Additive Pattern Databases for Decoupled Search: Additional Material

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This additional material contains full proofs for all claims of the paper (Sievers, Gnad, and Torralba 2022) with a proof sketch or without proof. It further contains full per-domain coverage results for all reported experiments. Finally, it also reports all experimental results of the main paper on the Autoscale 21.11 benchmarks (Torralba, Seipp, and Sievers 2021).

Proposition 2. *Let $h, h^{L\$}$ be two consistent and buy-leaves agnostic heuristics. Then, for every decoupled state $s^{\mathcal{F}}$ it holds that $h_{\mathcal{F},ex}(s^{\mathcal{F}}) \geq h_{\mathcal{F},comp}(s^{\mathcal{F}})$.*

Proof. Let $s \in [s^{\mathcal{F}}]$ be the state that minimizes $h_{\mathcal{F},\text{ex}}(s^{\mathcal{F}}) = \min_{s\in[s^{\mathcal{F}}]} \mathsf{price}(s^{\mathcal{F}}, s) + h(s)$. Then the sequence of corresponding buy actions $a[s[L]]$ is a path in $\Pi_{L\$}$ that is applicable in $s^{\mathcal{F}}_{L\$}$ and ends in $s^{L\$} = s \cup \{\mathsf{bought}[L] = \top \mid L \in \mathcal{L}\}$.

First, as argued in the proof of Proposition 1 of the main paper, every plan for $\Pi_{L\$}$ can be reordered such that all $|\mathcal{L}|$ buy actions $a[s[L]]$ are moved to the front. Therefore, it suffices to consider only those plans for the compilation that start with any combination of such actions, which we do in the following.

Second, we show that $h^{L\$}(s^{\mathcal{F}}_{L\$}) \leq \mathsf{price}(s^{\mathcal{F}}, s) + h^{L\$}(s^{L\$})$. This holds because the cost of the sequence of $a[s[L]]$ that leads from $s^{\mathcal{F}}_{L\$}$ to $s^{L\$}$ is exactly $\mathsf{price}(s^{\mathcal{F}}, s)$ and, because $h^{L\$}$ is consistent, the heuristic cannot decrease by more than the cost of this path.

Putting the pieces together, we get the claim as follows:

$$\begin{aligned} h_{\mathcal{F},\text{ex}}(s^{\mathcal{F}}) &= \mathsf{price}(s^{\mathcal{F}}, s) + h(s) \\ &= \mathsf{price}(s^{\mathcal{F}}, s) + h^{L\$}(s^{L\$}) \\ &\geq h^{L\$}(s^{\mathcal{F}}_{L\$}) = h_{\mathcal{F},\text{comp}}(s^{\mathcal{F}}) \end{aligned}$$

The first and last equalities hold by the definitions of $h_{\mathcal{F},\text{ex}}$, respectively $h_{\mathcal{F},\text{comp}}$, the second one because $\langle h, h^{L\$}\rangle$ is buy-leaves agnostic, and the inequality because $h^{L\$}$ is consistent. □

Proposition 4. *Let Π be a planning task with factoring $\mathcal{F}$, and h^P a PDB heuristic for Π. There exists a heuristic $h^{P'}_{\mathcal{F},comp}$ for the buy-leaves compilation $\Pi_{L\$}$ such that for all decoupled states $s^{\mathcal{F}}$: $h^{P'}_{\mathcal{F},comp}(s^{\mathcal{F}}) = h^{P}_{\mathcal{F},ex}(s^{\mathcal{F}})$.*

Proof. We set $P' = P \cup \{\mathsf{bought}[L] \mid L \in \mathcal{L}\}$ and show that abstract solutions π^P for $\Pi_{L\$}$ (which minimize $h^P_{\mathcal{F},\text{ex}}(s^{\mathcal{F}}) = \min_{s\in[s^{\mathcal{F}}]} \mathsf{price}(s^{\mathcal{F}}, s) + h^P(s)$) are in one-to-one correspondence with abstract solutions $\pi^{P'}$ for $h^{P'}$ in $\Pi_{L\$}$, which shows the claim. The selection of leaf states in $\mathsf{price}(s^{\mathcal{F}}, s)$ directly corresponds to the subsequence of actions $a[s[L]]$ of a plan $\pi^{P'}$ because incorporating $\mathsf{bought}[L]$ in P' forces the PDB to include exactly one action $a[s^L]$ for each L. The remaining actions in $\pi^{P'}$ are part of Π, possibly with a precondition $\mathsf{bought}[L] = \top$. Rearranging $\pi^{P'}$, as in the proof of Proposition 2, so that all $a[s^L]$ actions are in front, it remains to show that $h^P(s) = h^{P'}(s \cup \{\mathsf{bought}[L] = \top \mid L \in \mathcal{L}\})$. This is true because the abstract state spaces below these two states are isomorphic, as P' includes the $\mathsf{bought}[L]$ variables, so exactly the same actions are applicable and the descendant states are identical except for the no-longer relevant $\mathsf{bought}[L] = \top$ facts. □

Proposition 5. $h^P_{\mathcal{F},comp}(s^{\mathcal{F}}) \leq h^P_{\mathcal{F},ex}(s^{\mathcal{F}})$.

Proof. Let Π be a planning task, $\mathcal{F}$ a factoring, and h^P a PDB heuristic for Π. Let further s be the member state that minimizes $h^P_{\mathcal{F},\text{ex}}(s^{\mathcal{F}}) = \min_{s\in[s^{\mathcal{F}}]} \mathsf{price}(s^{\mathcal{F}}, s) + h^P(s)$. This corresponds to an abstract solution π^P for h^P in $\Pi_{L\$}$ that takes the buy actions $a[s[L]]$ for each L followed by the abstract path corresponding to $h^P(s)$. The abstract state spaces of h^P on Π and $\Pi_{L\$}$ differ only in the additional actions $a[s^L]$ of $\Pi_{L\$}$. Thus, every action sequence π^P is also an abstract solution for h^P in $\Pi_{L\$}$. The other way around, since an abstract solution for $\Pi_{L\$}$ can include an arbitrary number of actions $a[s^L]$ for each L, not every abstract solution for $\Pi_{L\$}$ corresponds to a solution for $h^P_{\mathcal{F},\text{ex}}(s^{\mathcal{F}})$, proving the claim. □

Proposition 6. *$h^{\mathcal{H}\text{-max}}_{\mathcal{F},\text{naïve}} \leq h^{\mathcal{H}\text{-max}}_{\mathcal{F},ex}$ and there are cases where the inequality is strict.*

Proof. We show that $h^{\mathcal{H}\text{-max}}_{\mathcal{F},\text{naïve}}$ and $h^{\mathcal{H}\text{-max}}_{\mathcal{F},\text{ex}}$ differ only on the order of the $\min$ and $\max$ operations, and the claim then follows with the max-min inequality. As all elements of $\mathcal{H}$ are singletons, we can drop the sum $\sum_{h\in H}$. Then $h^{\mathcal{H}\text{-max}}_{\mathcal{F},\text{ex}}(s^{\mathcal{F}}) = \min_{s\in[s^{\mathcal{F}}]} \mathsf{price}(s^{\mathcal{F}}, s) + \max_{\{h\}\in\mathcal{H}} h(s)$ and since the price of s is independent of $\mathcal{H}$ we can move it into the $\max$. For $h^{\mathcal{H}\text{-max}}_{\mathcal{F},\text{naïve}}$ we have: $h^{\mathcal{H}\text{-max}}_{\mathcal{F},\text{naïve}}(s^{\mathcal{F}}) = \max_{\{h\}\in\mathcal{H}} \min_{s\in[s^{\mathcal{F}}]} \mathsf{price}(s^{\mathcal{F}}, s) + h(s)$.

To see that the inequality is strict, consider a case where we take the maximum of two PDB heuristics h_1 and h_2, on a decoupled state $s^{\mathcal{F}}$ with two member states $[s^{\mathcal{F}}] = \{s_1, s_2\}$ with price 0. Assume $h_1(s_1) = 0$, $h_1(s_2) = \infty$, and $h_2(s_1) = \infty$, $h_2(s_2) = 0$. Then, $h^{\mathcal{H}\text{-max}}_{\mathcal{F},\text{naïve}}(s^{\mathcal{F}}) = 0$, as the minimum of each heuristic is 0. However, both member states are detected as dead-ends by one heuristic so $h^{\mathcal{H}\text{-max}}_{\mathcal{F},\text{ex}}(s^{\mathcal{F}}) = \infty$. □

Theorem 1. *The Decoupled Additive PDBs problem is **NP**-complete.*

Proof. Membership: Guessing a member state $s \in [s^{\mathcal{F}}]$, test whether $\mathsf{price}(s^{\mathcal{F}}, s) + h^{\mathcal{H}\text{-sum}}_{\mathcal{F},\text{ex}}(s) \leq B$ in polynomial time.

Hardness: Reduction from 3-SAT. Given any 3-CNF formula ϕ with Boolean propositions X and clauses $\{C^1, \dots, C^m\}$, we construct a planning task, and decoupled state $s^{\mathcal{F}}$ such that $h^{\mathcal{H}\text{-sum}}_{\mathcal{F},\text{ex}}(s^{\mathcal{F}}) = 0$ if ϕ is satisfiable, and $h^{\mathcal{H}\text{-sum}}_{\mathcal{F},\text{ex}}(s^{\mathcal{F}}) = \infty$ otherwise.

The (simplified) Π has the following variables:

- For each clause C_i over propositions $x, y, z \in X$, a leaf L_i with 4 variables $L_i = \{v^i, v^i_x, v^i_y, v^i_z\}$. v^i has domain $\{a, b\}$, with value a in the initial state. The rest have domain $\{u, 0, 1\}$, and have value u in the initial state.
- A center variable v_x for each proposition $x \in X$, plus an extra variable v_{center}, all with domain $\{i, g\}$, value i in the initial state and value g in the goal.

The set of actions in Π, and the pattern collection ensure that:

(1) In the initial decoupled state, all leaf states in L_i of the form $ba_xa_ya_z$ are reachable with price 0 where $a_xa_ya_z$ correspond to an assignment over propositions x, y, and z that satisfy C_i. Therefore $\mathsf{prices}(I^{\mathcal{F}})[s^{L_i}] = 0$ iff s^{L_i} satisfies the clause C_i, else $\mathsf{prices}(I^{\mathcal{F}})[s^{L_i}] = \infty$.

(2) Some state $s^{\mathcal{F}} = I^{\mathcal{F}}[a_{center}]$ is reachable where $v^i = b$ for all $i \in [m]$, and $\mathsf{prices}(s^{\mathcal{F}})[s^L] = \infty$ if $s^L[v_{i,x}] = u$. Therefore, no variable is allowed to have undefined value, and actions changing the assignment are no longer applicable. Member states in $s^{\mathcal{F}}$ correspond exactly to assignments that satisfy all clauses, though they may assign different values to propositions in different leaves.

(3) For any $x \in X$ appearing in clauses C_i and C_j, the collection has a PDB $P_{x,i,j}$ such that $h^{P_{x,i,j}}(s) = \infty$ for any state s in which $v_{i,x} \neq v_{i,y}$. Therefore, all assignments that are inconsistent are detected as dead-end by at least one PDB.

Note that (1-3) together imply that a member state $s \in [s^{\mathcal{F}}]$ corresponds to a satisfying assignment if and only if $\mathsf{price}(s^{\mathcal{F}}, s) + \sum_{x,i.j} h^{P_{x,i,j}}(s) = 0$ and otherwise the value is ∞. (1) and (2) make sure that $\mathsf{prices}(s^{\mathcal{F}})[s^L]$ are 0 iff variables v^i_x correspond to a satisfying assignment (i.e., they are compatible with C_i and they do not have value u). However, there are separate variables for each occurrence of the proposition in each clause. Then, by (3), we construct a collection of PDB heuristics such that, all states having inconsistent assignments (assigning true and false to the same proposition) have a heuristic value of ∞. Therefore, $h^{\mathcal{H}\text{-sum}}_{\mathcal{F},\text{ex}}(s^{\mathcal{F}}) < B$ if and only if there exists a satisfying assignment to ϕ.

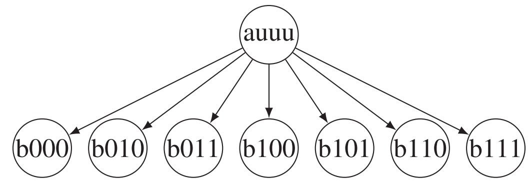


Figure 1: Example of the leaf state space for leaf $L_1 = \{v^1_x, v^1_y, v^1_z, v^1\}$ corresponding to clause $x \vee y \vee \neg z$.

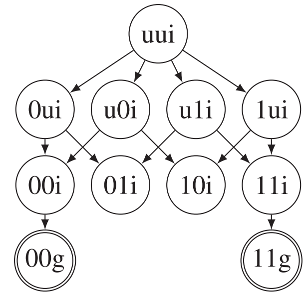


Figure 2: Reachable abstract state space of PDB with $\{v^1_x, x^2_x, v_x\}$.

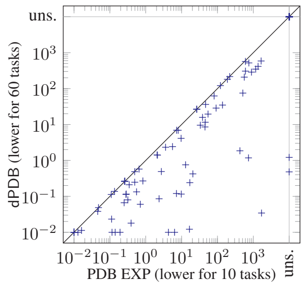
For (1), we introduce 0-cost leaf actions with precondition $v^i_x = v^i_y = v^i_z = u, v^i = a$, and effect $v^i_x = a_x, v^i_y = a_y, v^i_z = a_z, v^i = b$, where a_x, a_y, a_z corresponds to any assignment of x, y, z that satisfies C_i (7 actions in total, one per assignment). Figure 1 shows the reachable leaf states induced by these actions. Note that all leaf states have price of 0 in the initial state.

For (2), we introduce a center action a_{center} with precondition $\{v_{center} = i\} \cup \{v^i = b \mid i \in [m]\}$ and effect $v_{center} = g$. $s^{\mathcal{F}}$ is the state reached from $I^{\mathcal{F}}$ by applying a_{center}. Note that the only change to the pricing function is that the leaf state auuu has a price of ∞ in $s^{\mathcal{F}}$ due to not fulfilling the precondition $v^i = b$. All other leaf states still have a price of 0.

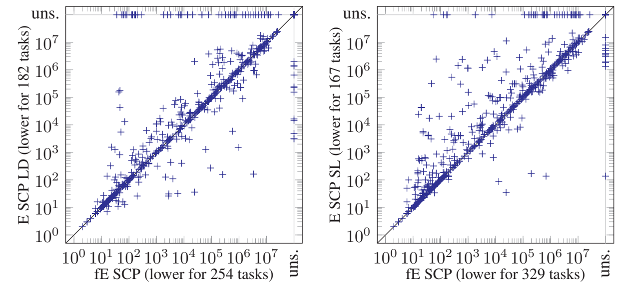
For (3), we introduce center actions $set(x, a_x)$, for $x \in X$ and $a_x \in \{0, 1\}$ with precondition $\{v_x = i\} \cup \{v^i_x = a_x \mid i \text{s.t.} x \in C_i\}$, and effect $v_x = g$. For each x, one of these two actions must be applied, and this is only possible for states where all $v_{i,x}$ agree on the value of x. Therefore, any state in which $v^i_x \neq v^j_x$ is a dead-end state.

Finally, our PDB collection has a PDB for each center variable and each pair of clauses i, j, $P = \{v^i_x, v^j_x, v_x\}$. Figure 2 shows the reachable abstract state space of one PDB. There are exactly two abstract states detected as dead-end: where $v^1_x = 0$ and $v^2_x = 1$ and viceversa. Note that, together, these PDBs detect all dead-end states.

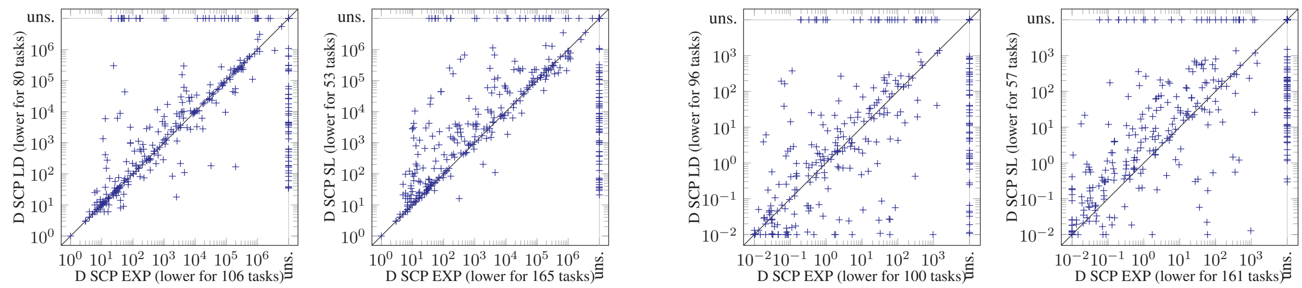
It is worth noting that, even though our PDBs are not orthogonal they can still be additive through cost-partitioning. □



(a) Search time of decoupled search with a single PDB heuristic, using explicit decoupled heuristic (EXP) vs. decoupled PDB (dPDB) computation with factorings F (left) and MM (right).



(b) Expansions of explicit search with the SCP heuristic and factoring MM, comparing using unrestricted PDBs (fE) vs. PDBs restricted to be leaf-disjoint (LD; left) or to affect a single leaf (SL; right).



(c) Expansions (2 plots on the left) and search time (2 plots on the right) of decoupled search with the SCP heuristic and factoring MM, comparing explicit decoupled heuristic computation (EXP) vs. leaf-disjoint (LD; left) and single-leaf (SL; right) approximations.

Figure 3: Like Figure 2 in the main paper but on Autoscale 21.11 benchmarks.

		explicit search (E)				decoupled search (D)					
						EXP					
		p	f	LD	SL	NP	NI	FD	AFF	LD	SL
CPDB	F	86	86	86	71	65	70	74	78	**120**	104
	IF	**92**	91	91	80	82	86	85	85	88	78
	MM	**345**	327	327	304	269	278	279	284	309	290
SCP	F	127	124	90	123	71	73	75	79	124	**143**
	IF	**108**	**108**	102	105	93	93	97	98	96	93
	MM	**399**	378	337	349	288	284	290	299	305	318

Table 1: Like Table 1 in the main paper but on Autoscale 21.11 benchmarks.

Table 1 and Figure 3 show the same results as Table 1 and Figure 2 in the main paper, respectively, but on the Autoscale 21.11 benchmarks (Torralba, Seipp, and Sievers 2021). Tables 2 and 3 show the full per-domain coverage results on the IPC and Autoscale benchmarks.

References

Sievers, S.; Gnad, D.; and Torralba, Á. 2022. Additive Pattern Databases for Decoupled Search. In *Proceedings of the 15th Annual Symposium on Combinatorial Search (SoCS 2022)*. AAAI Press.

Torralba, Á.; Seipp, J.; and Sievers, S. 2021. Automatic Instance Generation for Classical Planning. In Goldman, R. P.; Biundo, S.; and Katz, M., eds., *Proceedings of the Thirty-First International Conference on Automated Planning and Scheduling (ICAPS 2021)*, 376–384. AAAI Press.

	CPDB										SCP									
					decoupled search (D)										decoupled search (D)					
	explicit search (E)				EXP						explicit search (E)				EXP					
	p	f	LD	SL	NP	NI	FD	AFF	LD	SL	p	f	LD	SL	NP	NI	FD	AFF	LD	SL
driverlog (20)	**13**	**13**	**13**	**13**	12	12	12	12	12	12	14	**15**	14	14	12	12	13	12	13	13
logistics00 (28)	24	24	24	21	20	20	20	20	**28**	**28**	24	23	23	23	20	20	20	20	**28**	**28**
logistics98 (35)	**6**	**6**	**6**	5	**6**	**6**	**6**	**6**	**6**	5	**8**	**8**	6	7	7	7	7	7	6	7
miconic (145)	**60**	**60**	**60**	50	49	50	49	50	49	46	123	124	62	**137**	67	70	66	69	50	132
movie (30)	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**
nomystery-opt11 (20)	**20**	**20**	**20**	18	17	18	19	**20**	**20**	**20**	**20**	**20**	**20**	18	13	13	17	19	**20**	**20**
organic-synthesis-opt18 (13)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
pathways (29)	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**4**	**4**	3	**4**	**4**	**4**	**4**	**4**	3	**4**
psr-small (3)	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
rovers (40)	**8**	**8**	**8**	**8**	**8**	**8**	**8**	**8**	**8**	**8**	**9**	**9**	**9**	**9**	**9**	**9**	8	8	**9**	8
satellite (36)	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**8**	**8**	6	**8**	7	7	7	7	6	7
tpp (27)	5	5	5	5	8	10	12	13	**22**	**22**	11	11	9	11	8	8	8	8	**23**	**23**
woodworking-opt08 (13)	7	7	7	7	6	7	7	7	**8**	7	**11**	**11**	6	**11**	10	9	9	9	5	**11**
woodworking-opt11 (5)	**3**	**3**	**3**	**3**	2	**3**	**3**	**3**	**3**	**3**	**5**	**5**	2	**5**	4	4	4	4	1	**5**
zenotravel (20)	**13**	**13**	**13**	11	12	12	12	**13**	**13**	11	**13**	**13**	**13**	**13**	12	12	12	12	**13**	**13**
Sum F (464)	201	201	201	183	182	188	190	194	**211**	204	283	284	206	293	206	208	208	212	210	**304**
childsnack-opt14 (20)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
depot (22)	**11**	**11**	**11**	10	10	10	10	10	10	10	11	11	11	**12**	9	9	9	9	9	11
elevators-opt08 (30)	**22**	**22**	**22**	20	21	21	21	21	21	19	23	22	24	21	20	22	22	22	**25**	20
elevators-opt11 (20)	**18**	**18**	**18**	17	17	17	17	17	17	15	**19**	18	**19**	17	17	18	18	18	**19**	16
floortile-opt11 (20)	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**6**	**6**	5	**6**	5	5	5	5	2	5
floortile-opt14 (20)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3**	**3**	2	2	2	2	2	2	0	1
logistics00 (28)	**24**	**24**	**24**	22	22	23	22	23	23	22	24	22	23	**25**	20	21	20	20	22	22
logistics98 (35)	6	6	6	6	6	6	6	6	**7**	6	8	8	6	**10**	5	5	5	5	7	8
movie (30)	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**
mystery (4)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	0	**1**	0	0	0	0	0	0
organic-synthesis-opt18 (13)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
organic-synthesis-split-opt18 (3)	**1**	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0
rovers (38)	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**7**	**7**	6	6	6	6	6	6	5	6
satellite (34)	4	4	4	4	**5**	**5**	**5**	**5**	**5**	**5**	**6**	5	4	4	5	5	5	5	5	5
tpp (26)	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**8**	**8**	7	5	**8**	**8**	**8**	**8**	7	4
transport-opt08 (30)	**14**	**14**	**14**	11	**14**	**14**	**14**	**14**	**14**	11	**14**	**14**	**14**	11	**14**	**14**	**14**	13	13	11
transport-opt11 (20)	**11**	**11**	**11**	6	10	10	10	10	10	6	12	**13**	**13**	6	10	10	10	10	9	6
transport-opt14 (20)	**8**	**8**	**8**	6	**8**	**8**	**8**	**8**	**8**	7	**10**	**10**	9	6	8	8	8	8	9	7
woodworking-opt08 (24)	13	13	13	13	11	13	13	13	**14**	12	19	19	14	**20**	17	16	17	17	14	19
woodworking-opt11 (15)	**9**	**9**	**9**	**9**	7	**9**	**9**	**9**	**9**	8	**13**	**13**	10	**13**	11	12	11	12	9	12
zenotravel (18)	**11**	**11**	**11**	10	8	10	10	10	**11**	10	**11**	**11**	**11**	**11**	8	9	**11**	10	**11**	10
Sum IF (470)	**192**	191	191	174	179	186	185	186	189	171	**226**	221	208	206	195	200	201	200	196	193
agricola-opt18 (20)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	1	**2**	0	0	0	0	0	0	0	0
airport (44)	**30**	**30**	**30**	**30**	29	29	29	29	29	29	20	20	**29**	20	18	18	17	17	16	16
barman-opt11 (20)	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**
barman-opt14 (14)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
childsnack-opt14 (20)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
data-network-opt18 (20)	**11**	**11**	**11**	**11**	**11**	**11**	**11**	**11**	**11**	10	**13**	**13**	11	12	11	11	11	11	10	10
depot (22)	**11**	**11**	**11**	10	10	10	10	10	10	10	11	11	11	**12**	9	9	9	9	9	11
driverlog (20)	**13**	**13**	**13**	**13**	11	12	12	12	12	11	**14**	**14**	**14**	13	11	11	12	12	13	13
elevators-opt08 (30)	**22**	**22**	**22**	21	21	21	21	21	21	21	23	22	**25**	21	20	22	22	22	**25**	21
elevators-opt11 (20)	**18**	**18**	**18**	**18**	17	17	17	17	17	17	**19**	18	**19**	17	17	18	18	18	**19**	17
floortile-opt11 (20)	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**6**	**6**	5	5	2	2	2	2	2	2
floortile-opt14 (20)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3**	**3**	**3**	2	0	0	0	0	0	0
freecell (78)	**18**	**18**	**18**	**18**	17	17	17	17	17	17	**25**	24	20	24	20	20	20	20	18	19
ged-opt14 (20)	**19**	**19**	**19**	15	15	15	15	15	15	13	**19**	**19**	**19**	15	15	15	15	15	15	13
grid (5)	**3**	**3**	**3**	**3**	2	2	2	2	2	2	**3**	**3**	**3**	**3**	**3**	2	**3**	**3**	**3**	**3**
hiking-opt14 (15)	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**9**	**9**	**9**	8	8	8	8	8	8	7
logistics00 (28)	24	24	24	21	20	20	20	20	**28**	**28**	24	24	23	23	20	20	20	20	**28**	**28**
logistics98 (35)	**6**	**6**	**6**	5	**6**	**6**	**6**	**6**	**6**	5	**8**	**8**	6	7	**8**	7	7	7	6	7
miconic (145)	**60**	**60**	**60**	50	49	50	50	50	49	46	123	123	62	**136**	65	67	68	69	49	130
movie (30)	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**
mprime (35)	**23**	**23**	**23**	**23**	22	22	22	22	22	22	**28**	**28**	27	**28**	27	27	27	27	26	27
mystery (25)	**14**	**14**	**14**	**14**	13	13	13	13	13	13	**17**	**17**	16	**17**	**17**	**17**	**17**	**17**	15	**17**
nomystery-opt11 (20)	**20**	**20**	**20**	18	17	18	19	**20**	**20**	**20**	**20**	**20**	**20**	18	13	13	16	19	**20**	**20**
openstacks-opt08 (30)	**20**	**20**	**20**	**20**	16	16	16	16	16	16	**20**	**20**	**20**	**20**	16	16	16	16	16	16
openstacks-opt11 (20)	**15**	**15**	**15**	**15**	11	11	11	11	11	11	**15**	**15**	**15**	**15**	11	11	11	11	11	11
openstacks-opt14 (20)	**3**	**3**	**3**	**3**	1	1	1	1	1	1	**3**	**3**	**3**	**3**	1	1	1	1	1	1
openstacks (23)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	0	0	0	**1**	0	0	0	0	0	0
organic-synthesis-opt18 (16)	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
organic-synthesis-split-opt18 (20)	**9**	7	7	7	6	6	6	6	6	6	**10**	7	7	7	7	7	7	7	6	7
parcprinter-08 (26)	19	19	19	19	15	17	19	19	**21**	**21**	13	13	13	13	9	9	17	15	18	**19**
parcprinter-opt11 (19)	**17**	**17**	**17**	**17**	14	16	**17**	**17**	**17**	**17**	12	12	12	13	8	8	16	14	15	**17**
pathways (30)	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**5**	**5**	4	4	**5**	**5**	**5**	**5**	4	4
pipesworld-notankage (50)	**21**	**21**	**21**	**21**	16	16	16	16	16	16	23	23	21	**24**	19	18	19	19	17	18
pipesworld-tankage (48)	**15**	14	14	13	13	13	13	13	13	10	**14**	**14**	**14**	13	11	11	11	11	11	11
psr-small (50)	**49**	**49**	**49**	**49**	**49**	**49**	**49**	**49**	**49**	**49**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**
rovers (40)	**8**	**8**	**8**	7	**8**	**8**	**8**	**8**	**8**	**8**	**9**	**9**	**9**	8	**9**	**9**	8	8	**9**	**9**
satellite (36)	6	6	6	6	**7**	**7**	**7**	**7**	**7**	**7**	**8**	**8**	7	6	7	7	7	7	7	7
scanalyzer-08 (9)	**6**	**6**	**6**	**6**	5	5	5	5	5	5	**6**	**6**	**6**	**6**	5	5	5	5	**6**	**6**
scanalyzer-opt11 (5)	**4**	**4**	**4**	**4**	3	3	3	3	3	3	**4**	**4**	**4**	**4**	3	3	3	3	**4**	**4**
spider-opt18 (20)	**14**	12	12	12	12	12	12	12	12	12	**14**	12	12	12	12	12	12	12	12	12
storage (17)	**3**	**3**	**3**	**3**	2	2	2	2	2	2	**3**	**3**	2	**3**	2	2	2	2	2	2
tetris-opt14 (17)	**10**	5	5	5	6	5	6	6	6	5	**11**	6	6	6	6	6	6	6	6	6
tidybot-opt11 (20)	**14**	4	4	4	4	4	4	4	4	4	**16**	4	4	4	4	4	4	4	4	4
tidybot-opt14 (20)	**8**	0	0	0	0	0	0	0	0	0	**12**	0	0	0	0	0	0	0	0	0
tpp (29)	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**11**	**11**	**11**	7	**11**	**11**	**11**	**11**	**11**	7
transport-opt08 (30)	**14**	**14**	**14**	**14**	13	13	13	13	13	12	**14**	**14**	**14**	**14**	13	13	13	13	12	12
transport-opt11 (20)	**11**	**11**	**11**	**11**	9	9	9	9	9	8	12	**13**	12	11	9	9	9	9	8	8
transport-opt14 (20)	**8**	**8**	**8**	7	7	7	7	7	7	7	**10**	9	9	8	7	7	7	7	7	7
trucks (30)	8	8	8	8	**9**	**9**	**9**	**9**	**9**	8	**12**	**12**	8	**12**	11	11	**12**	**12**	9	**12**
woodworking-opt08 (30)	**18**	**18**	**18**	**18**	14	17	16	16	**18**	16	24	25	16	**28**	17	19	20	20	17	27
woodworking-opt11 (20)	**13**	**13**	**13**	**13**	9	12	11	11	**13**	11	17	17	11	**20**	12	14	16	15	12	**20**
zenotravel (20)	**13**	**13**	**13**	12	10	12	12	12	**13**	12	**13**	**13**	**13**	**13**	10	11	**13**	12	**13**	12
Sum MM (1441)	**672**	644	644	618	573	587	590	591	605	585	**784**	749	662	743	596	603	630	628	607	707

Table 2: Full per-domain coverage on the IPC benchmarks (Table 1 in the main paper).

	CPDB										SCP									
					decoupled search (D)										decoupled search (D)					
	explicit search (E)				EXP						explicit search (E)				EXP					
	p	f	LD	SL	NP	NI	FD	AFF	LD	SL	p	f	LD	SL	NP	NI	FD	AFF	LD	SL
agricola (2)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
driverlog (30)	**13**	**13**	**13**	10	6	6	7	8	10	7	13	13	13	**14**	5	5	7	8	10	9
logistics (28)	**16**	**16**	**16**	14	14	14	14	14	14	13	**18**	17	16	15	13	13	13	13	14	14
miconic (30)	**5**	**5**	**5**	4	**5**	**5**	**5**	**5**	**5**	**5**	18	19	5	**21**	5	5	5	5	5	19
nomystery (30)	13	13	13	9	7	8	9	12	**28**	24	13	13	11	9	7	7	9	10	**27**	22
pathways (29)	**8**	**8**	**8**	**8**	5	5	5	5	5	5	**13**	12	9	12	12	12	12	12	9	12
rovers (30)	3	3	3	3	**4**	**4**	**4**	**4**	**4**	**4**	3	3	3	3	**4**	**4**	3	3	**4**	**4**
satellite (30)	**6**	**6**	**6**	5	**6**	**6**	**6**	**6**	**6**	2	**17**	16	6	**17**	6	6	6	6	6	14
scanalyzer (3)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
tpp (30)	2	2	2	2	4	5	7	7	**28**	**28**	10	10	9	10	4	4	4	4	**28**	**28**
woodworking (24)	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	5	4	3	5	4	5	4	5	3	**6**
zenotravel (30)	**17**	**17**	**17**	13	11	14	14	14	**17**	13	17	17	15	17	11	12	12	13	**18**	15
Sum F (296)	86	86	86	71	65	70	74	78	**120**	104	127	124	90	123	71	73	75	79	124	**143**
agricola (2)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
childsnack (30)	4	4	4	4	**5**	**5**	**5**	**5**	**5**	**5**	4	4	4	4	**5**	**5**	**5**	**5**	**5**	4
depots (30)	**17**	**17**	**17**	**17**	15	15	15	15	15	15	16	17	17	**20**	16	16	16	16	15	17
elevators (30)	10	10	10	9	**11**	**11**	**11**	**11**	**11**	10	12	12	**14**	9	12	12	12	12	13	10
floortile (30)	**5**	**5**	**5**	**5**	4	4	4	4	4	4	**7**	**7**	**7**	**7**	6	6	6	6	6	6
logistics (30)	18	18	18	18	18	18	18	18	**19**	**19**	**20**	**20**	19	**20**	17	17	18	18	**20**	**20**
organic-synthesis-split (5)	**1**	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0
scanalyzer (3)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
tpp (30)	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	10	9	6	**11**	9	9	9	9	6	10
transport (30)	**20**	**20**	**20**	10	17	17	17	17	17	9	**20**	**20**	**20**	14	17	17	17	17	17	10
woodworking (27)	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	6	**7**	4	6	5	4	4	6	4	**7**
zenotravel (24)	**12**	**12**	**12**	**12**	7	11	10	10	**12**	11	12	12	11	**14**	6	7	10	9	10	9
Sum IF (271)	**92**	91	91	80	82	86	85	85	88	78	**108**	**108**	102	105	93	93	97	98	96	93
agricola (30)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**5**	**5**	1	1	0	0	0	0	0	0
airport (30)	**16**	**16**	**16**	**16**	15	15	15	15	15	15	7	8	**15**	7	6	6	5	4	7	6
barman (30)	**11**	**11**	**11**	**11**	9	9	9	9	9	9	**12**	**12**	**12**	**12**	9	9	9	9	9	9
childsnack (30)	4	4	4	4	**5**	**5**	**5**	**5**	**5**	**5**	4	4	4	4	**5**	**5**	**5**	**5**	**5**	4
data-network (30)	**13**	**13**	**13**	12	12	12	12	12	12	12	**15**	**15**	12	12	14	14	12	14	11	12
depots (30)	**17**	**17**	**17**	**17**	15	15	15	15	15	15	16	17	17	**20**	16	16	16	16	15	17
driverlog (30)	**13**	**13**	**13**	9	5	6	6	8	10	4	13	13	13	**15**	4	4	6	8	9	9
elevators (30)	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	9	12	13	**15**	13	12	13	13	13	13	11
floortile (30)	**5**	**5**	**5**	4	4	4	4	4	4	4	**7**	**7**	**7**	6	5	5	4	6	5	6
freecell (29)	**5**	**5**	**5**	**5**	1	1	1	1	1	1	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	4	**5**
ged (30)	**22**	**22**	**22**	16	16	16	16	16	16	15	**22**	**22**	**22**	16	16	16	16	16	16	14
grid (30)	20	20	20	**21**	19	19	19	19	19	19	**21**	**21**	**21**	20	19	18	20	19	20	20
hiking (15)	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**9**	**9**	8	8	**9**	**9**	**9**	**9**	8	6
logistics (30)	**18**	**18**	**18**	16	16	16	16	16	16	15	**20**	19	18	17	16	15	15	16	16	16
miconic (30)	**5**	**5**	**5**	4	**5**	**5**	**5**	**5**	**5**	**5**	18	18	5	**19**	5	5	5	6	5	**19**
mprime (30)	**11**	**11**	**11**	**11**	10	10	10	10	10	10	13	12	**14**	12	9	9	9	9	9	9
nomystery (30)	13	13	13	9	7	8	9	12	**28**	24	13	14	11	8	7	7	7	10	**28**	23
openstacks (30)	**6**	**6**	**6**	**6**	3	3	3	3	3	3	**6**	**6**	**6**	**6**	3	3	3	3	3	3
organic-synthesis-split (30)	**5**	3	3	3	2	2	2	2	2	2	**10**	3	3	3	4	3	3	4	2	3
parcprinter (27)	14	14	14	14	11	13	14	14	**18**	**18**	10	10	10	10	7	7	12	11	15	**16**
parking (2)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
pathways (30)	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**14**	**14**	10	9	13	13	13	**14**	10	10
pipesworld-notankage (30)	**19**	**19**	**19**	**19**	15	15	15	15	15	15	21	**22**	20	**22**	17	17	17	16	15	16
pipesworld-tankage (28)	**14**	13	13	12	12	12	12	12	12	9	**13**	**13**	**13**	12	10	10	10	10	10	10
rovers (30)	3	3	3	3	**6**	**6**	**6**	**6**	**6**	**6**	3	3	3	3	4	4	2	3	**6**	**6**
satellite (30)	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**17**	16	6	16	15	13	12	11	6	11
scanalyzer (3)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
storage (22)	**9**	**9**	**9**	**9**	5	5	5	5	5	5	**9**	**9**	7	**9**	5	5	5	5	4	5
tetris (29)	**14**	7	7	7	7	7	7	7	7	7	**12**	7	7	8	7	7	7	7	7	7
thoughtful (30)	**6**	**6**	**6**	5	5	5	5	5	5	5	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
tidybot (30)	**8**	0	0	0	0	0	0	0	0	0	**11**	0	0	0	0	0	0	0	0	0
tpp (30)	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**10**	**10**	6	5	9	9	9	9	6	4
transport (30)	**20**	**20**	**20**	**20**	18	18	18	18	18	18	**20**	**20**	**20**	**20**	17	17	17	17	18	17
woodworking (30)	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**9**	**9**	5	**9**	7	6	7	8	5	8
zenotravel (30)	**17**	**17**	**17**	14	9	14	13	13	16	13	**17**	**17**	16	**17**	8	9	12	11	13	11
Sum MM (965)	**345**	327	327	304	269	278	279	284	309	290	**399**	378	337	349	288	284	290	299	305	318

Table 3: Full per-domain coverage on the Autoscale 21.11 benchmarks (Table 1 in this document).