Stateless Model Checking for TSO and PSO

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Goals

Stateless Model Checking

- Find safety errors...
  - in given test case (fixed input program)
  - for all interleavings
  - for all reorderings (TSO/PSO)
- Works on real code in C/pthreads

Valid Test Case (in this presentation)

1. Terminates in bounded time
2. Nondeterminism: Interleavings, Reordering

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Valid Test Case (in this presentation)

1. Terminates in bounded time
2. Nondeterminism: Interleavings, Reordering

Partial Order Reduction (SC)

```
volatile int x = 0, y = 0;
```

p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

Executions

p:wx1 p:ry0 q:wy1 q:rx1	p:wx1 q:wy1 p:ry1 q:rx1	p:wx1 q:wy1 q:rx1 p:ry1
q:wy1 q:rx0 p:wx1 p:ry1	q:wy1 p:wx1 q:rx1 p:ry1	q:wy1 p:wx1 p:ry1 q:rx1

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volatile int x = 0, y = 0;
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p	q
`x = 1;`	`y = 1;`
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Executions

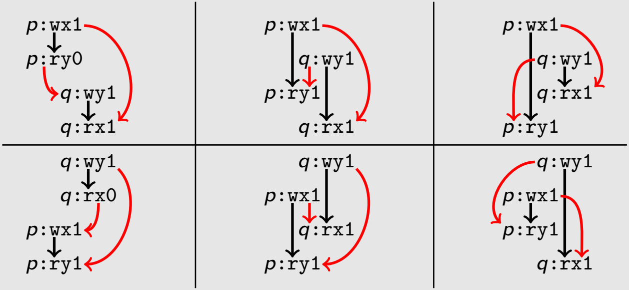
p:wx1	p:wx1	p:wx1
p:ry0	q:wy1	q:wy1
q:wy1	p:ry1	q:rx1
q:rx1	q:rx1	p:ry1
q:wy1	q:wy1	q:wy1
q:rx0	p:wx1	p:wx1
p:wx1	q:rx1	p:ry1
p:ry1	p:ry1	q:rx1

Partial Order Reduction (SC)

```
volatile int x = 0, y = 0;
```

p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

Executions (Happens-Before)

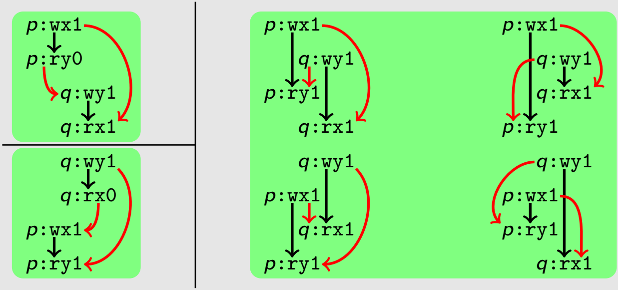


Partial Order Reduction (SC)

```
volatile int x = 0, y = 0;
```

p	*q*
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

Mazurkiewicz Traces ∼ Equivalence Classes over Executions



Stateless Model Checking with DPOR [Flanagan, Godefroid 2005]

Idea

- Explore one execution per Mazurkiewicz trace.
  - $\rightarrow$ Cover all observable behaviours.
- Keep only one execution in memory.
- Examine happens-before relation to find the next trace.

```
volatile int x = 0, y = 0;
```

p	*q*
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

```
volatile int x = 0, y = 0;
```

p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

p:`wx1`

p:`ry0`

q:`wy1`

q:`rx1`

`volatile int x = 0, y = 0;`

p	*q*
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

p:`wx1` → p:`ry0`

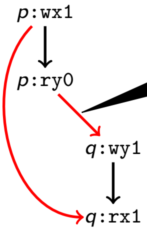
q:`wy1` → q:`rx1`

HB: Necessary Edges

- Program order (under SC)
- Thread spawning to child's first event
- ...

```
volatile int x = 0, y = 0;
```

p	*q*
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

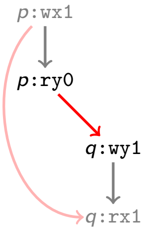


HB: Races

- Conflicting stores and loads.
- ...

`volatile int x = 0, y = 0;`

p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

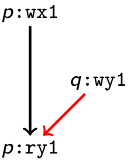


Reverse Races

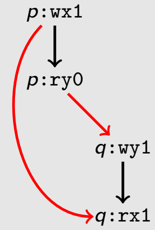
- Start from the end of the execution.

```
volatile int x = 0, y = 0;
```

p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`



Previous Trace



```
volatile int x = 0, y = 0;
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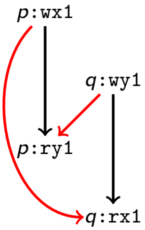
p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`



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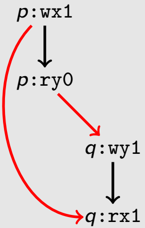
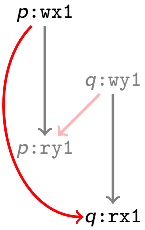
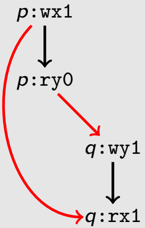


```
volatile int x = 0, y = 0;
```

p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

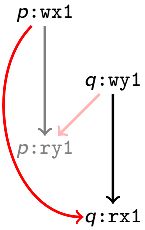


Previous Trace



```
volatile int x = 0, y = 0;
```

p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`



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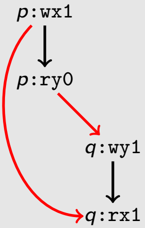
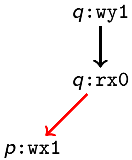
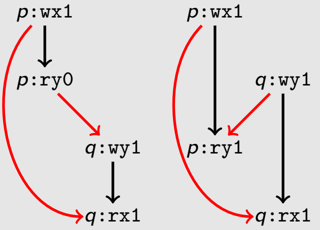


```
volatile int x = 0, y = 0;
```

p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

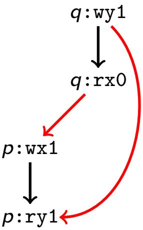


Previous Traces

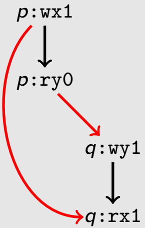


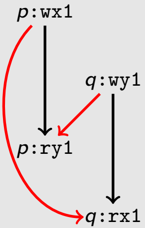
```
volatile int x = 0, y = 0;
```

p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`



Previous Traces

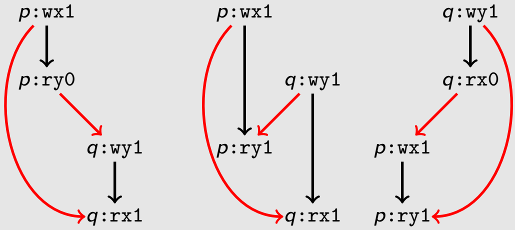




`volatile int x = 0, y = 0;`

p	q
`x = 1;`	`y = 1;`
`int a = y;`	`int b = x;`

All Traces



TSO

- Relaxes $W \to R$
- Store forwarding to own reads (ROWE)
- Operational semantics: store buffer per thread

Defining Traces for TSO

Extend Mazurkiewicz Traces to TSO

- Suitable equivalence classes
- Compatible with DPOR

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Shasha-Snir Traces

Capture observable order.

Defining Traces for TSO

Extend Mazurkiewicz Traces to TSO

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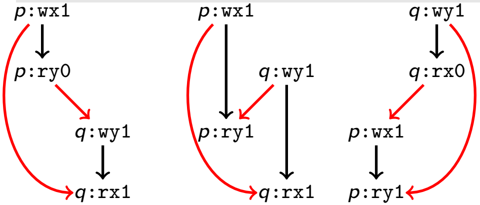


Shasha-Snir Traces

Same as Mazurkiewicz traces under SC!

Defining Traces for TSO

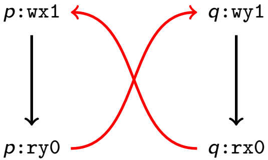
Extend Mazurkiewicz Traces to TSO

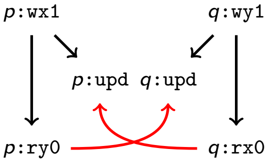
- Suitable equivalence classes
- Compatible with DPOR

$$
\begin{array}{ccc}
p\texttt{:wx1} & & q\texttt{:wy1} \\
\downarrow & & \downarrow \\
p\texttt{:ry0} & & q\texttt{:rx0}
\end{array}
$$

Shasha-Snir Traces

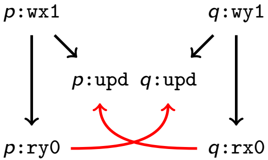
Not partial order.


p:wx1
q:wy1
p:ry0
q:rx0



Getting Rid of Cycles

- Operational semantics
- Ignores *which* events are reordered
- Canonical?

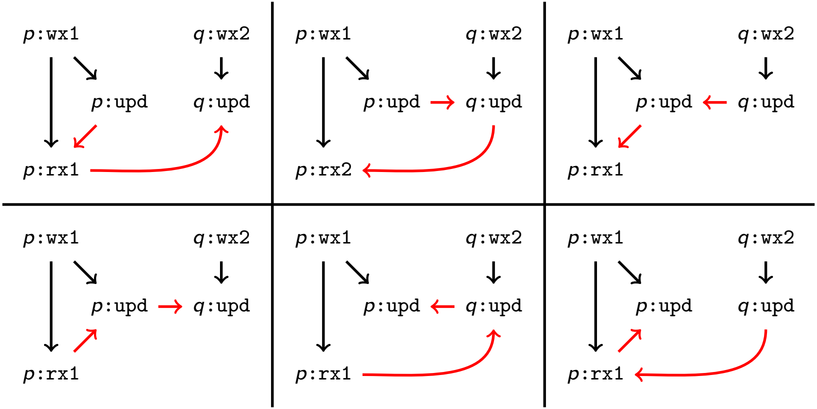


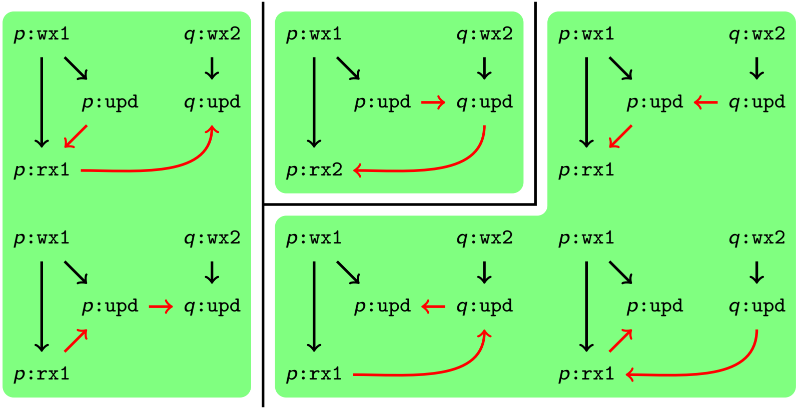
Getting Rid of Cycles

- Operational semantics
- Ignores *which* events are reordered
- Canonical?

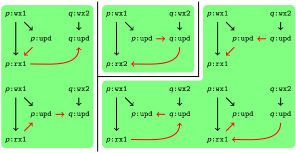
```
volatile int x = 0;
```

p	q
`x = 1;`	`x = 2;`
`int a = x;`	


p:wx1
q:wx2
p:upd
q:upd
p:rx1
p:wx1
q:wx2
p:upd
q:upd
p:rx2
p:wx1
q:wx2
p:upd
q:upd
p:rx1
p:wx1
q:wx2
p:upd
q:upd
p:rx1
p:wx1
q:wx2
p:upd
q:upd
p:rx1
p:wx1
q:wx2
p:upd
q:upd
p:rx1


p:wx1
q:wx2
p:upd
q:upd
p:rx1
p:rx2

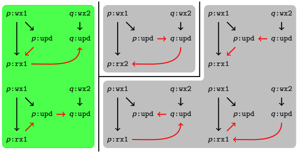
Solution: Chronological Traces



Two Rules

No order between load and update...

1. of the same thread.
2. when the update is "hidden" from the load.



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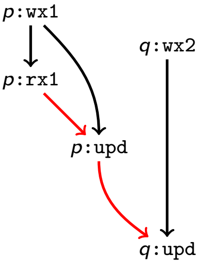

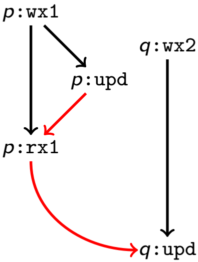

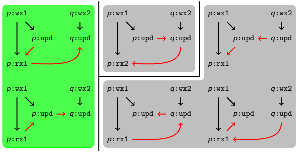

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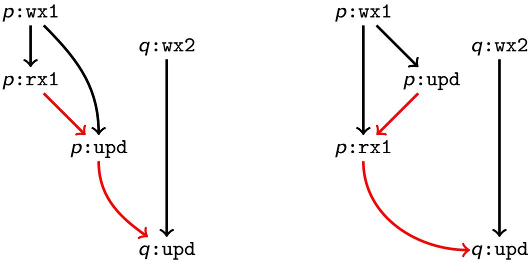

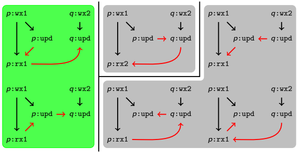

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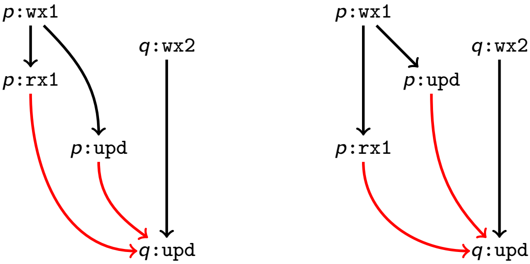

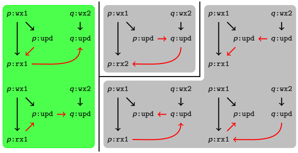

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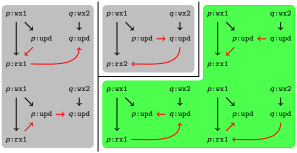

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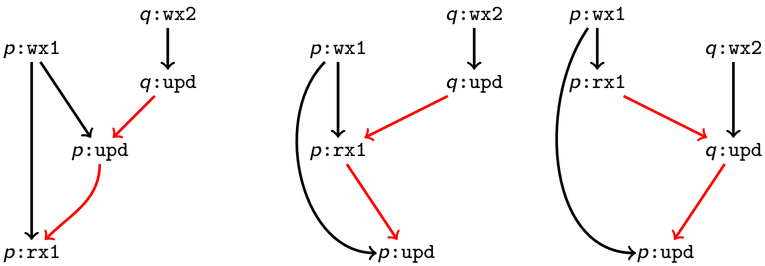

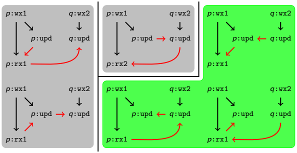

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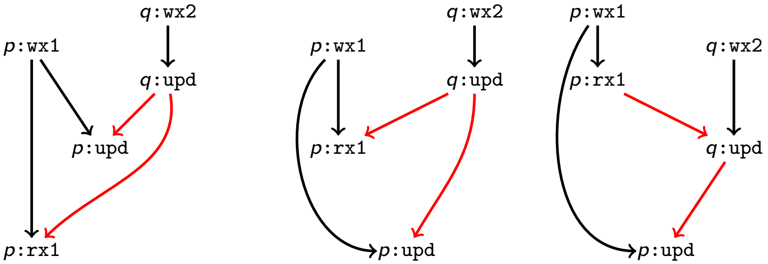

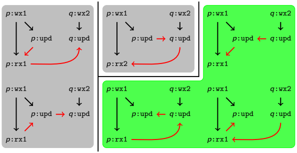

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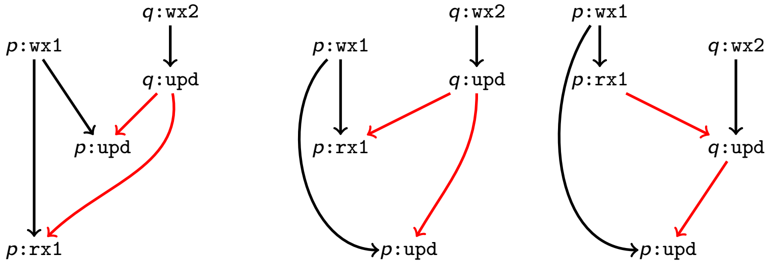

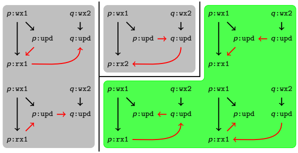

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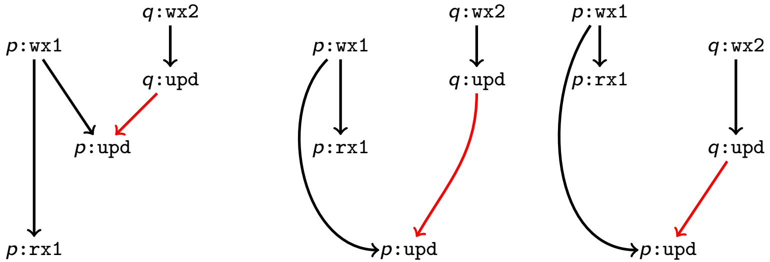

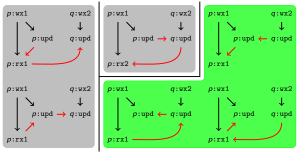

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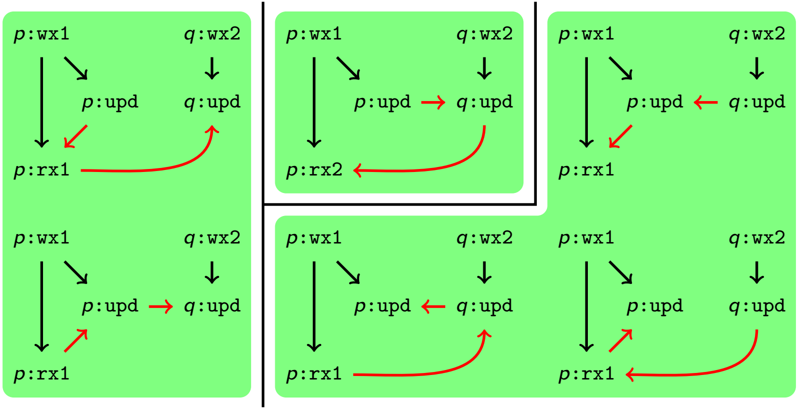

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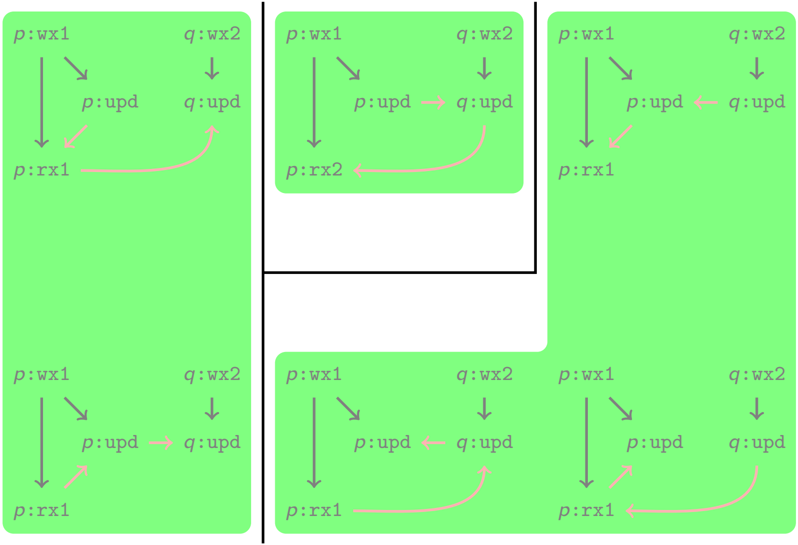

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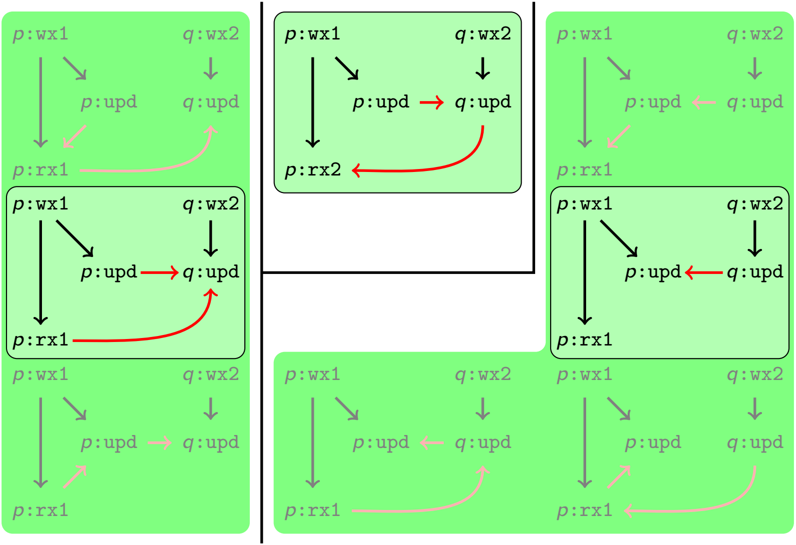

Our Contribution: Chronological Traces

- 1-to-1 with Shasha-Snir traces
- Compatible with DPOR
  - Executions under operational TSO/PSO semantics
  - Efficiently computable happens-before relation

Implementation: Nidhugg

Nidhugg

- Source-DPOR [Abdulla et al. 2014]
  - Near optimal.
  - Straight-forward.
- Works on C/Pthreads via LLVM IR.
- Runs on *one compilation* of test case.

Open source: `https://github.com/nidhugg/nidhugg`

Results: Time Consumption

	fence	LB	CBMC SC	CBMC TSO	CBMC PSO	goto-instrument SC	goto-instrument TSO	goto-instrument PSO	Nidhugg SC	Nidhugg TSO	Nidhugg PSO
apr_1.c	-	5	t/o	t/o	t/o	t/o	!	!	**5.88**	**6.06**	**16.98**
apr_2.c	-	5	t/o	t/o	t/o	!	!	!	**2.60**	**2.20**	**5.39**
dcl_singleton.c	-	7	5.95	31.47	*18.01	5.33	5.36	*0.18	**0.08**	**0.08**	***0.08**
dcl_singleton.c	pso	7	5.88	30.98	29.45	5.20	5.18	5.17	**0.08**	**0.08**	**0.08**
dekker.c	-	10	2.42	*3.17	*2.84	1.68	*4.00	*220.11	**0.10**	***0.11**	***0.09**
dekker.c	tso	10	2.39	5.65	*3.51	1.62	297.62	t/o	**0.11**	**0.12**	***0.08**
dekker.c	pso	10	2.55	5.31	4.83	1.72	428.86	t/o	**0.11**	**0.12**	**0.12**
fib_false.c	-	-	*1.63	*3.38	*3.00	***1.60**	***1.58**	***1.56**	*2.39	*5.57	*6.20
fib_false_join.c	-	-	*0.98	*1.10	*1.91	*1.31	*0.88	*0.80	***0.32**	***0.62**	***0.71**
fib_true.c	-	-	**6.28**	9.39	7.72	6.32	**7.63**	**7.62**	25.83	75.06	86.32
fib_true_join.c	-	-	6.61	8.37	10.81	7.09	5.94	5.92	**1.20**	**2.88**	**3.19**
indexer.c	-	5	193.01	210.42	214.03	191.88	70.42	69.38	**0.10**	**0.09**	**0.09**
lamport.c	-	8	7.78	*11.63	*10.53	6.89	t/o	t/o	**0.08**	***0.08**	***0.08**
lamport.c	tso	8	7.60	26.31	*15.85	6.80	513.67	t/o	**0.09**	**0.08**	***0.07**
lamport.c	pso	8	7.72	30.92	27.51	7.43	t/o	t/o	**0.08**	**0.08**	**0.08**
parker.c	-	10	12.34	*91.99	*86.10	11.63	~~9.70~~	~~9.65~~	**1.50**	***0.09**	***0.08**
parker.c	pso	10	12.72	141.24	166.75	11.76	10.66	10.64	**1.50**	**1.92**	**2.94**
peterson.c	-	-	0.35	*0.38	*0.35	0.18	*0.20	*0.21	**0.07**	***0.07**	***0.07**
peterson.c	tso	-	0.35	0.39	*0.35	0.19	0.18	~~0.56~~	**0.07**	**0.07**	***0.07**
peterson.c	pso	-	0.35	0.41	0.40	0.18	0.18	0.19	**0.07**	**0.07**	**0.08**
pgsql.c	-	8	19.80	60.66	*4.63	21.03	46.57	*296.77	**0.08**	**0.07**	***0.08**
pgsql.c	pso	8	23.93	71.15	121.51	19.04	t/o	t/o	**0.07**	**0.07**	**0.08**
pgsql_bnd.c	pso	(4)	**3.57**	**9.55**	**12.68**	3.59	t/o	t/o	89.44	106.04	112.60
stack_safe.c	-	-	44.53	516.01	496.36	45.11	42.39	42.50	**0.34**	**0.36**	**0.43**
stack_unsafe.c	-	-	*1.40	*1.87	*2.08	*1.00	*0.81	*0.79	***0.08**	***0.08**	***0.09**
szymanski.c	-	-	0.40	*0.44	*0.43	0.23	*0.89	*1.16	**0.07**	***0.13**	***0.07**
szymanski.c	tso	-	0.40	0.50	*0.43	0.23	0.23	~~2.48~~	**0.08**	**0.08**	***0.07**
szymanski.c	pso	-	0.39	0.50	0.49	0.23	0.24	0.24	**0.08**	**0.08**	**0.08**

Results: Time Consumption											
			CBMC			goto-instrument			Nidhugg		
	fence	LB	SC	TSO	PSO	SC	TSO	PSO	SC	TSO	PSO
apr_1.c	-	5	t/o	t/o	t/o	t/o	!	!	**5.88**	**6.06**	**16.98**
apr_2.c	-	5	t/o	t/o	t/o	!	!	!	**2.60**	**2.20**	**5.39**
dcl_singleton.c	-	7	5.95	31.47	*18.01	5.33	5.36	*0.18	**0.08**	**0.08**	***0.08**
dcl_singleton.c	pso	7	5.88	30.98	29.45	5.20	5.18	5.17	**0.08**	**0.08**	**0.08**
dekker.c	-	10	2.42	*3.17	*2.84	1.68	*4.00	*220.11	**0.10**	***0.11**	***0.09**
dekker.c	tso	10	2.39	5.65	*3.51	1.62	297.62	t/o	**0.11**	**0.12**	***0.08**
dekker.c	pso	10	2.55	5.31	4.83	1.72	428.86	t/o	**0.11**	**0.12**	**0.12**
fib_false.c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	*6.20
fib_false_join.c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	***0.71**
fib_true.c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	86.32
fib_true_join.c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**3.19**
indexer.c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**0.09**
lamport.c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	***0.08**
lamport.c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	***0.07**
lamport.c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**0.08**
parker.c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	***0.08**
parker.c	pso	10	12.72	141.24	166.75	11.76	10.66	10.64	**1.50**	**1.92**	**2.94**
peterson.c	-	-	0.35	*0.38	*0.35	0.18	*0.20	*0.21	**0.07**	***0.07**	***0.07**
peterson.c	tso	-	0.35	0.39	*0.35	0.19	0.18	~~0.56~~	**0.07**	**0.07**	***0.07**
peterson.c	pso	-	0.35	0.41	0.40	0.18	0.18	0.19	**0.07**	**0.07**	**0.08**
pgsql.c	-	8	19.80	60.66	*4.63	21.03	46.57	*296.77	**0.08**	**0.07**	***0.08**
pgsql.c	pso	8	23.93	71.15	121.51	19.04	t/o	t/o	**0.07**	**0.07**	**0.08**
pgsql_bnd.c	pso	(4)	**3.57**	**9.55**	**12.68**	3.59	t/o	t/o	89.44	106.04	112.60
stack_safe.c	-	-	44.53	516.01	496.36	45.11	42.39	42.50	**0.34**	**0.36**	**0.43**
stack_unsafe.c	-	-	*1.40	*1.87	*2.08	*1.00	*0.81	*0.79	***0.08**	***0.08**	***0.09**
szymanski.c	-	-	0.40	*0.44	*0.43	0.23	*0.89	*1.16	**0.07**	***0.13**	***0.07**
szymanski.c	tso	-	0.40	0.50	*0.43	0.23	0.23	~~2.48~~	**0.08**	**0.08**	***0.07**
szymanski.c	pso	-	0.39	0.50	0.49	0.23	0.24	0.24	**0.08**	**0.08**	**0.08**

Robust

	Nidhugg		
	SC	TSO	PSO
stack_safe.c	**0.34**	**0.36**	**0.43**

Future Work

Ongoing Work: POWER

- More relaxed model
- Order enforced by complex event interaction
- #traces probably similar to under SC
- Techniques carry over to ARM, Alpha, etc.