

Learning Action Models from State Observations

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Abstract

This paper presents a classical planning compilation for learning STRIPS action models from state observations. The compilation approach does not require observing the precise actions that produced the observed states because such actions, are determined by a planner. Furthermore, the compilation is also extensible to assess how well a STRIPS action model matches a given set of observations. Last but not least, the paper evaluates the performance of the compilation approach by learning action models for a wide range of classical planning domains from the International Planning Competition (IPC) and assessing the learned models with respect to (1), test sets of state observations and (2), the true (reference) models.

1 Introduction

Learning action models is a promising approach to relief the *knowledge acquisition bottleneck* of automated planning [Kambhampati, 2007]. The learning of planning action models has been addressed with various algorithms. ARMS [Yang *et al.*, 2007] receives plan traces, as training samples, and defines the learning task as a set of weighted constraints that the input plans must hold, which is then solved by a MAX-SAT solver. ARMS validates the learned models with test sets of example plans from six different IPC domains. The learning algorithm of SLAF [Amir and Chang, 2008] computes a CNF formula which is consistent with the input plan traces and partially observed states, and the quality of the learned models is assessed with respect to the corresponding reference model. In the case of LOCM [Cresswell *et al.*, 2013], the learning samples are only examples plans, without requiring any information about predicates or states. LOCM relies on assumptions on the kind of domain structure of the model and compares the learned models with the corresponding reference model [Gregory and Cresswell, 2016]. Finally, AMAN [Zhuo and Kambhampati, 2013] can work with incorrectly observed plan traces and validates the accuracy of the learned models in three IPC domains with respect to the reference model.

The learning samples required by all the aforementioned approaches are observations of plan executions, in the form

of plan traces, and all of them, but ARMS, evaluate learning performance by syntactically comparing the learned models with respect to the corresponding reference model.

Motivated by recent advances on the synthesis of generative models with classical planning [Bonet *et al.*, 2009; Segovia-Aguas *et al.*, 2016; 2017], we present a novel planning compilation for learning STRIPS action models from state observations. A solution to the classical planning task that results from our compilation is a sequence of actions that determines the preconditions/effects of the STRIPS operator schemas (the learned action model). **Learning action models as planning** leverages off-the-shelf planners and opens up a way towards the *bootstrapping* of planning action models, enabling a planner to gradually learn and update its action model. The practicality of the compilation approach allow us to report learning results over fifteen IPC planning domains.

For the training samples, we adopt a middle ground between unstructured inputs and plan traces, wherein only state observations are required, without further information about the state transitions. **Learning from state observations** is a relevant advancement as in many applications the actual actions executed by the observed agent are not available but instead, we can observe the resulting states. Learning action models from state observations broadens then the range of application to external observers and facilitates the representation of imperfect observability (as shown in plan recognition [Sohrabi *et al.*, 2016]) as well as learning from unstructured data (like state images [Asai and Fugunaga, 2018]).

Our compilation is extensible to accept a learned model as input besides the state observations. This extension allow us to compute a new model that induces the observations whilst assessing the amount of edition required by the input model to satisfy the given observations. Thus, our approach allows to **assess how well a STRIPS action model matches a given set of observations**, which enables model recognition. Finally, we propose a two-fold validation of the learned STRIPS action models. First the learned models are tested with a set of state observation sequences and second, the learned models are compared to the corresponding reference model.

2 Background

Our approach for learning STRIPS action schemas from state observations is compiling this learning task into a classical planning task with conditional effects.

2.1 Classical planning with conditional effects

We use F to denote the set of *fluents* (propositional variables) describing a state. A *literal* l is a valuation of a fluent $f \in F$, i.e. either $l = f$ or $l = \neg f$. A set of literals L represents a partial assignment of values to fluents (without loss of generality, we will assume that L does not assign conflicting values to any fluent). We use $\mathcal{L}(F)$ to denote the set of all literal sets on F , i.e. all partial assignments of values to fluents.

A *state* s is a full assignment of values to fluents, i.e. $|s| = |F|$, so the size of the state space is $2^{|F|}$. Explicitly including negative literals $\neg f$ in states simplifies subsequent definitions but often, we will abuse notation by defining a state s only in terms of the fluents that are true in s , as is common in STRIPS planning.

A *classical planning frame* is a tuple $\Phi = \langle F, A \rangle$, where F is a set of fluents and A is a set of actions. An action $a \in A$ is defined with preconditions, $\text{pre}(a) \subseteq \mathcal{L}(F)$, positive effects, $\text{eff}^+(a) \subseteq \mathcal{L}(F)$, and negative effects $\text{eff}^-(a) \subseteq \mathcal{L}(F)$. We say that an action $a \in A$ is *applicable* in a state s iff $\text{pre}(a) \subseteq s$. The result of applying a in s is the *successor state* denoted by $\theta(s, a) = \{s \setminus \text{eff}^-(a)\} \cup \text{eff}^+(a)$.

An action $a \in A$ with conditional effects is defined as a set of *preconditions* $\text{pre}(a) \in \mathcal{L}(F)$ and a set of *conditional effects* $\text{cond}(a)$. Each conditional effect $C \triangleright E \in \text{cond}(a)$ is composed of two sets of literals $C \in \mathcal{L}(F)$, the *condition*, and $E \in \mathcal{L}(F)$, the *effect*. An action $a \in A$ is *applicable* in a state s if and only if $\text{pre}(a) \subseteq s$, and the *triggered effects* resulting from the action application are the effects whose conditions hold in s :

$$\text{triggered}(s, a) = \bigcup_{C \triangleright E \in \text{cond}(a), C \subseteq s} E,$$

The result of applying action a in state s is the *successor state* $\theta(s, a) = \{s \setminus \text{eff}_c^-(s, a)\} \cup \text{eff}_c^+(s, a)$ where $\text{eff}_c^-(s, a) \subseteq \text{triggered}(s, a)$ and $\text{eff}_c^+(s, a) \subseteq \text{triggered}(s, a)$ are, respectively, the triggered *negative* and *positive* effects.

A *classical planning problem* is a tuple $P = \langle F, A, I, G \rangle$, where I is an initial state and $G \subseteq \mathcal{L}(F)$ is a goal condition. A *plan* for P is an action sequence $\pi = \langle a_1, \dots, a_n \rangle$ that induces the *state trajectory* $\langle s_0, s_1, \dots, s_n \rangle$ such that $s_0 = I$ and, for each $1 \leq i \leq n$, a_i is applicable in s_{i-1} and generates the successor state $s_i = \theta(s_{i-1}, a_i)$. The *plan length* is denoted with $|\pi| = n$. A plan π *solves* P iff $G \subseteq s_n$, i.e. if the goal condition is satisfied at the last state reached after following the application of the plan π in the initial state I .

2.2 STRIPS action schemas

This work addresses the learning of PDDL action schemas that follow the STRIPS requirement [McDermott *et al.*, 1998; Fox and Long, 2003]. Figure 1 shows the *stack* action schema, coded in PDDL, from a four-operator *blocksworld* [Slaney and Thiébaux, 2001].

To formalize the output of the learning task, we assume that fluents F are instantiated from a set of *predicates* Ψ , as in PDDL. Each predicate $p \in \Psi$ has an argument list of arity $\text{ar}(p)$. Given a set of *objects* Ω , the set of fluents F is induced by assigning objects in Ω to the arguments of predicates in Ψ ,

```
(:action stack
:parameters (?v1 ?v2 - object)
:precondition (and (holding ?v1) (clear ?v2))
:effect (and (not (holding ?v1))
(not (clear ?v2))
(handempty) (clear ?v1)
(on ?v1 ?v2)))
```

Figure 1: STRIPS operator schema coding, in PDDL, the *stack* action from a four-operator *blocksworld*.

i.e. $F = \{p(\omega) : p \in \Psi, \omega \in \Omega^{\text{ar}(p)}\}$ s.t. Ω^k is the k -th Cartesian power of Ω .

Let $\Omega_v = \{v_i\}_{i=1}^{\max_{a \in A} \text{ar}(a)}$ be a new set of objects ($\Omega \cap \Omega_v = \emptyset$), denoted as *variable names*, and that is bound by the maximum arity of an action in a given planning frame. For instance, in a three-block *blocksworld* $\Omega = \{\text{block}_1, \text{block}_2, \text{block}_3\}$ while $\Omega_v = \{v_1, v_2\}$ because the operators with the maximum arity, *stack* and *unstack*, have arity two.

We define F_v , a new set of fluents s.t. $F \cap F_v = \emptyset$, that results from instantiating Ψ using only the objects in Ω_v and defines the elements that can appear in an action schema. For the *blocksworld*, $F_v = \{\text{handempty}, \text{holding}(v_1), \text{holding}(v_2), \text{clear}(v_1), \text{clear}(v_2), \text{ontable}(v_1), \text{ontable}(v_2), \text{on}(v_1, v_1), \text{on}(v_1, v_2), \text{on}(v_2, v_1), \text{on}(v_2, v_2)\}$.

We assume also that actions $a \in A$ are instantiated from STRIPS operator schemas $\xi = \langle \text{head}(\xi), \text{pre}(\xi), \text{add}(\xi), \text{del}(\xi) \rangle$ where:

- $\text{head}(\xi) = \langle \text{name}(\xi), \text{pars}(\xi) \rangle$, is the operator *header* defined by its name and the corresponding *variable names*, $\text{pars}(\xi) = \{v_i\}_{i=1}^{\text{ar}(\xi)}$. The headers of a four-operator *blocksworld* are *pickup*(v_1), *putdown*(v_1), *stack*(v_1, v_2) and *unstack*(v_1, v_2).
- The preconditions $\text{pre}(\xi) \subseteq F_v$, the negative effects $\text{del}(\xi) \subseteq F_v$, and the positive effects $\text{add}(\xi) \subseteq F_v$ such that, $\text{del}(\xi) \subseteq \text{pre}(\xi)$, $\text{del}(\xi) \cap \text{add}(\xi) = \emptyset$ and $\text{pre}(\xi) \cap \text{add}(\xi) = \emptyset$.

Finally, we define $F_v(\xi) \subseteq F_v$ as the subset of elements that can appear in a given action schema ξ and that confine the space of possible action models. For instance, for the *stack* action schema $F_v(\text{stack}) = F_v$ while $F_v(\text{pickup}) = \{\text{handempty}, \text{holding}(v_1), \text{clear}(v_1), \text{ontable}(v_1), \text{on}(v_1, v_1)\}$ excludes the fluents from F_v that involve v_2 because the action header contains the single parameter v_1 .

3 Learning STRIPS action models

This paper addresses the learning task that corresponds to observing an agent acting in the world but watching only the results of its plan executions, the actual executed actions are unobserved. This learning task is defined as $\Lambda = \langle \mathcal{M}, \Psi, \mathcal{O} \rangle$:

- \mathcal{M} is the set of empty operator schemas, wherein each $\xi \in \mathcal{M}$ is only composed of $\text{head}(\xi)$.
- Ψ is the set of predicates, that define the abstract state space of a given classical planning frame.

```

;;;;; Headers in  $\mathcal{M}$ 
(pickup v1) (putdown v1)
(stack v1 v2) (unstack v1 v2)

;;;;; Predicates  $\Psi$ 
(handempty) (holding ?o - object)
(clear ?o - object) (ontable ?o - object)
(on ?o1 - object ?o2 - object)

;;;;; Observations  $\mathcal{O}$ 
;;; observation #0
(clear block2) (on block2 block1)
(ontable block1) (handempty)

;;; observation #1
(holding block2) (clear block1) (ontable block1)

;;; observation #2
(clear block1) (ontable block1)
(clear block2) (ontable block2) (handempty)

;;; observation #3
(holding block1) (clear block2) (ontable block2)

;;; observation #4
(clear block1) (on block1 block2)
(ontable block2) (handempty)

```

Figure 2: Example of a Λ task for learning a STRIPS action model in the *blocksworld* from a sequence of five state observations.

- $\mathcal{O} = \langle s_0, s_1, \dots, s_n \rangle$ is a sequence of *state observations* obtained observing the execution of an *unobserved* plan $\pi = \langle a_1, \dots, a_n \rangle$.

A solution to Λ is a set of operator schema \mathcal{M}' compliant with the headers in \mathcal{M} , the predicates Ψ , and the state observation sequence \mathcal{O} . A planning compilation is a suitable approach for addressing Λ because a solution must not only determine the STRIPS action model \mathcal{M}' but also, the *unobserved* plan $\pi = \langle a_1, \dots, a_n \rangle$, that explains \mathcal{O} . Figure 2 shows a Λ task for learning a STRIPS action model in the *blocksworld* from the five-state observations sequence that corresponds to inverting a 2-block tower.

3.1 Learning with classical planning

Our approach for addressing a Λ learning task is compiling it into a classical planning task P_Λ with conditional effects. The intuition behind the compilation is that a solution to the resulting classical planning task is a sequence of actions that:

1. **Programs the action model \mathcal{M}' .** A solution plan starts with a *prefix* that, for each $\xi \in \mathcal{M}$, determines which fluents $f \in F_v(\xi)$ belong to its $pre(\xi)$, $del(\xi)$ and $add(\xi)$ sets.
2. **Validates the action model \mathcal{M}' in \mathcal{O} .** The solution plan continues with a *postfix* that produces the given sequence of states $\langle s_0, s_1, \dots, s_n \rangle$ using the programmed action model \mathcal{M}' .

Given a learning task $\Lambda = \langle \mathcal{M}, \Psi, \mathcal{O} \rangle$ the compilation outputs a classical planning task $P_\Lambda = \langle F_\Lambda, A_\Lambda, I_\Lambda, G_\Lambda \rangle$:

- F_Λ contains:

- The set of fluents F built instantiating the predicates Ψ with the objects appearing in the input observations \mathcal{O} .
- Fluents $pre_f(\xi)$, $del_f(\xi)$ and $add_f(\xi)$, for every $f \in F_v(\xi)$, that represent the programmed action model. If a fluent $pre_f(\xi)/del_f(\xi)/add_f(\xi)$ holds, it means that f is a precondition/negative/positive effect in the schema $\xi \in \mathcal{M}'$. For instance, the preconditions of the *stack* schema (Figure 1) are represented by the pair of fluents `pre_holding_stack_v1` and `pre_clear_stack_v2` set to *True*.
- The fluents $mode_{prog}$ and $mode_{val}$ indicating whether the operator schemas are programmed or validated and fluents $\{test_i\}_{1 \leq i \leq n}$, indicating the observation where the action model is validated.

- I_Λ contains the fluents from F that encode s_0 (the first observation) and $mode_{prog}$ set to true. Our compilation assumes that initially operator schemas are programmed with every possible precondition (the most specific learning hypothesis), no negative effect and no positive effect. Therefore fluents $pre_f(\xi)$, for every $f \in F_v(\xi)$, hold also at the initial state.
- $G_\Lambda = \bigcup_{1 \leq i \leq n} \{test_i\}$, indicates that the programmed action model is validated in all the input observations.
- A_Λ comprises three kinds of actions:

1. Actions for *programming* operator schema $\xi \in \mathcal{M}$:
 - Actions for **removing** a *precondition* $f \in F_v(\xi)$ from the action schema $\xi \in \mathcal{M}$.

$$\begin{aligned}
pre(\text{programPre}_{f,\xi}) &= \{\neg del_f(\xi), \neg add_f(\xi), \\
&\quad mode_{prog}, pre_f(\xi)\}, \\
cond(\text{programPre}_{f,\xi}) &= \{\emptyset\} \triangleright \{\neg pre_f(\xi)\}.
\end{aligned}$$

- Actions for **adding** a *negative* or *positive* effect $f \in F_v(\xi)$ to the action schema $\xi \in \mathcal{M}$.

$$\begin{aligned}
pre(\text{programEff}_{f,\xi}) &= \{\neg del_f(\xi), \neg add_f(\xi), \\
&\quad mode_{prog}\}, \\
cond(\text{programEff}_{f,\xi}) &= \{pre_f(\xi)\} \triangleright \{del_f(\xi)\}, \\
&\quad \{\neg pre_f(\xi)\} \triangleright \{add_f(\xi)\}.
\end{aligned}$$

2. Actions for *applying* an already programmed operator schema $\xi \in \mathcal{M}$ bound with objects $\omega \subseteq \Omega^{ar}(\xi)$. Given that the operators headers are known, the variables $pars(\xi)$ are bound to the objects in ω appearing at the same position.

$$\begin{aligned}
pre(\text{apply}_{\xi,\omega}) &= \{pre_f(\xi) \implies p(\omega)\}_{\forall p \in \Psi, f=p(pars(\xi))} \\
&\quad \cup \{\neg mode_{val}\}, \\
cond(\text{apply}_{\xi,\omega}) &= \{del_f(\xi)\} \triangleright \{\neg p(\omega)\}_{\forall p \in \Psi, f=p(pars(\xi))}, \\
&\quad \{add_f(\xi)\} \triangleright \{p(\omega)\}_{\forall p \in \Psi, f=p(pars(\xi))}, \\
&\quad \{mode_{prog}\} \triangleright \{\neg mode_{prog}\}, \\
&\quad \{\emptyset\} \triangleright \{mode_{val}\}.
\end{aligned}$$

3. Actions for *validating* an observation $1 \leq i \leq n$.

$$\begin{aligned} \text{pre}(\text{validate}_i) &= s_i \cup \{\text{test}_j\}_{j \in 1 \leq j < i} \\ &\quad \cup \{\neg \text{test}_j\}_{j \in i \leq j \leq n} \cup \{\text{mode}_{\text{val}}\}, \\ \text{cond}(\text{validate}_i) &= \{\emptyset\} \triangleright \{\text{test}_i, \neg \text{mode}_{\text{val}}\}. \end{aligned}$$

3.2 Compilation properties

Lemma 1. Soundness. Any classical plan π that solves P_Λ induces an action model \mathcal{M}' that solves $\Lambda = \langle \mathcal{M}, \Psi, \mathcal{O} \rangle$.

Proof sketch. Once operator schemas \mathcal{M}' are programmed, they can only be applied because of the $\text{mode}_{\text{prog}}$ fluent. In addition, P_Λ is only solvable if fluents $\{\text{test}_i\}$, $1 \leq i \leq n$ hold at the last reached state. These goals can only be achieved executing an applicable sequence of programmed operator schemas that reaches every state $s_i \in \mathcal{O}$, starting from s_0 and following the sequence $1 \leq i \leq n$. This means that the programmed action model \mathcal{M}' complies with the provided observations \mathcal{O} and hence, solves Λ . \square

Lemma 2. Completeness. Any STRIPS action model \mathcal{M}' that solves a $\Lambda = \langle \mathcal{M}, \Psi, \mathcal{O} \rangle$ learning task, is computable solving the corresponding classical planning task P_Λ .

Proof sketch. By definition, $F_v(\xi) \subseteq F_\Lambda$ fully captures the full set of elements that can appear in a STRIPS action schema $\xi \in \mathcal{M}$ given its header and the set of predicates Ψ . The compilation does not discard any possible STRIPS action schema definable within F_v that satisfies the state trajectory constraints given by the \mathcal{O} sequence. \square

The size of the classical planning task P_Λ output by the compilation depends on:

- The arity of the actions headers in \mathcal{M} and the predicates Ψ given as input to the Λ learning task. The larger these numbers, the larger the $F_v(\xi)$ sets, that define the $\text{pre}_f(\xi)/\text{del}_f(\xi)/\text{add}_f(\xi)$ fluents and the corresponding actions for *programming* operator schema $\xi \in \mathcal{M}$.
- The number of given state observations, that is $|\mathcal{O}|$. The larger this number, the more test_i fluents and validate_i actions in P_Λ .

4 Evaluation of STRIPS action models

We assess how well a STRIPS action model \mathcal{M} explains a given sequence of observations \mathcal{O} according to the amount of *edition* that is required to apply in \mathcal{M} to induce \mathcal{O} .

4.1 Edition of STRIPS action models

We first define the allowed *operations* to edit a given action model. With the aim of keeping a tractable branching factor of the planning instance that results from our compilation, we only define two *edit operations*:

- *Deletion.* A fluent $\text{pre}_f(\xi)/\text{del}_f(\xi)/\text{add}_f(\xi)$ is removed from the operator schema $\xi \in \mathcal{M}$, $f \in F_v(\xi)$.
- *Insertion.* A fluent $\text{pre}_f(\xi)/\text{del}_f(\xi)/\text{add}_f(\xi)$ is added to the operator schema $\xi \in \mathcal{M}$, $f \in F_v(\xi)$.

We can now formalize an edit distance that quantifies how dissimilar two given STRIPS action models are. The distance is symmetric and meets the *metric axioms* provided that the two *edit operations* have the same positive cost.

Definition 3. Let \mathcal{M} and \mathcal{M}' be two STRIPS action models, both built from the same set of possible elements F_v . The **edit distance**, denoted as $\delta(\mathcal{M}, \mathcal{M}')$, is the minimum number of edit operations required to transform \mathcal{M} into \mathcal{M}' .

Since F_v is a bound set, the maximum number of edits that can be introduced to a given action model defined within F_v is bound as well. In more detail, for an operator schema $\xi \in \mathcal{M}$ the maximum number of edits that can be introduced to their precondition set is $|F_v(\xi)|$ while the max number of edits that can be introduced to the effects is twice $|F_v(\xi)|$.

Definition 4. The **maximum edit distance** of an STRIPS action model \mathcal{M} built from the set of possible elements F_v is $\delta(\mathcal{M}, *) = \sum_{\xi \in \mathcal{M}} 3|F_v(\xi)|$, which sets an upper bound on the distance from \mathcal{M} to any model definable within F_v .

4.2 The observation edit distance

We define now an edit distance to assess the quality of a learned model with respect to a sequence of state observations.

Definition 5. Given an action model \mathcal{M} built from the set of possible elements F_v and a sequence of observations \mathcal{O} . The **observation edit distance**, denoted by $\delta(\mathcal{M}, \mathcal{O})$, is the minimal edit distance from \mathcal{M} to any model \mathcal{M}' such that: (1) \mathcal{M}' is also definable within F_v and (2), \mathcal{M}' can produce a plan $\pi = \langle a_1, \dots, a_n \rangle$ that induces $\mathcal{O} = \langle s_0, s_1, \dots, s_n \rangle$:

$$\delta(\mathcal{M}, \mathcal{O}) = \min_{\forall \mathcal{M}' \rightarrow \mathcal{O}} \delta(\mathcal{M}, \mathcal{M}')$$

Due to its semantic nature, the *observation edit distance* is a robust measure to evaluate learning episodes where actions are *reformulated* and are still compliant with the learning inputs. For instance a learning episode can interchange the roles of two operators whose headers match or the roles of action parameters that belong to the same type (e.g. the *blocksworld* operator *stack* can be *learned* with the preconditions and effects of the *unstack* operator and vice versa).

Furthermore, the *observation edit distance* enables the recognition of STRIPS action models. The idea, taken from *plan recognition as planning* [Ramírez and Geffner, 2009], is to map distances into likelihoods. The *observation edit distance* can be mapped into a likelihood with the following expression $P(\mathcal{O}|\mathcal{M}) = 1 - \frac{\delta(\mathcal{M}, \mathcal{O})}{\delta(\mathcal{M}, *)}$. The larger the *observation edit distance* the lower the likelihood.

4.3 Computing the observation edit distance

Our compilation is extensible to compute the *observation edit distance* with the inclusion of a given non-empty model \mathcal{M} in $\Lambda = \langle \mathcal{M}, \Psi, \mathcal{O} \rangle$. In other words, now \mathcal{M} is the set of given operator schemas, wherein each $\xi \in \mathcal{M}$ initially contains $\text{head}(\xi)$, $\text{pre}(\xi)$, $\text{del}(\xi)$ and $\text{add}(\xi)$ sets. A solution to the planning task resulting from Λ is now a sequence of actions that:

1. **Edits the action model \mathcal{M} .** A solution plan starts with a *prefix* that modifies the preconditions and effects of the action schemas in \mathcal{M} using to the two *edit operations*.
2. **Validates the edited model \mathcal{M}' in \mathcal{O} .** The solution plan continues with a *postfix* that validates the edited model on the given observations \mathcal{O} .

```

00 : (insert_add_handempty_stack)
01 : (insert_add_clear_stack_var1)
02 : (apply_unstack block2 block1)
03 : (validate_1)
04 : (apply_putdown block2)
05 : (validate_2)
06 : (apply_pickup block1)
07 : (validate_3)
08 : (apply_stack block1 block2)
09 : (validate_4)

```

Figure 3: Plan for editing a given *blocksworld* schema and validating it at the state observations shown in Figure 2.

In this case Λ is not a learning task but the task of editing \mathcal{M} to produce the observations \mathcal{O} , which results in the edited model \mathcal{M}' . The output of the extended compilation is a classical planning task $P'_\Lambda = \langle F_\Lambda, A'_\Lambda, I'_\Lambda, G_\Lambda \rangle$:

- F_Λ and G_Λ are defined as in the previous compilation.
- I'_Λ contains the fluents from F that encode s_0 and $mode_{prog}$ set to true. In addition, the input action model \mathcal{M} is now encoded in the initial state. This means that the fluents $pre_f(\xi)/del_f(\xi)/add_f(\xi)$, $f \in F_v(\xi)$, hold in the initial state iff they appear in \mathcal{M} .
- A'_Λ , comprises the same three kinds of actions of A_Λ . The actions for *applying* an already programmed operator schema and the actions for *validating* an observation are defined exactly as in the previous compilation. The only difference here is that the actions for *programming* the operator schema now implement the two *edit operations* (i.e. actions for *inserting* a precondition and for *deleting* a negative/positive effect).

To illustrate this, the plan of Figure 3 solves the task of editing a *blocksworld* action model \mathcal{M} where the positive effects (`handempty`) and (`clear ?v1`) of the `stack` schema are missing. This plan edits the `stack` schema, *inserting* these two positive effects, and then validates the edited model \mathcal{M}' in the five-observation sequence of Figure 2.

When we compute the *observation edit distance*, our interest is not in \mathcal{M}' but in the number of required *edit operations* for that \mathcal{M}' is validated in the given observations, e.g. $\delta(\mathcal{M}, \mathcal{O}) = 2$ for the example in Figure 3. The *observation edit distance* is exactly computed if P'_Λ is optimally solved (according to the number of edit actions); and it will be an approximate value if P'_Λ is solved with a satisfying planner. Furthermore, it will be a less accurate estimate if the task to solve is a relaxation of P'_Λ [Bonet and Geffner, 2001].

5 Experimental Evaluation

This section evaluates the performance of our approach for learning STRIPS action models from state observations.

Reproducibility

We used 15 IPC domains that satisfy the STRIPS requirement [Fox and Long, 2003], taken from the `PLANNING.DOMAINS` repository [Muisé, 2016]. We only used observation sequences $\langle s_0, s_1, \dots, s_{24} \rangle$ composed of twenty

| | $\delta(\mathcal{M}, \mathcal{O})$ | $\delta(\mathcal{M}, *)$ | $1 - \frac{\delta(\mathcal{M}, \mathcal{O})}{\delta(\mathcal{M}, *)}$ |
|------------|------------------------------------|--------------------------|---|
| blocks | 0 | 90 | 1.0 |
| driverlog | 5 | 144 | 0.97 |
| ferry | 2 | 69 | 0.97 |
| floortile | 34 | 342 | 0.90 |
| grid | 42 | 153 | 0.73 |
| gripper | 2 | 30 | 0.93 |
| hanoi | 1 | 63 | 0.98 |
| hiking | 69 | 174 | 0.60 |
| miconic | 3 | 72 | 0.96 |
| npuzzle | 2 | 24 | 0.92 |
| parking | 5 | 111 | 0.95 |
| satellite | 24 | 75 | 0.68 |
| transport | 4 | 78 | 0.95 |
| visitall | 2 | 24 | 0.92 |
| zenotravel | 3 | 63 | 0.95 |

Table 1: Evaluation of the quality of the learned models with respect to an observations test set.

five states per domain. The set of training samples is fixed for all the experiments so the results reported by the different evaluation approaches is comparable. All experiments are run on an Intel Core i5 3.10 GHz x 4 with 4 GB of RAM.

MADAGASCAR is the classical planner we used to solve the instances that result from our compilations for its ability to deal with dead-ends [Rintanen, 2014]. Due to its SAT-based nature, MADAGASCAR can apply the actions for programming preconditions in a single planning step (in parallel) because there is no interaction between these actions. Actions for programming effects can also be applied in a single planning step, thus significantly reducing the planning horizon.

The compilation source code, evaluation scripts and benchmarks (including the training and test sets) are fully available at this anonymous repository <https://github.com/anonsub/observations-learning> so any experimental data reported in the paper can be reproduced.

Evaluating with a test set

When a reference model is not available, the learned models are tested with an observation set. Table 1 summarizes the results obtained when evaluating the quality of the learned models with respect to a test set of state observations. Each test set comprises between 20 and 50 observations and was generated executing the plans for various instances of the IPC domains and collecting the intermediate states.

The table shows, for each domain, the *observation edit distance* (computed with our extended compilation), the *maximum edit distance*, and their ratio. The reported results show that, despite learning only from 25 state observations, 12 out of 15 learned domains yield ratios of 90% or above. This fact evidences that the learned models require very small amounts of edition to match the observations of the given test set.

Evaluating with a reference model

Here we evaluate the learned models with respect to the actual generative model since. Opposite to what usually happens in ML, this model is available when learning is applied to IPC domains. The model learned for each domain is compared with its reference model, and the quality is measured with:

- *Precision* = $\frac{tp}{tp+fp}$, where tp is the number of *true positives* (predicates that correctly appear in the action model) and fp is the number of *false positives* (predicates of the learned model that should not appear). Precision gives a notion of *soundness*.
- *Recall* = $\frac{tp}{tp+fn}$, where fn is the number of *false negatives* (predicates that should appear in the learned model but are missing). Recall gives a notion of *completeness*.

Table 2 shows the Precision (**P**) and recall (**R**) computed separately for the preconditions (**Pre**), positive effects (**Add**) and negative Effects (**Del**) while the last two columns report averages values. The reason why the scores in Table 2 are lower than in Table 1 is because the syntax-based nature of *precision* and *recall* make these two metrics report low scores for learned models that are semantically correct but actually correspond to *reformulations* of the actual model (changes in the roles of actions with matching headers or parameters with matching types).

Precision and recall robust to model reformulations

To give an insight of the actual quality of the learned models, we defined a method for computing *Precision* and *Recall* that is robust to the mentioned model reformulations. Precision and recall are often combined using the *harmonic mean*. This expression, called the *F-measure* or the balanced *F-score*, is formally defined as $F = 2 \times \frac{Precision \times Recall}{Precision + Recall}$. Given the learned action model \mathcal{M} and the reference action model \mathcal{M}^* , the bijective function $f_{P\&R} : \mathcal{M} \mapsto \mathcal{M}^*$ is the mapping between the learned and the reference model that maximizes the accumulated *F-measure*.

Table 3 shows that significantly higher values of *precision* and *recall* are reported when a learned action schema, $\xi \in \mathcal{M}$, is compared to its corresponding reference schema given by the $f_{P\&R}$ mapping ($f_{P\&R}(\xi) \in \mathcal{M}^*$). These results evidence that in all of the evaluated domains, except for *ferry* and *satellite*, the learning task interchanges the roles of some actions or parameters with respect to their role in the reference model.

As we can see in Table 3, the *blocksworld* and *gripper* domains are perfectly learned from only 25 state observations. On the other hand, the learning scores of half of the domains in Table 3 are still lower than in Table 1. The reason lies in the particular observations comprised by the test sets. As an example, in the *driverlog* domain, the action schema *disembark-truck* is missing from the learned model because this action is never induced from the observations in the training set; that is, such action never appears in the *unobserved* plan. The same happens with the *paint-down* action of the *floortile* domain or *move-curb-to-curb* in the *parking* domain. Interestingly, these actions do not appear either in the test sets and so the learned action models are not penalized in Table 1. Generating *informative* observations for learning planning action models is still an open issue. Planning actions include preconditions that are only satisfied by specific sequences of actions, often, with a low probability of being chosen by chance [Fern *et al.*, 2004].

| | Pre | | Add | | Del | | P | R |
|------------|------|------|------|------|------|------|------|------|
| | P | R | P | R | P | R | | |
| blocks | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 |
| driverlog | 0.0 | 0.0 | 0.25 | 0.43 | 0.0 | 0.0 | 0.08 | 0.14 |
| ferry | 1.0 | 0.71 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.9 |
| floortile | 0.38 | 0.55 | 0.4 | 0.18 | 0.56 | 0.45 | 0.44 | 0.39 |
| grid | 0.5 | 0.47 | 0.33 | 0.29 | 0.25 | 0.29 | 0.36 | 0.35 |
| gripper | 0.83 | 0.83 | 0.75 | 0.75 | 0.75 | 0.75 | 0.78 | 0.78 |
| hanoi | 0.5 | 0.25 | 0.5 | 0.5 | 0.0 | 0.0 | 0.33 | 0.25 |
| hiking | 0.43 | 0.43 | 0.5 | 0.35 | 0.44 | 0.47 | 0.46 | 0.42 |
| miconic | 0.6 | 0.33 | 0.33 | 0.25 | 0.33 | 0.33 | 0.42 | 0.31 |
| npuzzle | 0.33 | 0.33 | 0.0 | 0.0 | 0.0 | 0.0 | 0.11 | 0.11 |
| parking | 0.25 | 0.21 | 0.0 | 0.0 | 0.0 | 0.0 | 0.08 | 0.07 |
| satellite | 0.6 | 0.21 | 0.8 | 0.8 | 1.0 | 0.5 | 0.8 | 0.5 |
| transport | 1.0 | 0.3 | 0.8 | 0.8 | 1.0 | 0.6 | 0.93 | 0.57 |
| visitall | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| zenotravel | 0.67 | 0.29 | 0.33 | 0.29 | 0.33 | 0.14 | 0.44 | 0.24 |

Table 2: Precision and recall values obtained without computing the $f_{P\&R}$ mapping with the reference model.

| | Pre | | Add | | Del | | P | R |
|------------|------|------|------|------|------|------|------|------|
| | P | R | P | R | P | R | | |
| blocks | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| driverlog | 0.67 | 0.14 | 0.33 | 0.57 | 0.67 | 0.29 | 0.56 | 0.33 |
| ferry | 1.0 | 0.71 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.9 |
| floortile | 0.44 | 0.64 | 1.0 | 0.45 | 0.89 | 0.73 | 0.78 | 0.61 |
| grid | 0.63 | 0.59 | 0.67 | 0.57 | 0.63 | 0.71 | 0.64 | 0.62 |
| gripper | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| hanoi | 1.0 | 0.5 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.83 |
| hiking | 0.78 | 0.6 | 0.93 | 0.82 | 0.88 | 0.88 | 0.87 | 0.77 |
| miconic | 0.8 | 0.44 | 1.0 | 0.75 | 1.0 | 1.0 | 0.93 | 0.73 |
| npuzzle | 0.67 | 0.67 | 1.0 | 1.0 | 1.0 | 1.0 | 0.89 | 0.89 |
| parking | 0.56 | 0.36 | 0.5 | 0.33 | 0.5 | 0.33 | 0.52 | 0.34 |
| satellite | 0.6 | 0.21 | 0.8 | 0.8 | 1.0 | 0.5 | 0.8 | 0.5 |
| transport | 1.0 | 0.3 | 1.0 | 1.0 | 1.0 | 0.6 | 1.0 | 0.63 |
| visitall | 0.67 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.89 | 1.0 |
| zenotravel | 1.0 | 0.43 | 0.67 | 0.57 | 1.0 | 0.43 | 0.89 | 0.48 |

Table 3: Precision and recall values obtained when computing the $f_{P\&R}$ mapping with the reference model.

6 Conclusions

Unlike extensive-data ML approaches, our work explores an alternative research direction to learn sound models from small amounts of state observations. To the best of our knowledge, this is the first work on learning STRIPS action models from state observations, using exclusively planning technology, and evaluated over a wide range of different domains. Recently, the work in [Stern and Juba, 2017] proposes a planning compilation for learning action models from plan traces following the *finite domain* representation for the state variables. This is a theoretical study on the boundaries of the learned models and no experimental results are reported.

Unlike statistical learning, our inference-based approach is able to produce good-quality models from very small data sets. The action models of the *blocksworld* or *gripper* domains were perfectly learned from only 25 state observations. Moreover, in 10 out of the 15 domains, the learned models yield *Precision* and *Recall* values over 0.75. The success of recent algorithms for exploring planning tasks [Francès *et al.*, 2017] motivates the development of novel techniques to autonomously collect informative learning examples. The combination of such exploration techniques with our learning approach is an appealing research direction towards the bootstrapping of planning action models.

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