Analysis of Concurrent Programs via Sequentializations

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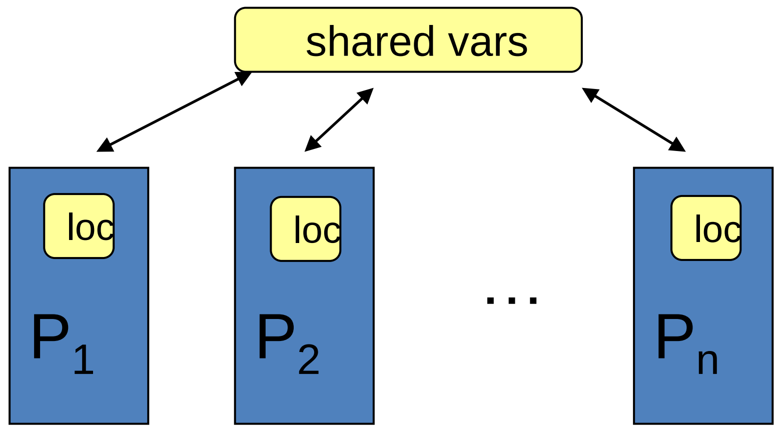
Concurrent (shared-memory) Programs

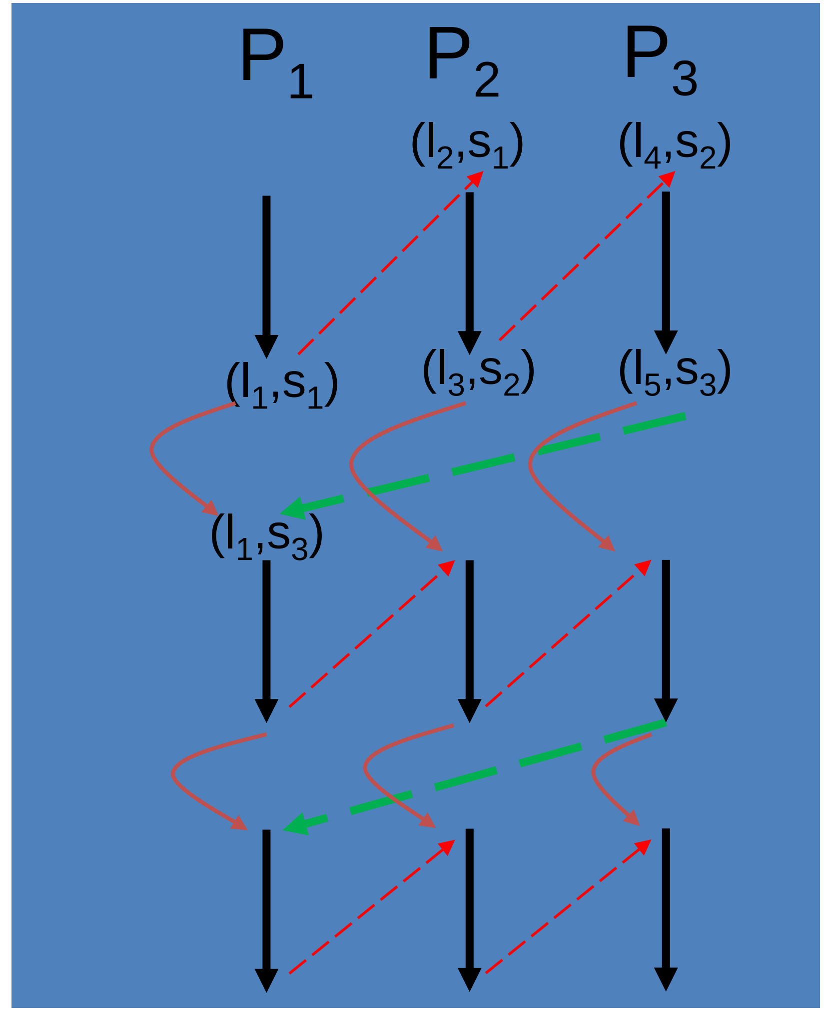
- Formed of sequential programs $P_1, \ldots, P_n$
  (each possibly with recursive function calls)



- Each program P_i can read and write shared vars
- We assume sequential consistency
  (writes are immediately visible to all the other programs)
- An execution is an interleaving of the executions of each program P_i

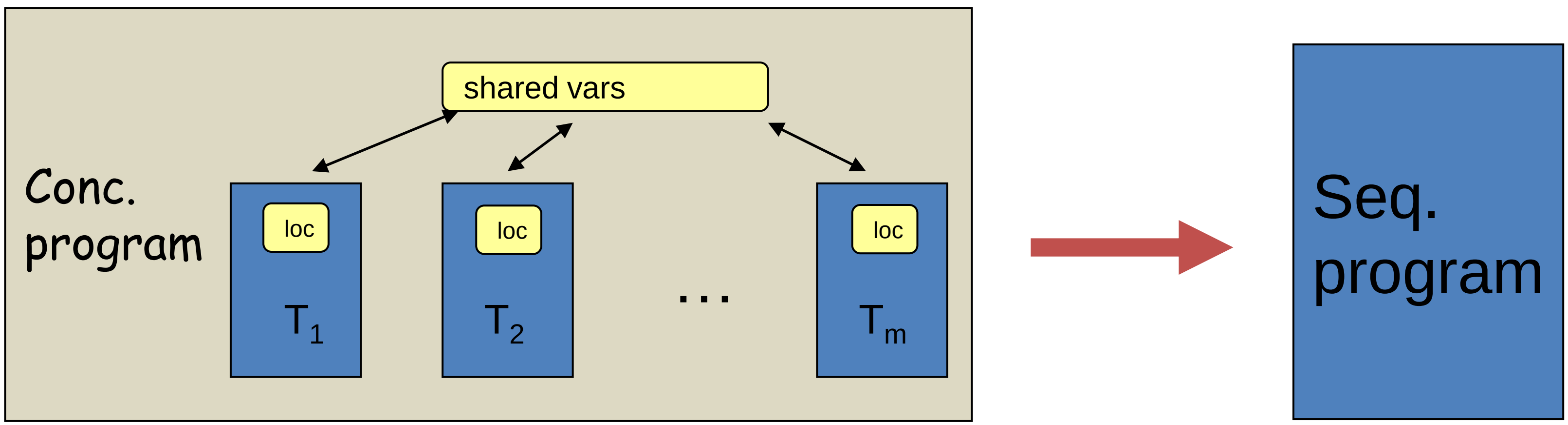
A concurrent execution (n=3)

- Programs are round-Robin scheduled in several rounds
  - round: formed of a context of each program
  - context: portion of run of a P_i
  - context-switch: active thread changes (global state is passed on to the next scheduled thread)
  - context-switching back to a thread resumes its local state

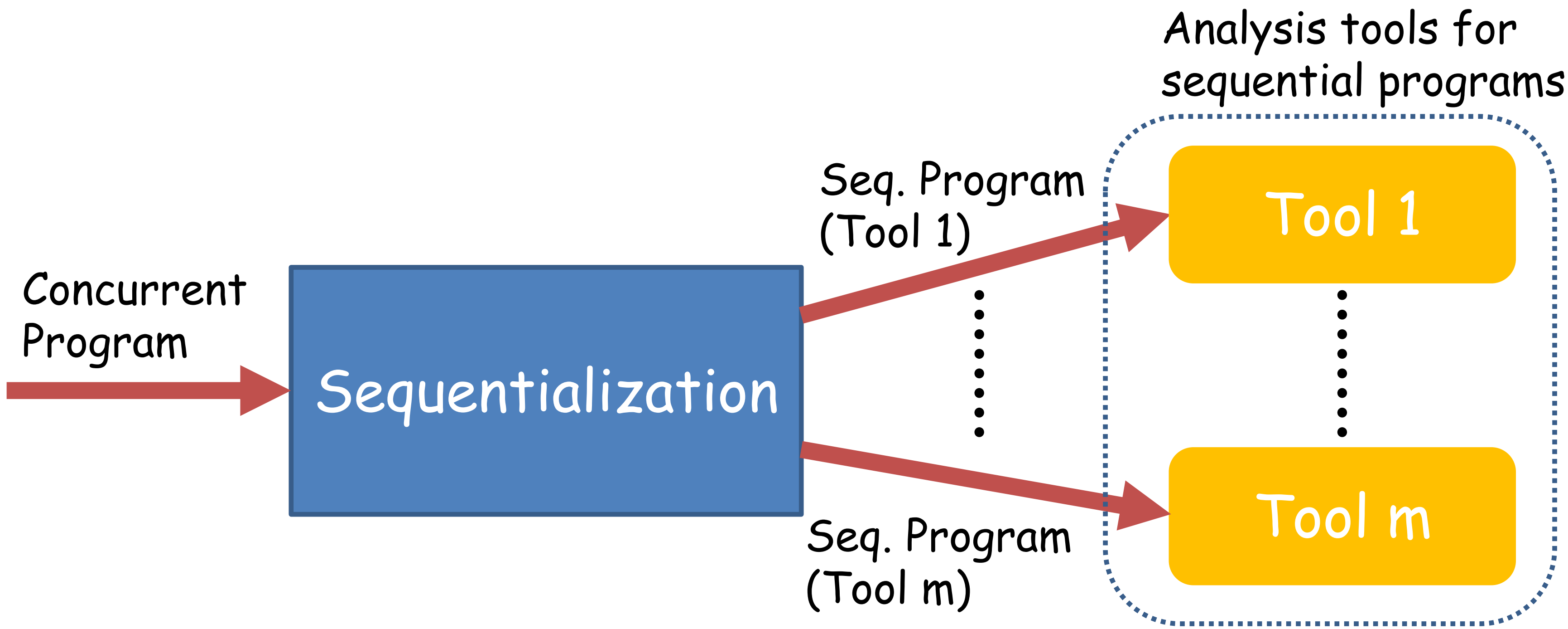


Sequentialization

- Code-to-code translation from a multithreaded program to an "equivalent" sequential one



Why sequentializing?



- Re-use of existing tools (delegate the analysis to the backend tool)
- Fast prototyping (designers can concentrate only concurrency features)
- Can work with different backends

Is this practical?

- Sequentializations inject control code in the original program
  - this can cause some overhead
  - performances of different translations may differ depending on the backend technology

- In the software verification competition (concurrency category) held at TACAS,

  gold medals went to tools using sequentializations
  - Lazy-CSeq and MU-CSeq

Some general observations

- Sequentialization is always possible using unbounded resources
  - Sequential program keeps the call-stacks and just exectutes threads in time-sharing for any scheduling
- Efficient sequentialization yields an under-approximation of the concurrent programs
  - use prioritized search strategies (e.g., bounded context-switching [Qadeer-Rehof, TACAS'05])
- Full coverage of the state space in very few cases
  - e.g., program abstractions with only two threads sharing only locks acquired/released under contextual locking

    [Chadha-Madhusudan-Viswanathan,TACAS'12]

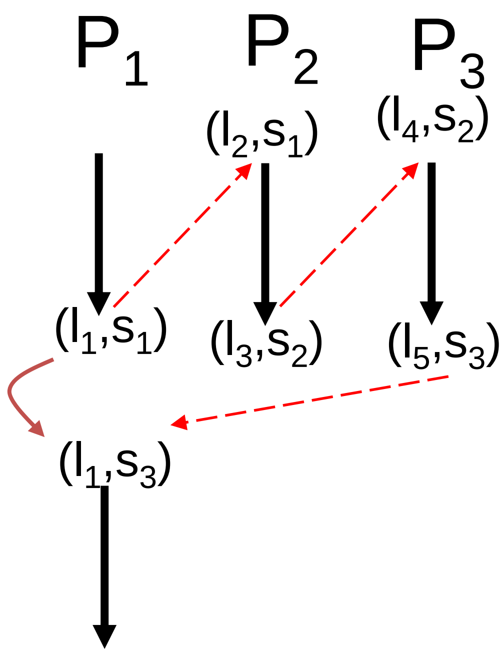
Outline

- First sequentialization
- Bounded context-switching
  - Eager approach
  - Lazy approach
- More sequentializations
- Conclusions

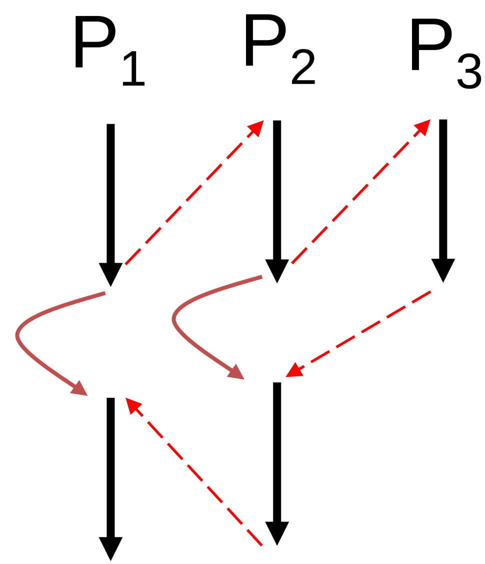
A first sequentialization

- KISS: Keep It Simple and Sequential (Microsoft tool) [Quadeer-Wu, PLDI'04]
- At context-switches either:
  - the active thread is terminated or
  - a not yet scheduled thread is started (by calling its main function)
- When a thread is terminated either:
  - the thread that has called it is resumed (if any) or
  - a not yet scheduled thread is started

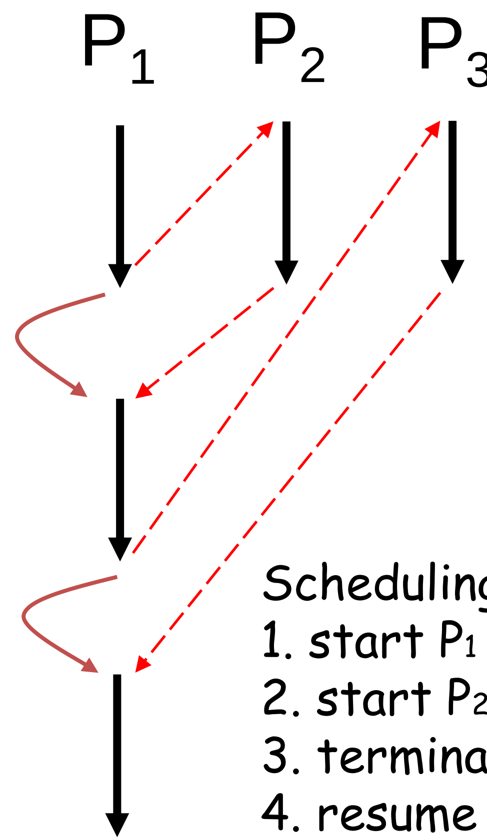
Example (n=3)



Scheduling 1:
1. start P_1
2. start P_2
3. terminate P_2
4. start P_3
5. terminate P_3
6. resume P_1



Scheduling 2:
1. start P_1
2. start P_2
3. start P_3
4. terminate P_3
5. resume P_2
6. terminate P_2
7. resume P_1



Scheduling 3:
1. start P_1
2. start P_2
3. terminate P_2
4. resume P_1
5. start P_3
6. terminate P_3
7. resume P_1

More on KISS

- Allows dynamic thread allocation in form of asynchronous calls
- Bounds the number of threads that have been created but not started yet
  - Scheduler starts a thread from this set (choosing it nondeterministically) or resumes the last suspended thread (if any)
- Used for assertion checking

Outline

✓ First sequentialization

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Bounded context-switching

- Switching between threads is allowed only a bounded number of times [Qadeer-Rehof, TACAS'05]

Under this restriction

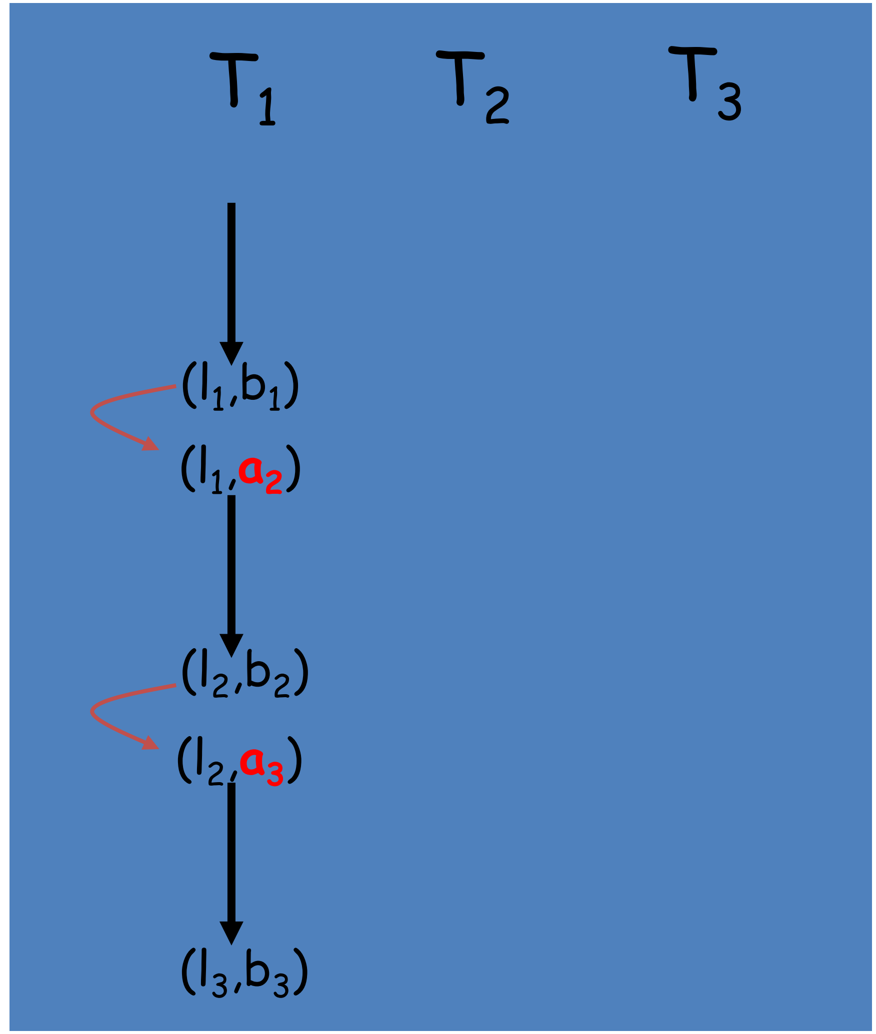
- Analysis is an effective technique for bug detection
  - bugs of concurrent programs are likely to occur within few context-switches [Musuvathi-Qadeer, PLDI'07]
  - Efficient sequentializations can be obtained
    1. Eager approach [Lal-Reps, CAV'08]
    2. Lazy approach [La Torre-Madhusudan-Parlato, CAV'09]

Eager sequentialization

- [Lal-Reps, CAV'08]

Sequential program (k-rounds)

1. Guess $a_2,\ldots, a_k$
2. Execute T_1 to completion
   - Computes local states $l_1,..,l_k$ and global states $b_1,\ldots,b_k$

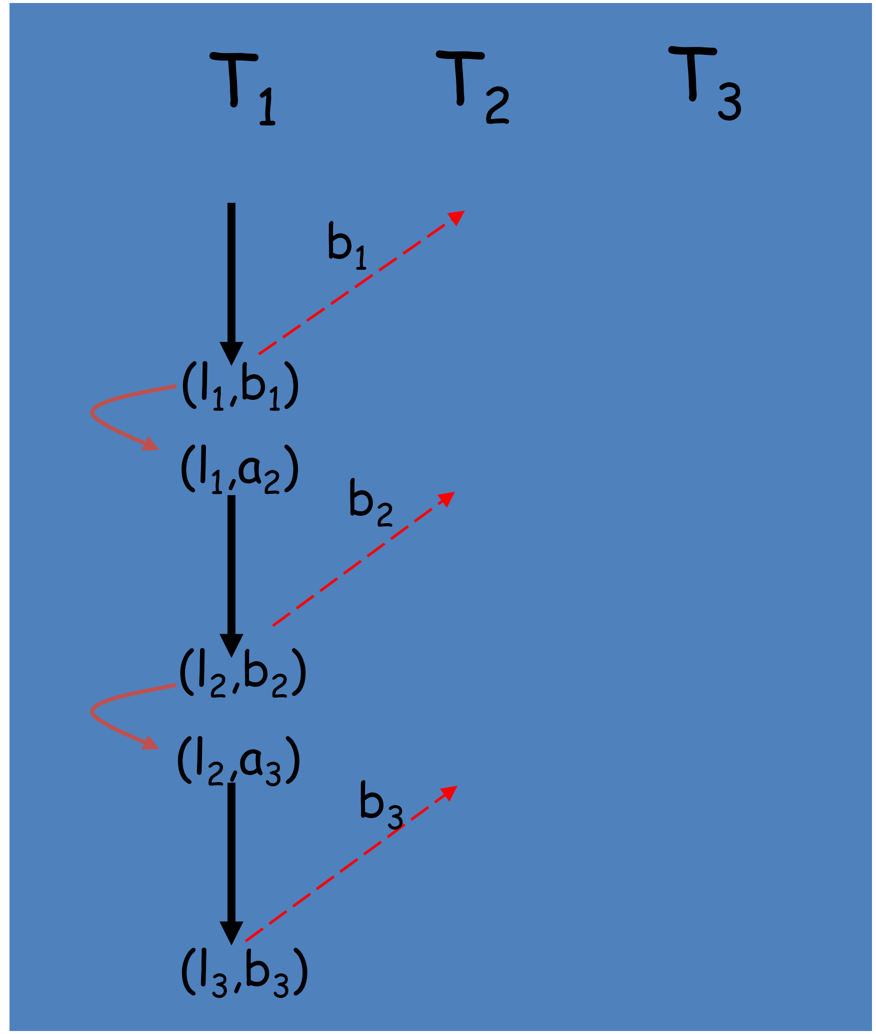


Eager sequentialization

- [Lal-Reps, *CAV'08*]

Sequential program (k-rounds)

1. Guess $a_2,\ldots,a_k$
2. Execute T_1 to completion
3. Pass $b_1,\ldots,b_k$ to T_2

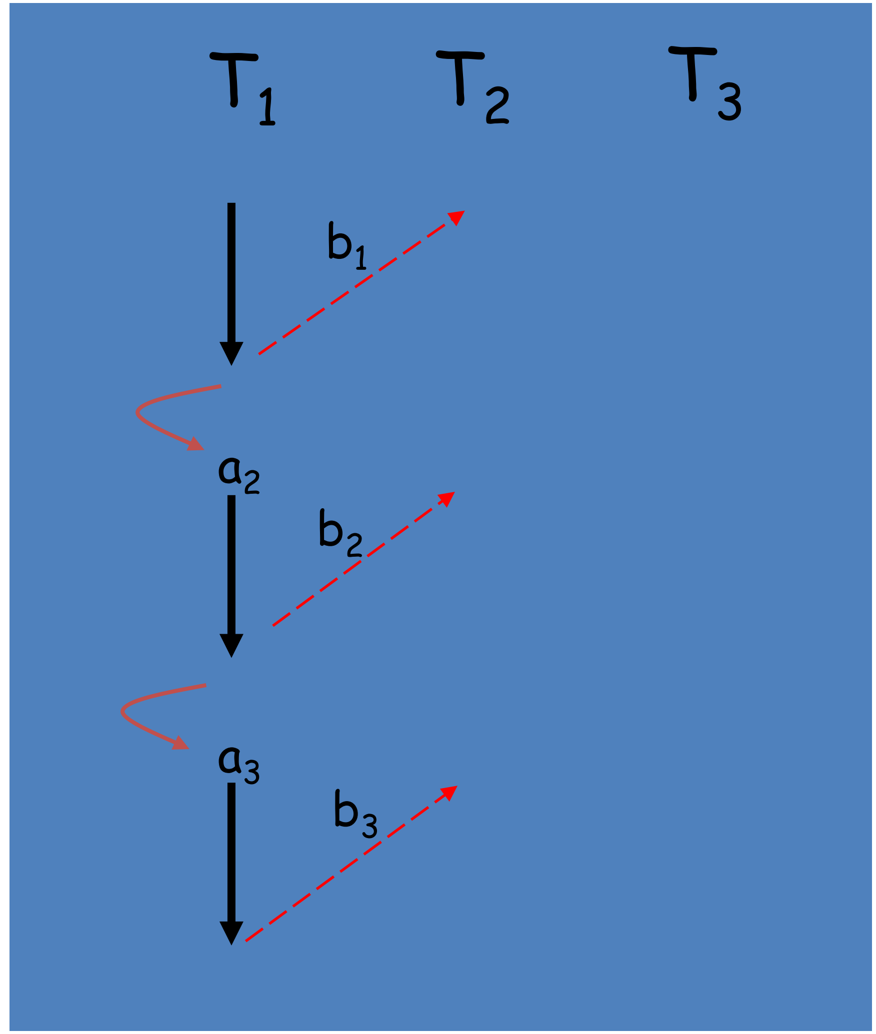


Eager sequentialization

- [Lal-Reps, CAV'08]

Sequential program (k-rounds)

1. Guess $a_2,\ldots,a_k$
2. Execute T_1 to completion
3. Pass $b_1,\ldots,b_k$ to T_2
   - We can forget of locals

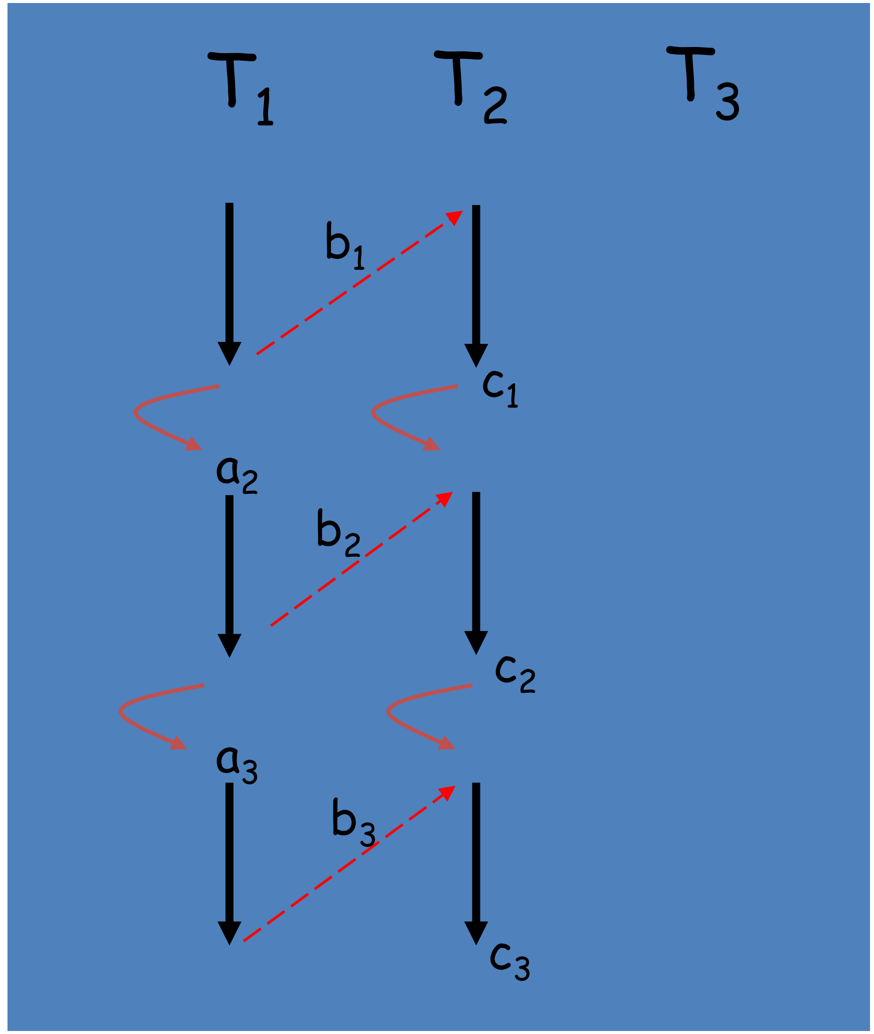


Eager sequentialization

- [Lal-Reps, *CAV'08*]

Sequential program (k-rounds)

1. Guess $a_2,\ldots,a_k$
2. Execute T_1 to completion
3. Pass $b_1,\ldots,b_k$ to T_2
4. Execute T_2 to completion

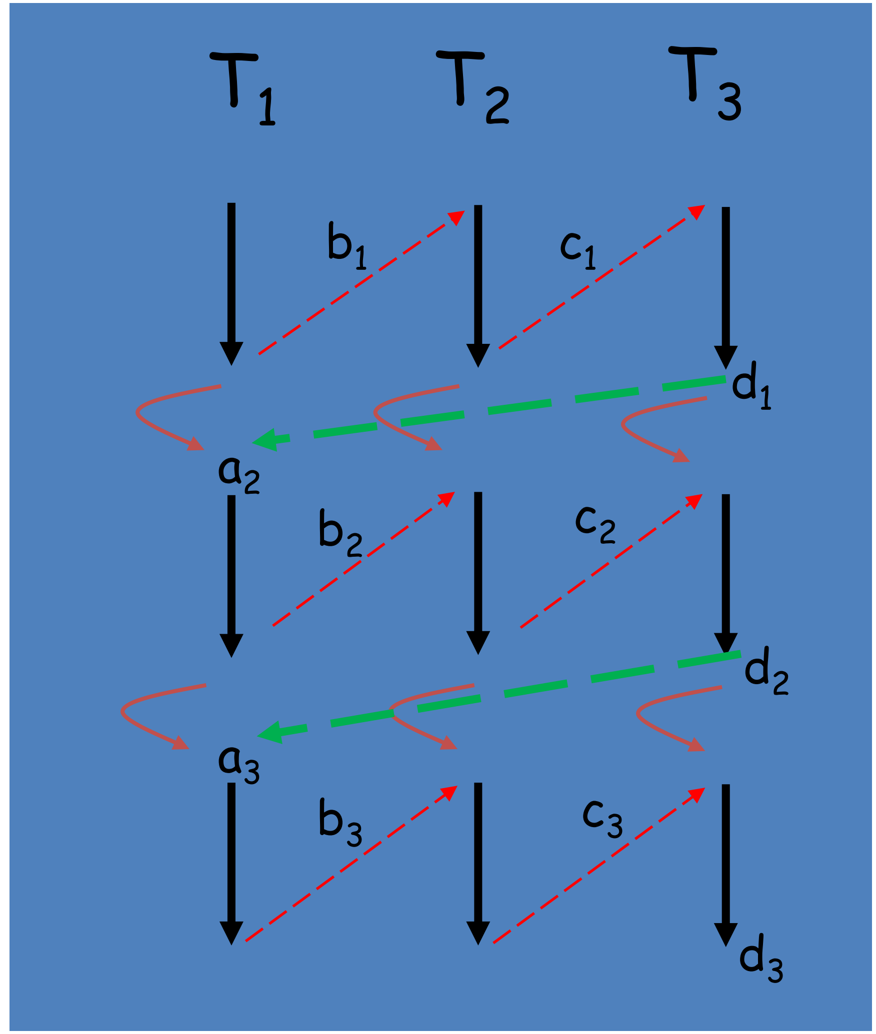


Eager sequentialization

- [Lal-Reps, *CAV'08*]

Sequential program (k-rounds)

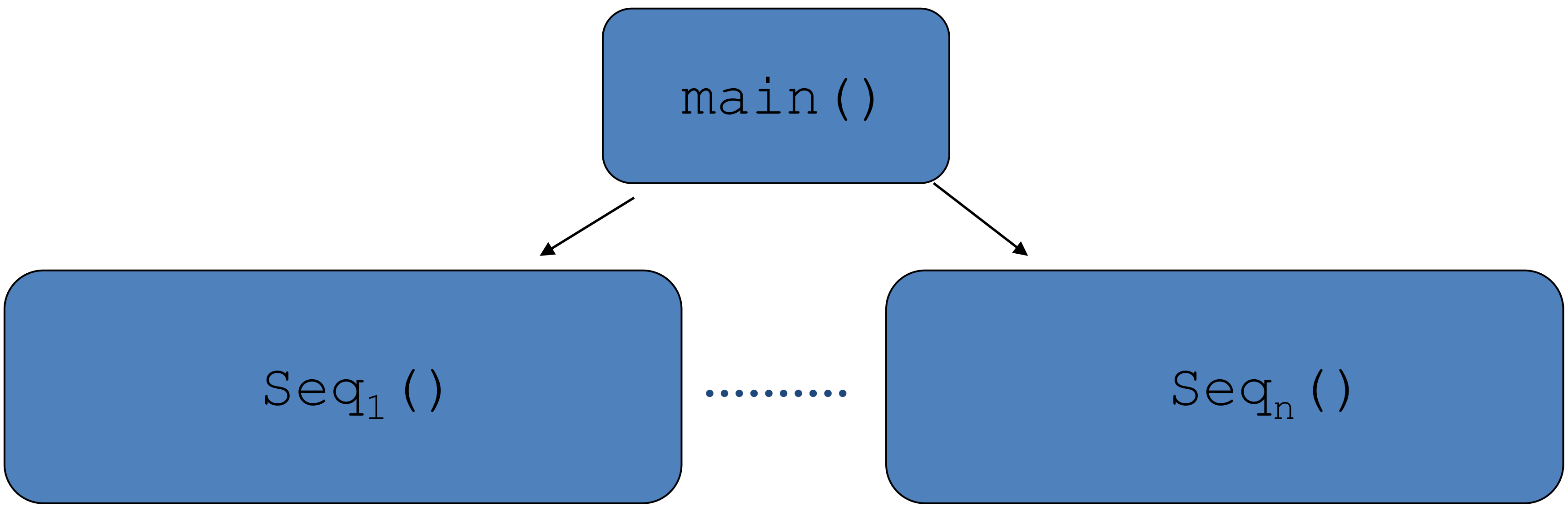
1. Guess $a_2,\ldots,a_k$
2. Execute T_1 to completion
3. Pass $b_1,\ldots,b_k$ to T_2
4. Execute T_2 to completion
5. Pass $c_1,\ldots,c_k$ to T_3
6. Execute T_3 to completion
7. Computation iff $d_i = a_{i+1}\ \forall i \in [1,k-1]$



Translation scheme

Input: concurrent program $P_1,\ldots,P_n$

Output is a sequential program consisting of:
(Seq$_i$ is the translation of P_i)



Eager translation (k-rounds)

- 2k-1 copies of shared vars
  - $r_2,\ldots,r_k$ (store guessed starting values)
  - $s_1,\ldots,s_k$ (copies per round of shared vars)
- main is very simple:

  guess $r_2,\ldots,r_k$
  $Seq_1()$
  ……
  $Seq_n()$
  Checker()
  Error()

- $Seq_i()$:
  - code of P_i using the copy s_j at round j
  - implements round-switching by moving to next copy of shared vars
  - returns to main after last round
- Checker():

  for i = 1 to K – 1 do
  assume ($s_i = r_{i+1}$)

- Error(): assert(goal)

Outline

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Eager seq. does not preserve assertions

```
// shared variables
bool blocked=true;
int x=0, y=0;
```

```
process P1:
  main() begin
   while (blocked)
        skip;
   assert(y!=0);
   x = x/y;
  end
```

```
process P2:
  main() begin
   x=12;
   y=2;
  //unblock threads of P1
   blocked=false;
  end
```

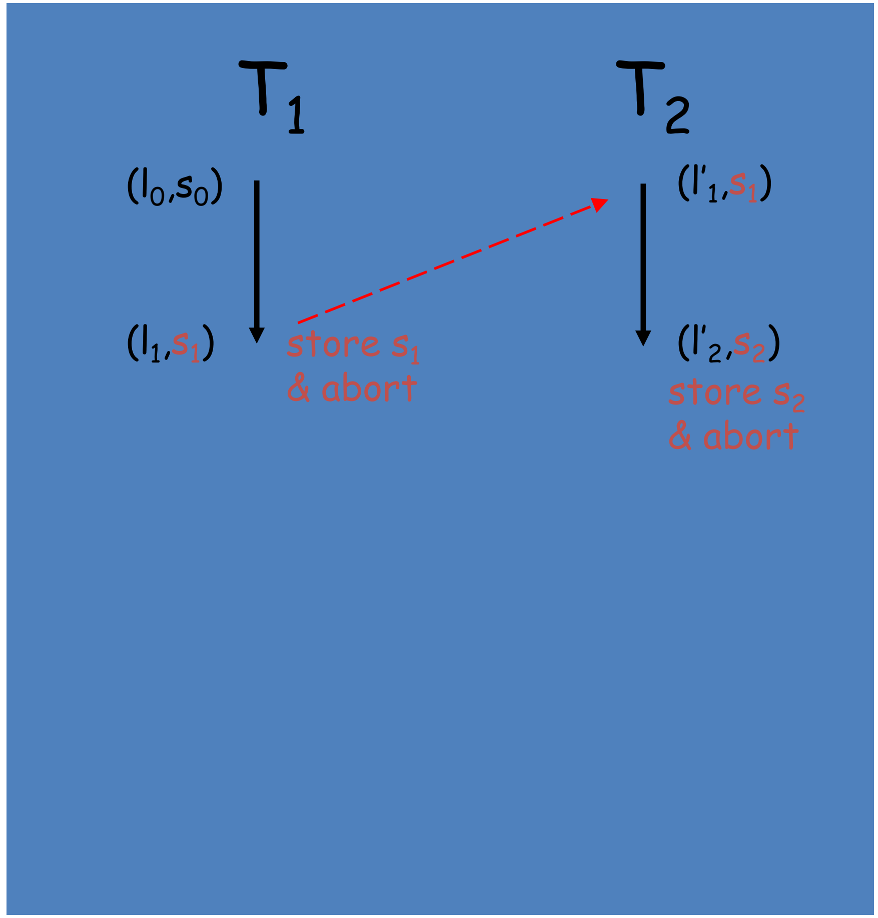
- y!=0 is an invariant of the statement x=x/y in the concurrent progr.
  - but not in the sequential program

  (blocked can be nondeterministically assigned to false across a context-switch while processing P1)

Lazy transformation: main idea

[La Torre-Madhusudan-Parlato, *CAV'09*]

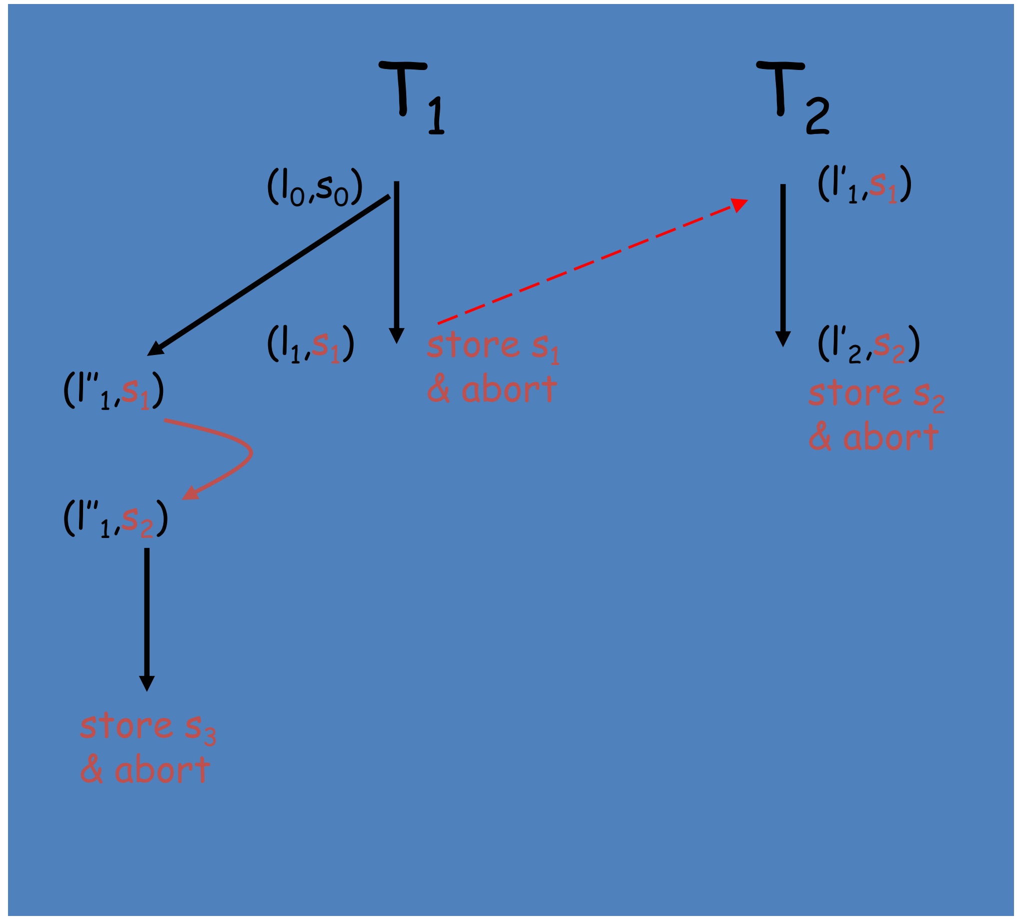
- Execute T_1
- Context-switch:
  store s_1 and abort
- Execute T_2 from s_1
- store s_2 and abort



Lazy transformation: main idea

[La Torre-Madhusudan-Parlato, CAV'09]

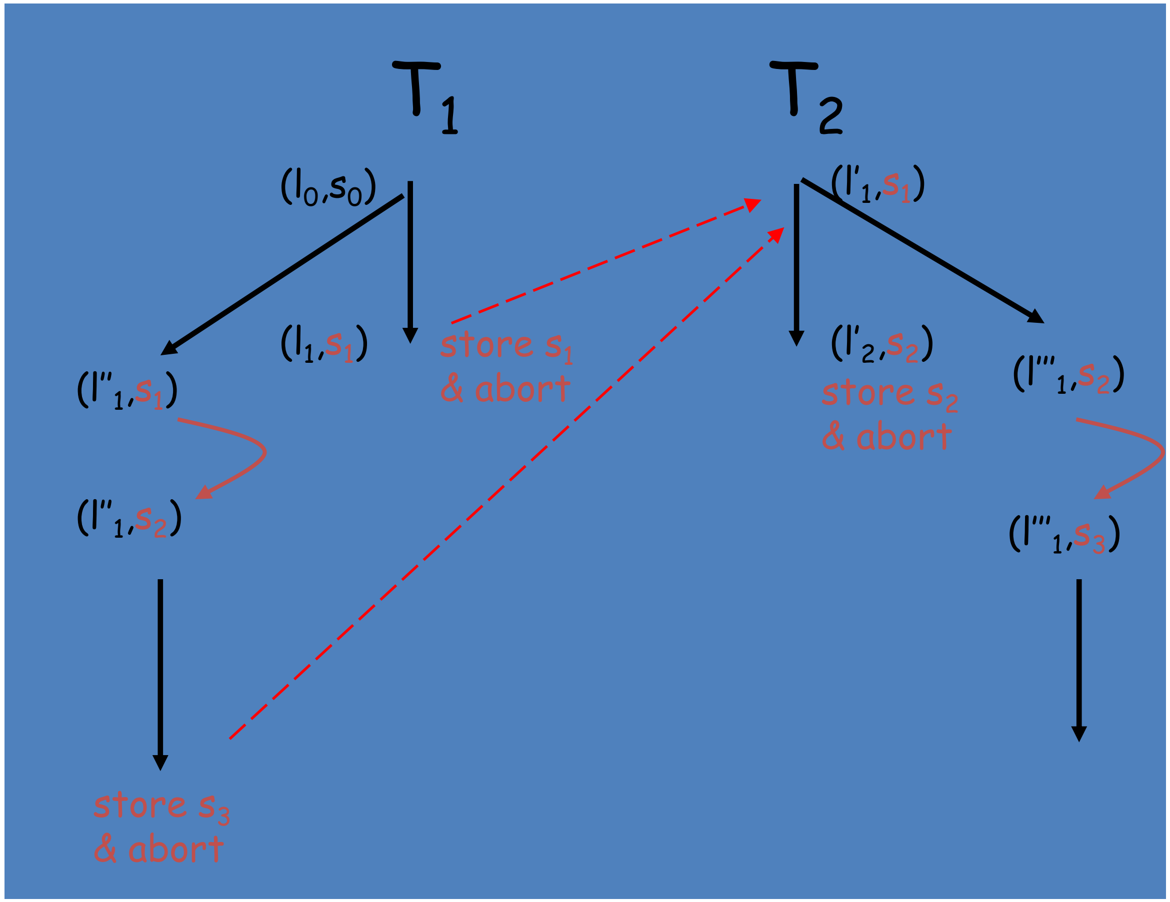
- Re-execute T1 till it reaches s1
  - May reach a new local state!
  - Anyway it is correct !!
- Restart from global s2 and compute s3



Lazy transformation: main idea

[La Torre-Madhusudan-Parlato, CAV'09]

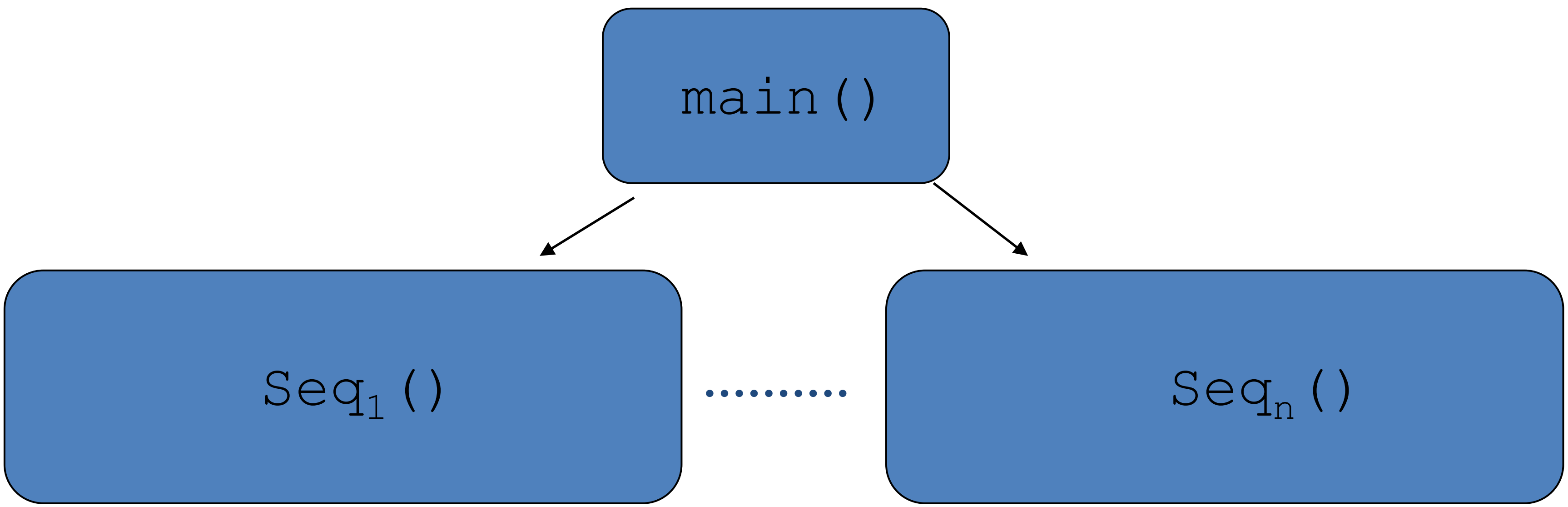
- Switch to T2
- Execute till it reaches s2
- Continue computation from global s3



Translation scheme (as in Eager)

Input: concurrent program $P_1, \ldots, P_n$

Output is a sequential program consisting of:
(Seq$_i$ is the translation of P_i)



Lazy translation (k-contexts)

- k copies of shared vars
  - $s_1,\ldots,s_k$ (copies of shared vars to store values at cs)
- main has more control stms:
  - No guessing
  - Keeps track of the current context
  - Starts a thread or its recomputation by assigning the values of sh. vars at first of its contexts

Lazy translation (k-contexts)

- $Seq_i()$:
  - code of P_i interleaved with control code

```
if (terminate) then return;
else
    if (*) then call contextSwitch( );
    if (terminate) then return;
```

- No special handling of error condition

- contextSwitch()
  - when recomputing contexts:
    1. matches values at cs
    2. set starting values for next context
  - when context-switching out the currently new computed context
    1. stores the sh vars in the appropriate copy
    2. set terminate to true

Summarizing lazy translation

- Explores only reachable states
- Preserves invariants across the translation
- Tracks local state of one thread at any time
- Tracks values of shared variables at context switches
  $(s_1, s_2, \ldots, s_k)$
- Requires recomputation of local states

Both translations reduce bounded reachability to sequential reachability

Theorem:
Let C be a concurrent program, $k>0$ and pc be a program counter of C

pc is reachable in C within k context switches iff pc is reachable in $SeqProg_k(C)$

Lazy vs. Eager: performace

- Tool Getafix implements both eager and lazy sequentialization for concurrent Boolean programs
- Lazy outperforms Eager in the experiments
- Sample results on Windows NT Bluetooth driver

Context switches	1-adder 1-stopper			2-adders 1-stopper			1-adder 2-stoppers			2-adders 2-stoppers		
		eager	lazy		eager	lazy		eager	lazy		eager	lazy
1	N	0.1	0.1	N	0.2	0.1	N	0.1	0.1	N	0.2	0.1
2	N	0.3	0.2	N	0.9	0.8	N	0.7	0.9	N	1.6	2.0
3	N	43.3	1.4	N	135.9	6.3	Y	70.1	0.4	Y	177.6	0.8
4	N	73.6	5.5	Y	1601.0	2.6	Y	597.2	2.9	Y	out of mem.	7.5
5	N	930.0	20.2	Y	-	18.0	Y	-	14.0	Y	out of mem.	66.5
6	N	-	66.8	Y	-	122.9	Y	-	66.1	Y	out of mem.	535.9

Lazy vs. Eager: performace

- Getafix uses as verification engine a fixed-point logic solver (Mucke)
  - It stores summaries, recomputations do not cause to repeat exploration
  - Explore the state space lazily gives some advantages

- Experiments using BMC (Bounded Model-checking) backends gives the opposite result
  - Eager outperforms Lazy

    [Ghafari-Hu-Rakamaric, SPIN'10]

Tools implementing LR seq.

- CSeq for Pthreads C programs
  [Fischer-Inverso-Parlato, ASE'13]
- STORM + dynamic memory allocation using maps [Lahiri-Qadeer-Rakamaric, CAV'09]
- Successors of STORM:
  - Corral [Lal-Qadeer-Lahiri, CAV'12]
  - Poirot [Qadeer, ICFEM'11]
    [Emmi-Qadeer-Rakamaric, POPL'11]

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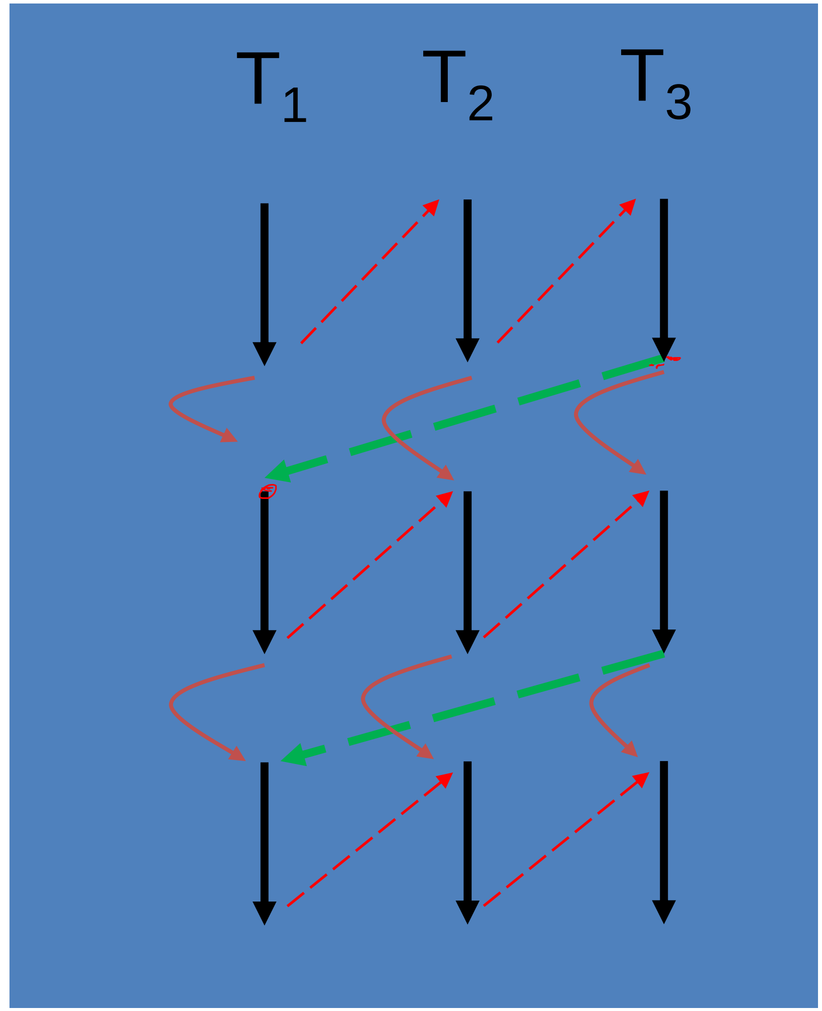
Parameterized programs

- Extend shared-memory concurrent programs
  - Computations can have an arbitrary number of threads
- Complex class of programs (infinite states):
  - each thread can have recursive calls
  - number of threads is unbounded
- Interesting class of programs (e.g., device drivers)
  - can be used to analyze programs with dynamic thread creation

Sequentialization of param. progs

[La Torre-Madhusudan-Parlato, FIT'12]

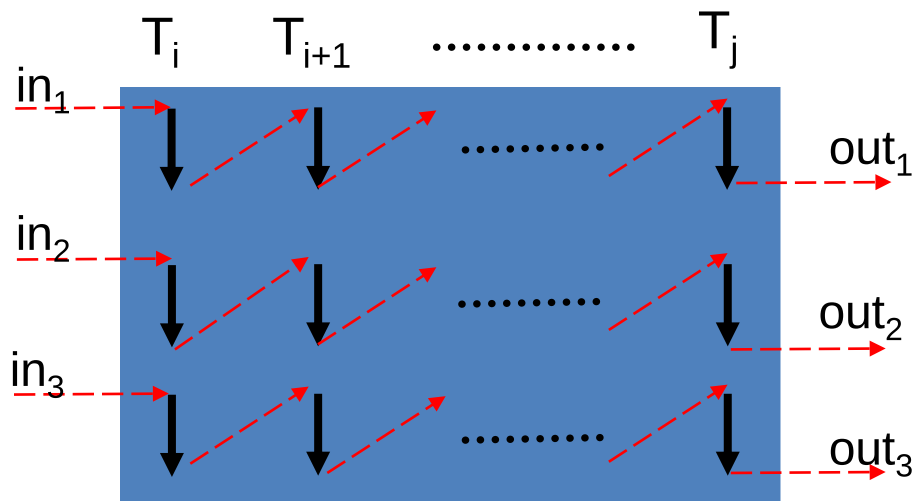
- Eager sequentialization can be easily obtained from that for concurrent programs:
  - each thread is executed up to completion (jumping across context-switches)
  - after computing a thread, nondeterministically (1) terminate and check if all the computed executions form a computation and (2) compute next thread
  - the values of shared variables at context-switches are passed to the next thread



Linear interfaces

- Summarize the effects of a block of unboundedly many threads on the shared variables
  – executions arranged in rounds of round-robin scheduling

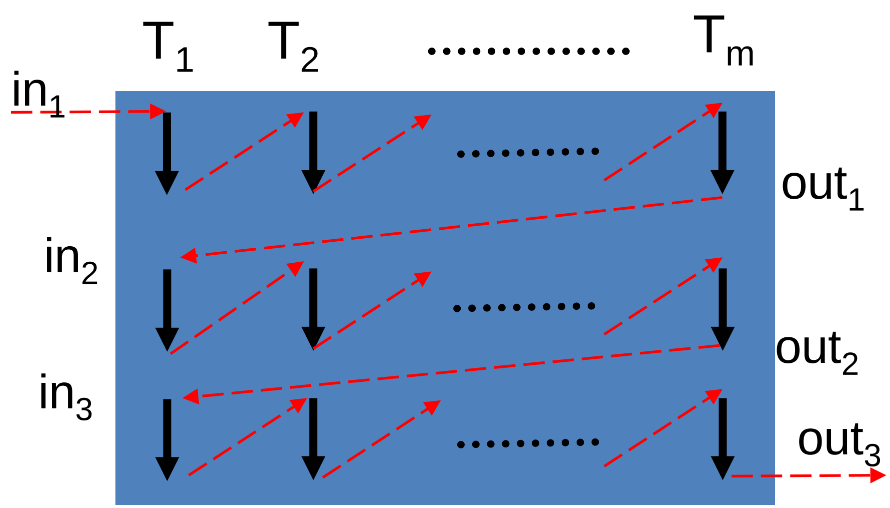
linear interface
(In,Out)
of dim. 3



Linear interface of a run

- (In,Out) s.t. $in_{i+1}=out_i$ $i=1,\ldots,k-1$

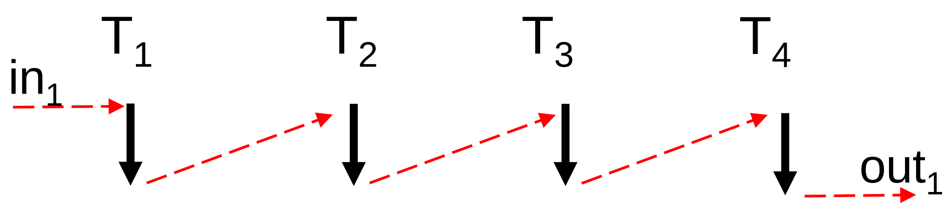
k=3



Lazy sequentialization

[La Torre-Madhusudan-Parlato, FIT'12]

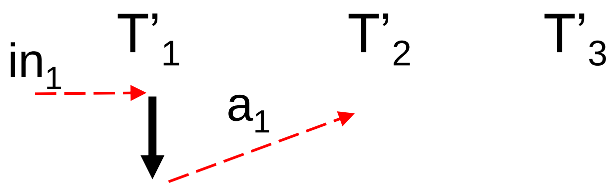
- P_{seq} mimics a computation of P
  - by increasing round numbers and
  - (within each round) by increasing context numbers



- nondeterministically chooses if this is the last thread in the round
- the linear interface ($\langle in_1, out_1 \rangle$) is stored

Lazy sequentialization

- Second round is executed matching $(\langle in_1, out_1 \rangle)$

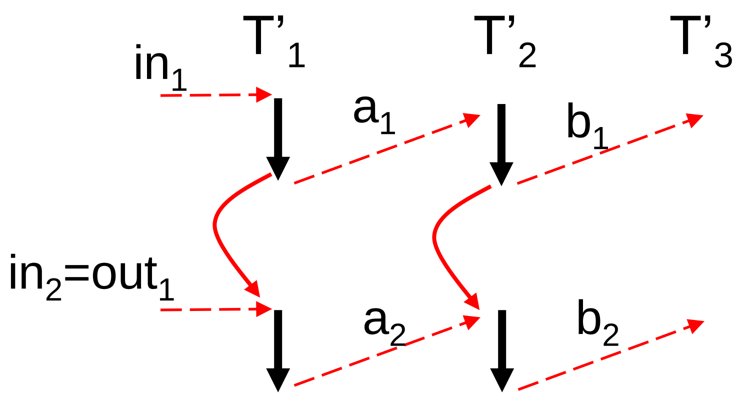


can context switch provided that $\langle a_1, out_1 \rangle$ is a linear interface

- Note that threads do not need to be the same we used in the first round and not even in the same number

Lazy sequentialization

- Second round is executed matching (<in_1,out_1>)

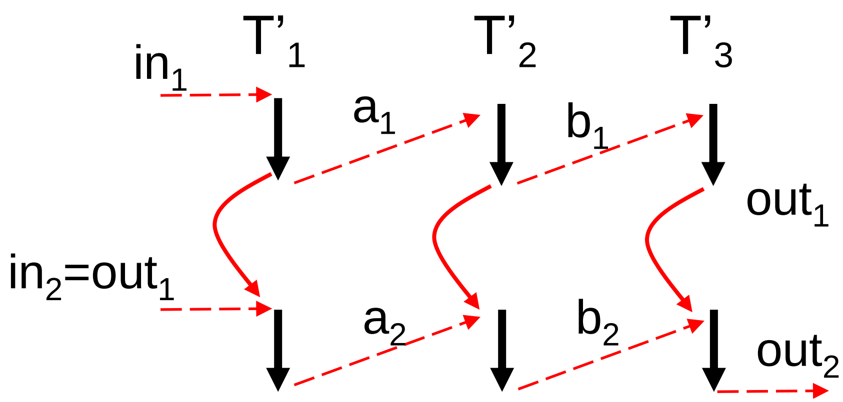


can context switch provided that <b_1,out_1> is a linear interface

- Note that threads do not need to be the same we used in the first round and not even in the same number

Lazy sequentialization

- Second round is executed matching ($\langle in_1, out_1 \rangle$)



context switch in last thread is allowed only with globals out_1

- Note that threads do not need to be the same we used in the first round and not even in the same number
- The third round is executed similarly by matching ($\langle in_1, in_2 \rangle, \langle out_1, out_2 \rangle$)

Dynamic thread creation

- New threads can be istantiated at runtime (e.g., thread creation, asynchronous calls)
- Computations may have unboundedly many threads running at the same time
- Main idea to handle dynamic creation:
  - schedule threads according to a (DFS) visit of the ordered thread-creation tree
  - this allows to use the call stack to explore the pending threads
- This nicely combines with the Eager scheme

Delay-bounded scheduling

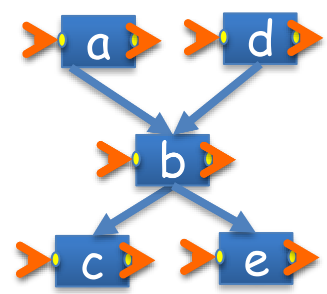
[Emmi-Qadeer-Rakamaric, POPL'11]

- Programs with asynchronous calls (creating tasks)
- Each task is executed to completion (no interleaving with other tasks)
- Sequentialization is according to a DFS scheduler of tasks
- When dispatched, a task can be delayed to next round
  - the total number of delays in a task-creation tree is bounded by k
  - total number of explored rounds is k+1
- The beginning of each round is guessed (eager)

General sequentialization

[Bouajjani-Emmi-Parlato, SAS'11]

- Programs with asynchronous calls
- Tasks can be interleaved with other ones
- Sequentialization based on generalization of Linear Interfaces
  - DAGs of contexts
  - Composition and compression operations



- Bound on the size of the DAGs
- Generalizes k-rounds Eager e delay bounded-scheduling sequentialization

Scope-bounded sequentialization

[La Torre-Napoli-Parlato, DLT'14] [La Torre-Parlato, FSTTCS'12]

- No dynamic thread creation
- k-scoped generalizes k-context analysis
  - bounds the number of times a thread is suspended/resumed between each matching call and returns
- Each scope is captured by a linear interface
- Sequentialization mantains a set of linear interfaces (one for each thread)
- Each thread contributes with many LI's in a computation
- Both Eager and Lazy schemes

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Conclusion

- Sequentialization is an effective approach to analyze concurrent programs
- Main features:
  - Fast prototyping
  - Re-use of mature technologies (tools for sequential programs)
  - Code-to-code translation
  - Introduces some overhead (variables, control code, recursive calls)

Conclusion

- Presented translations:
  - keep track only of the local state of the current thread (no cross product)
  - except for KISS, use # copies of the shared variables depending on the bounding parameter
  - thread creation is implemented with calls
- Eager translations require guessing of values of the shared variables and explore unreachable states
- Lazy translations preserve the invariants and introduces many recursive calls (re-computations)

Conclusions

- Experiments show:
  - Exploring only reachable states impacts positively the size of BDD's in the Getafix approach
  - Recursive calls impacts negatively the size of formulas in Bounded Model-Checking backends
- Sequentialization schemes should be targeted to a class of backends