Evaluation Strategies for Planning as Satisfiability

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This work

- We consider **evaluation strategies for satisfiability planning: find a (not necessarily shortest) plan**.
  Trade-off: quality vs. cost to produce.
- Application domain: any approach to planning in which basic step is finding a plan of a given length (like planning as satisfiability (or CSP, MILP, ...), Graphplan, ...)
- Significance: speed-ups of 0, 1, 2, 3, 4, ... orders of magnitude in comparison to the standard sequential evaluation strategy (as used in Graphplan, BLACKBOX, ...)

Strengths of satisfiability planning (SATP)

Satisfiability planning (Kautz & Selman, 1992/96) seems to be the most efficient and promising approach for solving (inherently) difficult planning problems:

- optimal solutions to otherwise easy problems
  (Most of the standard planning benchmarks are solvable by very simple poly-time algorithms!!!)
- problems in the phase transition region [Rintanen, KR'04]
- difficult real-world planning problems

SATP vs. heuristic state-space planning

Heuristic state-space search [Bonet & Geffner 2000], e.g. the HSP planner, seems to have been considered stronger than SATP on many problems, *but*

- apples vs. oranges: SATP planners like BLACKBOX give optimality guarantees, planners like HSP do not, and
- nobody has used SATP planners for non-optimal planning.

So how efficient SATP actually is when optimality is not required?????

SATP as non-optimal planning

- Relax all optimality requirements: any plan will do!
- Consequence (this work): SATP becomes extremely good on standard big-and-easy benchmarks.
- However, problems that are *very easy* and *very big* likely remain to be solved by more specialized planning techniques: After all, SAT solvers are general-purpose problem solvers and cannot be as efficient as more specialized techniques on all types of problems.

The sequential evaluation algorithm

Formula ϕ_j represents the question *Is there a plan of length j?*

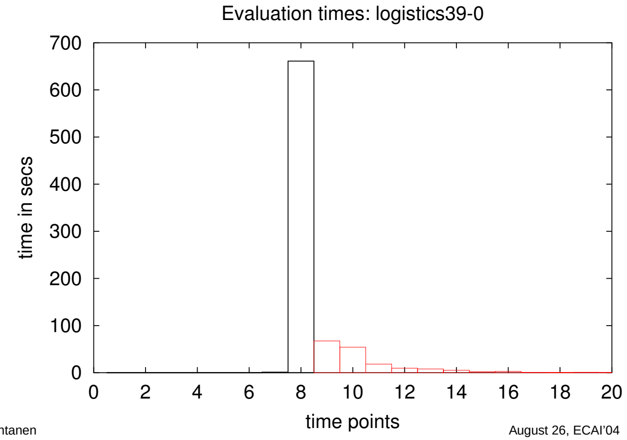
PROCEDURE AlgorithmS()
$i := 0$;
REPEAT
  test satisfiability of ϕ_i;
  IF ϕ_i is satisfiable *THEN* terminate;
  $i := i + 1$;
UNTIL 1=0;

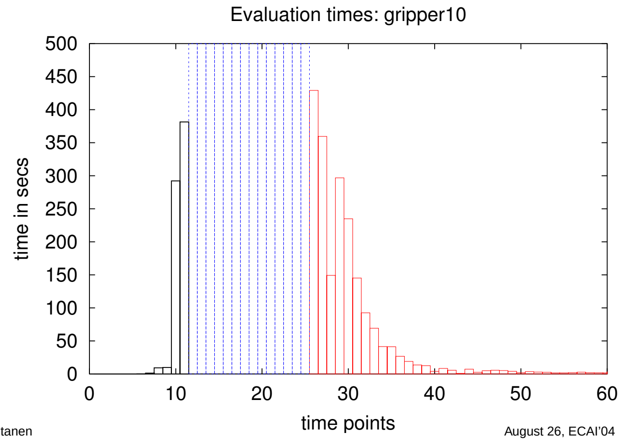
This algorithm **proves** that the plan has optimal length!!!

Experimentation

- How do runtime profiles of different benchmarks look like?
  1. benchmarks from planning competitions 1998, 2000, 2002
  2. samples from the set of all instances [Rintanen, KR'04]
- Tests were run with Siege SAT solver version 4 (by Lawrence Ryan of University of Washington and Synopsys).

  (This is one of the best SAT solvers for planning problems.)
- Siege randomizes ⇒ We give average runtimes over 40 runs.




Evaluation times: gripper10
time in secs
time points
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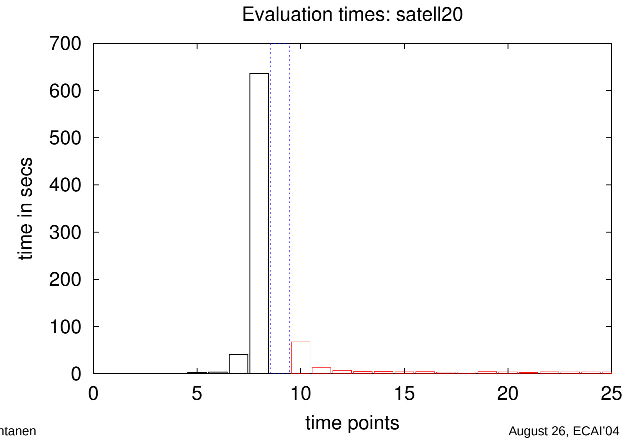
Evaluation times: satell20
time in secs
time points
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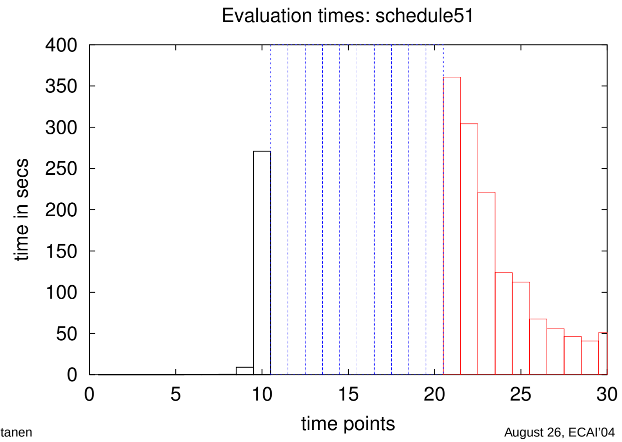
Evaluation times: schedule51
time in secs
time points
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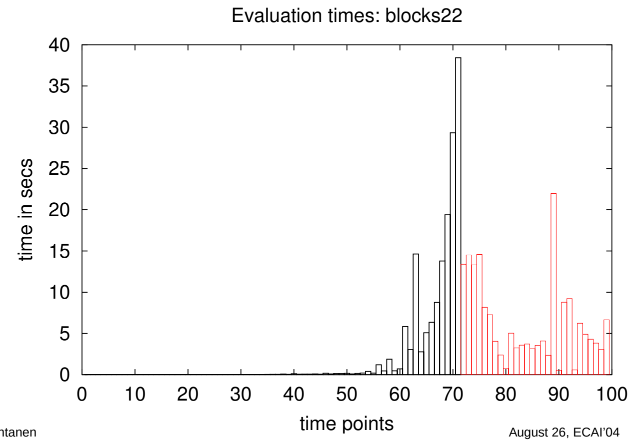
Evaluation times: blocks22
time in secs
time points
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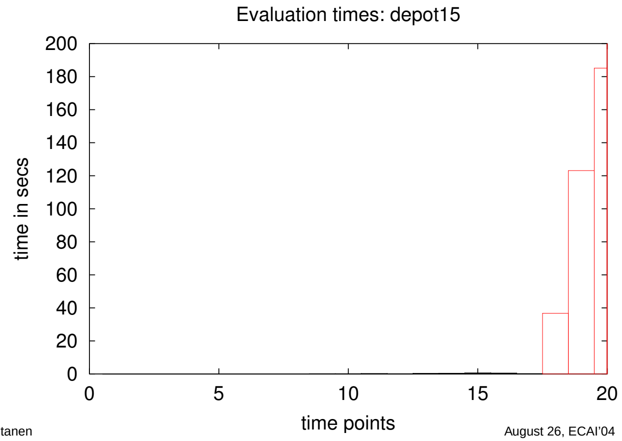
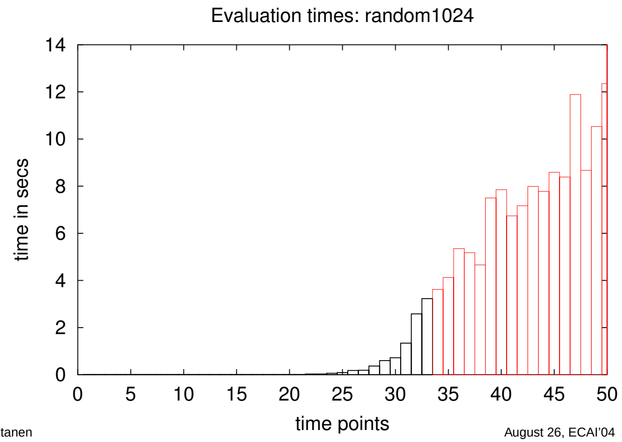
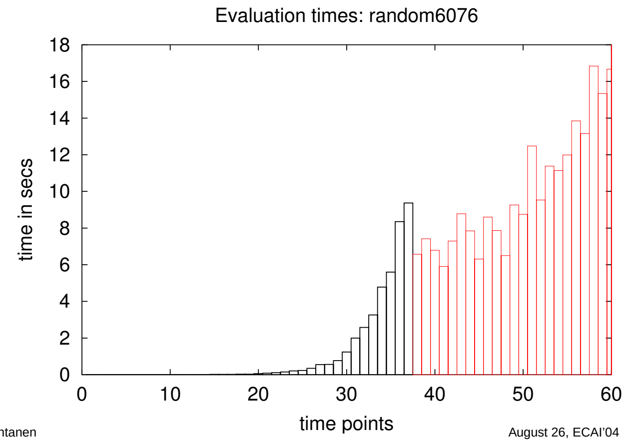
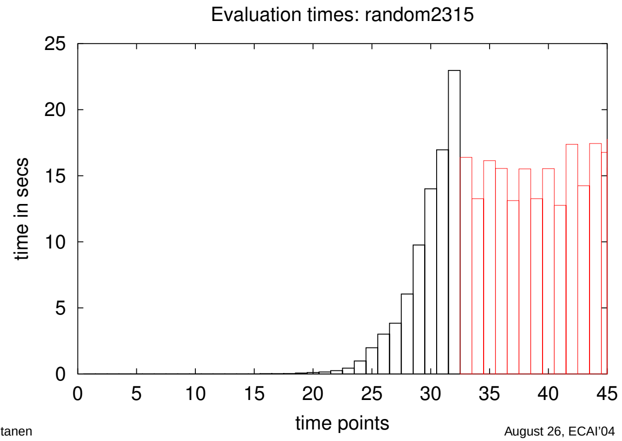


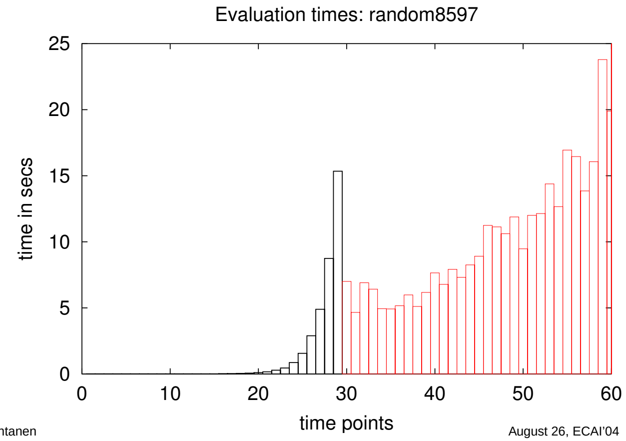
Difficult problems with 20 state variables

- Sampled from the space of all problems instances with 20 state variables, 40 or 42 STRIPS operators each having 3 precondition literals and 2 effect literals.
- This is in the phase transition region [Rintanen, KR'04].
- We show here some of the most difficult instances.
- Easier instances are solved (by satisfiability planners) in milliseconds. (Also ones with many more state variables.)



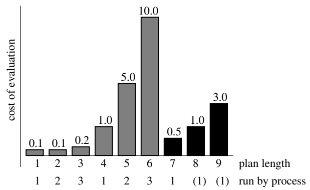






Observations

- Characteristic shape:



- Most of the difficulty is in the last unsatisfiable formulae.
- Devise evaluation strategies that get to evaluate the easier satisfiable formulae early!!

Algorithm A

- n processes: evaluate n plan lengths simultaneously (starting from lengths 0 to $n-1$)
- When a process finishes one length, in continues with the first unallocated one.
- Special case $n = 1$ is Algorithm S.

Algorithm B

- Evaluate all plan lengths simultaneously at **different rates**.
- If rate of length n is r, evaluate length $n+1$ at rate γr.

  γ is a constant $0 < \gamma < 1$.
- The CPU times allocated to the formulae form a geometric sequence

$$t\gamma^0, t\gamma^1, t\gamma^2, \ldots$$

  with a finite sum

$$\frac{t}{1-\gamma}.$$

Properties of Algorithm B

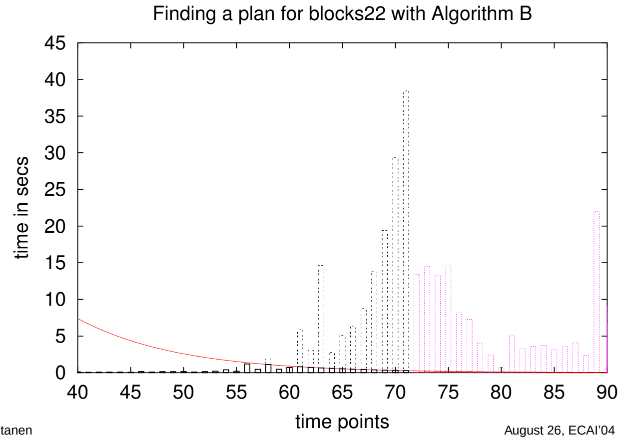
- The first unfinished formula gets $1-\gamma$ of the CPU.

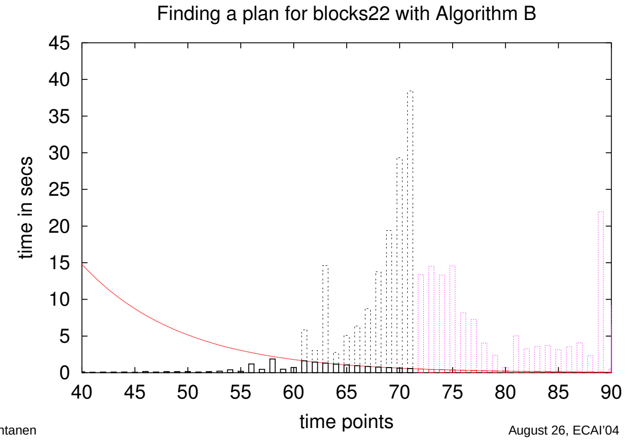
  With $\gamma = 0.9$ this is $\frac{1}{10}$, with $\gamma = 0.5$ it is $\frac{1}{2}$.
- Speed-up is between $1-\gamma$ and ∞.

  Speed-up = $\frac{\text{runtime with Algorithm S}}{\text{runtime with Algorithm B}}$

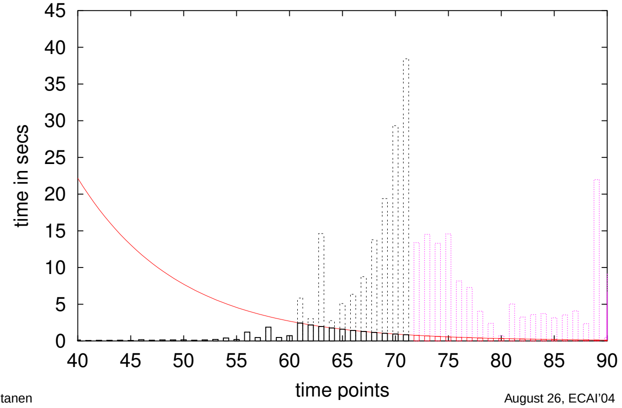
  Worst-case slow-down only a constant factor!

  Speed-up can be arbitrarily high!!

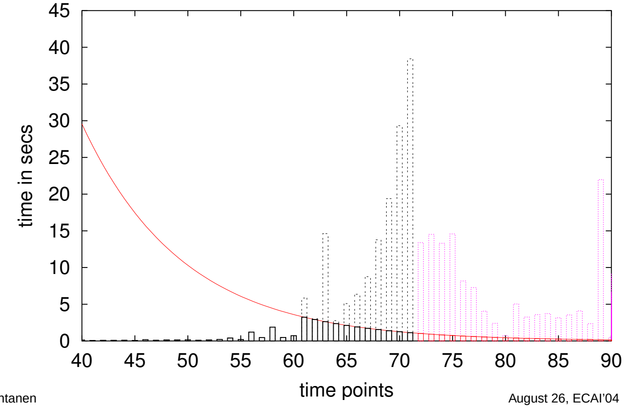




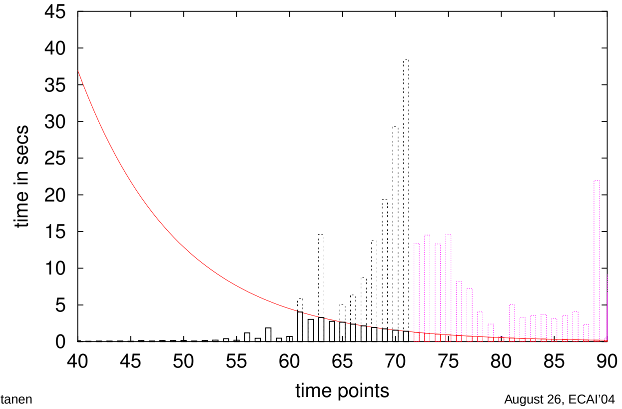
Finding a plan for blocks22 with Algorithm B



Finding a plan for blocks22 with Algorithm B



Finding a plan for blocks22 with Algorithm B



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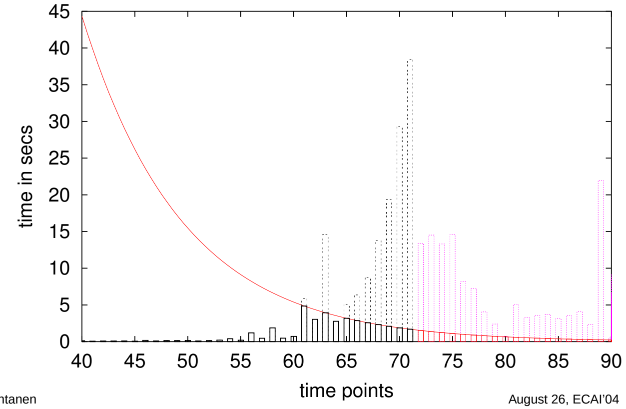
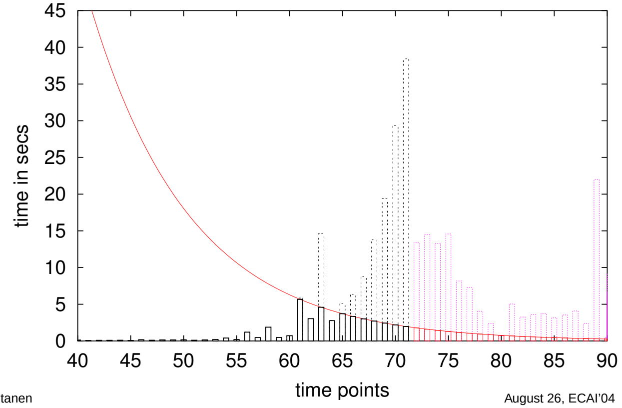


Finding a plan for blocks22 with Algorithm B



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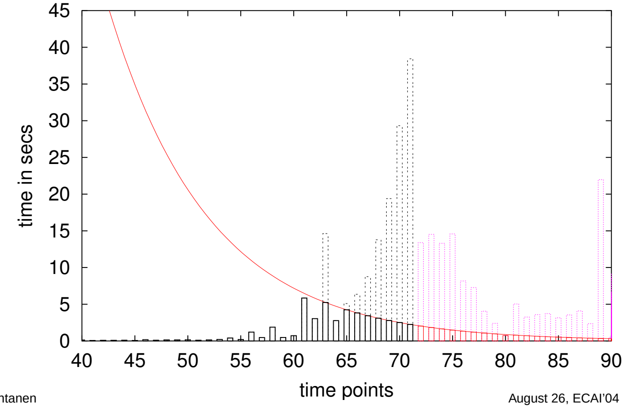

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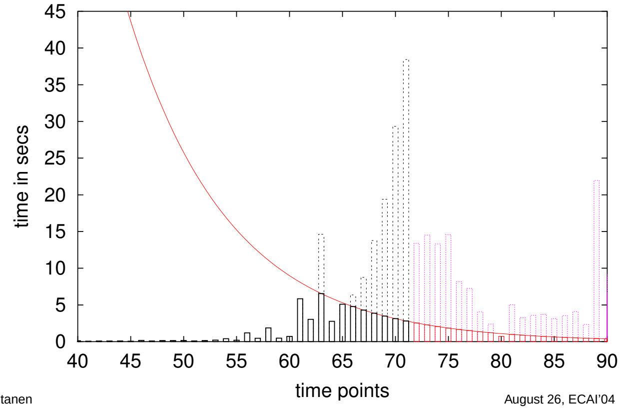
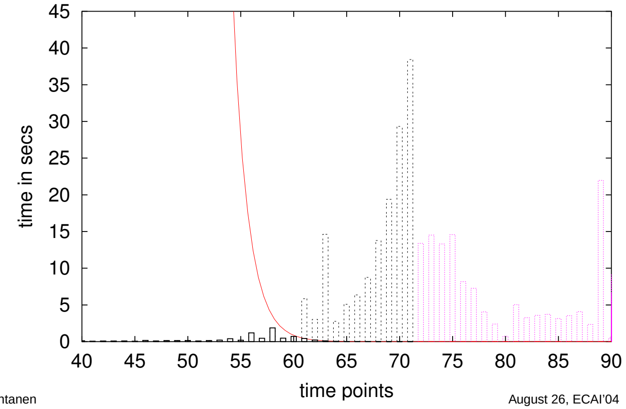


Finding a plan for blocks22 with Algorithm B



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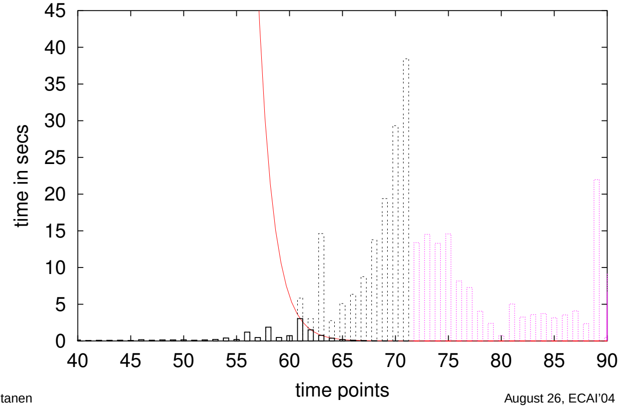

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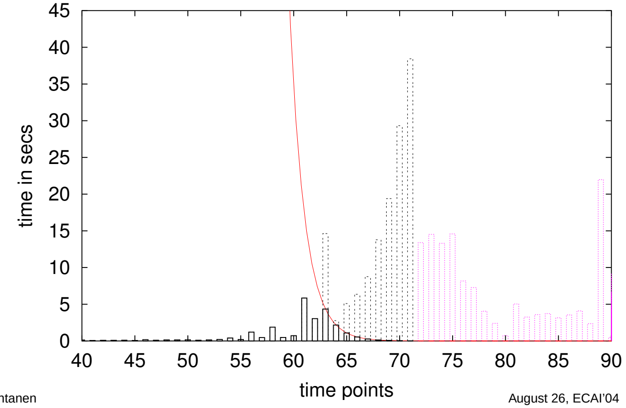

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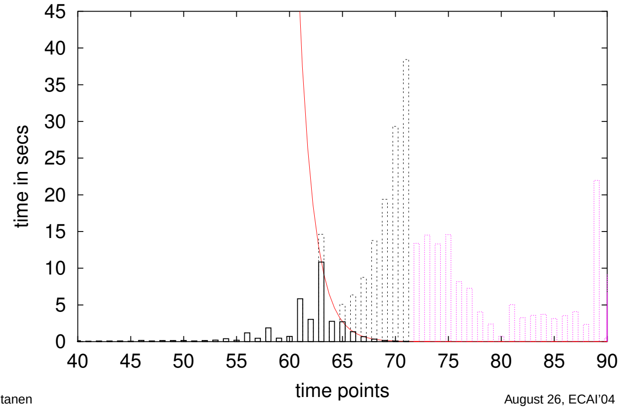

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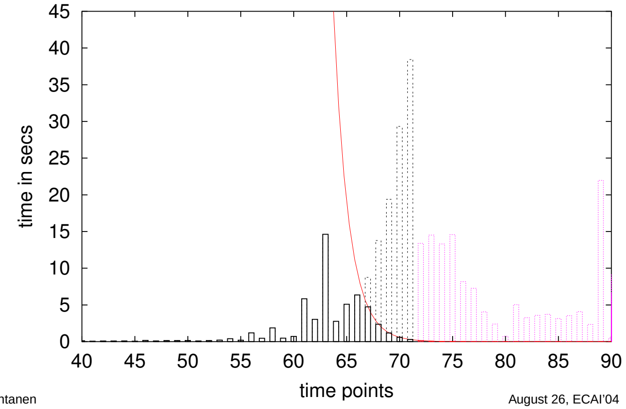

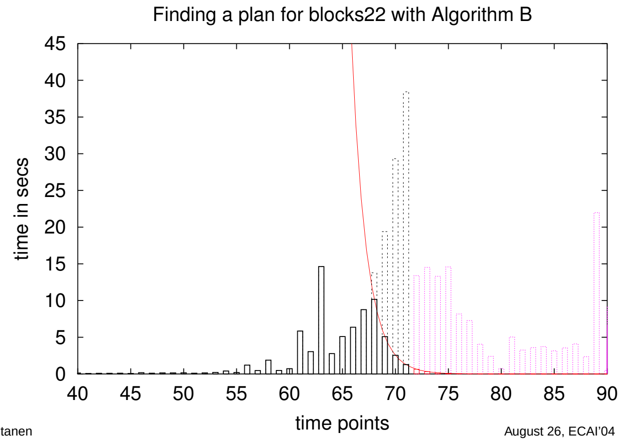
Finding a plan for blocks22 with Algorithm B
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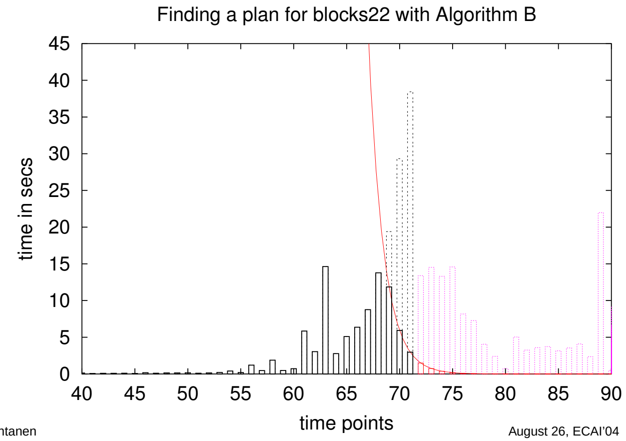
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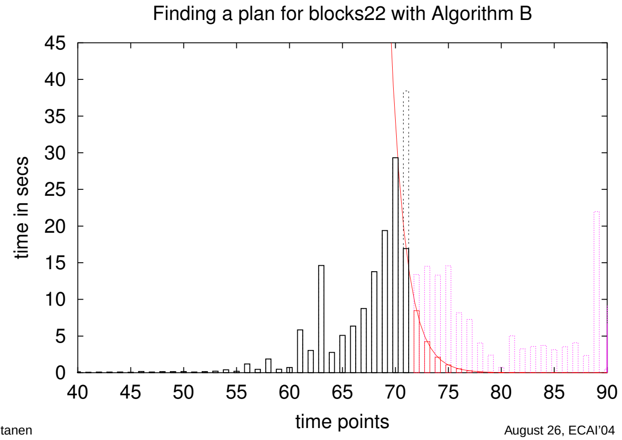
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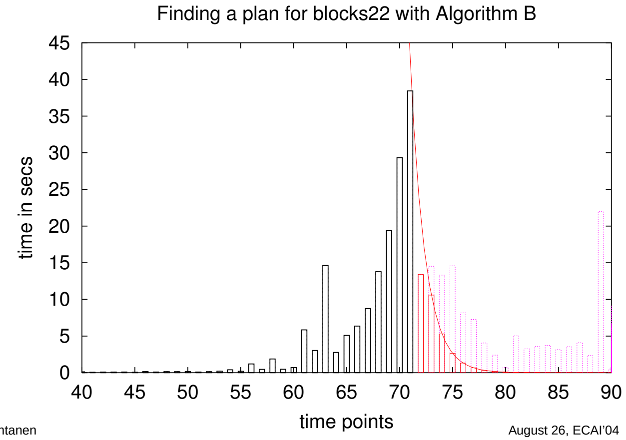
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time in secs
time points
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instance	Algorithm A with n 1	2	4	8	16
logistics-39-0	-	-	54.2	8.7	5.4
logistics-39-1	-	564.9	84.2	15.6	5.3
logistics-40-0	1279.0	732.8	86.7	10.6	5.1
logistics-40-1	-	-	59.9	42.7	8.3
logistics-41-0	-	-	375.0	4.6	8.6
logistics-41-1	-	-	138.3	18.8	7.7

instance	Alg. S	Algorithm B with γ 0.500	0.750	0.875	0.938
logistics-39-0	-	136.4	17.2	9.5	10.1
logistics-39-1	-	86.2	11.6	7.8	8.9
logistics-40-0	1279.0	83.8	11.5	7.5	8.7
logistics-40-1	-	206.3	29.5	15.6	15.7
logistics-41-0	-	70.9	13.9	11.1	13.7
logistics-41-1	-	219.2	26.0	14.2	14.5

instance	Alg. S	Algorithm B with γ 0.500	0.750	0.875	0.938
blocks-22-0	150.1	163.0	99.9	53.4	40.9
blocks-24-0	2355.8	1822.8	390.1	171.2	95.0
blocks-26-0	-	4100.6	1919.6	547.1	243.0
blocks-28-0	-	2041.3	545.6	229.4	155.7
blocks-30-0	-	22777.6	3573.0	1462.2	900.2
blocks-32-0	-	$> 27h$	$> 27h$	7590.5	2637.2
blocks-34-0	219.4	231.0	238.5	246.3	236.4

Note: We can "improve" most of the runtimes on these slides to fractions by considering only e.g. plan lengths $0, 10, 20, 30, \ldots$.

instance	Alg. S	Algorithm B with γ 0.500	0.750	0.875	0.938
gripper-3	0.5	0.5	0.2	0.2	0.3
gripper-4	14.2	3.6	1.4	0.5	0.4
gripper-5	710.1	10.4	1.8	0.6	0.4
gripper-6	-	28.6	4.7	2.3	2.3
gripper-7	-	1600.4	82.6	10.8	3.8
gripper-8	-	9786.4	393.0	42.1	17.5
gripper-9	-	$> 27h$	2999.7	117.9	26.6
gripper-10	-	$> 27h$	12027.4	183.3	34.7
gripper-11	-	$> 27h$	3712.5	55.1	9.4
gripper-12	-	$> 27h$	43813.2	198.9	19.4
gripper-13	-	$> 27h$	$> 27h$	761.4	119.6
gripper-14	-	$> 27h$	$> 27h$	20949.6	892.3
gripper-15	-	$> 27h$	$> 27h$	3412.9	160.3

instance	Alg. S	Algorithm B with γ 0.500	0.750	0.875	0.938
sched-47-1	-	7153.6	370.5	113.2	92.5
sched-47-2	-	1512.2	100.0	51.2	54.8
sched-48-0	-	380.3	107.9	105.3	80.4
sched-48-1	-	252.0	50.9	25.9	27.7
sched-48-2	-	238.7	40.5	28.9	32.9
sched-49-0	-	29178.4	802.6	103.0	59.7
sched-49-1	-	22.2	13.9	17.1	26.6
sched-49-2	152.0	95.7	45.5	33.7	39.7
sched-50-0	140.1	27.8	14.5	13.5	14.8
sched-50-1	-	$> 27h$	4813.1	664.0	358.7
sched-50-2	-	104.3	35.1	27.5	32.4
sched-51-0	-	$> 27h$	2768.4	389.3	212.9
sched-51-1	-	30011.7	1033.0	209.6	144.5
sched-51-2	-	$> 27h$	4236.0	825.8	605.7

instance	Alg. S	Algorithm B with γ 0.500	0.750	0.875	0.938
driver-4-4-8	0.3	0.4	0.6	0.9	1.6
driver-5-5-10	805.4	754.0	304.0	284.4	376.4
driver-5-5-15	83.1	111.1	136.5	170.3	272.9
driver-5-5-20	667.1	103.8	92.7	134.1	230.3
driver-5-5-25	-	$> 27h$	24641.5	10817.7	10851.0
driver-8-6-25	-	$> 27h$	$> 27h$	17485.9	5429.7

instance	Alg. S	Algorithm B with γ 0.500	0.750	0.875	0.938
depot-09-5451	12.5	21.4	39.1	74.7	145.8
depot-10-7654	0.1	0.1	0.1	0.2	0.2
depot-11-8765	0.4	0.6	0.7	1.1	1.8
depot-12-9876	148.1	3.2	2.9	3.9	6.0
depot-13-5646	0.1	0.1	0.1	0.2	0.2
depot-14-7654	0.2	0.3	0.5	0.8	1.4
depot-15-4534	63.8	124.6	246.1	489.1	975.1
depot-16-4398	0.1	0.1	0.1	0.2	0.2
depot-17-6587	0.1	0.1	0.1	0.1	0.2
depot-18-1916	2.6	1.4	1.7	2.4	4.0
depot-19-6178	0.2	0.2	0.3	0.5	0.7
depot-20-7615	51.2	6.8	4.5	5.4	8.1
depot-21-8715	0.3	0.5	0.9	1.7	3.0
depot-22-1817	174.9	347.3	692.1	1381.8	2761.2

New efficient SAT encodings (JELIA'04 paper)

Very efficient encodings of a relaxed notion of parallel plans (based on an idea of [Dimopoulos et al. 1997]):

Parallel application of operators is allowed if they can be linearized to *at least one total order*.

n Russian dolls can be nested in **one step**. Standard parallelism: need $n-1$ steps.

Conclusions

- Our work makes the trade-off between plan quality and planning difficulty in satisfiability planning explicit.
- Possibility of arbitrarily high performance gains is obtained by accepting the possibility of a small constant-factor slow-down and the loss of guarantees for plan optimality.
- A planner based on the new evaluation algorithms and new efficient encodings [Rintanen, Heljanko & Niemelä, JELIA'04] outperforms Kautz & Selman's BLACKBOX by ..,3,4,5,6,... orders of magnitude on some problems.

More on the topic

Jussi Rintanen. Automated planning, 2004.

Jussi Rintanen, Keijo Heljanko and Ilkka Niemelä. *Parallel encodings of classical planning as satisfiability*, Logics in Artificial Intelligence, Ninth European Conference, JELIA'04, Lecture Notes in Computer Science, Springer-Verlag, 2004.

Jussi Rintanen, *Phase transitions in classical planning: an experimental study*, in Proceedings of the 14th International Conference on Automated Planning and Scheduling, pages 101–110, AAAI Press, 2004. (+ also see slides on my web page)