

Principles of AI Planning

3. Normal forms

Albert-Ludwigs-Universität Freiburg



Bernhard Nebel and Robert Mattmüller

October 21st, 2016

Motivation



- Motivation
- Effect normal form
- Positive normal form
- STRIPS
- Summary

Similarly to normal forms in propositional logic (DNF, CNF, NNF, ...) we can define **normal forms for effects, operators and planning tasks**.

This is useful because algorithms (and proofs) then only need to deal with effects (resp. operators or tasks) in normal form.

October 21st, 2016

B. Nebel, R. Mattmüller – AI Planning

2 / 24

2 Effect normal form



- Motivation
- Effect normal form
- Equivalences
- Definition
- Example
- Positive normal form
- STRIPS
- Summary

- Equivalence of operators and effects
- Definition
- Example

October 21st, 2016

B. Nebel, R. Mattmüller – AI Planning

4 / 24

Equivalence of operators and effects



- Motivation
- Effect normal form
- Equivalences
- Definition
- Example
- Positive normal form
- STRIPS
- Summary

Definition (equivalent effects)

Two effects e and e' over state variables A are **equivalent**, written $e \equiv e'$, if for all states s over A , $[e]_s = [e']_s$.

Definition (equivalent operators)

Two operators o and o' over state variables A are **equivalent**, written $o \equiv o'$, if they are applicable in the same states, and for all states s where they are applicable, $app_o(s) = app_{o'}(s)$.

Theorem

Let $o = \langle \chi, e \rangle$ and $o' = \langle \chi', e' \rangle$ be operators with $\chi \equiv \chi'$ and $e \equiv e'$. Then $o \equiv o'$.

Note: The converse is not true. (Why not?)

October 21st, 2016

B. Nebel, R. Mattmüller – AI Planning

5 / 24

$$e_1 \wedge e_2 \equiv e_2 \wedge e_1 \quad (1)$$

$$(e_1 \wedge e_2) \wedge e_3 \equiv e_1 \wedge (e_2 \wedge e_3) \quad (2)$$

$$\top \wedge e \equiv e \quad (3)$$

$$\chi \triangleright e \equiv \chi' \triangleright e \quad \text{if } \chi \equiv \chi' \quad (4)$$

$$\top \triangleright e \equiv e \quad (5)$$

$$\perp \triangleright e \equiv \top \quad (6)$$

$$\chi_1 \triangleright (\chi_2 \triangleright e) \equiv (\chi_1 \wedge \chi_2) \triangleright e \quad (7)$$

$$\chi \triangleright (e_1 \wedge \dots \wedge e_n) \equiv (\chi \triangleright e_1) \wedge \dots \wedge (\chi \triangleright e_n) \quad (8)$$

$$(\chi_1 \triangleright e) \wedge (\chi_2 \triangleright e) \equiv (\chi_1 \vee \chi_2) \triangleright e \quad (9)$$

We can define a **normal form for effects**:

- Nesting of conditionals, as in $a \triangleright (b \triangleright c)$, can be eliminated.
- Effects e within a conditional effect $\varphi \triangleright e$ can be restricted to atomic effects (a or $\neg a$).

Transformation to this effect normal form only gives a small polynomial size increase.

Compare: transformation to CNF or DNF may increase formula size exponentially.

Definition

An operator $\langle \chi, e \rangle$ is in **effect normal form (ENF)** if for all occurrences of $\chi' \triangleright e'$ in e the effect e' is either a or $\neg a$ for some $a \in A$, and there is at most one occurrence of any atomic effect in e .

Theorem

For every operator there is an equivalent one in effect normal form.

Proof is constructive: we can transform any operator into effect normal form using the equivalence transformations for effects.

Example

$$(a \triangleright (b \wedge (c \triangleright (\neg d \wedge e)))) \wedge (\neg b \triangleright e)$$

transformed to effect normal form is

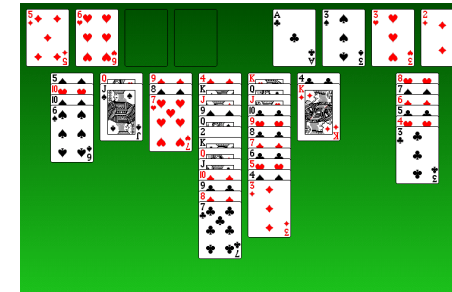
$$(a \triangleright b) \wedge ((a \wedge c) \triangleright \neg d) \wedge ((\neg b \vee (a \wedge c)) \triangleright e)$$

3 Positive normal form

- Motivation
- Definition & algorithm
- Example
- Advantage

Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

Example: Freecell



Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

Example (good and bad effects)

If we move a card c to a free tableau position, the **good effect** is that the card formerly below c is now available. The **bad effect** is that we lose one free tableau position.

What is a good or bad effect?

Question: Which operator effects are good, and which are bad?

Difficult to answer in general, because it depends on context:

- Locking the entrance door is **good** if we want to keep burglars out.
- Locking the entrance door is **bad** if we want to enter.

We will now consider a reformulation of planning tasks that makes the distinction between good and bad effects obvious.

Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

Positive normal form

Definition (operators in positive normal form)

An operator $o = \langle \chi, e \rangle$ is in **positive normal form** if it is in effect normal form, no negation symbols appear in χ , and no negation symbols appear in any effect condition in e .

Definition (planning tasks in positive normal form)

A planning task $\langle A, I, O, \gamma \rangle$ is in **positive normal form** if all operators in O are in positive normal form and no negation symbols occur in the goal γ .

Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

Positive normal form: existence



Theorem (positive normal form)

Every planning task Π has an equivalent planning task Π' in positive normal form.

Moreover, Π' can be computed from Π in polynomial time.

Note: Equivalence here means that the represented transition systems of Π and Π' , limited to the states that can be reached from the initial state, are isomorphic.

We prove the theorem by describing a suitable algorithm. (However, we do not prove its correctness or complexity.)

- Motivation
- Effect normal form
- Positive normal form
- Motivation
- Definition & algorithm
- Example
- Advantage
- STRIPS
- Summary

Positive normal form: algorithm



Transformation of $\langle A, I, O, \gamma \rangle$ to positive normal form

Convert all operators $o \in O$ to effect normal form.

Convert all conditions to negation normal form (NNF).

while any condition contains a negative literal $\neg a$:

Let a be a variable which occurs negatively in a condition.

$A := A \cup \{\hat{a}\}$ for some new state variable \hat{a}

$I(\hat{a}) := 1 - I(a)$

Replace the effect a by $(a \wedge \neg \hat{a})$ in all operators $o \in O$.

Replace the effect $\neg a$ by $(\neg a \wedge \hat{a})$ in all operators $o \in O$.

Replace $\neg a$ by \hat{a} in all conditions.

Convert all operators $o \in O$ to effect normal form (again).

Here, *all conditions* refers to all operator preconditions, operator effect conditions and the goal.

- Motivation
- Effect normal form
- Positive normal form
- Motivation
- Definition & algorithm
- Example
- Advantage
- STRIPS
- Summary

Positive normal form: example



Example (transformation to positive normal form)

$A = \{home, uni, lecture, bike, bike-locked\}$

$I = \{home \mapsto 1, bike \mapsto 1, bike-locked \mapsto 1, uni \mapsto 0, lecture \mapsto 0\}$

$O = \{ \langle home \wedge bike \wedge \neg bike-locked, \neg home \wedge uni \rangle, \langle bike \wedge bike-locked, \neg bike-locked \rangle, \langle bike \wedge \neg bike-locked, bike-locked \rangle, \langle uni, lecture \wedge ((bike \wedge \neg bike-locked) \triangleright \neg bike) \rangle \}$

$\gamma = lecture \wedge bike$

- Motivation
- Effect normal form
- Positive normal form
- Motivation
- Definition & algorithm
- Example
- Advantage
- STRIPS
- Summary

Positive normal form: example



Example (transformation to positive normal form)

$A = \{home, uni, lecture, bike, bike-locked\}$

$I = \{home \mapsto 1, bike \mapsto 1, bike-locked \mapsto 1, uni \mapsto 0, lecture \mapsto 0\}$

$O = \{ \langle home \wedge bike \wedge \neg bike-locked, \neg home \wedge uni \rangle, \langle bike \wedge bike-locked, \neg bike-locked \rangle, \langle bike \wedge \neg bike-locked, bike-locked \rangle, \langle uni, lecture \wedge ((bike \wedge \neg bike-locked) \triangleright \neg bike) \rangle \}$

$\gamma = lecture \wedge bike$

Identify state variable a occurring negatively in conditions.

- Motivation
- Effect normal form
- Positive normal form
- Motivation
- Definition & algorithm
- Example
- Advantage
- STRIPS
- Summary

Positive normal form: example



Example (transformation to positive normal form)

$A = \{home, uni, lecture, bike, bike-locked, \color{red}bike-unlocked\}$

$I = \{home \mapsto 1, bike \mapsto 1, bike-locked \mapsto 1, \\ uni \mapsto 0, lecture \mapsto 0, \color{red}bike-unlocked \mapsto 0\}$

$O = \{\langle home \wedge bike \wedge \neg bike-locked, \neg home \wedge uni \rangle, \\ \langle bike \wedge bike-locked, \neg bike-locked \rangle, \\ \langle bike \wedge \neg bike-locked, bike-locked \rangle, \\ \langle uni, lecture \wedge ((bike \wedge \neg bike-locked) \triangleright \neg bike) \rangle\}$

$\gamma = lecture \wedge bike$

Introduce new variable \hat{a} with complementary initial value.

Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

Positive normal form: example



Example (transformation to positive normal form)

$A = \{home, uni, lecture, bike, bike-locked, bike-unlocked\}$

$I = \{home \mapsto 1, bike \mapsto 1, bike-locked \mapsto 1, \\ uni \mapsto 0, lecture \mapsto 0, \color{red}bike-unlocked \mapsto 0\}$

$O = \{\langle home \wedge bike \wedge \neg bike-locked, \neg home \wedge uni \rangle, \\ \langle bike \wedge bike-locked, \neg bike-locked \rangle, \\ \langle bike \wedge \neg bike-locked, \color{red}bike-locked \rangle, \\ \langle uni, lecture \wedge ((bike \wedge \neg bike-locked) \triangleright \neg bike) \rangle\}$

$\gamma = lecture \wedge bike$

Identify effects on variable a .

Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

Positive normal form: example



Example (transformation to positive normal form)

$A = \{home, uni, lecture, bike, bike-locked, bike-unlocked\}$

$I = \{home \mapsto 1, bike \mapsto 1, bike-locked \mapsto 1, \\ uni \mapsto 0, lecture \mapsto 0, \color{red}bike-unlocked \mapsto 0\}$

$O = \{\langle home \wedge bike \wedge \neg bike-locked, \neg home \wedge uni \rangle, \\ \langle bike \wedge bike-locked, \neg bike-locked \wedge \color{red}bike-unlocked \rangle, \\ \langle bike \wedge \neg bike-locked, \color{red}bike-locked \wedge \neg bike-unlocked \rangle, \\ \langle uni, lecture \wedge ((bike \wedge \neg bike-locked) \triangleright \neg bike) \rangle\}$

$\gamma = lecture \wedge bike$

Introduce complementary effects for \hat{a} .

Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

Positive normal form: example



Example (transformation to positive normal form)

$A = \{home, uni, lecture, bike, bike-locked, bike-unlocked\}$

$I = \{home \mapsto 1, bike \mapsto 1, bike-locked \mapsto 1, \\ uni \mapsto 0, lecture \mapsto 0, \color{red}bike-unlocked \mapsto 0\}$

$O = \{\langle home \wedge bike \wedge \color{red}\neg bike-locked, \neg home \wedge uni \rangle, \\ \langle bike \wedge bike-locked, \neg bike-locked \wedge \color{red}bike-unlocked \rangle, \\ \langle bike \wedge \neg bike-locked, \color{red}bike-locked \wedge \neg bike-unlocked \rangle, \\ \langle uni, lecture \wedge ((bike \wedge \color{red}\neg bike-locked) \triangleright \neg bike) \rangle\}$

$\gamma = lecture \wedge bike$

Identify negative conditions for a .

Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

Positive normal form: example



Example (transformation to positive normal form)

$A = \{home, uni, lecture, bike, bike-locked, bike-unlocked\}$

$I = \{home \mapsto 1, bike \mapsto 1, bike-locked \mapsto 1, uni \mapsto 0, lecture \mapsto 0, bike-unlocked \mapsto 0\}$

$O = \{ \langle home \wedge bike \wedge bike-unlocked, \neg home \wedge uni \rangle, \langle bike \wedge bike-locked, \neg bike-locked \wedge bike-unlocked \rangle, \langle bike \wedge bike-unlocked, bike-locked \wedge \neg bike-unlocked \rangle, \langle uni, lecture \wedge ((bike \wedge bike-unlocked) \triangleright \neg bike) \rangle \}$

$\gamma = lecture \wedge bike$

Replace by positive condition \hat{a} .

Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

Positive normal form: example



Example (transformation to positive normal form)

$A = \{home, uni, lecture, bike, bike-locked, bike-unlocked\}$

$I = \{home \mapsto 1, bike \mapsto 1, bike-locked \mapsto 1, uni \mapsto 0, lecture \mapsto 0, bike-unlocked \mapsto 0\}$

$O = \{ \langle home \wedge bike \wedge bike-unlocked, \neg home \wedge uni \rangle, \langle bike \wedge bike-locked, \neg bike-locked \wedge bike-unlocked \rangle, \langle bike \wedge bike-unlocked, bike-locked \wedge \neg bike-unlocked \rangle, \langle uni, lecture \wedge ((bike \wedge bike-unlocked) \triangleright \neg bike) \rangle \}$

$\gamma = lecture \wedge bike$

Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

Why positive normal form is interesting



In positive normal form, good and bad effects are easy to distinguish:

- Effects that make state variables true are good (add effects).
- Effects that make state variables false are bad (delete effects).

This is of high relevance for some planning techniques that we will see later in this course.

Motivation
Effect normal form
Positive normal form
Motivation
Definition & algorithm
Example
Advantage
STRIPS
Summary

4 STRIPS operators



- Definition
- Properties

Motivation
Effect normal form
Positive normal form
STRIPS
Definition
Properties
Summary

Definition

An operator $\langle \chi, e \rangle$ is a **STRIPS operator** if

- χ is a conjunction of atoms, and
- e is a conjunction of atomic effects.

Hence every STRIPS operator is of the form

$$\langle a_1 \wedge \dots \wedge a_n, l_1 \wedge \dots \wedge l_m \rangle$$

where a_i are atoms and l_j are atomic effects.

Note: Sometimes we allow conjunctions of **literals** as preconditions. We denote this as **STRIPS with negative preconditions**.

- Motivation
- Effect normal form
- Positive normal form
- STRIPS
- Definition
- Properties
- Summary

- STRIPS operators are **particularly simple**, yet expressive enough to capture general planning problems.
- In particular, STRIPS planning is **no easier** than general planning problems.
- Most algorithms in the planning literature are **only presented for STRIPS operators** (generalization is often, but not always, obvious).

STRIPS

Stanford Research Institute Planning System
(Fikes & Nilsson, 1971)

- Motivation
- Effect normal form
- Positive normal form
- STRIPS
- Definition
- Properties
- Summary

- Not every operator is equivalent to a STRIPS operator.
- However, each operator can be transformed into a **set** of STRIPS operators whose “combination” is equivalent to the original operator. (How?)
- However, this transformation may exponentially increase the number of required operators. There are planning tasks for which such a blow-up is unavoidable.
- There are polynomial transformations of planning tasks to STRIPS, but these do not preserve the structure of the transition system (e. g., length of shortest plans may change).

- Motivation
- Effect normal form
- Positive normal form
- STRIPS
- Definition
- Properties
- Summary

- **Effect normal form** simplifies structure of operator effects: conditional effects contain only atomic effects; there is at most one occurrence of any atomic effect.
- **Positive normal form** allows to distinguish good and bad effects.
- The form of **STRIPS operators** is even more restrictive than effect normal form, forbidding complex preconditions and conditional effects.
- All three forms are expressive enough to capture general planning problems.
- Transformation to effect normal form and positive normal form possible with polynomial size increase.
- Structure preserving transformations of planning tasks to STRIPS can increase the number of operators exponentially.

- Motivation
- Effect normal form
- Positive normal form
- STRIPS
- Summary