compilation
gcc = arm-linux-gnueabi-gcc
ccopts = -march=armv7-a -O2
linkopt = -static
```

Notice the “cross-compilation” section: the name of the gcc cross-compiler is arm-linux-gnueabi-gcc, while the adequate version of the target ARM variant and static linking are specified.

We compile the tests from litmus source files to C source files in directory TST as follows:

% mkdir TST
% litmus7 -mach tegra3 -crossrun app_81@wifi-auth-188153:2222 tst-arm/@all -o TST

The extra option -crossrun app_81@wifi-auth-188153:2222 specifies the address to log onto the tablet by ssh, which is connected on a local WiFi network and runs a ssh daemon that listens on port 2222.

We compile to executables and run them as follows:

% cd TST
% make

It is important to notice that the shell script run.sh runs on the local machine, not on the remote tablet. Each test executable is copied (by using scp) to the tablet, runs there and is deleted (by using ssh), as can be seen with sh “-x” option:

% sh -x run.sh 2>&1 >ARM-LB.log
% grep -e scp -e ssh
+ scp -P 2222 -q ./LB.exe app_81@wifi-auth-188153:
+ ssh -p 2222 -q -n app_81@wifi-auth-188153 ./LB.exe -q && rm ./LB.exe
+ scp -P 2222 -q ./LB+data+po.exe app_81@wifi-auth-188153:
+ ssh -p 2222 -q -n app_81@wifi-auth-188153 ./LB+data+po.exe -q && rm ./LB+data+po.exe
...
Experiment results can be extracted from the log file quite easily, by reading the “Observation” information from test output:

```
% grep Observation ARM-LB.log
Observation LB Sometimes 1395 1998605
Observation LB+data+po Sometimes 360 1999640
Observation LB+ctrl+po Sometimes 645 1999355
Observation LB+isb+po Sometimes 1676 1998324
Observation LB+dmb+po Sometimes 18 1999982
Observation LB+datas Never 0 2000000
Observation LB+ctrl+data Never 0 2000000
Observation LB+isb+data Sometimes 654 1999346
Observation LB+dmb+data Never 0 2000000
Observation LB+ctrls Never 0 2000000
Observation LB+isb+ctrl Sometimes 1143 1998857
Observation LB+dmb+ctrl Never 0 2000000
Observation LB+isbs Sometimes 2169 1997831
Observation LB+dmb+isb Sometimes 178 1999822
Observation LB+dms Never 0 2000000
```

What is observed (Sometimes) or not (Never) is the occurrence of the non-SC behaviour of tests. All tests have the same structure and the observation of the non-SC behaviour can be interpreted as some read not being “before” the write by the same thread. This situation occurs for plain program order (plain test LB and po variations) and for the isb fence.

**References**


