Temporal Fast Downward

Using the Context-enhanced Additive Heuristic for Temporal and Numeric Planning

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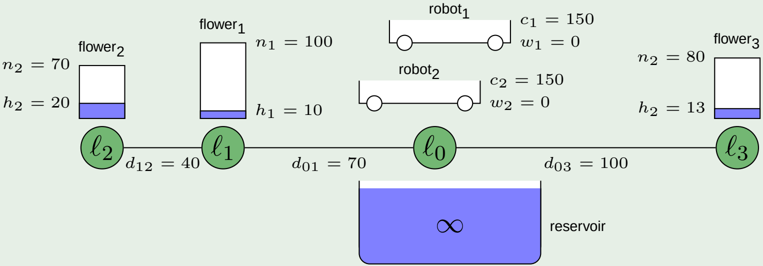
- Observations:
  - Time and resources important in real-world problems.
  - Heuristic search with context-enhanced additive (cea) heuristic successful in sequential planning.
- Question: Does the approach also work with time and resources?

Planning with Time and Resources

Example (Planning Task)

- Two gardening robots need to water flowers.
- Water levels, capacities and water needs are given.
- Robots can work concurrently.



Planning with Time and Resources

Durative Actions

- Actions have durations and may affect numeric variables.
- Conditions at-start, over-all, or at-end.
- Effects at-start or at-end.

Example (Durative Actions)

Walking from one location to an adjacent one.

(at r_i ℓ_j)
(connected ℓ_j ℓ_k)

$\boxed{\texttt{(walk } r_i\ \ell_j\ \ell_k\texttt{) [}d_{jk}\texttt{]}}$

(not (at r_i ℓ_j))

(at r_i ℓ_k)

Example (Durative Actions, ctd.)

Watering a flower at a certain location.

$w_i \geq n_k - h_k$
(in f_k ℓ_j)
(at r_i ℓ_j) (at r_i ℓ_j) (at r_i ℓ_j)

(water r_i ℓ_j f_k) [$n_k - h_k$]

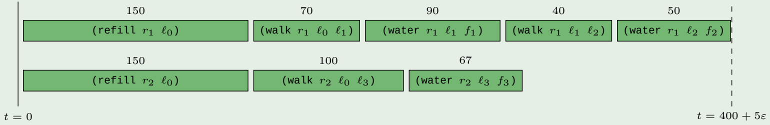
$h_k := n_k$
$w_i -= (n_k - h_k)$

Planning with Time and Resources
Temporal Plans

- Must respect causal and temporal constraints.
- May contain concurrent actions.

Example (Temporal Plan)

Robots robot$_1$ and robot$_2$ work concurrently.



Temporal Numeric SAS$^+$ Planning Tasks

Definition (Temporal Numeric SAS$^+$ Planning Task)

A temporal numeric SAS$^+$ planning task $\Pi = \langle \mathcal{V}, s_0, s_\star, \mathcal{A}, \mathcal{O} \rangle$ consists of the following components:

- A finite set $\mathcal{V}$ of state variables. Each variable is either:
  - A numeric variable with values in $\mathbb{R}$.
  - A comparison variable with values in $\{T, F\}$.
  - A logical variable with arbitrary finite domain.
- An initial state s_0.
- A goal description $s_\star$.
- A finite set $\mathcal{A}$ of axioms.
- A finite set $\mathcal{O}$ of durative actions.

Temporal Numeric SAS$^+$ Planning Tasks

Representation of Subterms via Auxiliary Variable and Axioms

- Axioms and auxiliary variables used to represent numeric and logic subterms.
- Allows sharing of subterms.
- Convenient for heuristic computation.

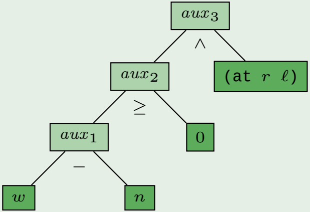
Temporal Numeric SAS$^+$ Planning Tasks

Representation of Subterms via Auxiliary Variable and Axioms

Example (Auxiliary variables and axioms for subterms)

Consider the condition

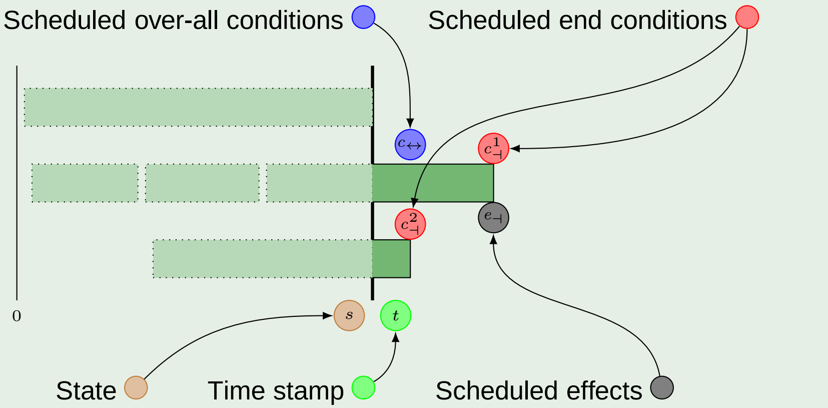
$$\underbrace{\underbrace{(\underbrace{w - n}_{aux_1} \geq 0)}_{aux_2} \wedge \texttt{(at } r\ \ell\texttt{)}}_{aux_3}$$



Temporal Fast Downward (TFD)

- Extends FAST DOWNWARD.
- Uses FAST DOWNWARD architecture.
  - Step 1: Translate PDDL to temporal numeric SAS^+.
  - Step 2: Preprocess temporal numeric SAS^+.
  - Step 3: Search for plan. [Topic of the rest of the talk]
    - Best-first search.
    - Context-enhanced additive heuristic.
    - Deferred heuristic evaluation.
    - Preferred operators.

Example (Time-stamped State)



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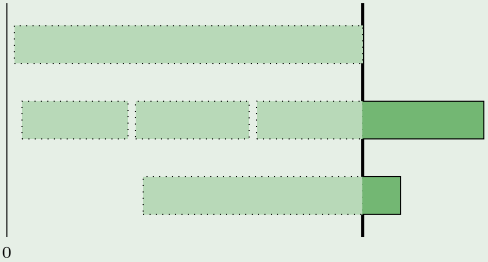

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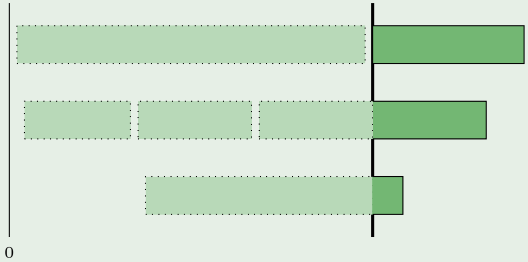

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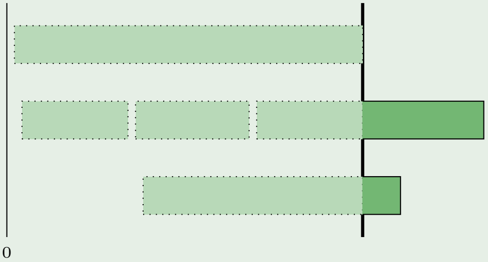

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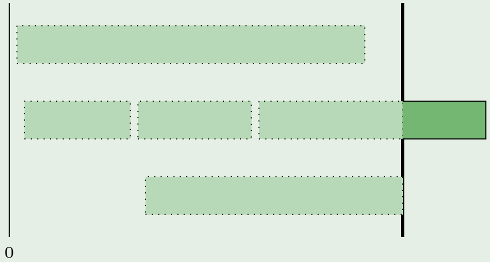


Context-Enhanced Additive Heuristic

- Idea:
  - Solve goals and
  - recursively take care of subgoals/preconditions

  to estimate makespan.

  Return accumulated costs.
- Local contexts: Used to keep track of (side-)effects.
- Drawback – inadmissibility:
  - Repeated solution of subproblems.
  - Transformation to instant-actions.
  - No concurrency-awareness.
- Advantage – preferred operators:
  - By-product of heuristic.
  - Used to guide search towards better operators.

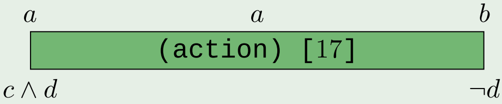
- Problem: Need to simplify durative actions for heuristic.
- Solution: Ignore start-end distinction for conditions and effects.
- General form: instant action = (conditions, effects, cost)

Context-Enhanced Additive Heuristic

Instant Actions

Example (Compressed-action transitions)

Pretend that action happens instantly.



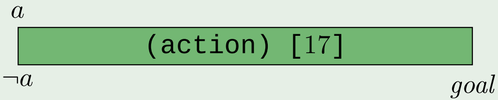
Corresponding compressed-action transitions:

- $cond = \{a, b\}; \quad eff = \{c, d, \neg d\}; \quad cost = 17$

Context-Enhanced Additive Heuristic

Instant Actions

Example (Waiting transitions)



Assume that

- `action` is currently under execution and
- no other action can restore a, and we need the end-effect $goal$.

Then the other types of instant actions do not help in reaching $goal$, even though we can actually obtain $goal$ by waiting long enough.

Corresponding waiting transitions:

- $cond = \emptyset; \quad \mathit{eff} = \{goal\}; \quad cost = \Delta t$

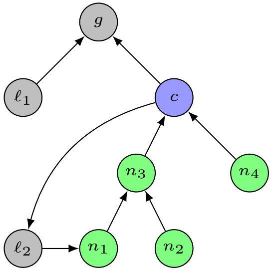
Example (Axiom transitions)

All axioms are interpreted as instant actions with cost 0.

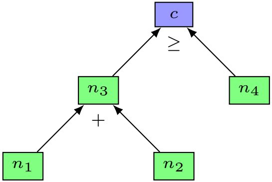
A local problem answers the question:
"What does it cost to change the value of v from w to w'?"

Context-Enhanced Additive Heuristic
Example

Causal graph



Comparison axiom



Current state: $g = F$

Goal: $g = T$

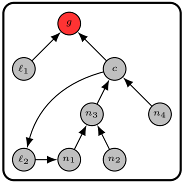
Context-Enhanced Additive Heuristic

Example

$h =$ accumulated cost

0

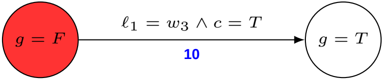
Causal Graph



Queue

Local context of active node

$n_1 = -10$	$c = F$
$n_2 = +5$	$l_1 = w_1$
$n_3 = -5$	$l_2 = w_1$
$n_4 = 0$	$g = F$



Context-Enhanced Additive Heuristic
Example

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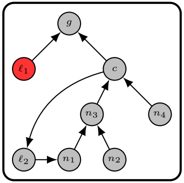
Causal Graph



Queue

$\ell_1 = w_1$

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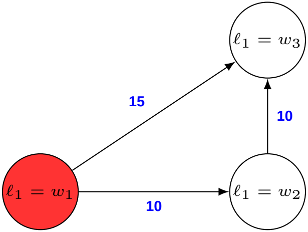

Context-Enhanced Additive Heuristic
Example

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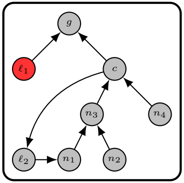
Causal Graph



Queue

$\ell_1 = w_2 \quad \ell_1 = w_3$

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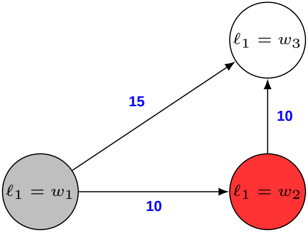


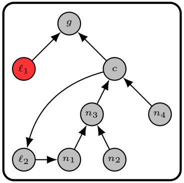
Context-Enhanced Additive Heuristic

Example

h = accumulated cost

15

Causal Graph



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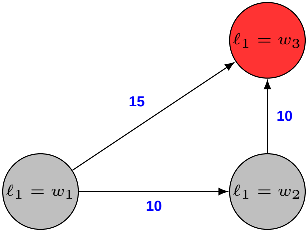

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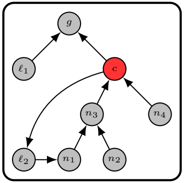

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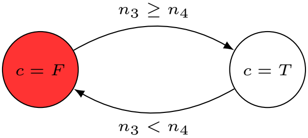

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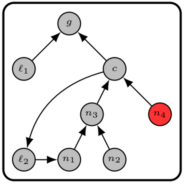

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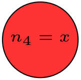

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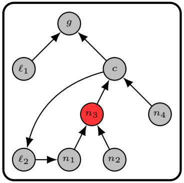

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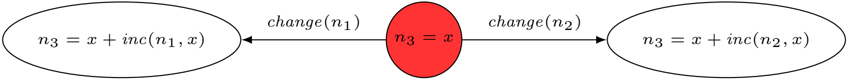

Context-Enhanced Additive Heuristic

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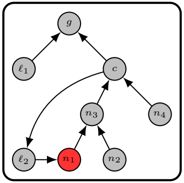
Causal Graph



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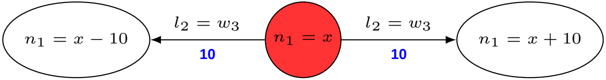

Context-Enhanced Additive Heuristic

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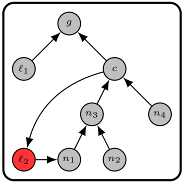
Causal Graph



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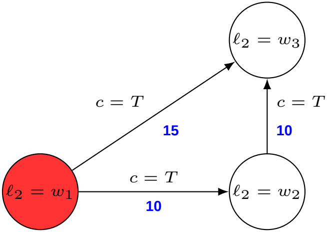

Context-Enhanced Additive Heuristic

Example

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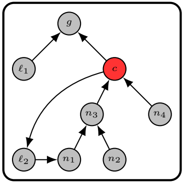
Causal Graph



Queue

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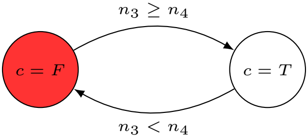

Context-Enhanced Additive Heuristic

Example

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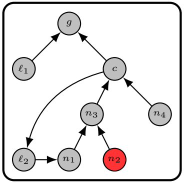
15

Causal Graph



Queue

$n_2 = +15$

Local context of active node

$n_1 = -10$	$c = F$
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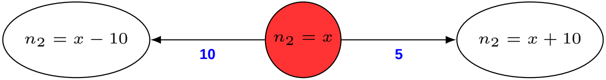


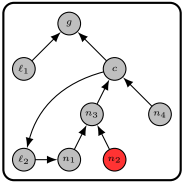
Context-Enhanced Additive Heuristic

Example

h = accumulated cost

20

Causal Graph



Queue

$n_3 = +5$

Local context of active node

$n_1 = -10$	$c = F$
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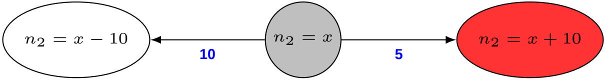

Context-Enhanced Additive Heuristic

Example

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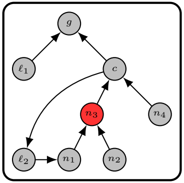
20

Causal Graph



Queue

$c = T$

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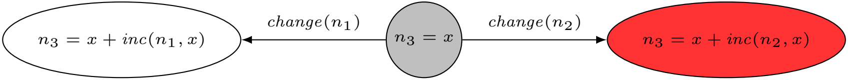

Context-Enhanced Additive Heuristic

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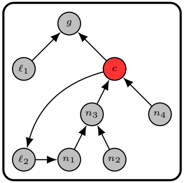
Causal Graph



Queue

$g = T$

Local context of active node

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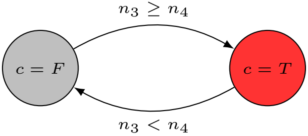

Context-Enhanced Additive Heuristic
Example

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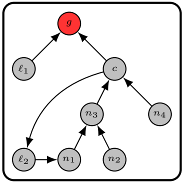
20

Causal Graph



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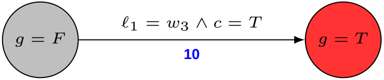

- Planners: Six temporal planning systems.
- Benchmarks: IPC 2008 deterministic temporal problems.
- Evaluation Scheme: Scheme used at IPC 2008

$$Score(Planner) = \sum_{\substack{\text{solved} \\ \text{problem } \pi \\ \text{(solution } p\text{)}}} \frac{\min_{\text{solution } p^* \text{ for } \pi} makespan(p^*)}{makespan(p)}$$

- Environment: 2.66 GHz Intel Xeon CPU, 2 GB memory limit, 30 minutes time limit per problem, anytime search.

Experimental Results

Planners' Scores

Domain	Base	Crikey	LPG	Sapa	SGP	TFD
Crewplanning	16.19	22.59	12.76	—	22.44	28.72
Elevators	18.38	2.60	22.75	5.64	15.09	19.38
Modeltrain	11.92	—	—	—	11.11	0.96
Openstacks	18.14	20.67	14.35	25.90	12.49	26.66
Parcprinter	13.84	8.58	18.20	5.25	11.00	9.10
Pegsol	24.35	18.30	25.81	18.98	15.39	27.57
Sokoban	15.52	7.03	11.95	0.00	8.73	13.00
Transport	5.50	2.83	11.57	1.91	7.46	6.91
Woodworking	12.14	11.96	26.37	9.36	10.44	16.04
Overall	**135.97**	**94.55**	**143.76**	**67.02**	**114.15**	**148.34**

- TEMPORAL FAST DOWNWARD scores highest.
- Reason for high score:
  - Not so much number of solved problems . . .
  - . . . but rather solution quality.

Experimental Results

How Much Longer the Plans From Other Planners Are On Average

Domain	Base		Crikey		LPG		Sapa		SGP	
Crewplanning	(18)	14%	(29)	38%	(13)	1%		—	(28)	39%
Elevators	(17)	58%	(10)	200%	(23)	11%	(12)	126%	(17)	84%
Modeltrain	(1)	5%		—		—		—	(1)	1%
Openstacks	(30)	55%	(30)	33%	(30)	166%	(30)	4%	(30)	144%
Parcprinter	(13)	37%	(13)	34%	(12)	-30%	(5)	12%	(13)	32%
Pegsol	(28)	19%	(28)	60%	(28)	12%	(24)	28%	(18)	21%
Sokoban	(13)	29%	(9)	50%	(12)	50%		—	(9)	22%
Transport	(7)	18%	(6)	79%	(7)	-25%	(3)	54%	(10)	37%
Woodworking	(27)	42%	(27)	44%	(28)	-34%	(20)	37%	(21)	29%
Overall	(154)	**36%**	(152)	**55%**	(153)	**31%**	(94)	**35%**	(147)	**60%**

Summary and Conclusion

- Temporal and numeric planning via forward search in space of time-stamped states.
- Heuristic guidance by extension of context-enhanced additive heuristic.
- Competitive with other approaches to temporal planning.

Future Work

- Make heuristic concurrency-aware.
- Use weaker relaxation of numeric features in heuristic.