Parallelizing Concuerror: A Dynamic Partial Order Reduction Testing Tool for Erlang Programs

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Summary

Aim of Thesis

- Develop parallel version for source-DPOR algorithm.

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- Develop parallel version for optimal-DPOR algorithm.

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- Implement those parallel algorithms at Concuerror.

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- Implement those parallel algorithms at Concuerror.
- Evaluate the performance of our implementation.

Section 1

Background

Concurrent Computing

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Essential because:

- Speed up execution time of programs
- Scale to multithreaded architectures
- Availability of services
- High responsiveness for I/O intensive programs

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Errors can occur only on specific rare interleavings. Detecting and reproducing bugs becomes extremely hard.

Modeling our Problem

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- The state space is the set of all possible interleavings.
- In order to verify a program, the complete state space must be explored.

Stateless Model Checking

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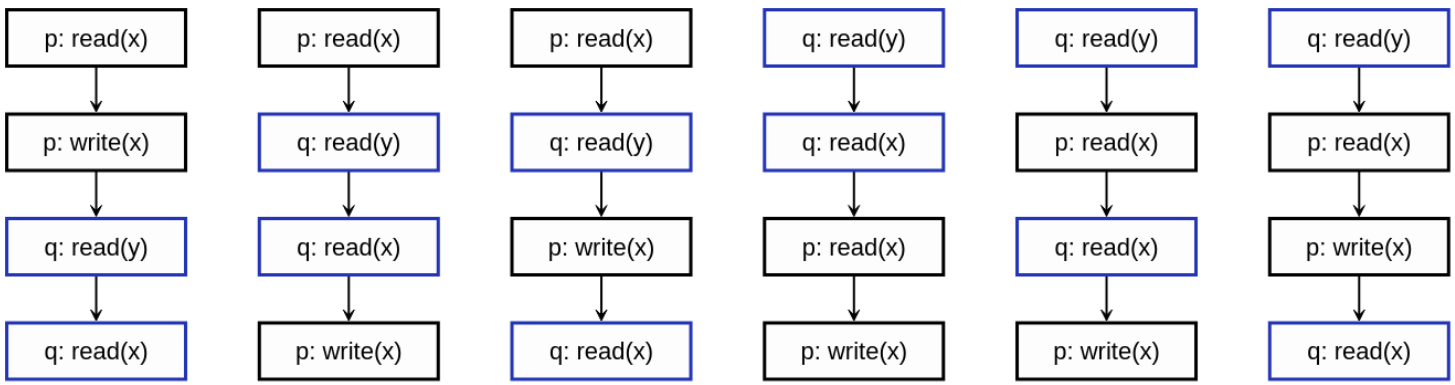

Figure: Stateless Model Checking Example

Partial Order Reduction

Partial Order Reduction tries to avoid exploring equivalent interleavings through race detection.

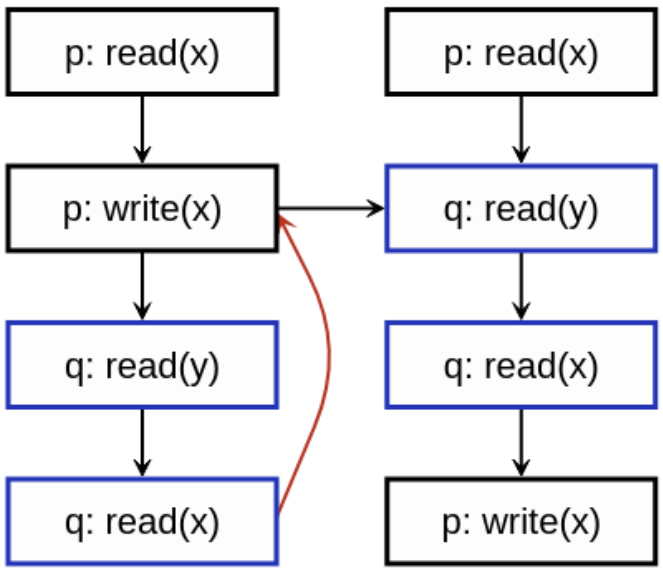

Figure: Partial Order Reduction Example

Partial Order Reduction

- Static Partial Order Reduction: Dependencies are tracked before execution, by statically analyzing the code.

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- Dynamic Partial Order Reduction (DPOR): Actual dependencies are observed during runtime.

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- The sequence of processes that perform steps in E also uniquely determines the global state of the system after E.
- We use $E \simeq E'$ to denote that E and E' are equivalent, and $[E]_{\simeq}$ to denote the equivalence class of E.

Explain races and happens-before???

Erlang

Erlang is a programming language that has build-in support for:

- Concurrency
- Distribution

Concurrent Erlang

In the core of concurrent Erlang are its lightweight processes which:

- are implemented by the Erlang VM's (BEAM) runtime system, not by operating system threads.
- are uniquely identified by their Pid (Process Identifier).
- communicate with each other mainly though message passing (actor model).

Erlang also has support for shared memory through the build-in ETS (Erlang Term Storage) module.

Distributed Erlang

- An Erlang node is an Erlang runtime system containing a complete virtual machine which contains its own address space and set of processes.
- Erlang nodes can connect with each other using cookies and they can communicate over the network.
- Multiple nodes can be easily started, either on the local host or at remote hosts (using ssh).
- Pids continue to be unique over different nodes (globally).
- Inside two different nodes, two different processes can have the same local Pid.
- Distributed Erlang Programs can run on different nodes.
- An Erlang process can be spawned on any node, local or remote. All primitives operate over the network similarly as they would on the same node.

Concuerror

Concuerror is a tool that various stateless model checking techniques in order to systematically test an Erlang program, with the aim of detecting and reporting concurrency-related runtime errors. Its main components are:

- the Instrumenter:
  - adds preemption points to various points in the code of a tested program.
  - makes it possible to produce specific interleaving.
- the Scheduler:
  - uses mainly source-DPOR or optimal-DPOR, to determine which interleavings need to be checked.
  - controls the execution of the processes to produce those interleavings.

Section 2

Sequential DPOR Algorithms

General DPOR Concepts

DPOR: performs a DFS using a backtrack set. Exploration is based on two techniques that reduce the amount of the explored interleavings:

- Persistent sets: only a provably sufficient subset of the enabled processes gets explored.

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- Persistent sets: only a provably sufficient subset of the enabled processes gets explored.
- Sleep sets: contain processes, whose exploration would be redundant, preventing equivalent interleavings from being fully explored.

Optimality in DPOR

- A DPOR algorithm is optimal if, for every maximal execution sequence E, it explores exactly one interleaving from $[E]_{\simeq}$.
- Sleep-set blocking: most DPOR algorithms are not optimal.

Source Sets

Definition 1 (Initials after an execution sequence $E.w$, $I_{[E]}(w)$)

$p \in I_{[E]}(w)$ if and only if there is a sequence w' such that $E.w \simeq E.p.w'$.

Definition 2 (Weak Initials after an execution sequence $E.w$, $WI_{[E]}(w)$)

$p \in WI_{[E]}(w)$ if and only if there are sequences w' and v such that $E.w.v \simeq E.p.w'$.

Definition 3 (Source Sets)

Let E be an execution sequence, and let W be a set of sequences, such that $E.w$ is an execution sequence for each $w \in W$. A set T of processes is a source set for W after E if for each $w \in W$ we have $WI_{[E]}(w) \cap T \neq \emptyset$.

Intuitively, source sets contain the processes that can perform "first steps" in the possible future execution sequences.

Source-DPOR

Function *Explore(E,Sleep)*
  if $\exists p \in (enabled(s_{[E]}) \backslash Sleep)$ **then**
    $backtrack(E) := p$;
    while $\exists p \in (backtrack(E) \backslash Sleep)$ **do**
      foreach $e \in dom(E)$ *such that* $e \lesssim_{E.p} next_{[E]}(p)$ **do**
        let $E' = pre(E, e)$;
        let $u = notdep(e, E).p$;
        if $I_{[E']}(u) \cap backtrack(E') = \emptyset$ **then**
          add some $q' \in I_{[E']}(u)$ to $backtrack(E')$;
        end
      end
      let $Sleep' := \{q \in Sleep \mid E \models p \diamondsuit q\}$;
      $Explore(E.p, Sleep')$;
      add p to $Sleep$;
    end
  end

Algorithm 1: Source-DPOR

Source-DPOR

Lets note that:

- the algorithm works in two phases: race detection (or planning) and state exploration.
- $Explore(E, Sleep)$ is responsible for exploring the complete subtree of our state space rooted at E. More formally, for all maximal execution of form $E.w$, at least on trace from every $[E.w]_{\simeq}$ gets explored.

Source-DPOR

Source-DPOR in action:

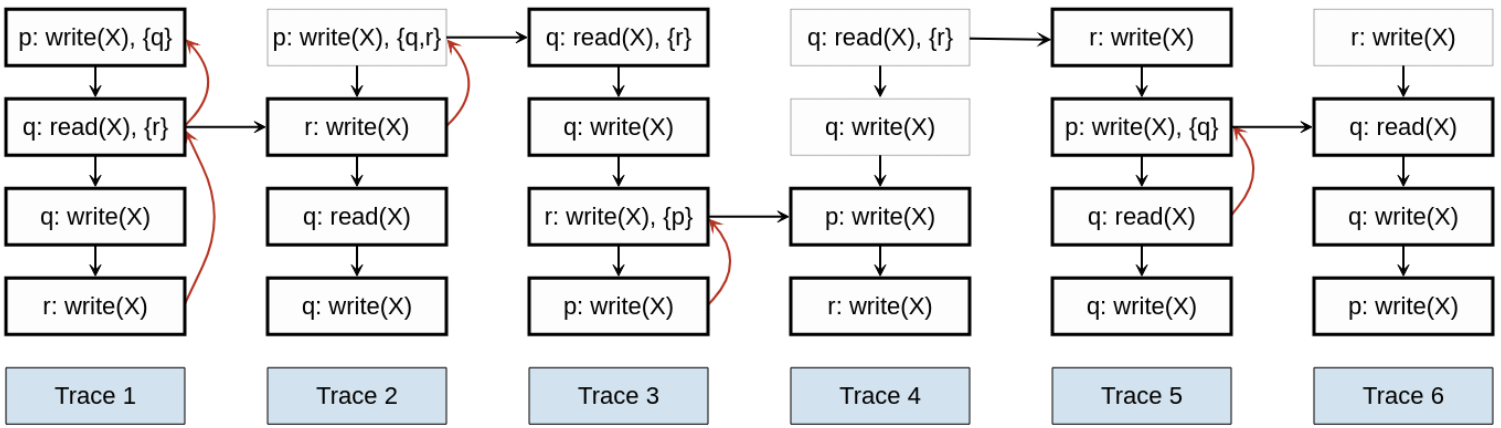


Figure: Interleavings explored by the source-DPOR.

Motivation for Wakeup Trees

Function *Explore(E,Sleep)*
- **if** $\exists p \in (enabled(s_{[E]}) \backslash Sleep)$ **then**
  - $backtrack(E) := p$;
  - **while** $\exists p \in (backtrack(E) \backslash Sleep)$ **do**
    - **foreach** $e \in dom(E)$ *such that* $e \lesssim_{E.p} next_{[E]}(p)$ **do**
      - **let** $E' = pre(E, e)$;
      - **let** $u = notdep(e, E).p$;
      - **if** $I_{[E']}(u) \cap backtrack(E') = \emptyset$ **then**
        - add some $q' \in I_{[E']}(u)$ to $backtrack(E')$;
      - **end**
    - **end**
    - **let** $Sleep' := \{q \in Sleep \mid E \vDash p \diamondsuit q\}$;
    - $Explore(E.p, Sleep')$;
    - add p to $Sleep$;
  - **end**
- **end**

- $E'.u$ needs to be explored.
- But only a single process gets added to the backtrack.
- This may lead to sleep-set blocking.

Wakeup Trees

Definition 4

(Ordered Tree)

An $ordered\ tree$ is a pair $\langle B, \prec \rangle$, where B (the set of nodes) is a finite prefix-closed set of sequences of processes with the empty sequence $\langle\rangle$ being the root. The children of a node w, of form $w.p$ for some set of processes p, are ordered by $\prec$. In $\langle B, \prec \rangle$, such an ordering between children has been extended to the total order $\prec$ on B by letting $\prec$ be the induced post-order relation between the nodes in B. This means that if the children $w.p_1$ and $w.p_2$ are ordered as $w.p_1 \prec w.p_2$, then $w.p_1 \prec w.p_2 \prec w$ in the induced post-order.

Definition 5

(Wakeup Tree)

Let E be an execution sequence and P a set of processes. a $wakeup\ tree$ after $\langle E, P \rangle$ is an ordered tree $\langle B, \prec \rangle$, for which the following properties hold:

- $WI_{[E]}(w) \cap P = \emptyset$ for every leaf w of B.
- For every node in B of the form $u.p$ and $u.w$ such that $u.p \prec u.w$ and $u.w$ is a leaf the $p \notin WI_{[E.u]}(w)$ property must hold true.

Wakeup Trees

Intuitively, wakeup trees hold in the form of a tree the fragments that need to be explored in order to explore the necessary interleavings. They can visualized in the following way:

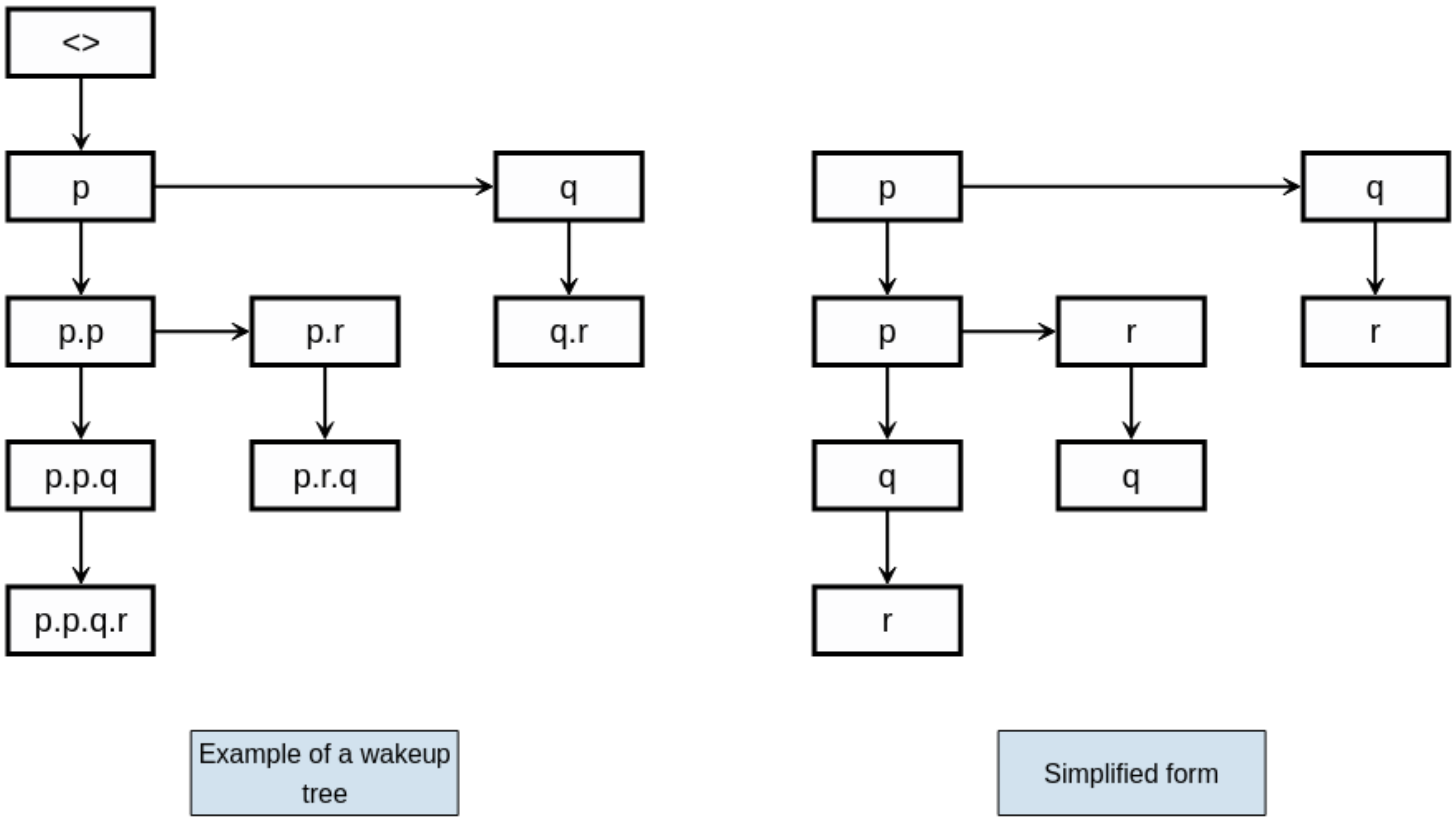


Figure: Visualizing wakeup trees.

Wakeup Trees

Inserting new sequences ($insert_{[E]}(w, \langle B, \prec \rangle)$) in the wakeup tree has the following properties:

- $insert_{[E]}(w, \langle B, \prec \rangle)$ is also a wakeup tree after $\langle E, P \rangle$.
- Any leaf of $\langle B, \prec \rangle$ remains a leaf of $insert_{[E]}(w, \langle B, \prec \rangle)$.
- $insert_{[E]}(w, \langle B, \prec \rangle)$, while it may not contain w as a leaf, it contains a leaf u with $u \sim_{[E]} w$.

Optimal-DPOR

Function *Explore*$(E, Sleep, WuT)$
  if $enabled(s_{[E]}) = \emptyset$ **then**
    foreach $e, e' \in dom(E)$ *such that* $(e \lesssim_E e')$ **do**
      let $E' = pre(E, e)$;
      let $v = notdep(e, E).proc(e')$;
      if $sleep(E') \cap WI_{[E']}(v) = \emptyset$ **then**
        $insert_{[E']}(v, wut(E'))$;
      end
    end
  else
    if $WuT \neq \langle\{\langle\rangle\}, \emptyset\rangle$ **then**
      $wut(E) := WuT$;
    else
      choose $p \in enabled(s_{[E]})$;
      $wut(E) := \langle\{p\}, \emptyset\rangle$;
    end
    $sleep(E) := Sleep$;
    while $\exists p \in wut(E)$ **do**
      let $p = min_{\prec}\{p \in wut(E)\}$;
      let $Sleep' := \{q \in sleep(E) \mid E \vDash p \diamondsuit q\}$;
      let $WuT' = subtree(wut(E), p)$;
      $Explore(E.p, Sleep', WuT')$;
      add p to $sleep(E)$;
      remove all sequences of form $p.w$ from $wut(E)$;
    end
  end

Algorithm 2: Optimal-DPOR

TODO: Add example here

Section 3

Parallelizing source-DPOR and optimal-DPOR

Parallel source-DPOR

How would we parallelize a simple backtrack search algorithm?
Lets assume that we have an execution sequence E and that p and q are processes in $backtrack(E)$. We could:

- Assign the exploration of $E.p$ and $E.q$ to different workers-schedulers i.e., assign to different schedulers different subtrees of our state space.
- However, the exploration frontier gets updated in a non-local manner: some process r can be added at $backtrack(E)$ by both our schedulers.
- Who would be responsible for exploring $E.r$?
- How do we now that the subtrees are balanced?

Basic Idea

We are going to use a centralized Controller who will be responsible for:

- assigning work to different schedulers.
- resolving conflicts concerning backtrack entries that may have been discovered by multiple schedulers.

The Controller will keep track of:

- the Frontier of our search: the set of the execution sequences assigned to different schedulers.
- the Execution Tree: the subset of the state space that is currently being explored i.e., the Frontier combined in a tree form. A path from the root of tree to a leaf uniquely determines an execution sequence.

Basic Idea

Also, lets introduce the concept of Execution Tree node ownership:

- A scheduler exclusively **owns** a node of the state space if:
  - it is contained as a backtrack entry within the part of the Frontier that was assigned to that specific scheduler, or
  - it is a descendant of a node that the scheduler owns.
- All other nodes, are considered to have a **disputed** ownership.

Parallel source-DPOR

Function *controller_loop*$(N,\ Budget,\ Schedulers)$

```
E_0 ← an arbitrary initial execution sequence;
Frontier ← [E_0];
T ← an execution tree rooted at E_0;
while Frontier ≠ ∅ do
    Frontier ← partition(Frontier, N);
    while exists an idle scheduler S and an unassigned execution sequence E
     in Frontier do
        E_c ← a copy of E;
        mark E as assigned in Frontier;
        spawn(S, explore_loop(E_c, Budget));
    end
    Frontier, T ← wait_scheduler_response(Frontier, T);
end
```

Algorithm 3: Controller Loop

Parallel source-DPOR

Function *partition*$(Frontier,\ N)$

- **for** *all* $E \in$ *Frontier* **do**
  - **while** $total\_backtrack\_entries(E) > 1$ ***and*** $size(Frontier) < N$ **do**
    - $E' \leftarrow$ the smallest prefix of E that has a backtrack entry ;
    - $p \leftarrow$ a process $\in backtrack(E')$;
    - $E'_c \leftarrow$ a copy of E';
    - remove p from $backtrack(E')$;
    - add p to $sleep(E')$;
    - add $backtrack(E')$ to $sleep(E'_c)$;
    - add E'_c to $Frontier$;
  - **end**
- **end**
- **return** $Frontier$;

Algorithm 4: Frontier Partitioning

Parallel source-DPOR

Function *explore_loop*(E_0, $Budget$)

$StartTime \leftarrow get\_time()$;
$E \leftarrow E_0$;
repeat
  $E' \leftarrow explore(E)$;
  $E' \leftarrow plan\_more\_interleavings(E')$;
  $E \leftarrow get\_next\_execution\_sequence(E')$;
  $CurrentTime \leftarrow get\_time()$;
until $CurrentTime - StartTime > Budget$ ***or*** $size(E) \leq size(E_0)$;
send E to Controller ;

Algorithm 5: Scheduler Exploration Loop

Parallel source-DPOR

Function *wait_scheduler_response(Frontier, T)*

```
receive E from a scheduler;
remove E from Frontier;
E', T ← update_execution_tree(E, T);
if E' has at least one backtrack entry then
    add E' to Frontier;
end
return Frontier, T;
```

Algorithm 6: Handling Scheduler Response

Load Balancing

TODO: explain how load balancing works

Parallel source-DPOR

TODO: add example

Parallel optimal-DPOR - A first attempt

While trying to parallelize optimal-DPOR following the same technique we encounter two main issues:

- In the sequential optimal-DPOR calls to $Explore(E, Sleep, WuT)$ guarantee that the complete subtree rooted at E will be explored. However, for this to hold true, all sequences in $wut(E)$ that were ordered before WuT must have been explored. This means that the concept of ownership cannot be applied to complete wakeup trees.
- $insert_{[E]}(v, wut(E))$ may end up inserting at $wut(E)$ an execution sequence different than v (but one that will lead to equivalent interleavings).

Parallel optimal-DPOR - A first attempt

However, we do know that any leaf of $\langle B, \prec \rangle$ remains a leaf of $insert_{[E]}(w, \langle B, \prec \rangle)$.
We use this to develop a parallel algorithm that uses:

- a single planner that is responsible for race detecting interleavings sequentially.
- multiple schedulers that simply explore in parallel the interleavings that generated by the planner
- a Controller who is responsible for managing the queue of the planner and for assigning interleavings to schedulers for exploration

Parallel optimal-DPOR - A first attempt

This attempt fails to provide any speedup (info about the test cases will be provided at the Performance Evaluation section):

Benchmark	Planning Time (%)	Exploration Time(%)	Sequential Time	Time for 4 Schedulers	Time for 24 Schedulers
readers 15	71.7%	28.3%	52m43.585s	98m28.251s	97m13.762s
lastzero 15	80.5%	19.5%	13m32.843s	24m98,312s	24m21,219s
readers 10	59.1%	40.9%	43.267s	59.699s	54.592s

Table: Parallel optimal-DPOR performance.

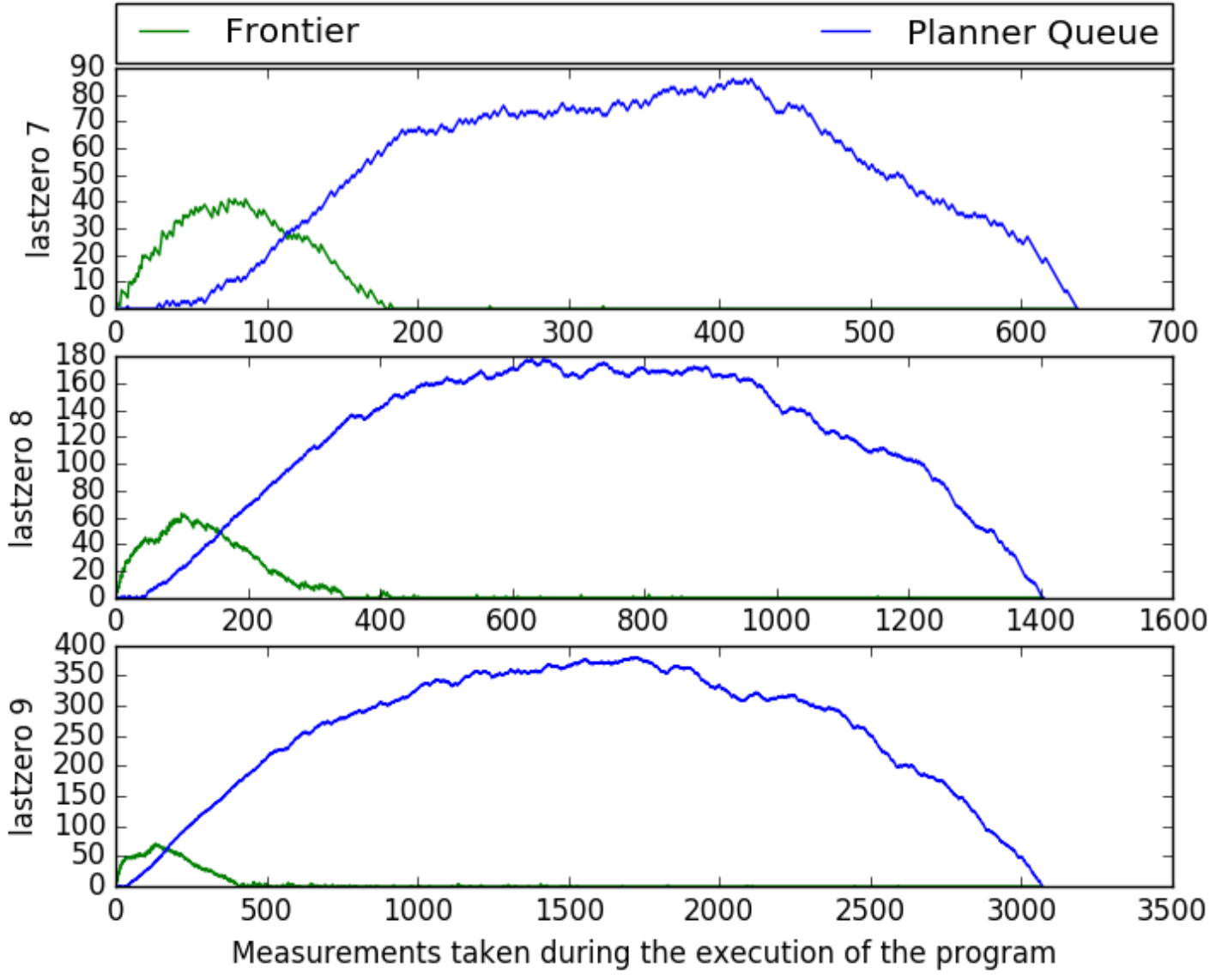
Parallel optimal-DPOR - A first attempt

Our attempt fails because:

- We have parallelized the exploration phase of our algorithm, but have kept the most time consuming phase sequential.
- We have noticed that the planner, during most of the execution of our program, does not generate enough interleavings to keep the schedulers busy.

Parallel optimal-DPOR - A first attempt

This behavior can be observed from the following graphs:



Scalable parallel optimal-DPOR

Here I will present how I solved the two main issues, the algorithm and an example

Section 4

Implementation Details

Here I will why erlang pids need to be the same for every process of the tested program with Concuerror
I will present how I solved it
Present disadvantages of this Distributed implementation
Should I merge this with Erlang and Concuerror brief overview in the beginning?

Section 5

Performance Evaluation

Benchmarks

- The benchmarks were performed on a multiprocessor with 64 AMD Opteron 6276(2.3 GHz) cores, 126 GB of memory, running Linux 4.9.0-8amd64 and running the later Erlang version (Erlang/OTP 21.1).
- While running our tests, we are using the $-keep\_going$ flag to continue exploring our state space, even after an error is found. We do this so we can evaluate how fast the complete state space gets explored, regardless of whether errors exist.

Benchmarks

Lets give a brief overview of our benchmarks:

- $indexer\ N$: This test uses a Compare and Swap (CAS) primitive instruction to check if a specific element of a matrix is set to 0 and if so, set it to a new value. This is implemented in Erlang by using ETS tables and specifically the $insert\_new/2$ function. This function returns false if the key of the inserted tuple exists (the entry is set to 0) or it inserts the tuple if the key is not found. N refers to the number of threads that are performing this function.
- $readers\ N$: This benchmark uses a writer process that writes a variable and N reader processes that read that variable.
- $lastzero\ N$: In this test we have $N + 1$ processes that read and write on an array of $N + 1$ size, which has all its values initialized with zero. The first process reads the array in order to find the zero element with the highest index. The other N processes read an array element and update the next one.
- $rush\ hour$: a program that uses processes and ETS tables to solve the Rush Hour puzzle in parallel, using A*search. Rush hour is a complex but self-contained (917 lines of code) program.

Results for sequential algorithms

Lets present here number of interleavings for our benchmarks, as well as their performance for sequential algorithm and the parallel algorithm with one scheduler:

Benchmark	Traces for source-DPOR	Traces for optimal-DPOR	Time for source-DPOR	Time for parallel source-DPOR with 1 scheduler	Time for optimal-DPOR	Time for parallel optimal-DPOR with 1 scheduler
lastzero 11	60073	7168	49m8.510s	53m59.169s	14m8.266s	17m50.494s
indexer 15	4096	4096	TODO	TODO	TODO	TODO
readers 15	32768	32768	37m68.865s	46m28.711s	51m40.792s	67m50.643s
rush hour	46656	46656	52m36.889s	56m3.521s	51m11.184s	58m32.962s

Table: Sequential source-DPOR vs optimal-DPOR for our benchmarks.

We can notice that the overhead for our parallel optimal-DPOR appears to be larger than the overhead of the parallel source-DPOR. This is to be expected since updating the execution tree in the Controller should be more expensive for the optimal algorithm.

Evaluation on readers 15

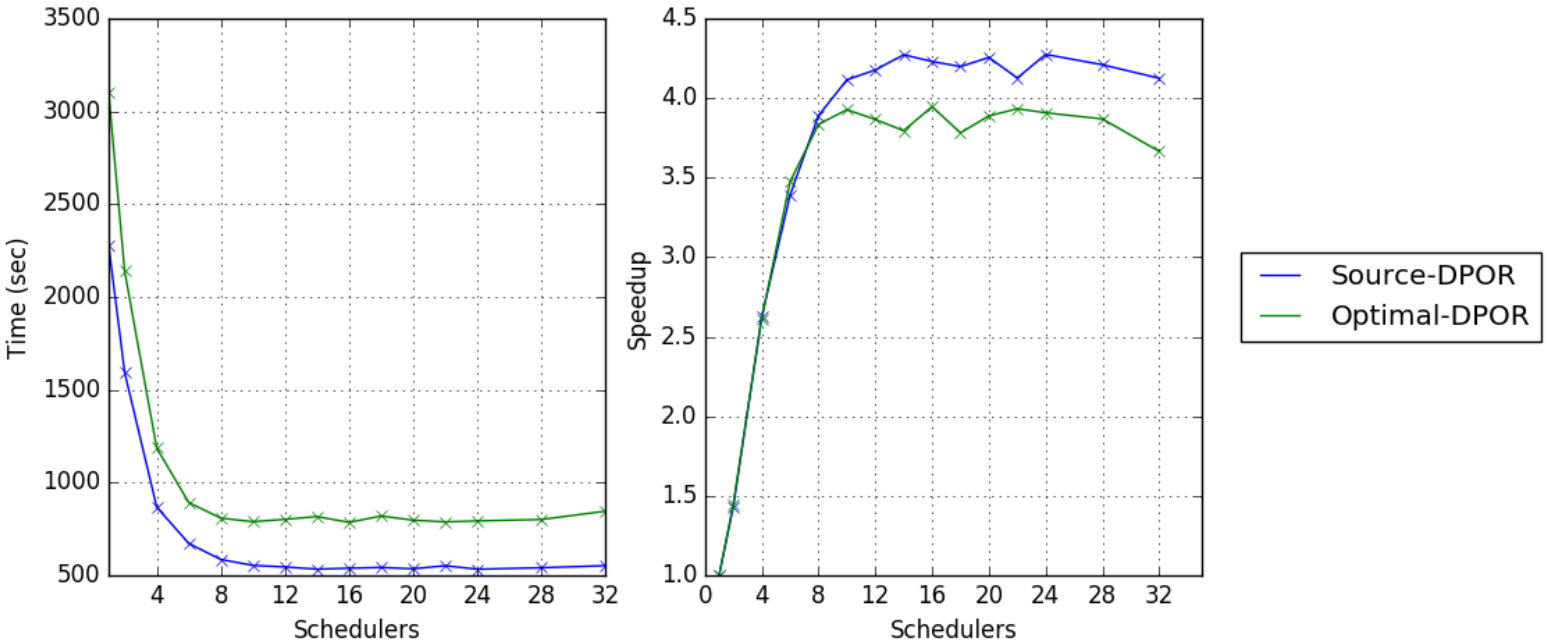


Figure: Performance of readers 15 with Budget of 10000.

Evaluation on readers 15

Trying to figure out why our algorithm fails scale for readers 15:

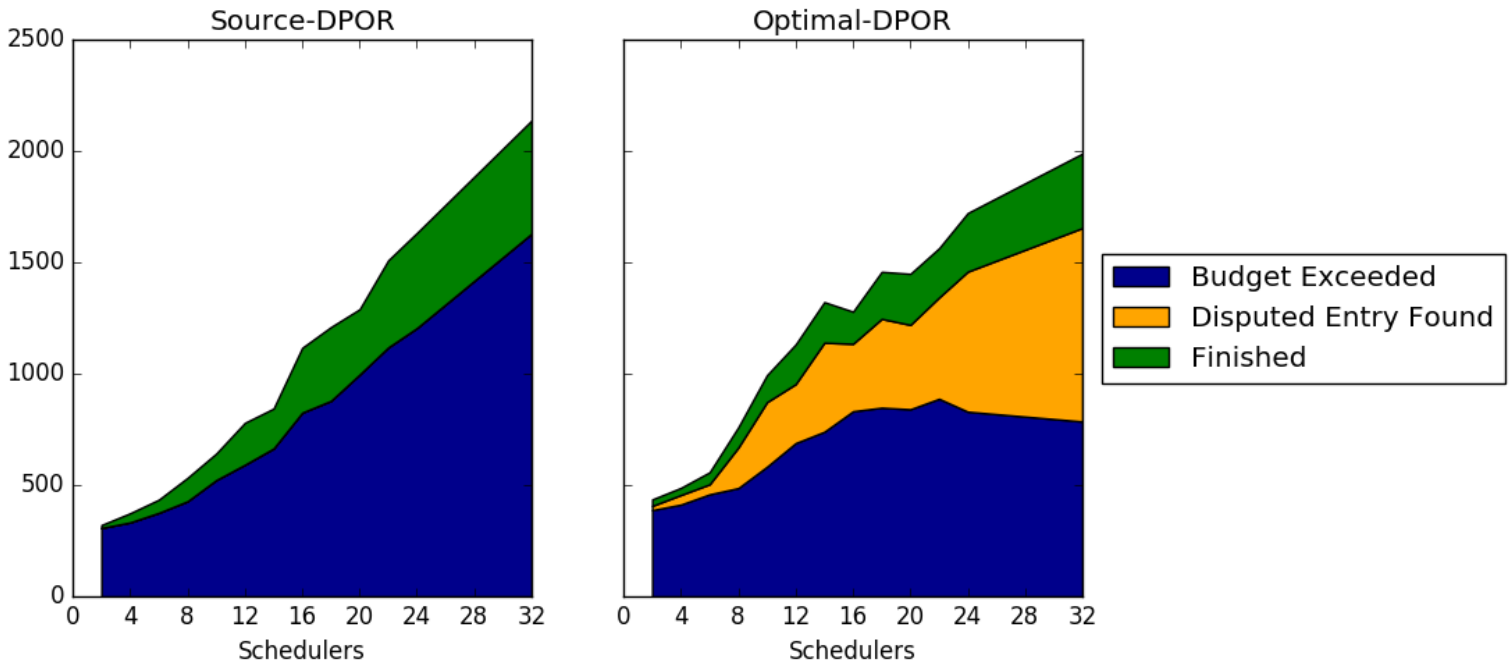


Figure: Number of times schedulers stopped their execution with a Budget of 10000.

Evaluation on readers 15

Increase budget to 30000ms:

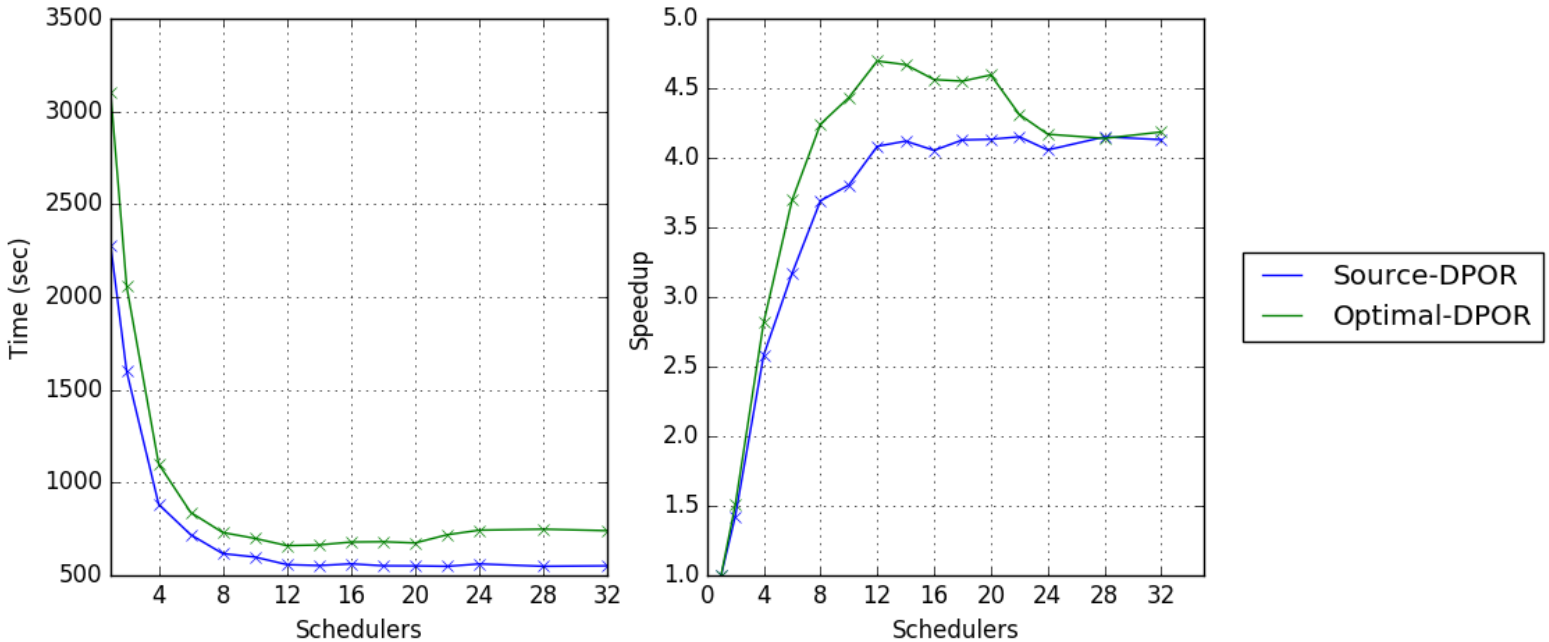


Figure: Performance of readers 15 with budget of 30000.

Evaluation on readers 15

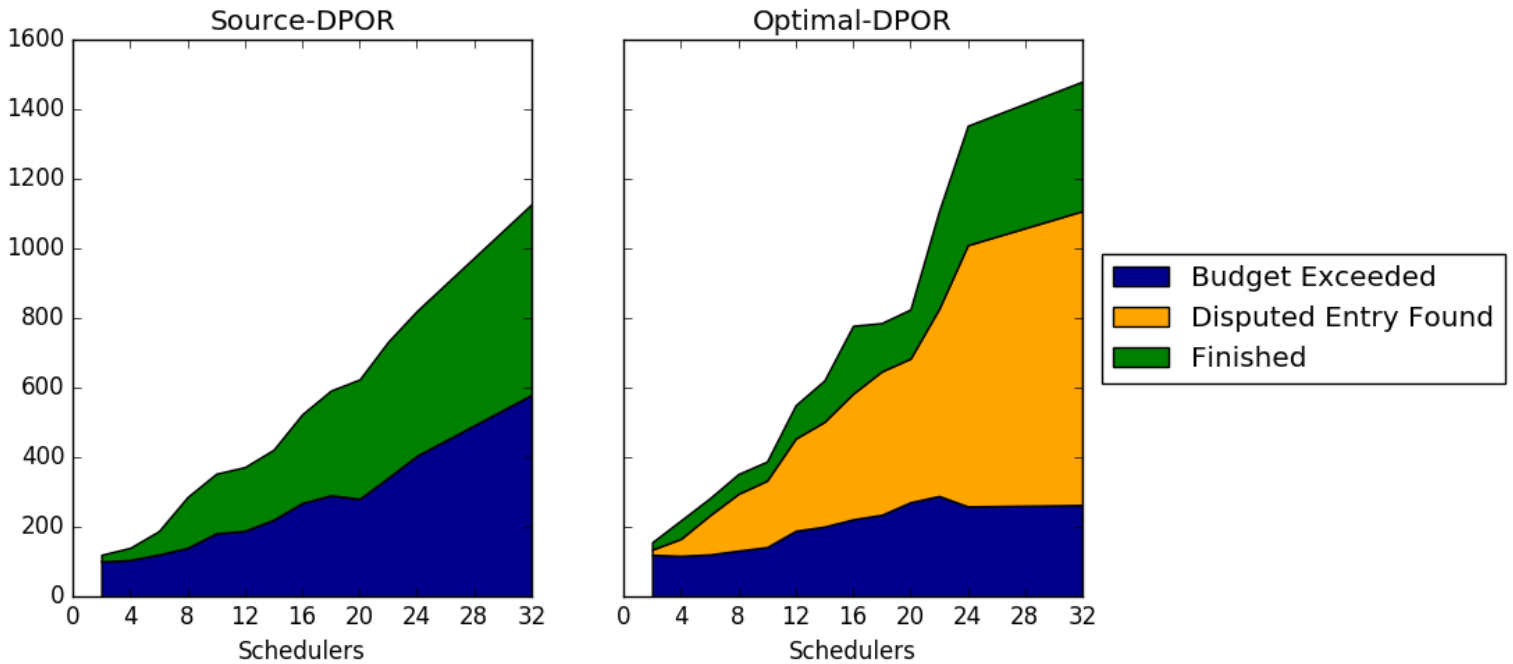


Figure: Number of times schedulers stopped their execution with a Budget of 30000.

Evaluation on readers 15

Increasing the Budget:

- Reduces the performance of source-DPOR, since it causes load imbalance.
- Increases the performance of optimal-DPOR, since finding disputed entries also leads to load balancing and therefore, optimal-DPOR does not need as frequent load balance.

Evaluation on rush hour

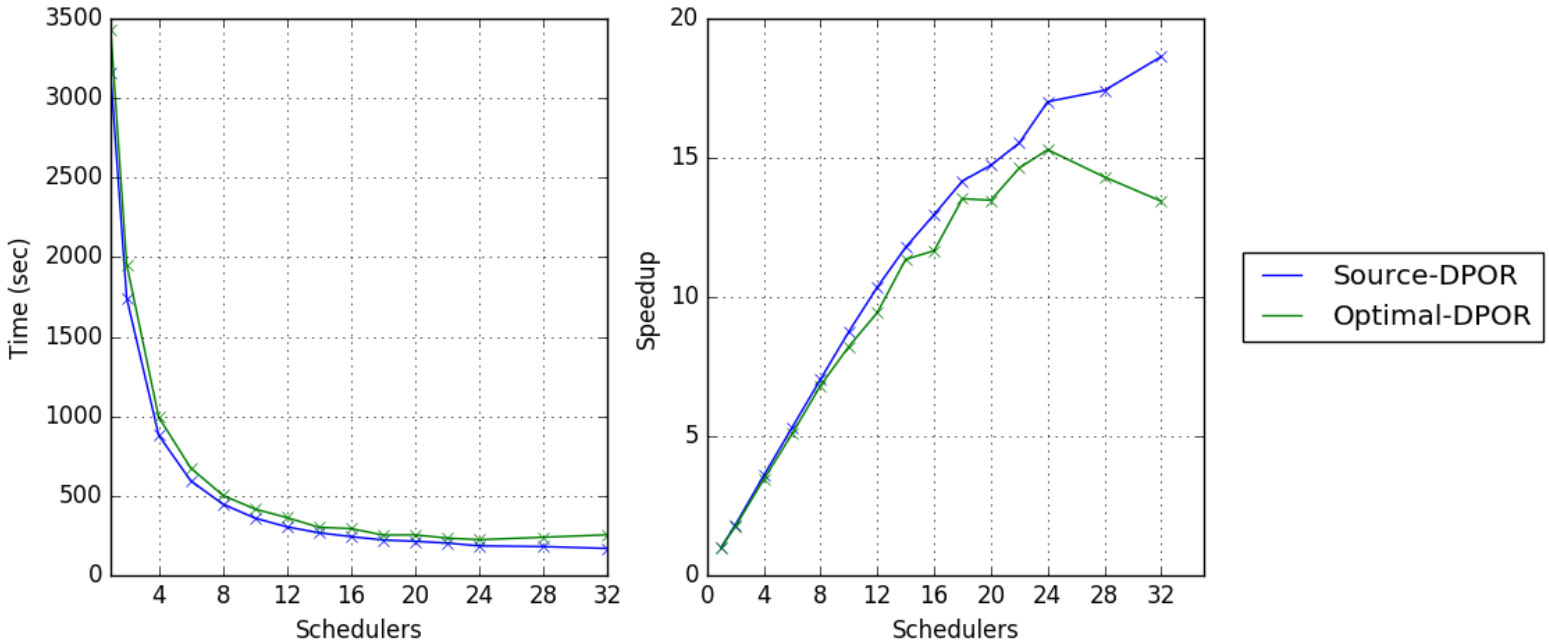


Figure: Performance of rush hour with Budget of 10000 for source and 30000 for optimal.

Evaluation on rush hour

Both of our algorithms provide high speed and decent scalability on this test case. However, after 24 schedulers we notice that the scalability of optimal-DPOR starts to break. This is because:

- the communication between the Controller and the schedulers in the case of optimal-DPOR is substantially more frequent.
- the $update\_execution\_tree$ function in optimal-DPOR is more "expensive".
- each execution sequence send between the schedulers and the Controller of the optimal-DPOR is larger, since it also contains wakeup trees from other fragments

Evaluation on indexer

TODO add evaluation of indexer and lastzero

Conclusion

- We managed to develop parallel versions for both source-DPOR and optimal-DPOR algorithms.
- We showed that developing a parallel version that is based on sequentially race detecting interleavings and exploring them in parallel will fail to provide any substantial speedup.
- We implemented our algorithms on Concuerror, while encountering and solving complex implementation issues.
- We showed that our algorithms achieve good speedups and even continue to scale up to 32 schedulers (24 for optimal-DPOR) on specific benchmarks.

Bibliography

Add Bibliography??