Space Profiling for Parallel Functional Programs

Daniel Spoonhower[1], Guy Blelloch[1], Robert Harper[1], & Phillip Gibbons[2]

[1]Carnegie Mellon University
[2]Intel Research Pittsburgh

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Improving Performance – Profiling Helps!

Profiling improves functional program performance.

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Good performance in parallel programs is also hard.

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This work: space profiling for parallel programs

Example: Matrix Multiply

Naïve NESL code for matrix multiplication

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Given a parallel functional program, can we determine,

"How much space will it use?"

Short answer: It depends on the implementation.

Scheduling Matters

Parallel programs admit many different executions

- not all impl. of matrix multiply are $O(n^3)$

Determined (in part) by scheduling policy

- lots of parallelism; policy says what runs next

Semantic Space Profiling

Our approach: factor problem into two parts.

1. Define parallel structure (as graphs)
   - circumscribes all possible executions
   - deterministic (independent of policy, &c.)
   - include approximate space use
2. Define scheduling policies (as traversals of graphs)
   - used in profiling, visualization
   - gives specification for implementation

Contributions

Contributions of this work:

- cost semantics accounting for...
  - scheduling policies
  - space use
- semantic space profiling tools
- extensible implementation in MLton

Talk Summary

Cost Semantics, Part I: Parallel Structure

Cost Semantics, Part II: Space Use

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Program Execution as a Dag

Model execution as directed acyclic graph (dag)

One graph for all parallel executions

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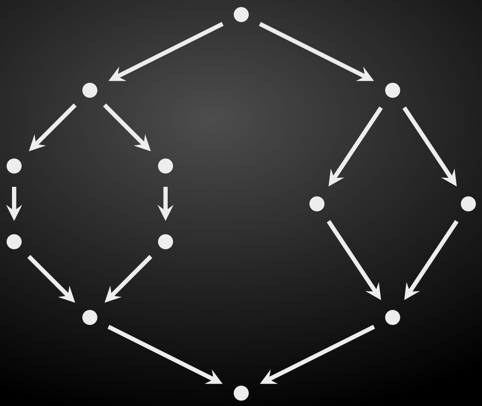
A policy determines schedule for every program

Program Execution as a Dag (con't)



Program Execution as a Dag (con't)

Graphs are NOT...

- control flow graphs
- explicitly built at runtime

Graphs are...

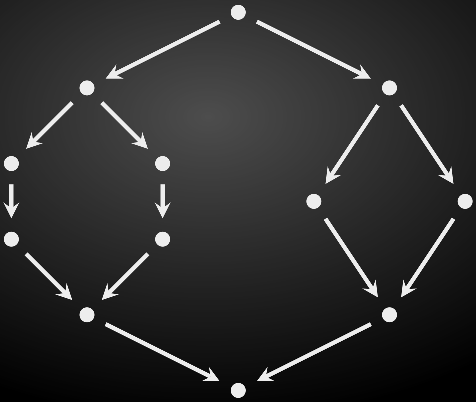
- derived from cost semantics
- unique per closed program
- independent of scheduling

Breadth-First Scheduling Policy

Scheduling policy defined by:

- breadth-first traversal of the dag
  (*i.e.* visit nodes at shallow depth first)
- break ties by taking leftmost node
- visit at most p nodes per step
  (p = number of processor cores)

Breadth-First Illustrated ($p = 2$)



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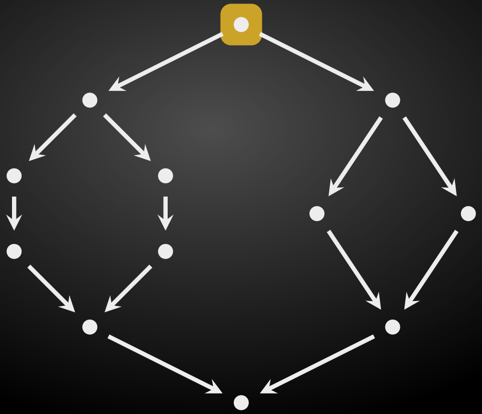

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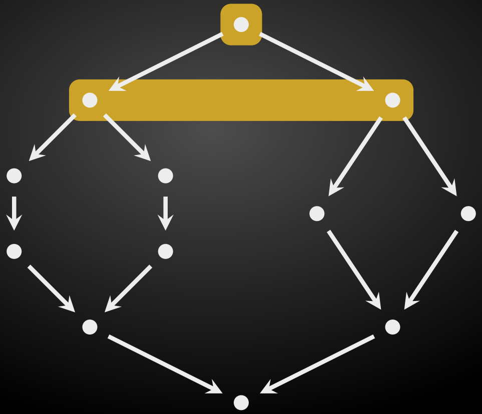

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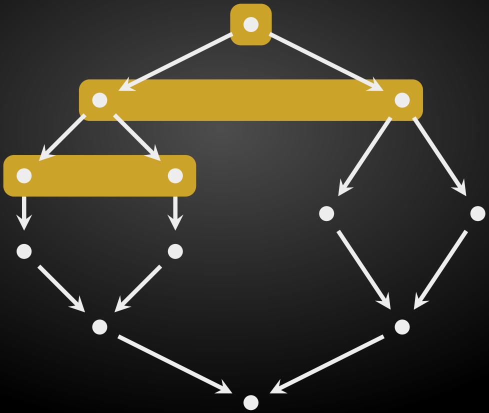

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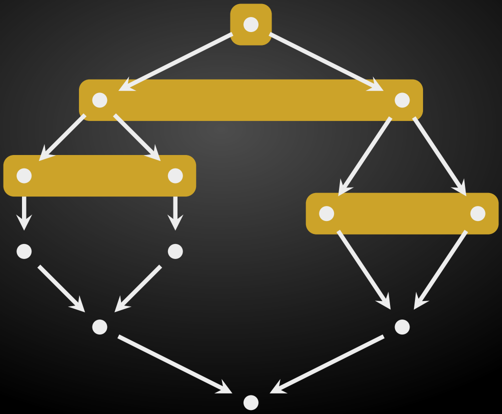

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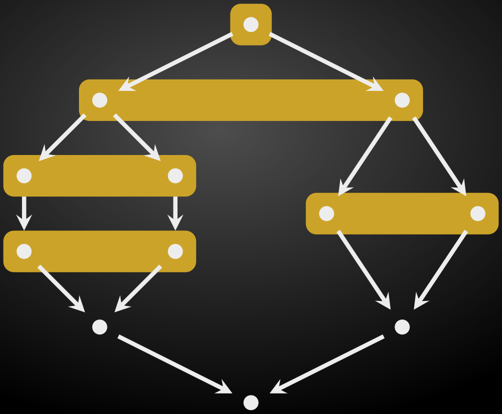

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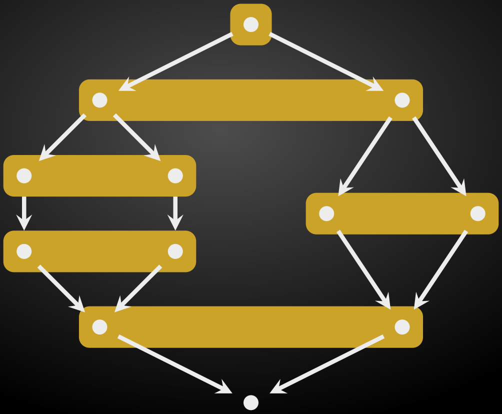

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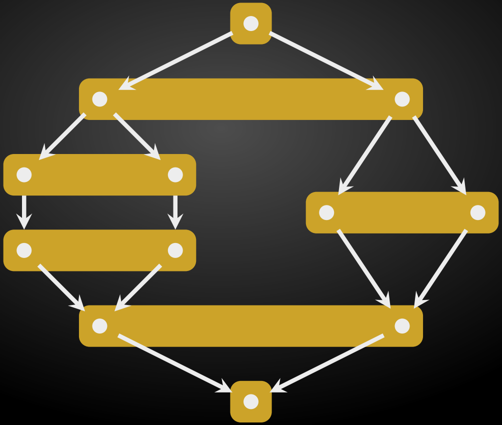

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Variation implicit in impls. of NESL
& Data Parallel Haskell

- vectorization bakes in schedule

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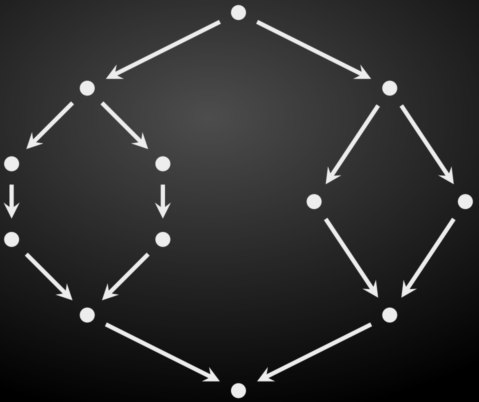

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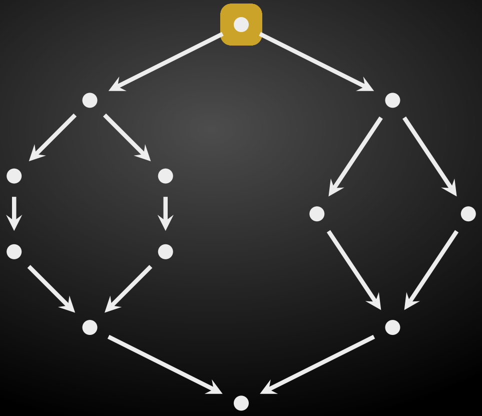

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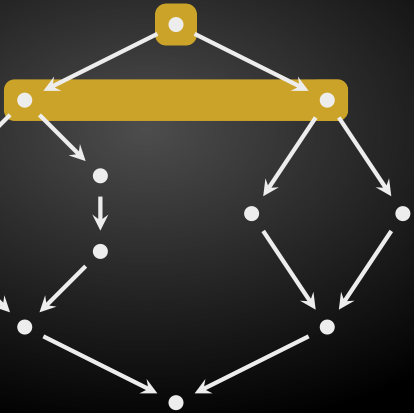

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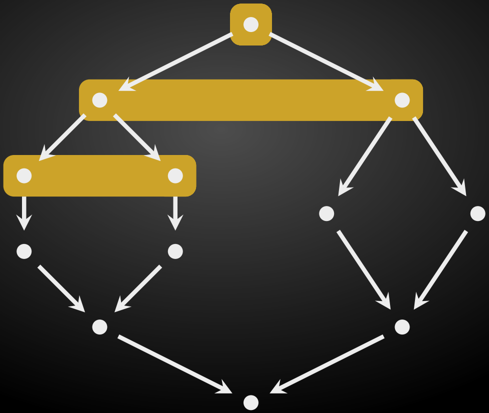

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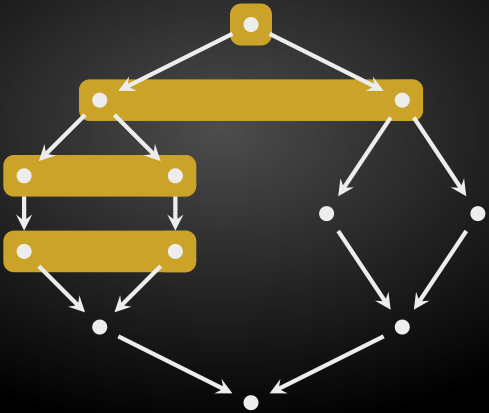

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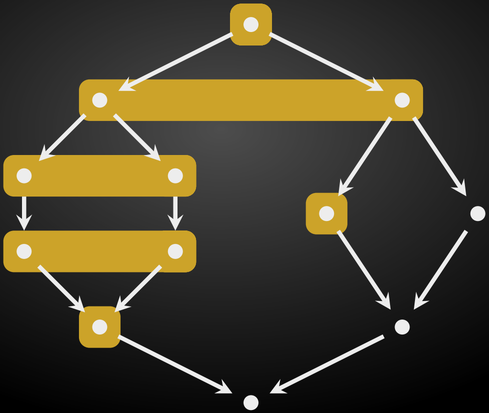

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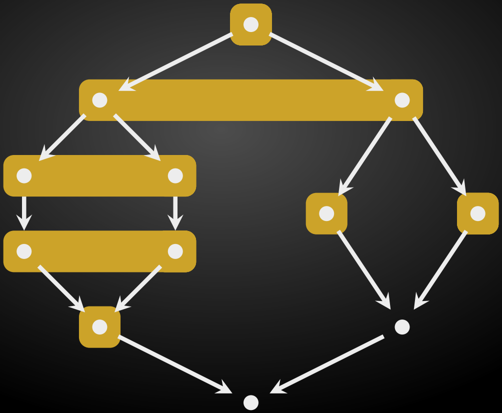

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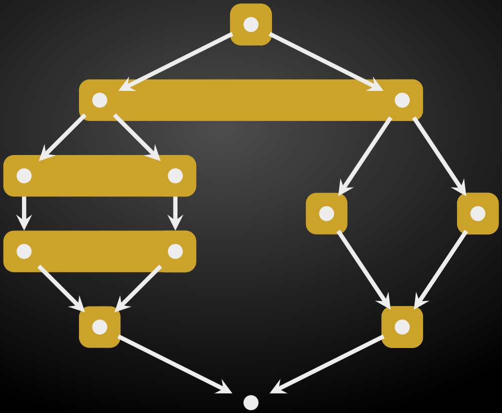

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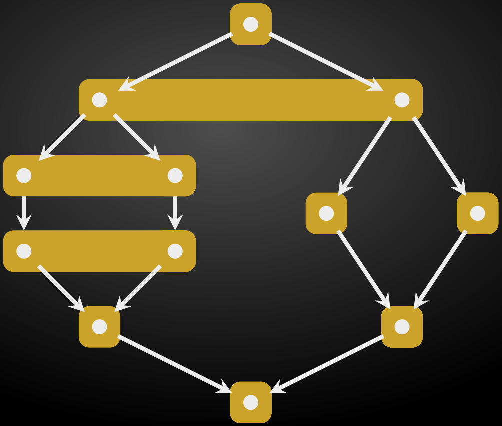

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Sequential execution
 = one processor depth-first schedule

Work-Stealing Scheduling Policy

"Work-stealing" means many things:

- idle procs. shoulder burden of communication
- specific implementations, *e.g.* Cilk
- implied ordering of parallel tasks

For the purposes of space profiling, ordering is important

- briefly: globally breadth-first, locally depth-first

Computation Graphs: Summary

Cost semantics defines graph for each closed program

- *i.e.*. defines parallel structure
- call this graph computation graph

Scheduling polices defined on graphs

- describe behavior *without* data structures, synchronization, &c.

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Heap Graphs

Goal: describe space use independently of schedule

- our innovation: add heap graphs

Heap graphs also act as a specification

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Computation & heap graphs share nodes.

- think: one graph w/ two sets of edges

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Generate costs for parallel pair,

$$\{e_1, e_2\}$$

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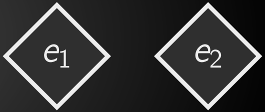

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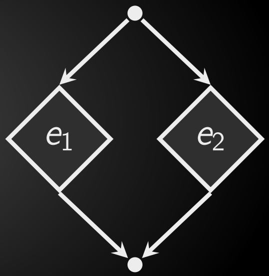

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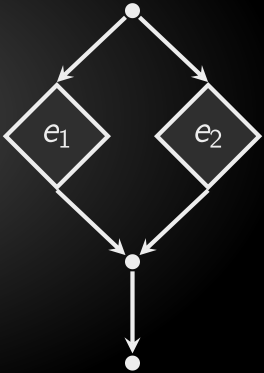

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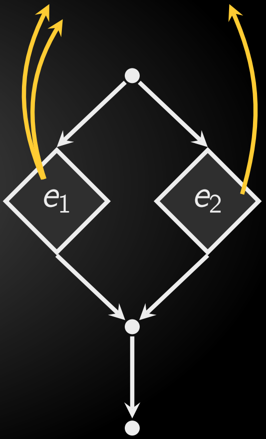

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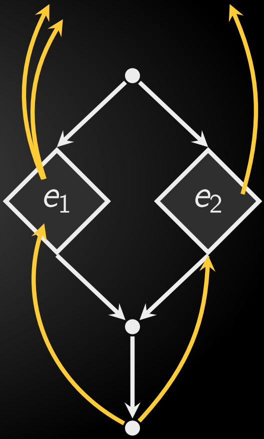

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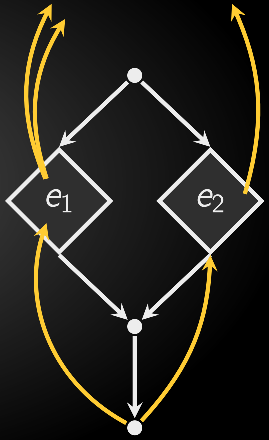

From Cost Graphs to Space Use

Recall, schedule = traversal of computation graph

- visiting p nodes per step to simulate p processors

Each step of traversal divides set of nodes into:

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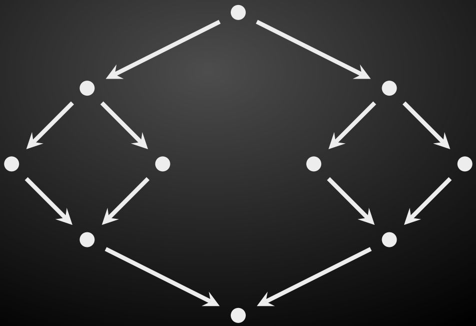
Heap edges crossing from future to past are "roots"

- *i.e.* future uses of existing values

Determining Space Use



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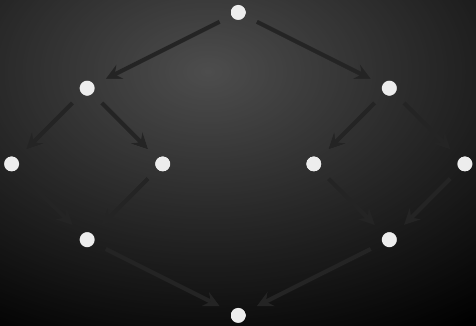

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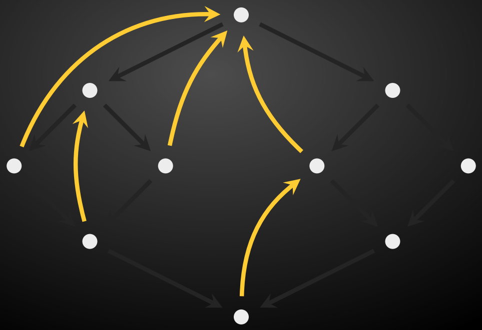

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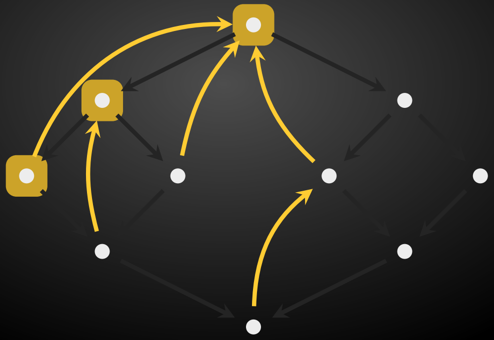

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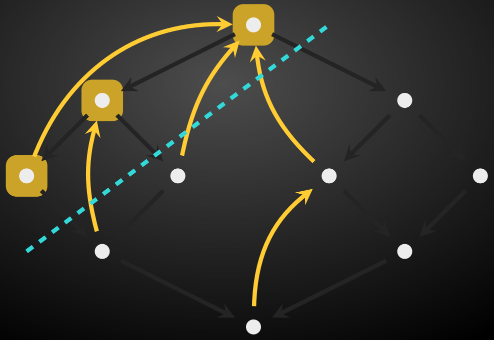

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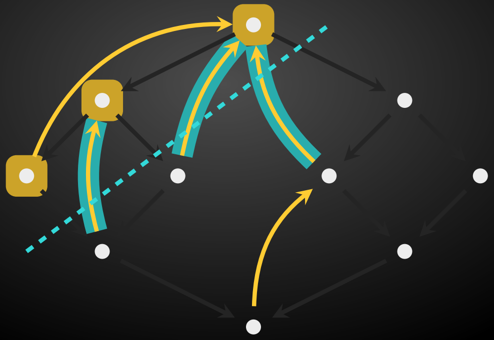

Heap Edges Also Track Uses

Heap edges also added as "possible last-uses," *e.g.*,

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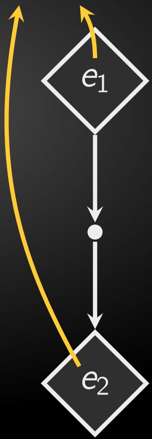

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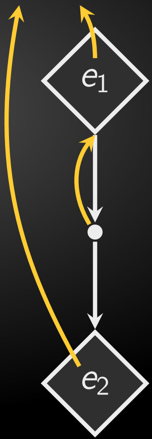

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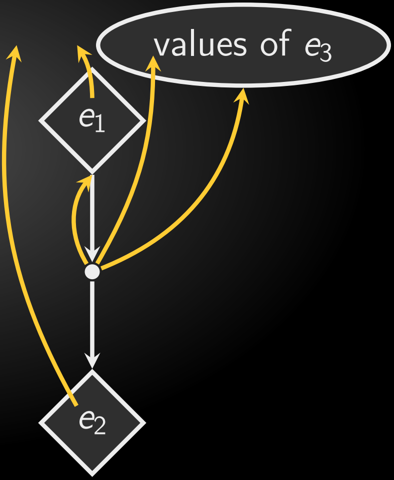

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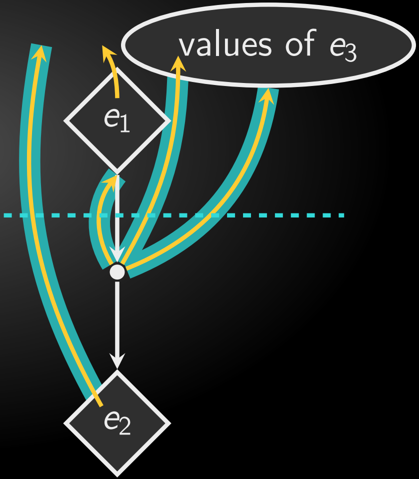

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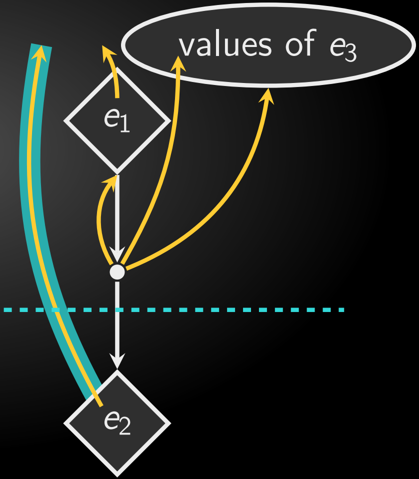

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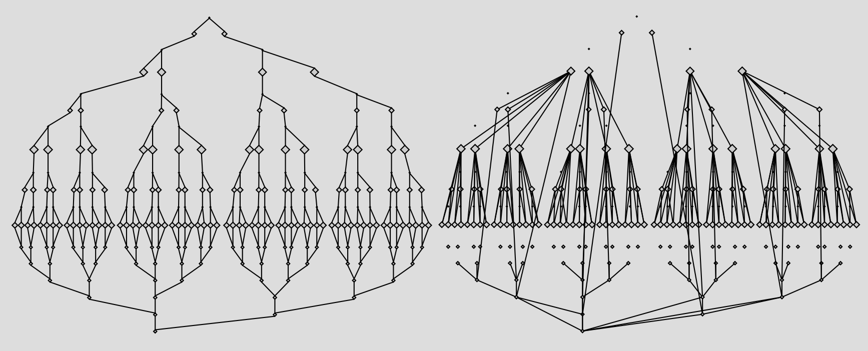
Some push back on semantics from implementation

- semantics must be implement*able*
- *e.g.*, “true” vs. “provable” garbage

Example Graphs

Matrix multiplication

- computation graph on left; heap on right



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✖ loses some precision

✔ acts as specification

Visualizing Schedules

Distill graphs, focusing on parallel structure

- coalesce sequential computation
- use size, color, relative position
- omit less interesting edges

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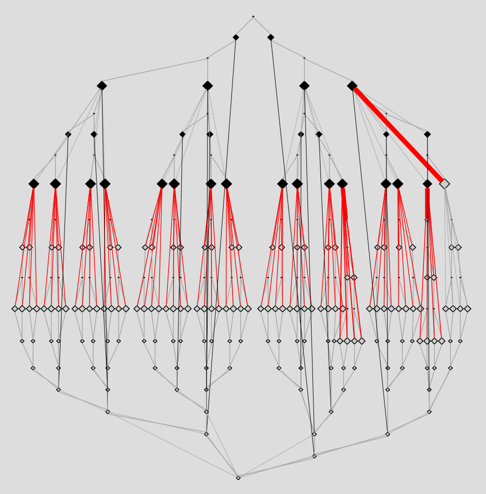
Graphs derived from semantics,
. . . compressed mechanically,
. . . then laid out with GraphViz

Matrix Multiply (Breadth-First, $p = 2$)



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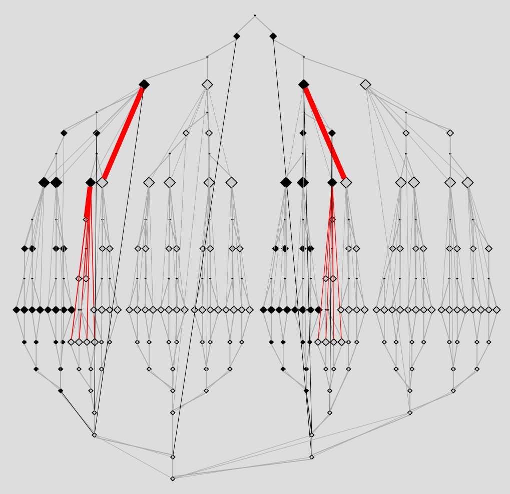
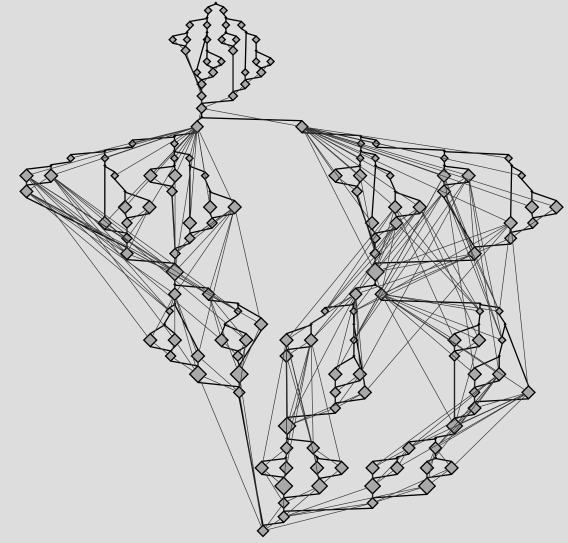


Quick Hull



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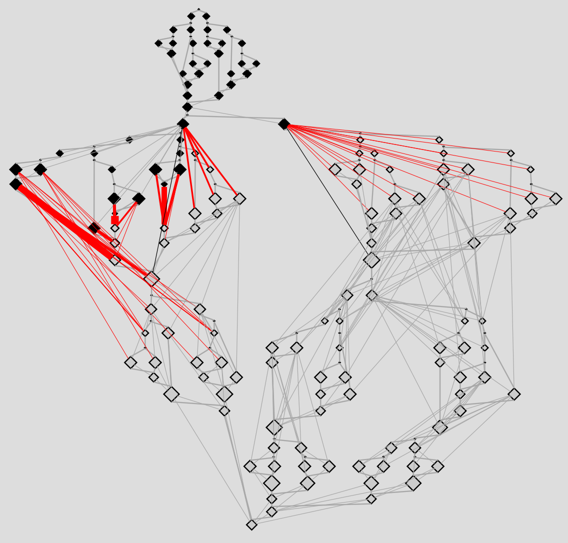

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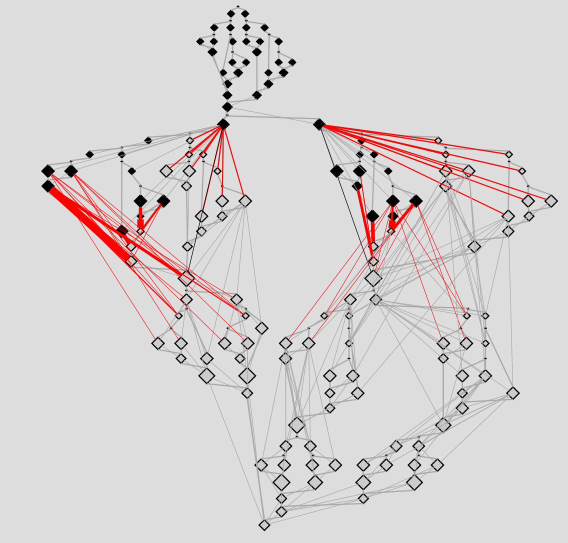
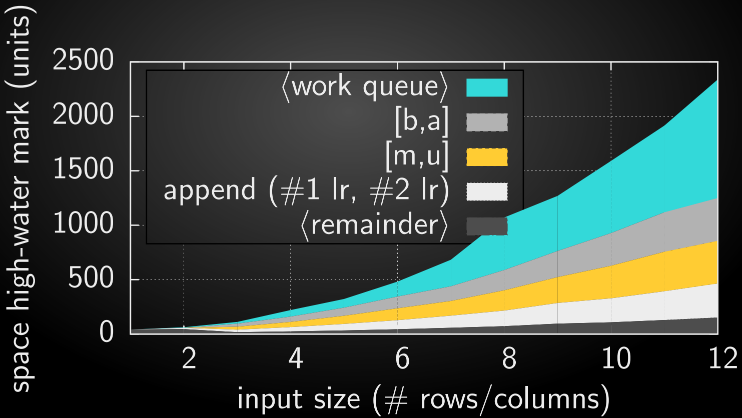


Space Use By Input Size

Matrix multiply w/ breadth-first scheduling policy:



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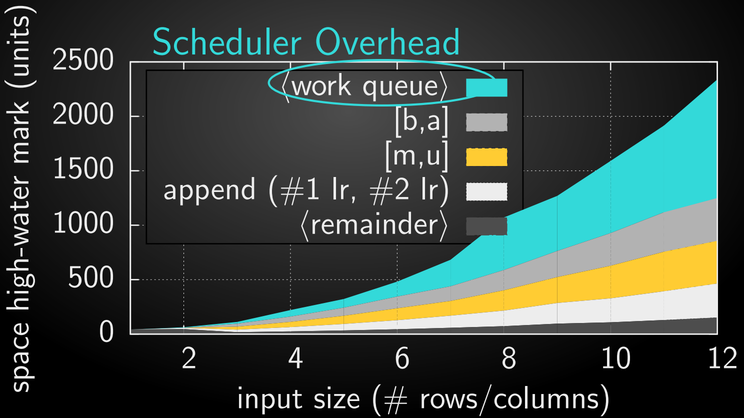

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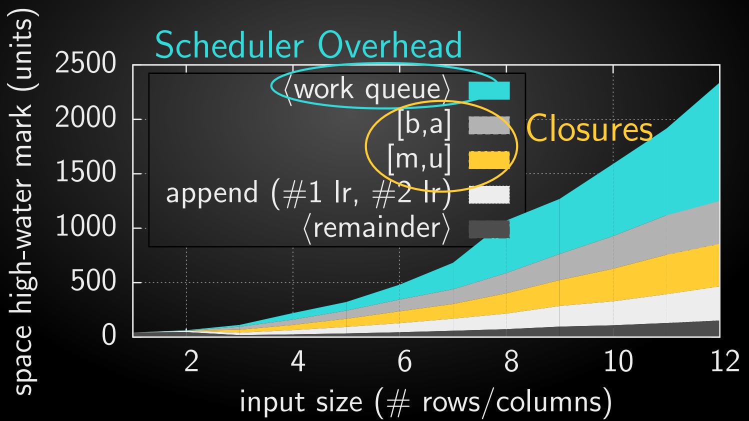

Verifying Profiling Results

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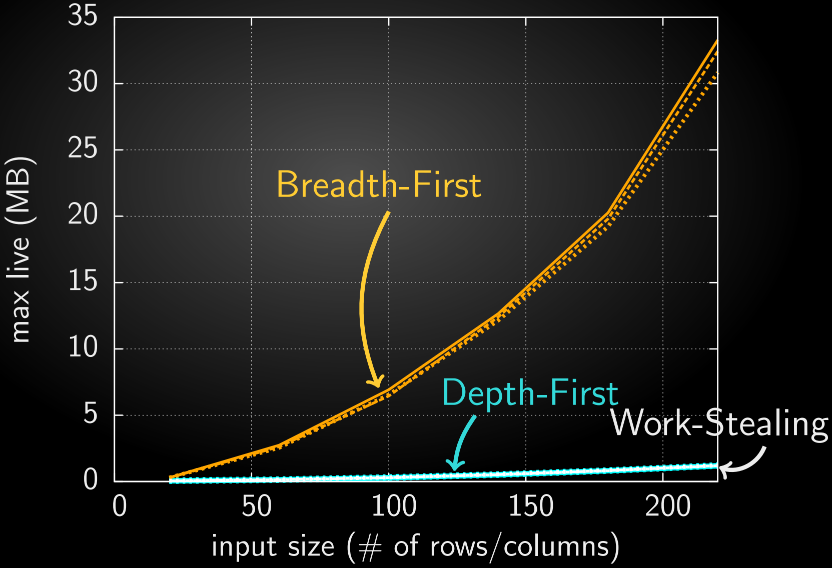
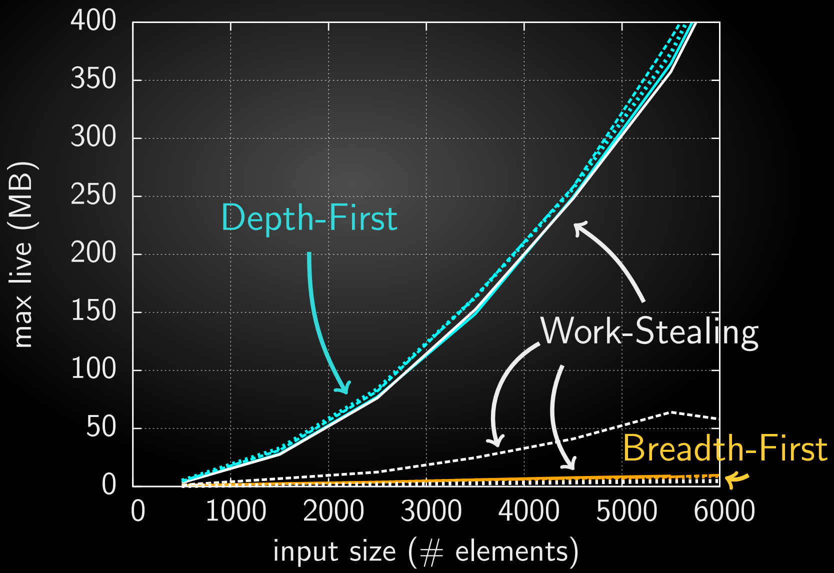
Implemented a parallel extension to MLton

- including three different schedulers
- compared predicted and actual space use

Matrix Multiply – MLton Space Use

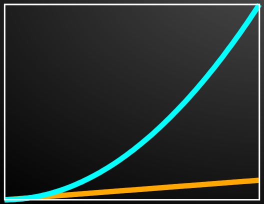


Quicksort – MLton Space Use



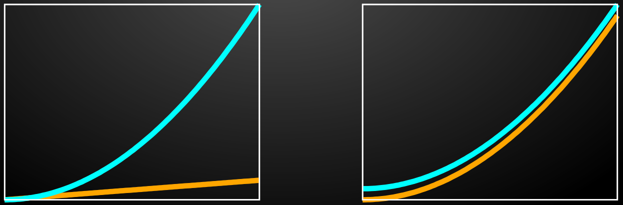
Initial Quicksort Results

- predicted: breadth-first outperforms depth-first



Initial Quicksort Results

- predicted: breadth-first outperforms depth-first
- initial observation: same results!



Space Leak Revealed

Cause: reference flattening optimization
(representing reference cells directly in records)

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Now fixed in MLton source repository

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Without a cost semantics, there is no bug!

Also in the Paper

More details, including...

- rules for cost semantics
- discussion of MLton implementation
  - efficient method for space measurements
- more plots (profiling, speedup, &c.)
- application to vectorization (in TR)

Selected Related Work

Cost semantics

- Sansom & Peyton Jones. *POPL '95*
- Blelloch & Greiner. *ICFP '96*

Scheduling

- Blelloch, Gibbons, & Matias. *JACM '99*
- Blumofe & Leiserson. *JACM '99*

Profiling

- Runciman & Wakeling. *JFP '93*
- *ibid. Glasgow FP '93*

Conclusion

Conclusion

Semantic profiling for parallel programs. . .

- accounts for scheduling, space use
- constrains implementation (and finds bugs!)
- supports visualization &
  predicts actual performance

Thanks!

Thanks to MLton developers, and
Thank you for listening!

Questions?

`spoons@cmu.edu`

Download binaries, source code, papers, slides:

```
http://www.cs.cmu.edu/~spoons/parallel/
svn co svn://mlton.org/mlton/...
    branches/shared-heap-multicore mlton
```