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# From Qualitative to Quantitative Dominance Pruning for Optimal Planning

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Domin	ance				





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 $\leq B$ 

$$A \preceq T$$

and and



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В

$$\blacksquare: A \preceq T \preceq$$



t does not dominate s:  $s \not\leq t$ 

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Qualita	ative Do	minance			

#### **Dominance Relation**

If  $s \leq t$ , then  $h^*(s) \geq h^*(t)$ : *t* is at least as good as *s* 

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### **Dominance Relation**

If  $s \leq t$ , then  $h^*(s) \geq h^*(t)$ : *t* is at least as good as *s* 

Prune  $n_s$  if there exists  $n_t$  s.t.  $g(n_t) \le g(n_s)$  and  $s \le t$ 

Open or closed list



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### **Dominance Relation**

If  $s \leq t$ , then  $h^*(s) \geq h^*(t)$ : *t* is at least as good as *s* 

Prune  $n_s$  if there exists  $n_t$  s.t.

$$g(n_t) \leq g(n_s)$$
 and  $s \leq t$ 

- Open or closed list
- Closed list
- Parent →Never unload a package in any location other than its destination!



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## Qualitative Dominance

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Quant	itativo D	ominance			

### By how much *t* dominates *s*? $\rightarrow$ function $\mathcal{D} : S \times S \rightarrow \mathbb{R} \cup \{-\infty\}$

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Quanti	tative Do	ominance			

By how much *t* dominates *s*?  $\rightarrow$  function  $\mathcal{D} : S \times S \rightarrow \mathbb{R} \cup \{-\infty\}$ 

Dominance Function:  $\mathcal{D}(s,t) \leq h^*(s) - h^*(t)$ 

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## Quantitative Dominance

By how much *t* dominates *s*?  $\rightarrow$  function  $\mathcal{D} : S \times S \rightarrow \mathbb{R} \cup \{-\infty\}$ 

Dominance Function:  $\mathcal{D}(s,t) \leq h^*(s) - h^*(t)$ 

$$\mathcal{D}(s,t) = \begin{cases} C & t \text{ is strictly closer to the goal than s (by at least C)} \\ 0 & t \text{ is at least as close as } s \\ -C & t \text{ is at most C units of cost farther than } s \\ -\infty & \text{we know nothing} \end{cases}$$

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## Quantitative Dominance

By how much *t* dominates *s*?  $\rightarrow$  function  $\mathcal{D} : S \times S \rightarrow \mathbb{R} \cup \{-\infty\}$ 

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ightarrow Qualitative dominance is a special case if we use only  $0 ext{ or } -\infty$ 

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 Leveraging Quantitative Dominance
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Prune  $n_s$  if there exists  $n_t$  s.t.  $g(n_t) \le g(n_s)$  and  $s \le t$ 



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Qualitative

Quantitative

Qualitative Quantitative **Finding Dominance** Action Selection Pruning Experiments Conclusions 000 Leveraging Quantitative Dominance

Qualitative

Prune  $n_s$  if there exists  $n_t$  s.t.  $g(n_t) < g(n_s)$  and  $s \prec t$ Quantitative  $\mathcal{D}(s,t) + g(n_s) - g(n_t) > 0$  if  $\mathcal{D}(s,t) > 0$ 



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Qualitative Quantitative Finding Dominance Action Selection Pruning Experiments conclusions

# Leveraging Quantitative Dominance

Qualitative Quantitative Prune  $n_s$  if there exists  $n_t$  s.t.  $g(n_t) \le g(n_s)$  and  $s \le t$   $\mathcal{D}(s,t) + g(n_s) - g(n_t) \ge 0$  if  $\mathcal{D}(s,t) \ge 0$  $\mathcal{D}(s,t) + g(n_s) - g(n_t) > 0$  if  $\mathcal{D}(s,t) < 0$ 



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Compositional Approach

Consider a partition of the problem:  $\Theta_1, \ldots, \Theta_k$ 

 $\{ \leq_1, \ldots, \leq_k \}$  is a label-dominance simulation if, whenever  $s \leq_i t$ :

- Goal-respecting:  $s \in S_i^G$  implies that  $t \in S_i^G$
- For all  $s \xrightarrow{l} s'$  in  $\Theta_i$ , there exists  $t \xrightarrow{l'} t'$  in  $\Theta_i$  s.t.:

$$\begin{array}{c} \mathbf{0} \quad s' \preceq_i t', \\ \mathbf{0} \quad s' \neq_i t', \\ \mathbf{0} \quad s' \in \mathbf{0} \quad s' \neq_i t', \\ \mathbf{0} \quad s' \in \mathbf{0} \quad s' \in$$

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$$c(l') \leq c(l)$$
, and

*l'* dominates *l* elsewhere

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## Compositional Approach

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 $\{ \leq_1, \ldots, \leq_k \}$  is a label-dominance simulation if, whenever  $s \leq_i t$ :

- Goal-respecting:  $s \in S_i^G$  implies that  $t \in S_i^G$
- For all  $s \xrightarrow{l} s'$  in  $\Theta_i$ , there exists  $t \xrightarrow{l'} t'$  in  $\Theta_i$  s.t.:
  - $\begin{array}{ccc} \bullet & s' \preceq_i t', \\ \bullet & c(l') \leq c(l), \text{ and} \end{array}$
  - $\bigcirc$  *l'* dominates *l* elsewhere

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## Compositional Approach

Consider a partition of the problem:  $\Theta_1, \ldots, \Theta_k$ 

 $\{ \leq_1, \ldots, \leq_k \}$  is a label-dominance simulation if, whenever  $s \leq_i t$ :

- Goal-respecting:  $s \in S_i^G$  implies that  $t \in S_i^G$
- For all  $s \xrightarrow{l} s'$  in  $\Theta_i$ , there exists  $t \xrightarrow{l'} t'$  in  $\Theta_i$  s.t.:
  - $\begin{array}{ccc} \bullet & s' \preceq_i t', \\ \bullet & c(l') \leq c(l), \text{ and} \end{array}$
  - I dominates l elsewhere

$$\rightarrow s \preceq t \text{ iff } \forall i \in [1,k] \ s_i \preceq_i t_i$$

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# Quantifying Label-Dominance Simulation

For all  $s \xrightarrow{l} s'$  in  $\Theta_i$ , there exists  $t \xrightarrow{l'} t'$  in  $\Theta_i$  s.t.:

- $\bigcirc s' \preceq_i t',$
- 2  $c(l') \leq c(l)$ , and
- *l'* dominates *l* elsewhere

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# Quantifying Label-Dominance Simulation

For all 
$$s \xrightarrow{l} s'$$
 in  $\Theta_i$ , there exists  $t \xrightarrow{l'} t'$  in  $\Theta_i$  s.t.:

- $1 s' \preceq_i t',$
- 2  $c(l') \leq c(l)$ , and
- *l'* dominates *l* elsewhere

 $\{\mathcal{D}_1, \dots, \mathcal{D}_k\}$  is a quantitative LD simulation for  $\{\Theta_1, \dots, \Theta_k\}$  if:

$$\mathcal{D}_i(s,t) \le \min_{s \xrightarrow{l} s'} \max_{t \xrightarrow{l'} t'} \mathcal{D}_i(s',t') + c(l) - c(l') + \sum_{j \ne i} \mathcal{D}_j^L(l,l')$$

$$\mathcal{D}(s,t) = \sum_{i \in [1,k]} \mathcal{D}_i(s_i,t_i)$$

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## Discovering negative dominance



We can always drive between *s* and *t*: D(t, s) = D(s, t) = -1

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## Discovering negative dominance



We can always drive between *s* and *t*: D(t, s) = D(s, t) = -1

 $\tau$ -label: no preconditions or negative side effects elsewhere

 $s \xrightarrow{l} s'$  can be simulated by a path  $t \xrightarrow{\tau} u' \xrightarrow{\tau} t'$ 

$$\mathcal{D}_P(A,T) = \mathcal{D}_P(T,B) = +1$$
$$\mathcal{D}_T(A,B) = \mathcal{D}_T(B,A) = -1$$

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Action	Selectio	on Pruning		

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Action	Selection	n Prunina			



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- Prune every other successor
- Reduce branching factor to 1!

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- Prune every other successor
- Reduce branching factor to 1!
- In our example. If possible:
  - load a package
  - unload a package in its destination

 $\rightarrow$ Branch only over drive actions!

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943 **396** 

91

40

2.618

204

2820

1627



Rovers

Satellite

Woodworking

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Pruning Ratio wrt. baseline

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# Great Pruning Power in LM-Cut!



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# Great Pruning Power in LM-Cut!



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# Great Pruning Power in LM-Cut!



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Cov	erage										
				1	Blind			L	M-cut		
			В	$\preceq$	AS + p	POR	В	$\preceq$	AS + p	POR	
	Driverlog	20	7	9	10	7	13	13	13	13	•
	Floortile	40	2	11	16	2	13	16	16	13	
	Logistics	63	12	21	27	12	26	26	33	27	
	Miconic	150	55	60	77	50	141	141	142	141	
	Nomystery	20	8	16	20	8	14	20	20	14	
	Openstacks	100	49	51	55	50	47	51	52	49	
	Parcprinter	50	16	32	44	<b>50</b>	31	35	48	<b>50</b>	
	Pathwaysnoneg	30	4	4	5	4	5	5	5	5	
	Rovers	40	6	8	8	7	7	9	10	10	
	Satellite	36	6	6	6	6	7	10	12	12	
	Sokoban	50	41	43	43	39	50	49	49	50	
	TPP	30	6	6	6	6	7	7	8	6	
	Trucksstrips	30	6	8	8	6	10	10	10	10	
	Visitall	40	12	13	12	12	15	16	15	15	
	Woodworking	50	11	30	38	24	29	48	50	46	
	Zenotravel	20	8	9	9	8	13	13	13	13	
	Total	1612	610	659	738	613	835	856	896	881	•

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Conclusions								

- Quantitative Dominance:
  - Bound difference in goal distance between states
  - Useful for dominance and action selection pruning
  - Good results and even more potential to be unleashed!
- Future work:
  - New ways to discover (quantitative) dominance
  - More efficient ways to perform dominance pruning
  - New uses for dominance