

Planning and Optimization

A7. Invariants and Mutexes

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A7.1 Invariants

A7.2 Computing Invariants

A7.3 Mutexes

A7.4 Summary

A7.1 Invariants

Invariants

- ▶ When we as humans reason about planning tasks, we implicitly make use of “obvious” properties of these tasks.
 - ▶ **Example:** we are never in two places at the same time
- ▶ We can represent such properties as a logical formulas φ that are **true in all reachable states**.
 - ▶ **Example:** $\varphi = \neg(at\text{-}uni \wedge at\text{-}home)$
- ▶ Such formulas are called **invariants** of the task.

Invariants: Definition

Definition (Invariant)

An **invariant** of a planning task Π with state variables V is a logical formula φ over V such that $s \models \varphi$ for all reachable states of Π .

A7.2 Computing Invariants

Computing Invariants

How does an **automated** planner come up with invariants?

- ▶ Theoretically, testing if an arbitrary formula φ is an invariant is **as hard as planning** itself.
 - ↪ **proof idea**: a planning task is **unsolvable** iff the negation of its goal is an invariant
- ▶ Still, many practical invariant synthesis algorithms exist.
- ▶ To remain efficient (= polynomial-time), these algorithms only compute a **subset** of all useful invariants.
 - ↪ **sound**, but not **complete**
- ▶ Empirically, they tend to at least find the “obvious” invariants of a planning task.

Invariant Synthesis Algorithms

Most algorithms for generating invariants are based on the **generate-test-repair** approach:

- ▶ **Generate**: Suggest some invariant candidates, e.g., by enumerating all possible formulas φ of a certain size.
- ▶ **Test**: Try to prove that φ is indeed an invariant. Usually done **inductively**:
 - 1 Test that **initial state** satisfies φ .
 - 2 Test that if φ is true in the current state, it remains true after applying a single operator.
- ▶ **Repair**: If invariant test fails, replace candidate φ by a **weaker** formula, ideally exploiting **why** the proof failed.

Exploiting Invariants

Invariants have many uses in planning:

- ▶ **Regression search:**
Prune states that violate (are inconsistent with) invariants.
- ▶ **Planning as satisfiability:**
Add invariants to a SAT encoding of a planning task to get tighter constraints.
- ▶ **Reformulation:**
Derive a **more compact** state space representation (i.e., with fewer unreachable states).

We now briefly discuss the last point because it is important for **planning tasks in finite-domain representation**, introduced in the following chapter.

A7.3 Mutexes

Mutexes

Invariants that take the form of **binary clauses** are called **mutexes** because they express that certain variable assignments cannot be simultaneously true and are hence **mutually exclusive**.

Example (Blocks World)

The invariant $\neg A\text{-on-}B \vee \neg A\text{-on-}C$ states that $A\text{-on-}B$ and $A\text{-on-}C$ are mutex.

We say that a larger **set of literals** is mutually exclusive if every subset of two literals is a mutex.

Example (Blocks World)

Every pair in $\{B\text{-on-}A, C\text{-on-}A, D\text{-on-}A, A\text{-clear}\}$ is mutex.

Encoding Mutex Groups as Finite-Domain Variables

Let $L = \{\ell_1, \dots, \ell_n\}$ be mutually exclusive literals over n different variables $V_L = \{v_1, \dots, v_n\}$.

Then the planning task can be rephrased using a single **finite-domain** (i.e., non-binary) state variable v_L with $n + 1$ possible values in place of the n variables in V_L :

- ▶ n of the possible values represent situations in which **exactly one** of the literals in L is true.
- ▶ The remaining value represents situations in which **none of the literals** in L is true.
 - ▶ **Note:** If we can prove that one of the literals in L must be true in each state (i.e., $\ell_1 \vee \dots \vee \ell_n$ is an invariant), this additional value can be omitted.

In many cases, the reduction in the number of variables dramatically improves performance of a planning algorithm.

A7.4 Summary

Summary

- ▶ **Invariants** are common properties of all reachable states, expressed as logical formulas.
- ▶ A number of algorithms for **computing invariants** exist.
- ▶ These algorithms will not find **all useful invariants** (which is too hard), but try to find some useful subset with reasonable (polynomial) computational effort.
- ▶ **Mutexes** are invariants that express that certain pairs of literals are mutually exclusive.