Planning and Optimization
D3. Pattern Databases: Introduction

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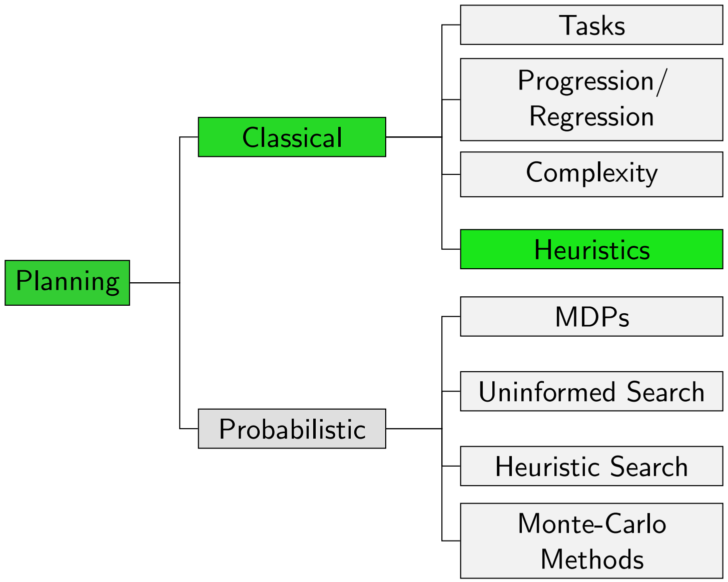
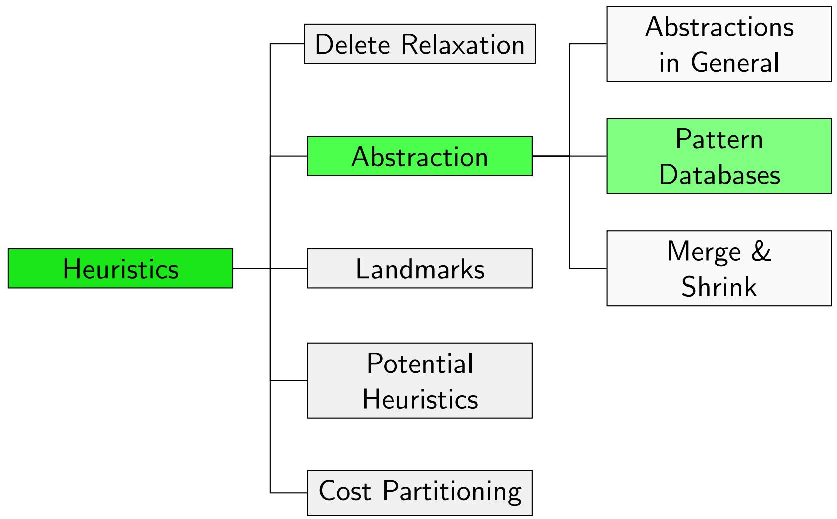
Content of this Course



Content of this Course: Heuristics



D3.1 Projections and Pattern Database Heuristics

Pattern Database Heuristics

- The most commonly used abstraction heuristics in search and planning are pattern database (PDB) heuristics.
- PDB heuristics were originally introduced for the 15-puzzle (Culberson & Schaeffer, 1996) and for Rubik's cube (Korf, 1997).
- The first use for domain-independent planning is due to Edelkamp (2001).
- Since then, much research has focused on the theoretical properties of pattern databases, how to use pattern databases more effectively, how to find good patterns, etc.
- Pattern databases are a very active research area both in planning and in (domain-specific) heuristic search.
- For many search problems, pattern databases are the most effective admissible heuristics currently known.

Pattern Database Heuristics Informally

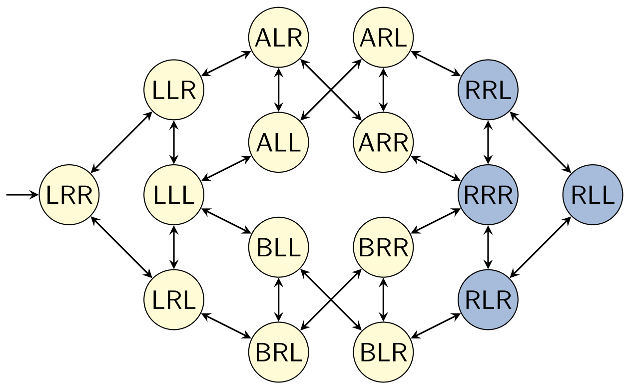
Pattern Databases: Informally

A pattern database heuristic for a planning task is an abstraction heuristic where

- some aspects of the task are represented in the abstraction with perfect precision, while
- all other aspects of the task are not represented at all.

This is achieved by projecting the task onto those variables that describe the aspects that are represented.

Example: Transition System

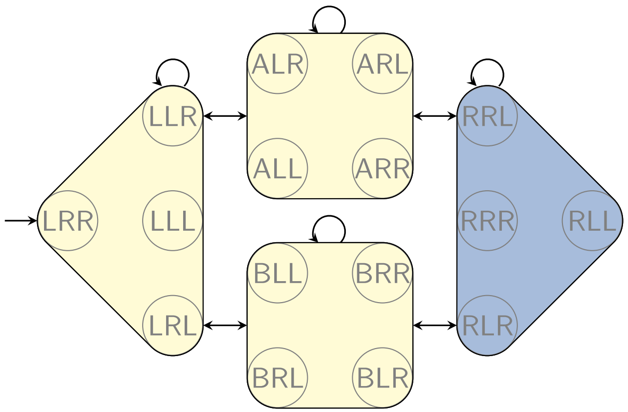


Logistics problem with one package, two trucks, two locations:

- state variable package: $\{L, R, A, B\}$
- state variable truck A: $\{L, R\}$
- state variable truck B: $\{L, R\}$

Example: Projection (1)

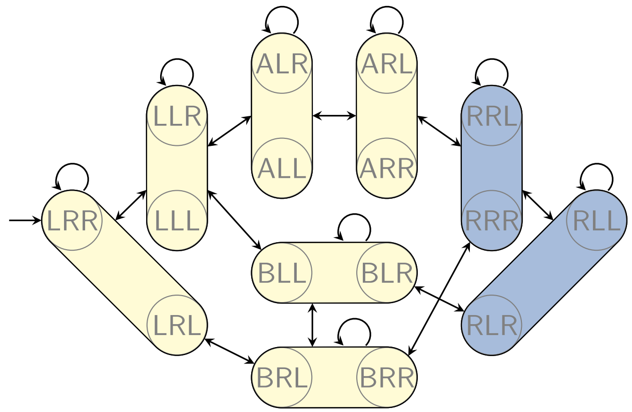
Abstraction induced by $\pi_{\{\text{package}\}}$:



$h^{\{\text{package}\}}(\text{LRR}) = 2$

Example: Projection (2)

Abstraction induced by $\pi_{\{\text{package},\text{truck A}\}}$:



$h^{\{\text{package},\text{truck A}\}}(\text{LRR}) = 2$

Projections

Formally, pattern database heuristics are abstraction heuristics induced by a particular class of abstractions called projections.

Definition (Projection)

Let Π be an FDR planning task with variables V and states S. Let $P \subseteq V$, and let S' be the set of states over P.

The projection $\pi_P : S \to S'$ is defined as $\pi_P(s) := s|_P$, where $s|_P(v) := s(v)$ for all $v \in P$.

We call P the pattern of the projection π_P.

In other words, π_P maps two states s_1 and s_2 to the same abstract state iff they agree on all variables in P.

Pattern Database Heuristics

Abstraction heuristics based on projections are called pattern database (PDB) heuristics.

Definition (Pattern Database Heuristic)

The abstraction heuristic induced by π_P is called a pattern database heuristic or PDB heuristic. We write h^P as a shorthand for h^{π_P}.

Why are they called pattern database heuristics?

- Heuristic values for PDB heuristics are traditionally stored in a 1-dimensional table (array) called a pattern database (PDB). Hence the name "PDB heuristic".

Pattern Databases: Chapter Overview

In the following, we will discuss:

- how to implement PDB heuristics
  ⇝ this chapter
- how to effectively make use of multiple PDB heuristics
  ⇝ Chapter D4
- how to find good patterns for PDB heuristics
  ⇝ Chapter D5

Pattern Database Implementation

Assume we are given a pattern P for a planning task Π.
How do we implement h^P?

1. In a precomputation step, we compute a graph representation for the abstraction $\mathcal{T}(\Pi)^{\pi_P}$ and compute the abstract goal distance for each abstract state.
2. During search, we use the precomputed abstract goal distances in a lookup step.

D3.2 Implementing PDBs: Precomputation

Precomputation Step

Let Π be a planning task and P a pattern.
Let $\mathcal{T} = \mathcal{T}(\Pi)$ and $\mathcal{T}' = \mathcal{T}^{\pi_P}$.

- We want to compute a graph representation of $\mathcal{T}'$.
- $\mathcal{T}'$ is defined through an abstraction of $\mathcal{T}$.
  - For example, each concrete transition induces an abstract transition.
- However, we cannot compute $\mathcal{T}'$ by iterating over all transitions of $\mathcal{T}$.
  - This would take time $\Omega(\|\mathcal{T}\|)$.
  - This is prohibitively long (so long that we could solve the task using uniform-cost search or similar techniques).
- Hence, we need a way of computing $\mathcal{T}'$ in time which is polynomial only in $\|\Pi\|$ and $\|\mathcal{T}'\|$.

Syntactic Projections

Definition (Syntactic Projection)

Let $\Pi = \langle V, I, O, \gamma \rangle$ be an FDR planning task, and let $P \subseteq V$ be a subset of its variables.
The syntactic projection $\Pi|_P$ of Π to P is the FDR planning task $\langle P, I|_P, \{o|_P \mid o \in O\}, \gamma|_P \rangle$, where

- $\varphi|_P$ for formula φ is defined as the formula obtained from φ by replacing all atoms $(v = d)$ with $v \notin P$ by $\top$, and
- $o|_P$ for operator o is defined by replacing all formulas φ occurring in the precondition or effect conditions of o with $\varphi|_P$ and all atomic effects $(v := d)$ with $v \notin P$ with the empty effect $\top$.

Put simply, $\Pi|_P$ throws away all information not pertaining to variables in P.

Trivially Inapplicable Operators

Definition (Trivially Inapplicable Operator)

An operator o of a SAS$^+$ task is called trivially inapplicable if

- $pre(o)$ contains the atoms $(v = d)$ and $(v = d')$ for some variable v and values $d \neq d'$, or
- $eff(o)$ contains the effects $(v := d)$ and $(v := d')$ for some variable v and values $d \neq d'$.

Notes:

- Trivially inapplicable operators are never applicable and can thus be safely omitted from the task.
- Trivially inapplicable operators can be detected in linear time.

Trivially Unsolvable SAS$^+$ Tasks

Definition (Trivially Unsolvable)

A SAS$^+$ task $\Pi = \langle V, I, O, \gamma \rangle$ is called trivially unsolvable if γ contains the atoms $(v = d)$ and $(v = d')$ for some variable v and values $d \neq d'$.

Notes:

- Trivially unsolvable SAS$^+$ tasks have no goal states and are hence unsolvable.
- Trivially unsolvable SAS$^+$ tasks can be detected in linear time.

Equivalence Theorem for Syntactic Projections

Theorem (Syntactic Projections vs. Projections)

Let Π be a SAS$^+$ task that is not trivially unsolvable and has no trivially inapplicable operators, and let P be a pattern for Π.
Then $\mathcal{T}(\Pi|_P) \overset{G}{\sim} \mathcal{T}(\Pi)^{\pi_P}$.

Proof.

$\rightsquigarrow$ exercises □

PDB Computation

Using the equivalence theorem, we can compute pattern databases for (not trivially unsolvable) SAS$^+$ tasks Π and patterns P:

Computing Pattern Databases

def compute-PDB(Π, P):
  Remove trivially inapplicable operators from Π.
  Compute $\Pi' := \Pi|_P$.
  Compute $\mathcal{T}' := \mathcal{T}(\Pi')$.
  Perform a backward uniform-cost search from the goal states of $\mathcal{T}'$ to compute all abstract goal distances.
  $PDB :=$ a table containing all goal distances in $\mathcal{T}'$
  return PDB

The algorithm runs in polynomial time and space in terms of $\|\Pi\| + |PDB|$.

Generalizations of the Equivalence Theorem

- The restrictions to SAS$^+$ tasks and to tasks without trivially inapplicable operators are necessary.
- We can slightly generalize the result if we allow general negation-free formulas, but still forbid conditional effects.
  - In that case, the weighted graph of $\mathcal{T}(\Pi)^{\pi_P}$ is isomorphic to a subgraph of the weighted graph of $\mathcal{T}(\Pi|_P)$.
  - This means that we can use $\mathcal{T}(\Pi|_P)$ to derive an admissible estimate of h^P.
- With conditional effects, not even this weaker result holds.

Going Beyond SAS$^+$ Tasks

- Most practical implementations of PDB heuristics are limited to SAS$^+$ tasks (or modest generalizations).
- One way to avoid the issues with general FDR tasks is to convert them to equivalent SAS$^+$ tasks.
- However, most direct conversions can exponentially increase the task size in the worst case.

$\rightsquigarrow$ We will only consider SAS$^+$ tasks in the chapters dealing with pattern databases.

D3.3 Implementing PDBs: Lookup

Lookup Step: Overview

- During search, the PDB is the only piece of information necessary to represent h^P. (It is not necessary to store the abstract transition system itself at this point.)
- Hence, the space requirements for PDBs during search are linear in the number of abstract states S': there is one table entry for each abstract state.
- During search, $h^P(s)$ is computed by mapping $\pi_P(s)$ to a natural number in the range $\{0, \dots, |S'| - 1\}$ using a perfect hash function, then looking up the table entry for this number.

Lookup Step: Algorithm

Let $P = \{v_1, \dots, v_k\}$ be the pattern.

- We assume that all variable domains are natural numbers counted from 0, i.e., $\mathrm{dom}(v) = \{0, 1, \dots, |\mathrm{dom}(v)| - 1\}$.
- For all $i \in \{1, \dots, k\}$, we precompute $N_i := \prod_{j=1}^{i-1} |\mathrm{dom}(v_j)|$.

Then we can look up heuristic values as follows:

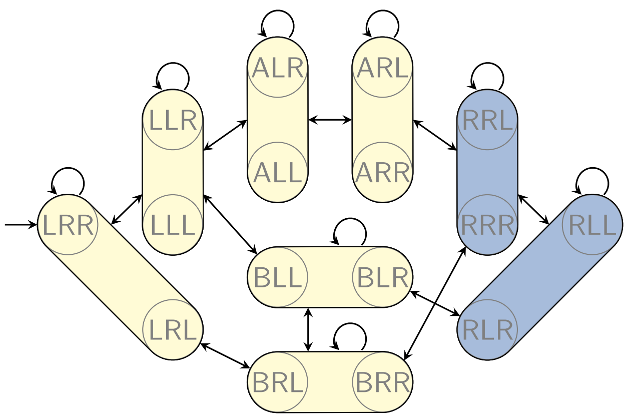
Computing Pattern Database Heuristics

def PDB-heuristic(s):
  $index := \sum_{i=1}^{k} N_i s(v_i)$
  return $PDB[index]$

- This is a very fast operation: it can be performed in $O(k)$.
- For comparison, most relaxation heuristics need time $O(\|\Pi\|)$ per state.

Lookup Step: Example (1)

Abstraction induced by $\pi_{\{\text{package},\text{truck A}\}}$:



Lookup Step: Example (2)

- $P = \{v_1, v_2\}$ with $v_1 =$ package, $v_2 =$ truck A.
- $\mathrm{dom}(v_1) = \{\mathrm{L}, \mathrm{R}, \mathrm{A}, \mathrm{B}\} \approx \{0, 1, 2, 3\}$
- $\mathrm{dom}(v_2) = \{\mathrm{L}, \mathrm{R}\} \approx \{0, 1\}$

$\rightsquigarrow$ $N_1 = \prod_{j=1}^{0} |\mathrm{dom}(v_j)| = 1$, $N_2 = \prod_{j=1}^{1} |\mathrm{dom}(v_j)| = 4$

$\rightsquigarrow$ $index(s) = 1 \cdot s(\text{package}) + 4 \cdot s(\text{truck A})$

Pattern database:

abstract state	LL	RL	AL	BL	LR	RR	AR	BR
index	0	1	2	3	4	5	6	7
value	2	0	2	1	2	0	1	1

D3.4 Summary

Summary

- Pattern database (PDB) heuristics are abstraction heuristics based on projection to a subset of variables.
- For SAS$^+$ tasks, they can easily be implemented via syntactic projections of the task representation.
- PDBs are lookup tables that store heuristic values, indexed by perfect hash values for projected states.
- PDB values can be looked up very fast, in time $O(k)$ for a projection to k variables.