Lazy Sequentialization for TSO and PSO via Shared Memory Abstractions

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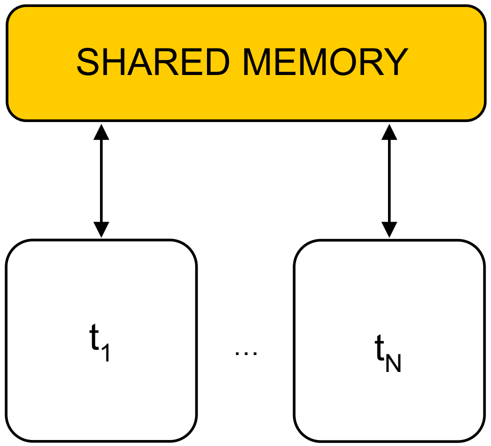
Relaxed Memory Consistency



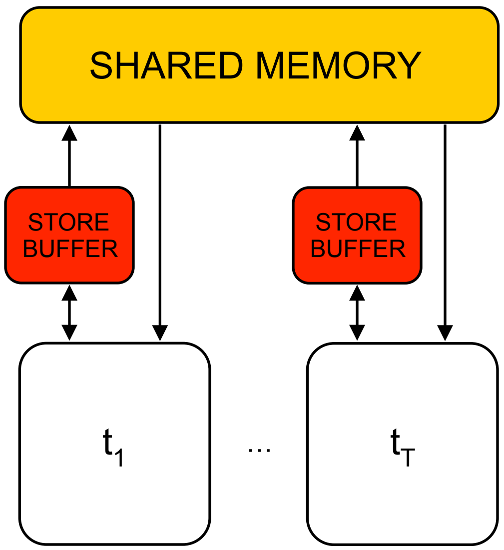
sequential consistency (SC)

- memory operations executed in program order within each thread
- changes to the shared memory immediately visible to all threads
- relatively simple to reason about but not realistic

weak memory models (WMMs)

- memory operations may be reordered
- used in practice to fully exploit modern hardware

Relaxed Memory Consistency



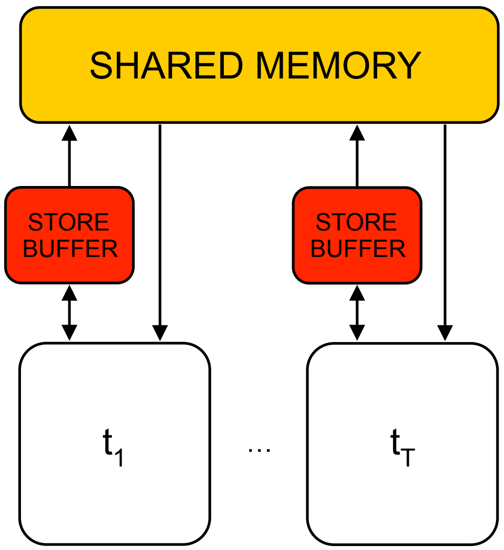
total store order (TSO)

- writes executed in their order for each thread
- reads may overtake writes

partial store order (PSO)

- writes to the same location executed in their order for each thread
- writes to different locations may be reordered
- reads may overtake writes

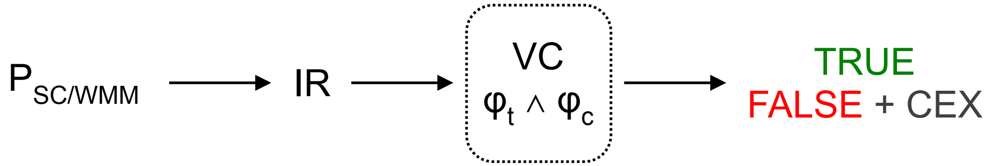
Relaxed Memory Consistency



limitations of testing

- generally ineffective for rare concurrency errors
- cannot control additional nondeterminism introduced by WMMs
- need to be complemented with symbolic analysis

Symbolic Bug Finding: BMC



concurrency handling at formula level

- encode threads separately
- add φ_c to capture thread interleaving

[Sinha, Wang – POPL 2011]

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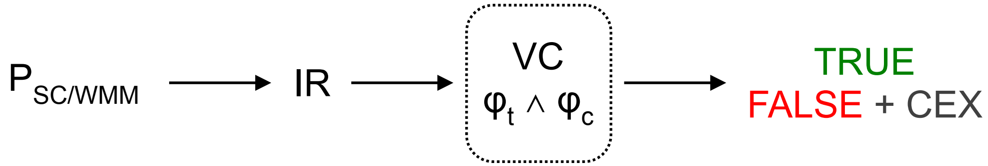


concurrency handling at formula level

- encode threads separately
- add φ_c to capture thread interleaving

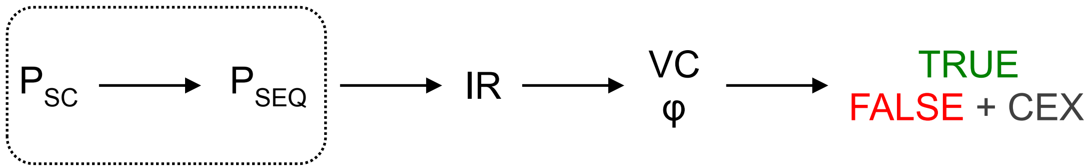
[Sinha, Wang – POPL 2011]

extension to WMMs is natural

- change φ_c to capture extra interactions due to weaker consistency

[Alglave, Kroening, Tautschnig – CAV 2013]

Symbolic Bug Finding:
Lazy Sequentialization + BMC

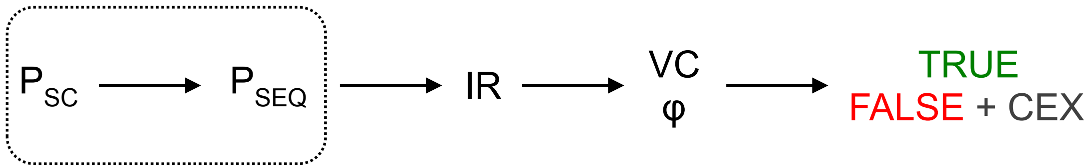


concurrency handling at code level

- reduction to sequential programs analysis
- implemented as source transformation
- lazy sequentialization tailored to BMC for effective in bug-hunting

[Inverso, Tomasco, Fischer, La Torre, Parlato – CAV 2014]

Symbolic Bug Finding: Lazy Sequentialization + BMC



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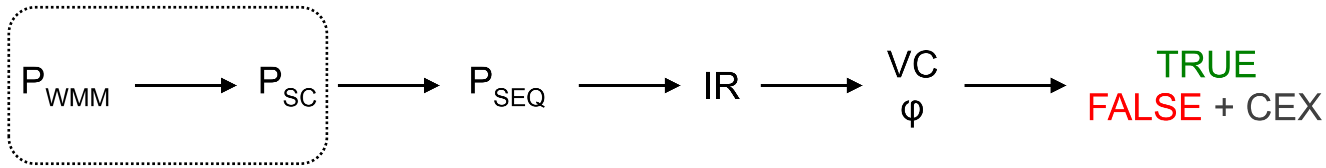
how to extend to WMMs?

how does it compare?

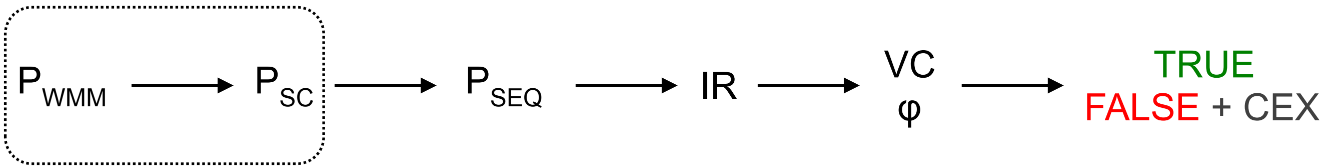
Extending Lazy Sequentialization to TSO and PSO



how to extend to WMMs?

- reduction to concurrent program analysis under SC
- again, implemented as source transformation

Extending Lazy Sequentialization to TSO and PSO



how to extend to WMMs?

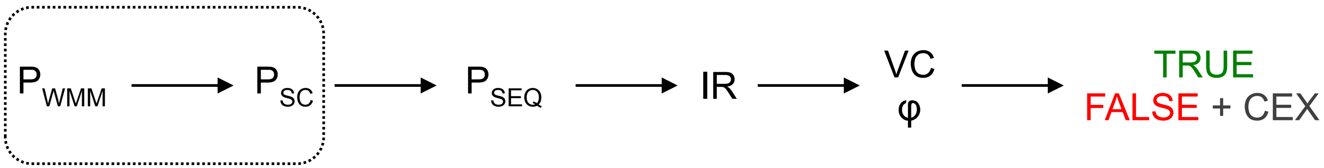
- reduction to concurrent program analysis under SC
- again, implemented as source transformation
  - replace shared memory access with explicit function calls to SMA API:

    `read(v,t)`, `write(v,val,t)`

    `lock(m,t)`, `unlock(m,t)`, `fence(t)`, …

    example: `x=y+3` is changed to `write(x,read(y)+3)`

Extending Lazy Sequentialization to TSO and PSO



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    `lock(m,t)`, `unlock(m,t)`, `fence(t)`, …

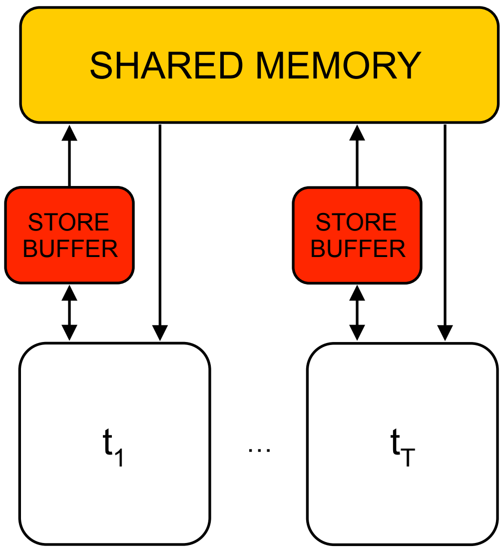
    example: `x=y+3` is changed to `write(x,read(y)+3)`
  - plug in implementation for specific semantics

    TSO-SMA - simple implementation

    eTSO-SMA - efficient implementation

    PSO-SMA - extension to PSO

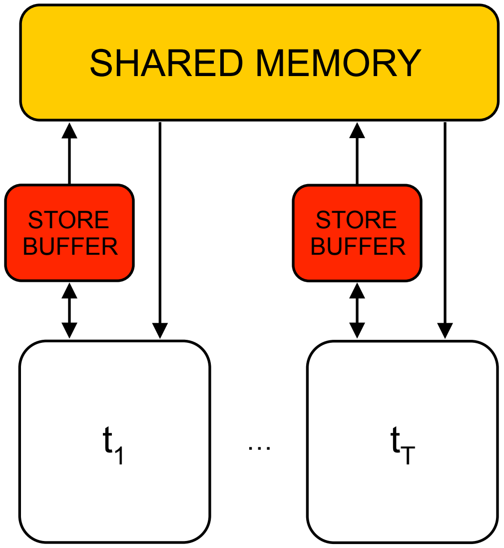
TSO-SMA



simple simulation of the store buffer

- introduce <u>one array for each thread</u>
- `read(v,t)`
  - look up buffer for pending writes
  - fetch from memory
- `write(v,val,t)`
  - update store buffer
  - inject nondeterministic memory flush

TSO-SMA



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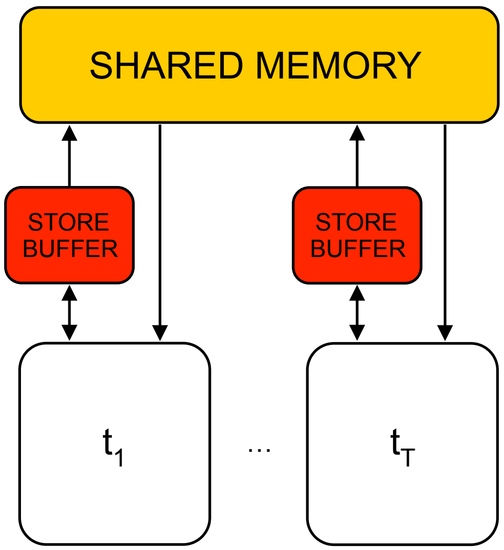

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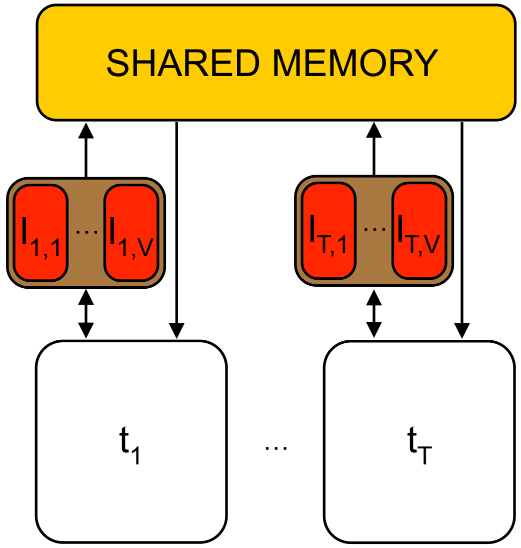
formula size depends on store buffer size

formula size proportional to
no. memory accesses
no. of store buffers
max no. of elems in the buffer

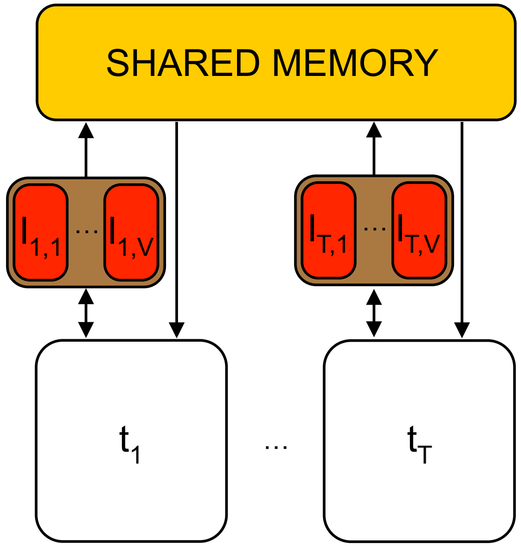
eTSO-SMA



efficient simulation of the store buffer

- introduce <u>one list for each shared variable and thread</u>
- use global clock and timestamp memory writes
- `read(v,t)`
  - buffer look up, return value from latest pending write
  - return value from latest expired write
- `write(v,val,t)`
  - guess timestamp, enforce non-decreasing order
  - update buffer

eTSO-SMA



efficient simulation of the store buffer

- introduce <u>one list for each shared variable and thread</u>
- use global clock and timestamp memory writes
- `read(v,t)` constant size
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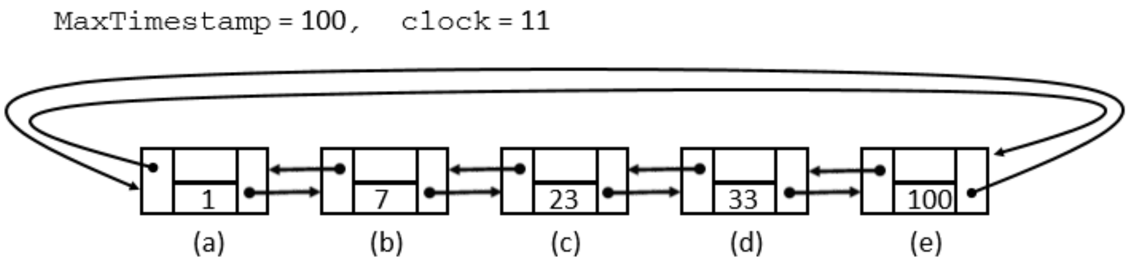
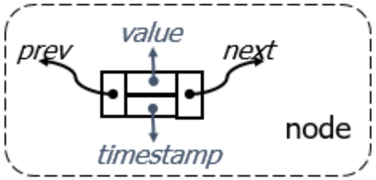
Variable Write Lists (T-CDLL)





- store pairs *(value,timestamp)*
- clock determines expired nodes
- expired nodes not removed

special nodes

- **sentinel node**
  has max *timestamp*
  does not correspond to any actual write
- **head**
  only node to contain an expired write
  followed by a non-expired write

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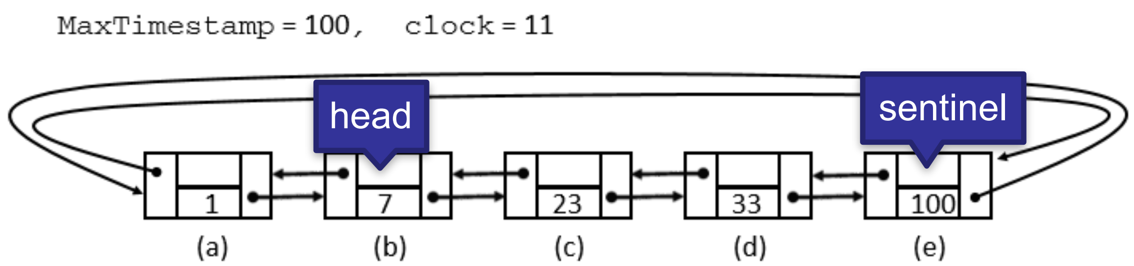

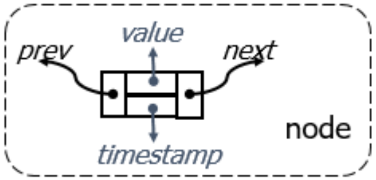

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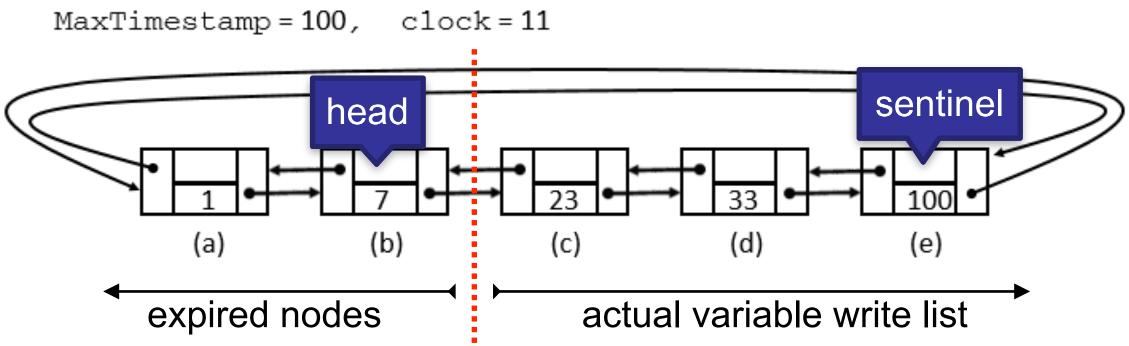

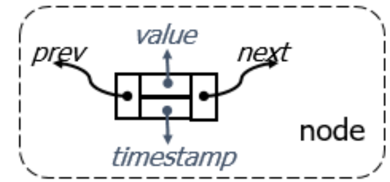

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Auxiliary Data Structures

parameters

`T` max no. of threads

`V` max no. of tracked locations (or write lists)

`N` max no. of nodes for each variable write list

`K` max timestamp

variables

```
int clock;
```

- variable write lists

```
int value[V][N+1],
    tstamp[V][N+1],
    prev[V][N+1],
    next[V][N+1];
```

- last values and timestamps

```
int last_value[V][T],
    last_tstamp[V][T];
```

- max timestamp so far

```
int max_tstamp[T];
```

eTSO-SMA: read operation

```
int clock_update() {
  int tmp = *;
  assume(clock <= tmp && tmp <= K);
  clock = tmp;
}

int read(int v, int t) {
  clock_update();

  if (last_tstamp[v][t] > clock)
    return last_value[v][t];

  int node = *;
  assume(node < N &&
         tstamp[v][node] <= clock &&
         tstamp[v][next[v][node]] > clock);
  return value[v][node];
}
```

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```

clock follows non-decreasing order

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if the last write by **t** on **v** has not expired, return the corresponding value

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if the last write by **t** on **v** has not expired, return the corresponding value

return the value from the latest expired write, which is guaranteed to exist and correspond to the value of **v** in the memory

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if the last write by **t** on **v** has not expired, return the corresponding value

return the value from the latest expired write, which is guaranteed to correspond to the value of v

representation of the memory no longer needed

eTSO-SMA: write operation

select expired node with min timestamp for the new write

```
int write(int v, int t) {
  clock_update();
  int node = next[v][N];
  assume(tstamp[v][next[v][node]] <= clock);
  next[v][N] = next[v][node];
  prev[v][next[v][N]] = N;

  int succ = *;
  assume(succ <= N && tstamp[v][succ] > clock);
  int pred = prev[v][succ];

  int ts = *;
  assume(ts >= clock && ts >= max_tstamp[t]);
  assume(ts >= tstamp[v][pred] && ts < tstamp[v][succ]);

  value[v][node] = val;
  tstamp[v][t] = ts;
  …
  last_tstamp[v][t] = ts;
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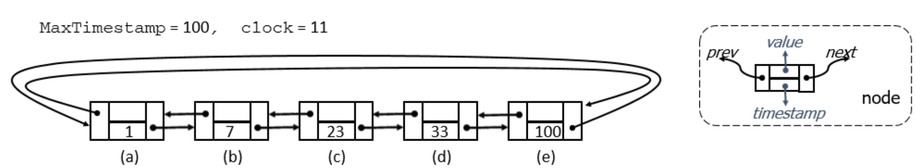
}
```



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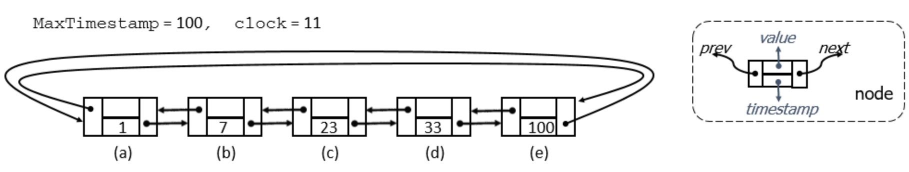
select expired node with min timestamp for the new write

position the new node by nondeterministically selecting its successor among the non-expired nodes



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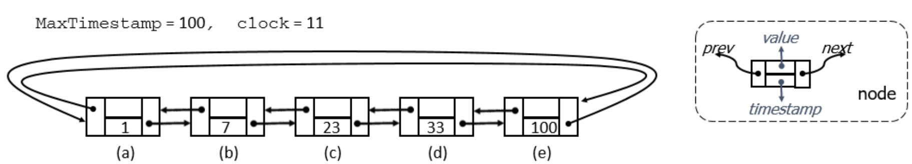
select expired node with min timestamp for the new write

position the new node by nondeterministically selecting its successor among the non-expired nodes

guess suitable timestamp, must respect non-decreasing order



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  tstamp[v][t] = ts;
  …
  last_tstamp[v][t] = ts;
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  max_tstamp[t] = ts;
}
```

select expired node with min timestamp for the new write

position the new node by nondeterministically selecting its successor among the non-expired nodes

guess suitable timestamp, must respect non-decreasing order

update variable write list and auxiliary variables

extension to PSO

```
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  clock_update();
  int node = next[v][N];
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  next[v][N] = next[v][node];
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  int succ = *;
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  tstamp[v][t] = ts;
  …
  last_tstamp[v][t] = ts;
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  max_tstamp[t] = ts;
}
```

write to different variables may be reordered, guessed timestamps no longer need to be the maximum over all variables, but the maximum for the relevant variable:

```
ts >= last_tstamp[t][v]
```

extension to PSO

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  value[v][node] = val;
  tstamp[v][t] = ts;
  …
  last_tstamp[v][t] = t
  last_value[v][t] = va
  max_tstamp[t] = ts;
}
```

write to different variables may be reordered, guessed timestamps no longer need to be the maximum over all variables, but the maximum for the relevant variable:

```
ts >= last_tstamp[t][v]
```

guessed timestamps may be smaller than the max timestamp:

```
max_tstamp[t] =
max(max_tstamp[t],ts)
```

Experimental Evaluation: common benchmarks

	bug?	unwind	qsize (N)	naddr	nmalloc	bitwidth	rounds	maxclock (K)	TSO runtime (s) LazySMA	TSO CBMC	TSO NIDHUGG	PSO runtime (s) LazySMA	PSO CBMC	PSO NIDHUGG
dekker	●	1	2	0	0	4	2	2	0.77	0.29	**0.04**	0.75	0.25	**0.05**
lamport	●	1	2	0	0	4	2	2	0.88	0.31	**0.05**	0.88	0.29	**0.05**
peterson	●	1	3	0	0	4	2	2	0.66	0.26	**0.04**	0.65	0.25	**0.04**
szymanski	●	1	3	0	0	4	2	3	0.81	0.34	**0.07**	0.80	0.32	**0.04**
fib_longer_unsafe	●	6	2	0	0	10	6	2	**6.47**	8.19	94.84	6.51	**1.69**	135.45
fib_longer_safe		6	2	0	0	10	6	2	**9.78**	22.5	t.o.	**8.82**	31.8	t.o.
parker	●	1	2	0	0	4	2	3	1.68	0.31	**0.05**	2.19	0.28	**0.05**
stack_unsafe	●	2	2	1	2	5	2	2	1.50	0.41	**0.05**	1.49	0.35	**0.05**
litmus_safe (avg)		5	2	0	0	10	2	20	1.26	**0.17**	2.35	1.22	**0.15**	6.65
litmus_unsafe (avg)	●	5	2	0	0	10	2	20	1.27	**0.16**	3.86	1.26	**0.12**	1.58

timeout = 600s

transformation overhead shows on small programs

Experimental Evaluation: common benchmarks

	bug?	unwind	qsize (N)	naddr	nmalloc	bitwidth	rounds	maxclock (K)	TSO runtime (s) LazySMA	TSO CBMC	TSO NIDHUGG	PSO runtime (s) LazySMA	PSO CBMC	PSO NIDHUGG
dekker	●	1	2	0	0	4	2	2	0.77	0.29	**0.04**	0.75	0.25	**0.05**
lamport	●	1	2	0	0	4	2	2	0.88	0.31	**0.05**	0.88	0.29	**0.05**
peterson	●	1	3	0	0	4	2	2	0.66	0.26	**0.04**	0.65	0.25	**0.04**
szymanski	●	1	3	0	0	4	2	3	0.81	0.34	**0.07**	0.80	0.32	**0.04**
fib_longer_unsafe	●	6	2	0	0	10	6	2	**6.47**	8.19	94.84	6.51	**1.69**	135.45
fib_longer_safe		6	2	0	0	10	6	2	**9.78**	22.5	t.o.	**8.82**	31.8	t.o.
parker	●	1	2	0	0	4	2	3	1.68	0.31	**0.05**	2.19	0.28	**0.05**
stack_unsafe	●	2	2	1	2	5	2	2	1.50	0.41	**0.05**	1.49	0.35	**0.05**
litmus_safe (avg)		5	2	0	0	10	2	20	1.26	**0.17**	2.35	1.22	**0.15**	6.65
litmus_unsafe (avg)	●	5	2	0	0	10	2	20	1.27	**0.16**	3.86	1.26	**0.12**	1.58

timeout = 600s

competitive on twisted interleavings

Experimental Evaluation: common benchmarks

	bug?	unwind	qsize (N)	naddr	nmalloc	bitwidth	rounds	maxclock (K)	TSO runtime (s) LazySMA	TSO CBMC	TSO NIDHUGG	PSO runtime (s) LazySMA	PSO CBMC	PSO NIDHUGG
dekker	●	1	2	0	0	4	2	2	0.77	0.29	**0.04**	0.75	0.25	**0.05**
lamport	●	1	2	0	0	4	2	2	0.88	0.31	**0.05**	0.88	0.29	**0.05**
peterson	●	1	3	0	0	4	2	2	0.66	0.26	**0.04**	0.65	0.25	**0.04**
szymanski	●	1	3	0	0	4	2	3	0.81	0.34	**0.07**	0.80	0.32	**0.04**
fib_longer_unsafe	●	6	2	0	0	10	6	2	**6.47**	8.19	94.84	6.51	**1.69**	135.45
fib_longer_safe		6	2	0	0	10	6	2	**9.78**	22.5	t.o.	**8.82**	31.8	t.o.
parker	●	1	2	0	0	4	2	3	1.68	0.31	**0.05**	2.19	0.28	**0.05**
stack_unsafe	●	2	2	1	2	5	2	2	1.50	0.41	**0.05**	1.49	0.35	**0.05**
litmus_safe (avg)		5	2	0	0	10	2	20	1.26	**0.17**	2.35	1.22	**0.15**	6.65
litmus_unsafe (avg)	●	5	2	0	0	10	2	20	1.27	**0.16**	3.86	1.26	**0.12**	1.58

timeout = 600s

slower

Experimental Evaluation: common benchmarks

	bug?	parameters: unwind	qsize (N)	naddr	nmalloc	bitwidth	rounds	maxclock (K)	TSO runtime (*s*): LazySMA	CBMC	NIDHUGG	PSO runtime (*s*): LazySMA	CBMC	NIDHUGG
dekker	●	1	2	0	0	4	2	2	0.77	0.29	**0.04**	0.75	0.25	**0.05**
lamport	●	1	2	0	0	4	2	2	0.88	0.31	**0.05**	0.88	0.29	**0.05**
peterson	●	1	3	0	0	4	2	2	0.66	0.26	**0.04**	0.65	0.25	**0.04**
szymanski	●	1	3	0	0	4	2	3	0.81	0.34	**0.07**	0.80	0.32	**0.04**
fib_longer_unsafe	●	6	2	0	0	10	6	2	**6.47**	8.19	94.84	6.51	**1.69**	135.45
fib_longer_safe		6	2	0	0	10	6	2	**9.78**	22.5	t.o.	**8.82**	31.8	t.o.
parker	●	1	2	0	0	4	2	3	1.68	0.31	**0.05**	2.19	0.28	**0.05**
stack_unsafe	●	2	2	1	2	5	2	2	1.50	0.41	**0.05**	1.49	0.35	**0.05**
litmus_safe (avg)		5	2	0	0	10	2	20	1.26	**0.17**	2.35	1.22	**0.15**	6.65
litmus_unsafe (avg)	●	5	2	0	0	10	2	20	1.27	**0.16**	3.86	1.26	**0.12**	1.58

timeout = 600s

faster than Nidhugg

Experimental Evaluation: Safestack

parameters			TSO analysis (3 bits)			CEX check (32 bits)		PSO analysis (3 bits)		CEX check (32 bits)	
K	N	rounds	Time	Mem.	Reach?	CEX?	Time	Time	Reach?	CEX?	Time
1	2	4	10m18s	0.8GB	Yes	Yes	23s	11m42s	Yes	Yes	4.82s
1	2	3	12m2s	0.6GB	No	-	-	11m16s	No	-	-
1	3	4	13m45s	1.2GB	Yes	Yes	30s	21m6s	Yes	Yes	6.40s
1	3	3	12m50s	0.9GB	No	-	-	12m20s	No	-	-
3	2	4	26m55s	1.4GB	Yes	Yes	24s	20m47s	Yes	Yes	4.33s
3	2	3	24m34s	1.0GB	No	-	-	27m15s	No	-	-
3	3	4	74m22s	3.4GB	Yes	Yes	31s	31m16s	Yes	Yes	5.47s
3	3	3	62m22s	1.0GB	Yes	Yes	30s	20m7s	Yes	Yes	2.84s
3	3	2	12m14s	0.6GB	No	-	-	11m14s	No	-	-
7	2	4	47m17s	2.4GB	Yes	Yes	27s	104m35s	Yes	Yes	6.05s
7	2	3	35m7s	1.3GB	No	-	-	36m14s	No	-	-

maxclock=K=1 forces SC analysis,
TSO puts 3x-4x overhead on lazy schema (SC times not shown in table)

Experimental Evaluation: Safestack

parameters			TSO analysis (3 bits)			CEX check (32 bits)		PSO analysis (3 bits)		CEX check (32 bits)	
K	N	rounds	Time	Mem.	Reach?	CEX?	Time	Time	Reach?	CEX?	Time
1	2	4	10m18s	0.8GB	Yes	Yes	23s	11m42s	Yes	Yes	4.82s
1	2	3	12m2s	0.6GB	No	-	-	11m16s	No	-	-
1	3	4	13m45s	1.2GB	Yes	Yes	30s	21m6s	Yes	Yes	6.40s
1	3	3	12m50s	0.9GB	No	-	-	12m20s	No	-	-
3	2	4	26m55s	1.4GB	Yes	Yes	24s	20m47s	Yes	Yes	4.33s
3	2	3	24m34s	1.0GB	No	-	-	27m15s	No	-	-
3	3	4	74m22s	3.4GB	Yes	Yes	31s	31m16s	Yes	Yes	5.47s
3	3	3	62m22s	1.0GB	Yes	Yes	30s	20m7s	Yes	Yes	2.84s
3	3	2	12m14s	0.6GB	No	-	-	11m14s	No	-	-
7	2	4	47m17s	2.4GB	Yes	Yes	27s	104m35s	Yes	Yes	6.05s
7	2	3	35m7s	1.3GB	No	-	-	36m14s	No	-	-

quicker to spot the bug under PSO
as it requires a smaller number of thread interactions;
performance comparable when no bugs are found

Experimental Evaluation: Safestack

parameters			TSO analysis (3 bits)			CEX check (32 bits)		PSO analysis (3 bits)		CEX check (32 bits)	
K	N	rounds	Time	Mem.	Reach?	CEX?	Time	Time	Reach?	CEX?	Time
1	2	4	10m18s	0.8GB	Yes	Yes	23s	11m42s	Yes	Yes	4.82s
1	2	3	12m2s	0.6GB	No	-	-	11m16s	No	-	-
1	3	4	13m45s	1.2GB	Yes	Yes	30s	21m6s	Yes	Yes	6.40s
1	3	3	12m50s	0.9GB	No	-	-	12m20s	No	-	-
3	2	4	26m55s	1.4GB	Yes	Yes	24s	20m47s	Yes	Yes	4.33s
3	2	3	24m34s	1.0GB	No	-	-	27m15s	No	-	-
3	3	4	74m22s	3.4GB	Yes	Yes	31s	31m16s	Yes	Yes	5.47s
3	3	3	62m22s	1.0GB	Yes	Yes	30s	20m7s	Yes	Yes	2.84s
3	3	2	12m14s	0.6GB	No	-	-	11m14s	No	-	-
7	2	4	47m17s	2.4GB	Yes	Yes	27s	104m35s	Yes	Yes	6.05s
7	2	3	35m7s	1.3GB	No	-	-	36m14s	No	-	-

increase maxlock to covers more reorderings,
more resource demanding..

Thank You

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