On the Relationship Between State-Dependent Action Costs and Conditional Effects in Planning

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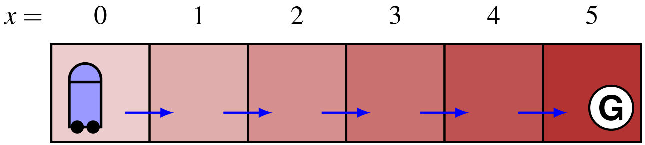
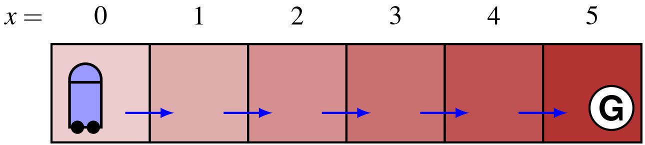
Relaxations with State-Dependent Costs and Effects



Relaxations with State-Dependent Costs and Effects



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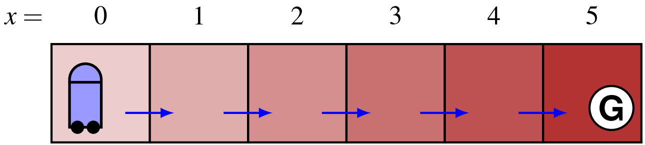
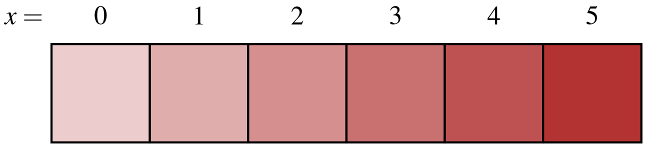
\begin{aligned}
\mathit{cost}(\rightarrow) &= x+1 \\
\mathit{eff}(\rightarrow) &= x' := x+1
\end{aligned}
$$

Relaxations with State-Dependent Costs and Effects



$$\begin{aligned} \mathit{cost}(\rightarrow) &= x+1 \\ \mathit{eff}(\rightarrow) &= x' := x+1 \\ h^*(x=0) &= 1+2+3+4+5 = 15 \end{aligned}$$

Relaxations with State-Dependent Costs and Effects



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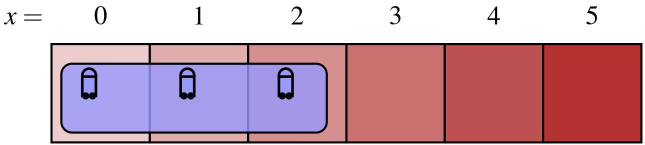

$$x^+ = \{0, 1, 2\}$$

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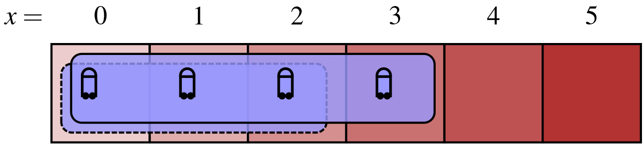

$x^+ = \{0, 1, 2\}$

cost($\rightarrow$) : $\color{red}{\min}\{1, 2, 3\}$

eff($\rightarrow$) : $x^{+\prime} := \{0\} \color{red}{\cup} \{1\} \color{red}{\cup} \{2\} \color{red}{\cup} \{3\}$

$$\begin{aligned}
\mathit{cost}(\rightarrow) &= x + 1 \\
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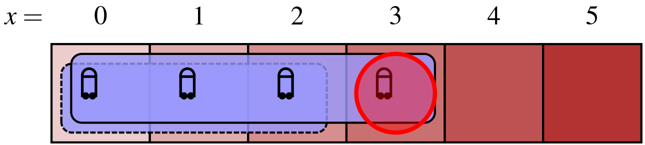

$x^+ = \{0, 1, 2\}$ *cost*($\rightarrow$) : 1

eff($\rightarrow$) : $x^{+\prime} := \{0, 1, 2, 3\}$

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Relaxations with State-Dependent Costs and Effects

- cost-effect mismatch!
- $\rightsquigarrow$ uninformative heuristic
  - $h^+(x=0) = 5$ vs.
  - $h^*(x=0) = 15$

Relaxations with State-Dependent Costs and Effects

Question: what went wrong?

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Answer: handled costs and effects separately.

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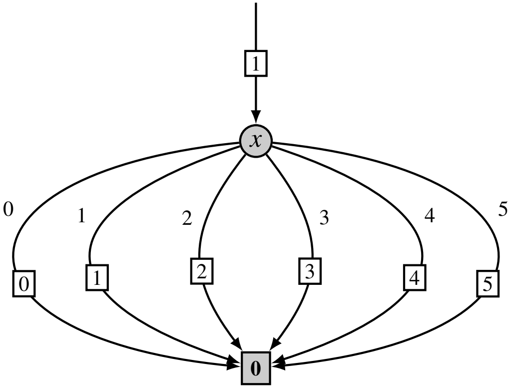
Answer: handled costs and effects separately.

Proposal: handle uniformly!

- "compact" representation: DD exploiting additive separability
- edge-valued multi-valued decision diagrams (EVMDDs)
  (Ciardo and Siminiceanu 2002; Lai, Pedram, Vrudhula 1996)

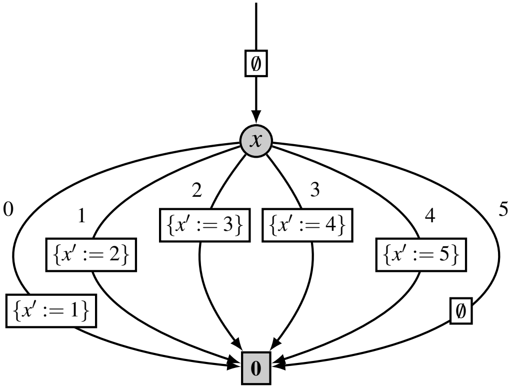
Uniform Representation using EVMDDs

EVMDD for *StateDependentCosts* $(x+1)$



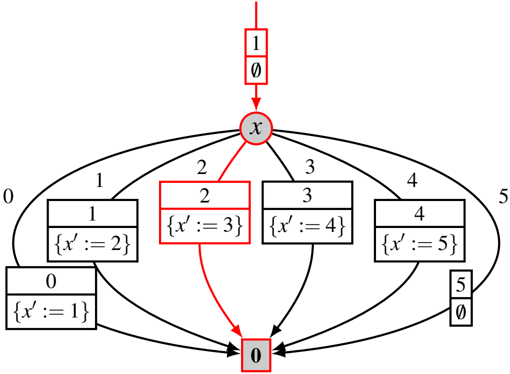
Uniform Representation using EVMDDs

EVMDD for *ConditionalEffects* ($x' := x + 1$)



Uniform Representation using EVMDDs

Combined EVMDD



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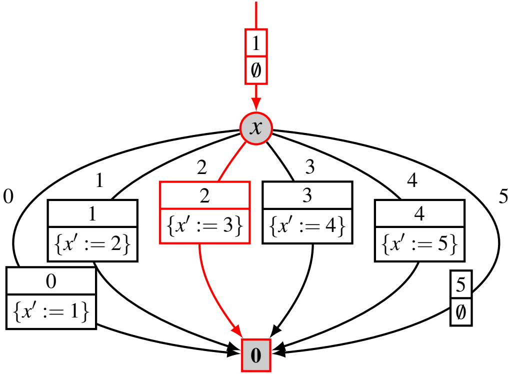
Combined EVMDD



Consequence: effect $x' := 3$ now associated with cost 3.

EVMDD Construction

Next: how to construct those EVMDDs?

Procedure: top-down, using repeated cofactor expansions
(Lai, Pedram, Vrudhula 1996; cf. Bryant 1986)

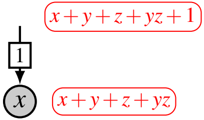
EVMDD Construction for Costs

Example (Multivariate Polynomial)

$\boxed{x+y+z+yz+1}$

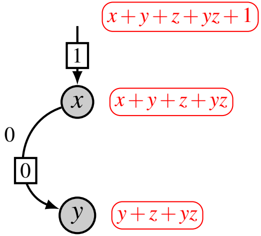
EVMDD Construction for Costs

Example (Multivariate Polynomial)



EVMDD Construction for Costs

Example (Multivariate Polynomial)



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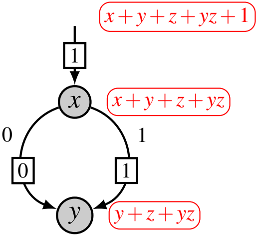

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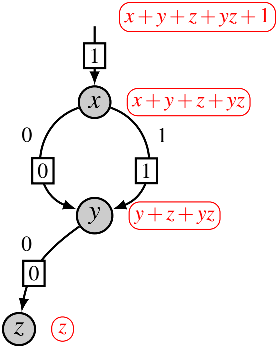

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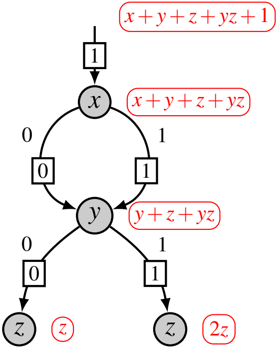

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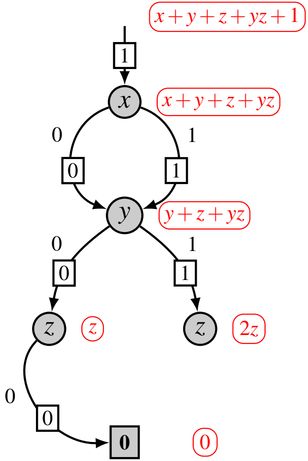

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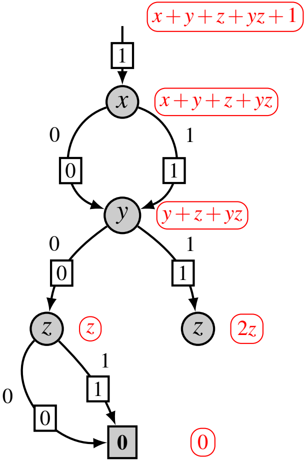

EVMDD Construction for Costs

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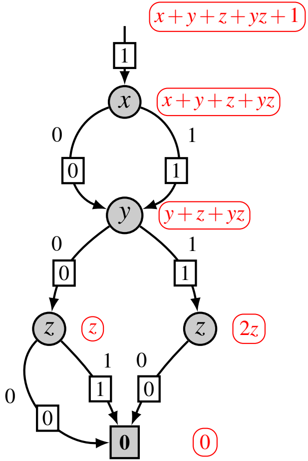

EVMDD Construction for Costs

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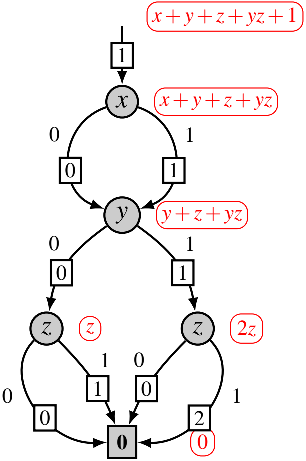


Correct Representation of Costs

Proposition

Such cost EVMDDs correctly encode cost functions. $\square$

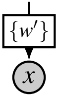
EVMDD Construction for Effects

Example (Effect in Normal Form, Rintanen 2003)

$$\boxed{\begin{array}{l}(\neg x \rhd \neg v') \wedge (x \rhd u') \wedge \\ ((x \vee y) \rhd \neg z') \wedge ((x \wedge z) \rhd v') \wedge w'\end{array}}$$

EVMDD Construction for Effects

Example (Effect in Normal Form, Rintanen 2003)



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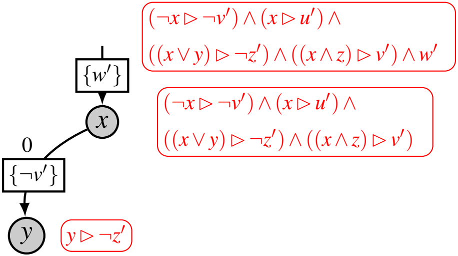

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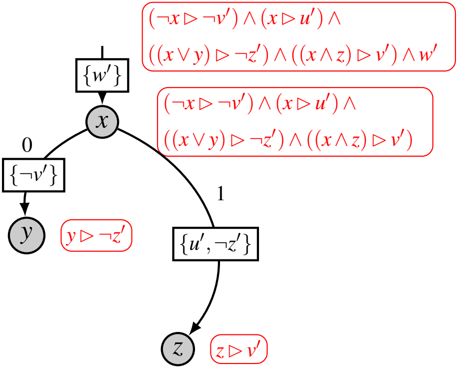

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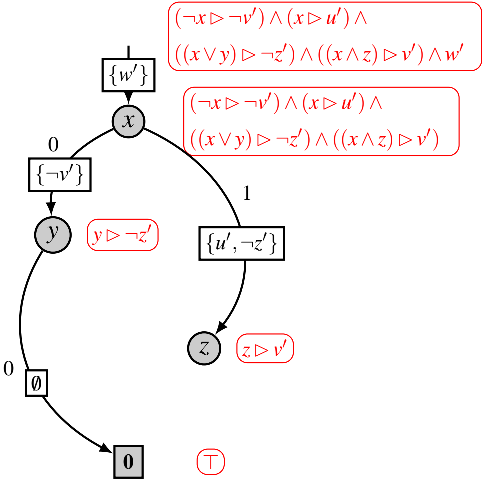

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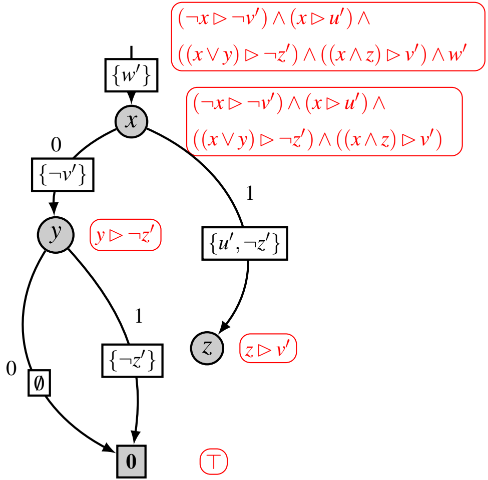

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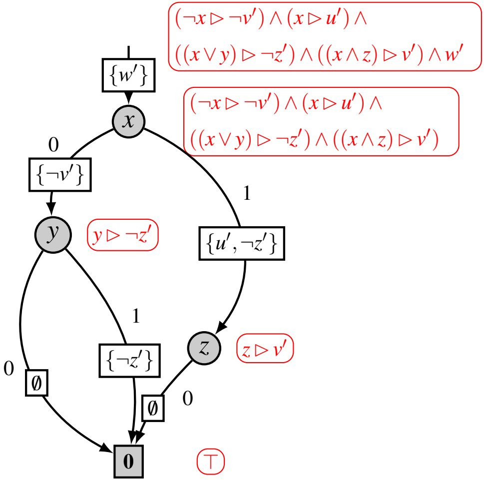

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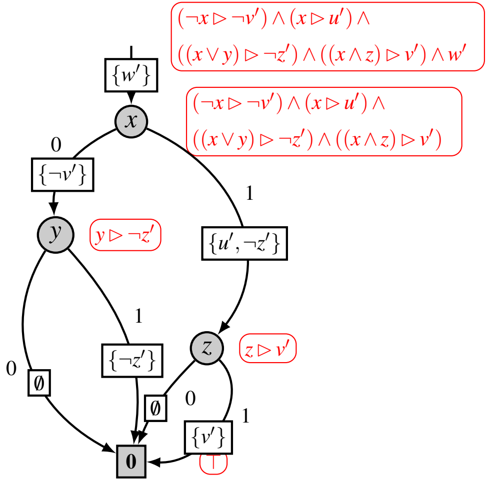


Correct Representation of Effects

Proposition

Such effect EVMDDs correctly encode semantics of conditional effects (= sets of active effects (Rintanen 2003)). □

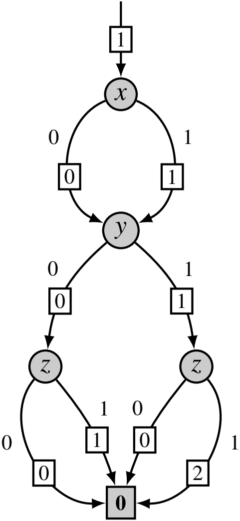
EVMDD Product Construction

Product EVMDD construction:

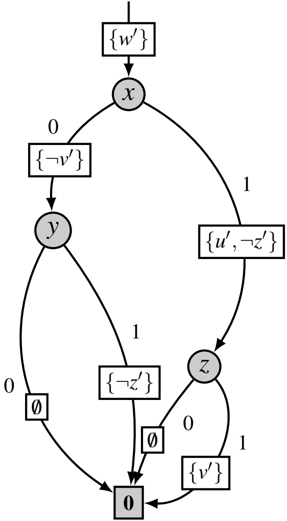
- Option 1: top-down construction in product space (straightforward)
- Option 2: product of cost and effect EVMDD

EVMDD Product Construction

Example (option 2, cost and effect EVMDDs)

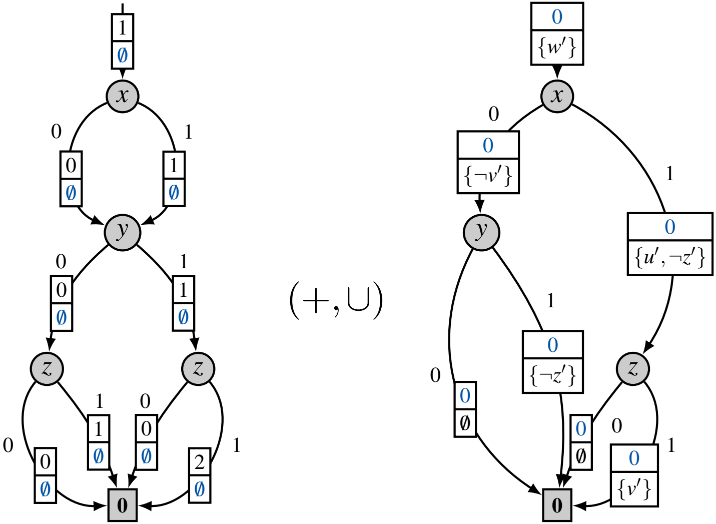


$\otimes$



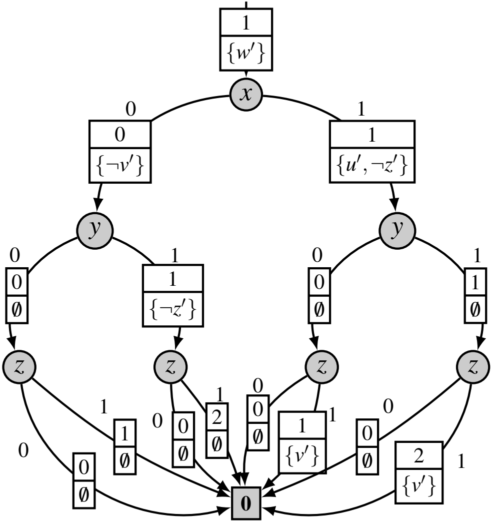
EVMDD Product Construction

Example (option 2, after step 1)



EVMDD Product Construction

Example (option 2, cost-effect product)



Properties of the Construction

Claim: Product construction does the right thing.

Proposition

If

- EVMDD $\mathcal{E}_1$ represents function f_1 and
- EVMDD $\mathcal{E}_2$ represents function f_2,

then

- EVMDD $\mathcal{E}_1 \otimes \mathcal{E}_2$ represents function $f(s) = (f_1(s), f_2(s))$. $\square$

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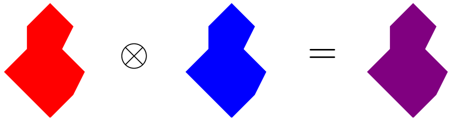
Advantage: need only generic apply procedure
(Lai, Pedram, Vrudhula 1996; cf. Bryant 1986).

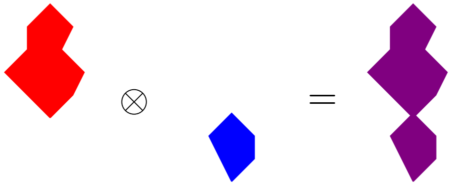
Properties of the Construction

Size of product EVMDD:

- worst case: product of factor sizes
- best cases: $\max/\sum$ of factor sizes if
  - factors have identical structure:



  - or factors depend on disjoint variable sets:



Relaxed Operator Semantics under State-Dependent Costs and Effects

Definition (relaxed active effects with associated costs)

Given:

- relaxed state s^+,
- effect *eff*, and
- cost function $c : S \to \mathbb{N}$.

Then: the change set $[\mathit{eff}]^c_{s^+}$ is the set of facts that *eff* makes true in s^+ together with the cheapest possible cost of doing so in s^+.

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Example:

$$
\begin{aligned}
[x' := x+1]^{x+1}_{\{(x,0),(x,1),(x,2)\}} = \{&(x' := 1,\ 1),\\
&(x' := 2,\ 2),\\
&(x' := 3,\ 3)\}
\end{aligned}
$$

Relaxed Operator Semantics under State-Dependent Costs and Effects

Problem: efficient computation of $[\mathit{eff}]^{c}_{s^+}$.

Relaxed Operator Semantics under State-Dependent Costs and Effects

Problem: efficient computation of $[\mathit{eff}]^{c}_{s^+}$.

Solution: topsort traversal of cost-effect product EVMDD.

- fact made true on some edge $\rightsquigarrow$ store cost
- fact made true along different paths $\rightsquigarrow$ only keep cheapest cost
- note: not just independent $\sum / \max$!
- linear-time in EVMDD size

Properties of the Computation

Proposition

The EVMDD-based change set computation computes $[\mathit{eff}]^{c}_{s^+}$. $\square$

Summary

- informative heuristics necessitate ...
- ... uniform treatment of state-dependent costs and effects.
- representation: cost and effect EVMDDs
- construction: cofactor expansions, product EVMDD via *apply*
- $\rightsquigarrow$ relaxed semantics computable using product EVMDDs

Discussion and Future Work

Discussion:

- effect EVMDD related to Fast Downward successor generator
- also: cf. Nebel's compilation of conditional effects (2000)

Future Work:

- define and compute relaxation and abstraction heuristics with state-dependent costs and effects
- define compilation based on product EVMDDs
- variable orderings and EVMDD relaxations