# Structural-Pattern Databases

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## Classical Planning

Planning task is 5-tuple $\langle V, A, \mathcal{C}, s^0, G \rangle$:

- $V$: finite set of finite-domain state variables
- $A$: finite set of actions of form $\langle \text{pre}, \text{eff} \rangle$
  (preconditions/effects; partial variable assignments)
- $\mathcal{C} : A \mapsto \mathbb{R}^{0+}$ captures action cost
- $s^0$: initial state (variable assignment)
- $G$: goal description (partial variable assignment)

## Cost-Optimal Planning

Given: planning task $\Pi = \langle V, A, \mathcal{C}, s^0, G \rangle$

Find: action sequence $a_1 \dots a_n \in A^*$
transforming $s^0$ into some state $s_n \supseteq G$,
while minimizing $\sum_{i=1}^{n} \mathcal{C}(a_i)$

Approach: A$^*$ + admissible heuristic $h : S \mapsto \mathbb{R}^{0+}$

Admissible $\equiv$ underestimate goal distance

## Abstraction heuristics

Heuristic estimate is goal distance in abstracted state space $S'$

## Examples

Explicit: Projection (pattern database) heuristics
M&S (merge & shrink aka HHH aka FA) heuristics

Implicit: Structural-pattern heuristics

# Explicit Abstractions

## Abstract space is maintained explicitly

PDB: Projection of the original space on variables $V' \subseteq V$
M&S: More flexible contraction of original states

## Problems

Abstract spaces are searched exhaustively $\rightsquigarrow$

$O(1)$ bound on the number of abstract states $\rightsquigarrow$

(sometimes) price in heuristic accuracy in long-run

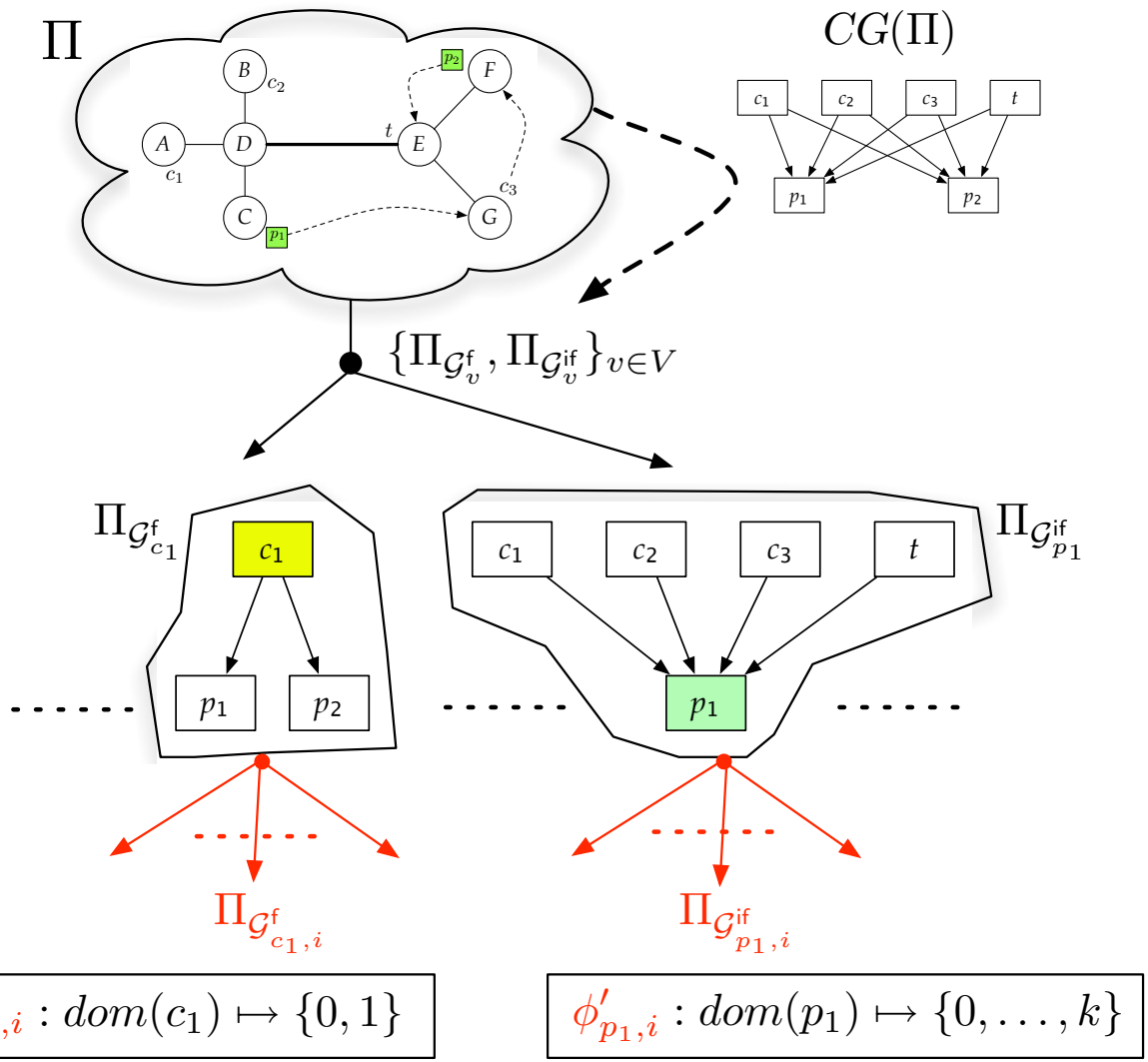
# Implicit Abstractions

## Structural Pattern Heuristics: Main Idea (K & Domshlak, 2008)

Abstract the task in hand into instances of provably tractable fragments of optimal planning

- ♠ guarantee abstract space can be searched (implicitly) in poly-time

# Fork Decomposition
(K & Domshlak, ICAPS08)




+ ensuring proper action cost partitioning

# Planning / Logistics-00

## Expanded nodes

| # | $h^*$ | $MS_{10^5}$ | | $h^{\mathcal{F}}$ | |
|---|---|---|---|---|---|
| | | *nodes* | *time* | *nodes* | *time* |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 12 | 44 | 49 | 4.94 | 1689 | 13.03 |
| 13 | 31 | 32 | 6.9 | 32 | 0.53 |
| 14 | 44 | 45 | 7.21 | 45 | 0.86 |
| 15 | 36 | 37 | 9.46 | 37 | 0.7 |
| 16 | 30 | 31 | 9.43 | 31 | 0.64 |
| 17 | 45 | 668834 | 29.73 | 46 | 3.08 |
| 18 | 42 | 1457130 | 43 | 43 | 2.86 |
| 19 | 48 | 701106 | 37.42 | 697 | 37.13 |
| 20 | 60 | | | 21959 | 951.18 |
| 21 | 42 | 775996 | 43.56 | 43 | 3.77 |
| 22 | 68 | 2222340 | 87.47 | 106534 | 4690.29 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

# Planning / Logistics-00

## Expanded nodes and Time

| # | $h^*$ | $MS_{10^5}$ | | $h^{\mathcal{F}}$ | |
|---|---|---|---|---|---|
| | | *nodes* | *time* | *nodes* | *time* |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 12 | 44 | 49 | *4.94* | 1689 | *13.03* |
| 13 | 31 | 32 | *6.9* | 32 | *0.53* |
| 14 | 44 | 45 | *7.21* | 45 | *0.86* |
| 15 | 36 | 37 | *9.46* | 37 | *0.7* |
| 16 | 30 | 31 | *9.43* | 31 | *0.64* |
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| 20 | 60 | | | 21959 | *951.18* |
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| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

# h-partition

$$\{h(s)|s \in S' \subseteq S\}$$

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**Pre-Search (offline)**

Explicit : Build abstract space, compute distances in it

Implicit : Build abstract tasks

# h-partition

$$\{h(s)|s \in S' \subseteq S\}$$

$$\Downarrow$$

$$O(X + |S'| \cdot Y)$$

$$\swarrow \qquad \searrow$$

**Pre-Search (offline)**

Explicit : Build abstract space, compute distances in it

Implicit : Build abstract tasks

**Per-Node (online)**

Explicit : Lookup

Implicit : Actual heuristic calculations

# Heuristics Complexity - Abstractions

$S^\alpha$ - abstract state space, $D = \sum_v |Dom(v)|$, $d = \max_v |Dom(v)|$

| | Pre-Search ($X$) | Per-Node ($Y$) |
|---|---|---|
| Projection | $\|S^\alpha\| \cdot (\log(\|S^\alpha\|) + \|A\|)$ | $1$ |
| M&S | $\|V\| \cdot \|S^\alpha\| \cdot (\log(\|S^\alpha\|) + \|A\|)$ | $\|V\|$ |
| Forks | $D \cdot \|\|\Pi\|\|$ | $D \cdot (d^3 \cdot \|V\| + \|A\|)$ |

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| Projection | $\|S^\alpha\| \cdot (\log(\|S^\alpha\|) + \|A\|)$ | $1$ |
| M&S | $\|V\| \cdot \|S^\alpha\| \cdot (\log(\|S^\alpha\|) + \|A\|)$ | $\|V\|$ |
| Forks | $D \cdot \|\|\Pi\|\|$ | $D \cdot (d^3 \cdot \|V\| + \|A\|)$ |
| ForksDB | $D \cdot (\|\|\Pi\|\| + d^3 \cdot \|V\| + \|A\|)$ | $D \cdot d \cdot \|V\|$ |

# Planning / Logistics-00

## Expanded nodes and Time

| # | $h^*$ | $MS_{10^5}$ | | $h^{\mathcal{F}}$ | | $h^{\mathcal{F}\text{-}DB}$ |
|---|---|---|---|---|---|---|
| | | *nodes* | *time* | *nodes* | *time* | *time* |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 12 | 44 | 49 | *4.94* | 1689 | *13.03* | *0.07* |
| 13 | 31 | 32 | *6.9* | 32 | *0.53* | *0* |
| 14 | 44 | 45 | *7.21* | 45 | *0.86* | *0* |
| 15 | 36 | 37 | *9.46* | 37 | *0.7* | *0.01* |
| 16 | 30 | 31 | *9.43* | 31 | *0.64* | *0.01* |
| 17 | 45 | 668834 | *29.73* | 46 | *3.08* | *0.02* |
| 18 | 42 | 1457130 | *43* | 43 | *2.86* | *0.01* |
| 19 | 48 | 701106 | *37.42* | 697 | *37.13* | *0.09* |
| 20 | 60 | | | 21959 | *951.18* | *2.13* |
| 21 | 42 | 775996 | *43.56* | 43 | *3.77* | *0.02* |
| 22 | 68 | 2222340 | *87.47* | 106534 | *4690.29* | *11.08* |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

# Solved Instances

| Domain | $MS_{10^4}$ | $MS_{10^5}$ | $h^{\mathcal{F}}$ |
|---|---|---|---|
| airport-ipc4 | 16 | 16 | 11 |
| blocks-ipc2 | 18 | 20 | 18 |
| depots-ipc3 | 7 | 4 | 2 |
| driverlog-ipc3 | 12 | 12 | 8 |
| freecell-ipc3 | 5 | 1 | 3 |
| grid-ipc1 | 2 | 2 | 1 |
| gripper-ipc1 | 7 | 7 | 5 |
| logistics-ipc1 | 4 | 5 | 4 |
| logistics-ipc2 | 16 | 21 | 21 |
| miconic-strips-ipc2 | 54 | 55 | 45 |
| mprime-ipc1 | 21 | 12 | 17 |
| mystery-ipc1 | 16 | 12 | 16 |
| openstacks-ipc5 | 7 | 7 | 7 |
| pathways-ipc5 | 3 | 4 | 4 |
| pipesworld-notankage-ipc4 | 20 | 12 | 8 |
| pipesworld-tankage-ipc4 | 13 | 7 | 6 |
| psr-small-ipc4 | 50 | 50 | 47 |
| rovers-ipc5 | 6 | 7 | 5 |
| satellite-ipc4 | 6 | 6 | 6 |
| schedule-strips | 22 | 1 | 40 |
| tpp-ipc5 | 6 | 6 | 5 |
| trucks-ipc5 | 6 | 5 | 5 |
| zenotravel-ipc3 | 11 | 11 | 8 |
| Total | 328 | 283 | 292 |

# Solved Instances

| Domain | $MS_{10^4}$ | $MS_{10^5}$ | $h^{\mathcal{F}}$ | $h^{\mathcal{F}\text{-}DB}$ |
|---|---|---|---|---|
| airport-ipc4 | 16 | 16 | 11 | 20 |
| blocks-ipc2 | 18 | 20 | 18 | 21 |
| depots-ipc3 | 7 | 4 | 2 | 7 |
| driverlog-ipc3 | 12 | 12 | 8 | 12 |
| freecell-ipc3 | 5 | 1 | 3 | 5 |
| grid-ipc1 | 2 | 2 | 1 | 2 |
| gripper-ipc1 | 7 | 7 | 5 | 7 |
| logistics-ipc1 | 4 | 5 | 4 | 6 |
| logistics-ipc2 | 16 | 21 | 21 | 22 |
| miconic-strips-ipc2 | 54 | 55 | 45 | 51 |
| mprime-ipc1 | 21 | 12 | 17 | 23 |
| mystery-ipc1 | 16 | 12 | 16 | 20 |
| openstacks-ipc5 | 7 | 7 | 7 | 7 |
| pathways-ipc5 | 3 | 4 | 4 | 4 |
| pipesworld-notankage-ipc4 | 20 | 12 | 8 | 16 |
| pipesworld-tankage-ipc4 | 13 | 7 | 6 | 10 |
| psr-small-ipc4 | 50 | 50 | 47 | 49 |
| rovers-ipc5 | 6 | 7 | 5 | 6 |
| satellite-ipc4 | 6 | 6 | 6 | 6 |
| schedule-strips | 22 | 1 | 40 | 46 |
| tpp-ipc5 | 6 | 6 | 5 | 6 |
| trucks-ipc5 | 6 | 5 | 5 | 6 |
| zenotravel-ipc3 | 11 | 11 | 8 | 11 |
| Total | 328 | 283 | 292 | **363** |

# Solved Instances

| Domain | $MS_{10^4}$ | $MS_{10^5}$ | $h^{\mathcal{F}}$ | $h^{\mathcal{F}\text{-}DB}$ | blind | GAMER |
|---|---|---|---|---|---|---|
| airport-ipc4 | 16 | 16 | 11 | 20 | 17 | 11 |
| blocks-ipc2 | 18 | 20 | 18 | 21 | 18 | 30 |
| depots-ipc3 | 7 | 4 | 2 | 7 | 4 | 4 |
| driverlog-ipc3 | 12 | 12 | 8 | 12 | 7 | 11 |
| freecell-ipc3 | 5 | 1 | 3 | 5 | 4 | 2 |
| grid-ipc1 | 2 | 2 | 1 | 2 | 1 | 2 |
| gripper-ipc1 | 7 | 7 | 5 | 7 | 7 | 20 |
| logistics-ipc1 | 4 | 5 | 4 | 6 | 2 | 6 |
| logistics-ipc2 | 16 | 21 | 21 | 22 | 10 | 20 |
| miconic-strips-ipc2 | 54 | 55 | 45 | 51 | 50 | 85 |
| mprime-ipc1 | 21 | 12 | 17 | 23 | 19 | 9 |
| mystery-ipc1 | 16 | 12 | 16 | 20 | 17 | 8 |
| openstacks-ipc5 | 7 | 7 | 7 | 7 | 7 | 7 |
| pathways-ipc5 | 3 | 4 | 4 | 4 | 4 | 4 |
| pipesworld-notankage-ipc4 | 20 | 12 | 8 | 16 | 14 | 11 |
| pipesworld-tankage-ipc4 | 13 | 7 | 6 | 10 | 10 | 6 |
| psr-small-ipc4 | 50 | 50 | 47 | 49 | 48 | 47 |
| rovers-ipc5 | 6 | 7 | 5 | 6 | 5 | 5 |
| satellite-ipc4 | 6 | 6 | 6 | 6 | 4 | 6 |
| schedule-strips | 22 | 1 | 40 | 46 | 29 | 3 |
| tpp-ipc5 | 6 | 6 | 5 | 6 | 5 | 5 |
| trucks-ipc5 | 6 | 5 | 5 | 6 | 5 | 3 |
| zenotravel-ipc3 | 11 | 11 | 8 | 11 | 7 | 10 |
| Total | 328 | 283 | 292 | **363** | 294 | 315 |

# Summary

## Contributions

1. "Databasing" can be feasible even for exponential size abstract spaces
2. Structural Patterns + "Databasing" = State of the art admissible heuristics