Compiling Uncertainty Away:

Solving Conformant Planning Problems Using a Classical Planner (Sometimes)

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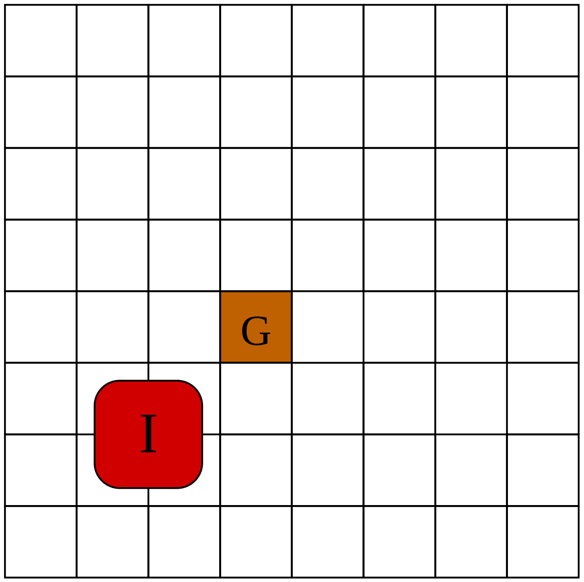
Outline

- Conformant and Classical Planning
- Intuitions
- Proposed Translation
- Experiments
- Discussion

Incomplete Information makes Planning Harder



Problem: A robot must move from an **uncertain** I into G with **certainty**, one cell at a time, in a grid nxn

- Conformant and classical planning look similar except for uncertain I
- Yet plans may be quite different: best **conformant plan** above **must move the robot to a corner first!**

Model for Conformant Planning

- a **set** of possible initial states $b_0 \subseteq S$
- a set $b_F \subseteq S$ of goal states
- actions $A(s) \subseteq A$ applicable in each $s \in S$
- a **non-deterministic** function F s.t. $F(a, s)$ is the **set** of next states

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- a **non-deterministic** function F s.t. $F(a, s)$ is the **set** of next states

– *call a set of possible states, a **belief state***

– *actions then map a belief state b into a belief state b_a*

$$b_a \overset{\textit{def}}{=} \{s' \mid s' \in F(a, s) \ \& \ s \in b\}$$

– ***task** is to find **action sequence** that maps b_0 into target b_F*

Computing Conformant Plans

- Search in **belief space** using an heuristic $h(bel)$ [Bonet and Geffner; AIPS2000]
- **Variations** in both the heuristic and the representation of bel states (formulas, OBDDs, . . .)
- Problem: **not easy** to come up with **good h** for search in bel space ..

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  - the **verification** of classical plans is **polynomial** in the plan size
  - the **verification** of conformant plans is **exponential**

Complexity of Conformant Planning and Restricted Versions

- Conformant planning harder than classical planning as **belief space exponentially larger** than state space
- From a theoretical point of view, the difficulty is that while
  - the **verification** of classical plans is **polynomial** in the plan size
  - the **verification** of conformant plans is **exponential**
- This however also means that
  - Computing **conformant plans** that can be **verified in poly-time**
  - is **not** more complex than computing **classical plans**

Goal

In this paper we propose

- **Translation of a class ’easy to verify’ conformant problems P into classical problems $K(P)$**
- Which can then be solved by an **off-the-shelf classical planner**
- Classical plans of $K(P)$ will be conformant plans for P

How?

Two forms of inference accounted for in the translation:

- *Limited* form of **’disjunctive reasoning’**:
- *Limited* form of **’epistemic reasoning’**

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  Introduction of **fluents** L/X that are true in $K(P)$

  when the conditionals **’if** X **then** L**’** are true in P after a given plan

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- *Limited* form of **’disjunctive reasoning’**:

  Introduction of **fluents** L/X that are true in $K(P)$

  when the conditionals **’if** X **then** L**’** are true in P after a given plan

- *Limited* form of **’epistemic reasoning’**

  Introduction of **literals** KL that are true in $K(P)$

  when L **is true in the belief states** that results in P after a given plan

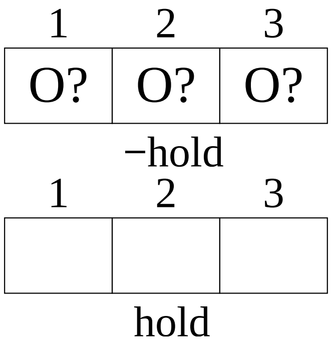
Results

Problem P	`cf2cs(ff)` $K(P)$		CFF P	
	Secs	Length	Secs	Length
Logistics-4-10-10	5.91	125	11.74	121
Bomb-100-60	9.64	140	23.53	140
Sqr-8-Ctr	0.03	22	140.5	50
Sqr-12-Ctr	0.04	32	—	—
Sqr-240-Ctr	858.0	716	—	—

Translation from **P into K(P) takes a few seconds** at most

Translating Conformant into Classical: Intuitions (1)

Pick example



Conformant Problem P

Init: $$\begin{cases} \neg hold \quad \wedge \\ at(p1) \vee at(p2) \vee at(p3) \end{cases}$$

Goal: $hold$

Actions:

pick(pos):

$$at(pos) \rightarrow hold$$

Classical Problem $K(P)$

Plan for both P and $K(P)$: `pick(p1)`, `pick(p2)`, `pick(p3)`

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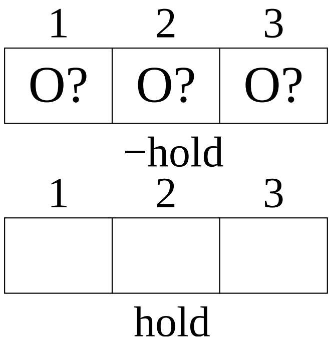

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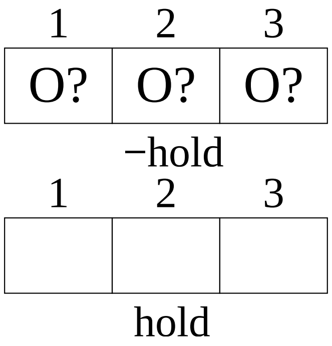

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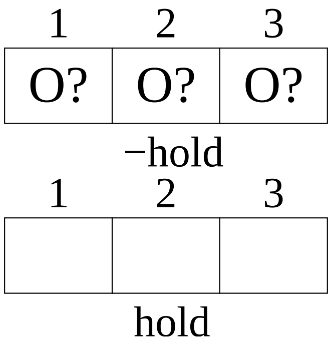

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Actions:

pick(pos):

$at(pos) \longrightarrow hold$

Classical Problem $K(P)$

Init: $K\neg hold$

Goal: $K\ hold$

Actions:

pick(pos):

$\texttt{true} \longrightarrow hold/at(pos)$

Plan for both P and $K(P)$: `pick(p1)`, `pick(p2)`, `pick(p3)`

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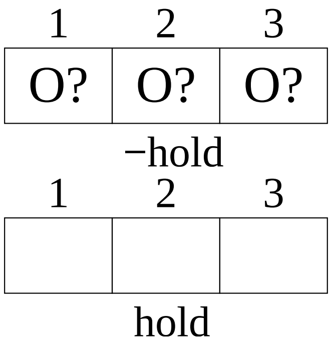

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Classical Problem $K(P)$

Init: $K\neg hold$

Goal: $K\, hold$

Actions:

pick(pos**)**:

$$\texttt{true} \longrightarrow hold/at(pos)$$

merge$_{hold}$**()**:

$$hold/at(p1) \wedge$$
$$hold/at(p2) \wedge$$
$$hold/at(p2) \longrightarrow \; K\, hold$$

Plan for both P and $K(P)$: `pick(p1)`, `pick(p2)`, `pick(p3)`

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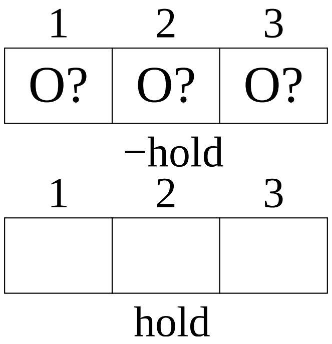

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$hold/at(p2) \rightarrow \ K\ hold$

Plan for both P and $K(P)$: `pick(p1)`, `pick(p2)`, `pick(p3)`, `merge`

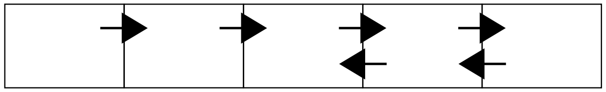
Translating Conformant into Classical: Intuitions (2)

Line example

	1	2	3	4	5	
Init:	I?	I?	I?	I?	I?	$X_1 \lor X_2 \lor X_3 \lor X_4 \lor X_5$
Goal:			G			X_3

Actions: `left`: . . . `right` (→) : $X_i \rightarrow \neg X_i \land X_{i+1}$

Plan:



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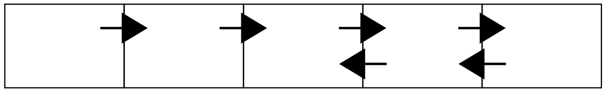
Actions: `left`: ... `right` (→) : $X_i \rightarrow \neg X_i \wedge X_{i+1}$

Plan:



- After →, **know that not in first cell**: $K\neg X_1$

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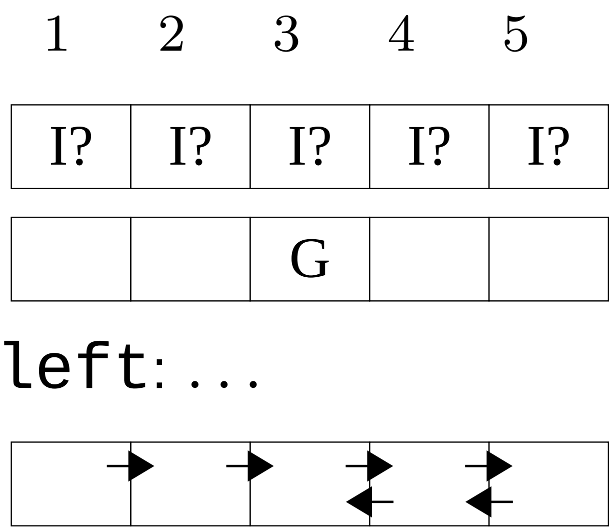

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Goal: X_3

Actions: `left`: . . . `right` (→) : $X_i \longrightarrow \neg X_i \wedge X_{i+1}$

Plan:

- After →, **know that not in first cell**: $K \neg X_1$
- After →, → also that: $K \neg X_2$

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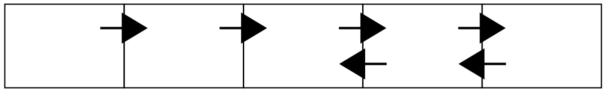

- After →, **know that not in first cell**: $K\neg X_1$
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- After →, →, →, →, also that: $K\neg X_3 \wedge K\neg X_4$

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	1	2	3	4	5	**Disjunction**
Init:	I?	I?	I?	I?	I?	$X_1 \lor X_2 \lor X_3 \lor X_4 \lor X_5$
Goal:			G			X_3

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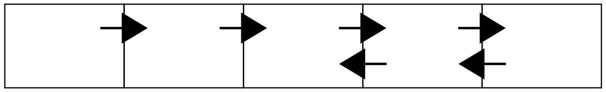

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- After →, →, →, →, also that: $K\neg X_3 \land K\neg X_4$
- We also know the **disjunction**

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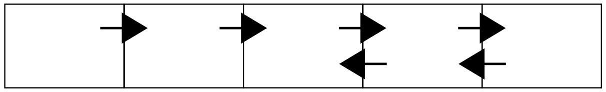

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- After →, → also that: $K\neg X_2$
- After →, →, →, →, also that: $K\neg X_3 \wedge K\neg X_4$
- We also know the **disjunction**
- Thus, KX_5 follows and reaching goal KX_3 is easy

Translating Conformant into Classical: Intuitions (3)

Line example

Conformant P $\Rightarrow$ **Classical** $K(P)$

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Translating Conformant into Classical: Intuitions (3)

Line example

Conformant P	$\Rightarrow$	**Classical** $K(P)$
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Translating Conformant into Classical: Intuitions (3)

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Goal X_3 $\Rightarrow$ KX_3

Action right (➔):

$X_i \longrightarrow \neg X_i \wedge X_{i+1}$ $\Rightarrow$ right (➔): $\begin{cases} \text{true} \longrightarrow K\neg X_1 \\ K\neg X_i \longrightarrow K\neg X_{i+1} \end{cases}$

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		merge$_{X_5}$: $\begin{cases} K\neg X_1 \wedge K\neg X_2 \wedge \\ K\neg X_3 \wedge K\neg X_4 \longrightarrow \ KX_5 \end{cases}$

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merge$_{X_5}$: $\begin{cases} K\neg X_1 \wedge K\neg X_2 \wedge \\ K\neg X_3 \wedge K\neg X_4 \longrightarrow \; KX_5 \end{cases}$

Plan for both P **and** $K(P)$: ➔, ➔, ➔, ➔, merge$_{X_5}$, ⬅, ⬅

Basic Translation: from P into $K(P)$

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Fluent L $\Rightarrow$ $KL, K\neg L$ *(two fluents)*

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Init Known lit L ⇒ $KL \wedge \neg K\neg L$

Init Unknown lit L ⇒ $\neg KL \wedge \neg K\neg L$ *(both false)*

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Basic Translation: from P into $K(P)$

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Fluent L	$\Rightarrow$	$KL, K\neg L$ *(two fluents)*
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Init Unknown lit L	$\Rightarrow$	$\neg KL \wedge \neg K\neg L$ *(both false)*
Goal wff over lits L	$\Rightarrow$	wff over lits KL
Action a: $C \rightarrow L$	$\Rightarrow$	$\begin{cases} a: \quad KC \rightarrow KL \\ a: \quad \neg K\neg C \rightarrow \neg K\neg L \end{cases}$

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Weak (**yet**): works when **uncertainty is not relevant**

Translation from P into $K(P)$: extensions

Action Compilation: For a with one cond effect

$$a : C \wedge L \rightarrow \neg L \quad \Rightarrow \quad a : KC \rightarrow K\neg L$$

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$$a : C \wedge L \rightarrow \neg L \quad \Rightarrow \quad a : KC \rightarrow K\neg L$$

For every $X_1 \vee \cdots \vee X_n \in$ Init(P):

Split: $$a : C \wedge X_i \rightarrow L \quad \Rightarrow \quad a : KC \rightarrow L/X_i$$

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Merge: add **new action** merge$_{X,L}$ with cond effect

$$a : (K\neg X_1 \vee L/X_1) \wedge \cdots \wedge (K\neg X_n \vee L/X_n) \wedge Flag_{X,L} \ \rightarrow \ KL$$

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$\Rightarrow$ **Invariant required** for achieve KL: $\quad X_1 \vee \cdots \vee X_n \vee L$

$Flag_{X,L}$ is deleted when the invariant is **not preserved**.

Translation from P into $K(P)$: extensions

Action Compilation: For a with one cond effect

$$a : C \wedge L \rightarrow \neg L \;\; \Rightarrow \;\; a : KC \rightarrow K\neg L$$

For every $X_1 \vee \cdots \vee X_n \in$ Init(P):

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$\Rightarrow$ **Invariant required** for achieve KL: $X_1 \vee \cdots \vee X_n \vee L$

$Flag_{X,L}$ is deleted when the invariant is **not preserved**.

Theorem:

Classical plans of $K(P)$ are Conformant Plans of P

Results

- Linear translation: a few seconds
- Deals with **most** used benchmarks
- Solves **3 of 6** domains on IPC-2006
- Not (**yet**) ring, sortnet, blocks

Problem P	`cf2cs(ff)` $K(P)$		CFF P	
	Secs	Length	Secs	Length
Bomb-100-1	0.84	199	96.2	199
Bomb-100-60	9.64	140	23.53	140
Cube-7-Ctr	0.02	24	38.2	39
Cube-9-Ctr	0.05	33	—	—
Cube-75-Ctr	484.0	330	—	—
Sqr-8-Ctr	0.03	22	140.5	50
Sqr-12-Ctr	0.04	32	—	—
Sqr-240-Ctr	858.0	716	—	—
Safe-50	0.05	50	134.4	50
Safe-70	0.08	70	561.8	70
Safe-100	0.28	100	—	—
Logistics-4-10-10	5.91	125	11.74	121

Discussion

- **Belief States**:

  Represented by KL's,

  conditionals L/X_i

  and invariants.

  (Incomplete)

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- **Scope** of the
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Discussion

- **Belief States**: Represented by KL's, conditionals L/X_i and invariants. (Incomplete)
- **Scope** of the approach: plans whose **verification** requires at most **one-step non-nested** subproofs

Classical:

$$\begin{array}{r|ll} 1 & p \xrightarrow{a} q & \\ 2 & q \xrightarrow{b} g & \\ 3 & p & \\ \hline 4 & q & (\text{MP } 3, 1) \\ 5 & g & (\text{MP } 4, 2) \end{array}$$

Discussion

- **Belief States**:

  Represented by KL's, conditionals L/X_i and invariants.

  (Incomplete)

- **Scope** of the approach: plans whose **verification** requires at most **one-step non-nested** subproofs

Classical:

1	$p \xrightarrow{a} q$	
2	$q \xrightarrow{b} g$	
3	p	
4	q	(MP 3, 1)
5	g	(MP 4, 2)

Conformant:

1	$p \xrightarrow{a} g$	
2	$q \xrightarrow{b} g$	
3	$p \vee q$	
4	p	
5	g	(MP 4,1)
6	q	
7	g	(MP 6,2)
8	g	($\vee$ elim: 3,5,7)

Discussion(2)

- We transform **verifications** requiring at most **one-step** **non-nested** subproofs into **linear** verifications
- Future work: **extend the scope**/type of proofs accommodated.

Conformant P:

1	$p \xrightarrow{a} g$	
2	$q \xrightarrow{b} g$	
3	$p \vee q$	
4	p	
5	g	(MP 4,1)
6	q	
7	g	(MP 6,2)
8	g	($\vee$ elim: 3,5,7)

Classical $K(P)$:

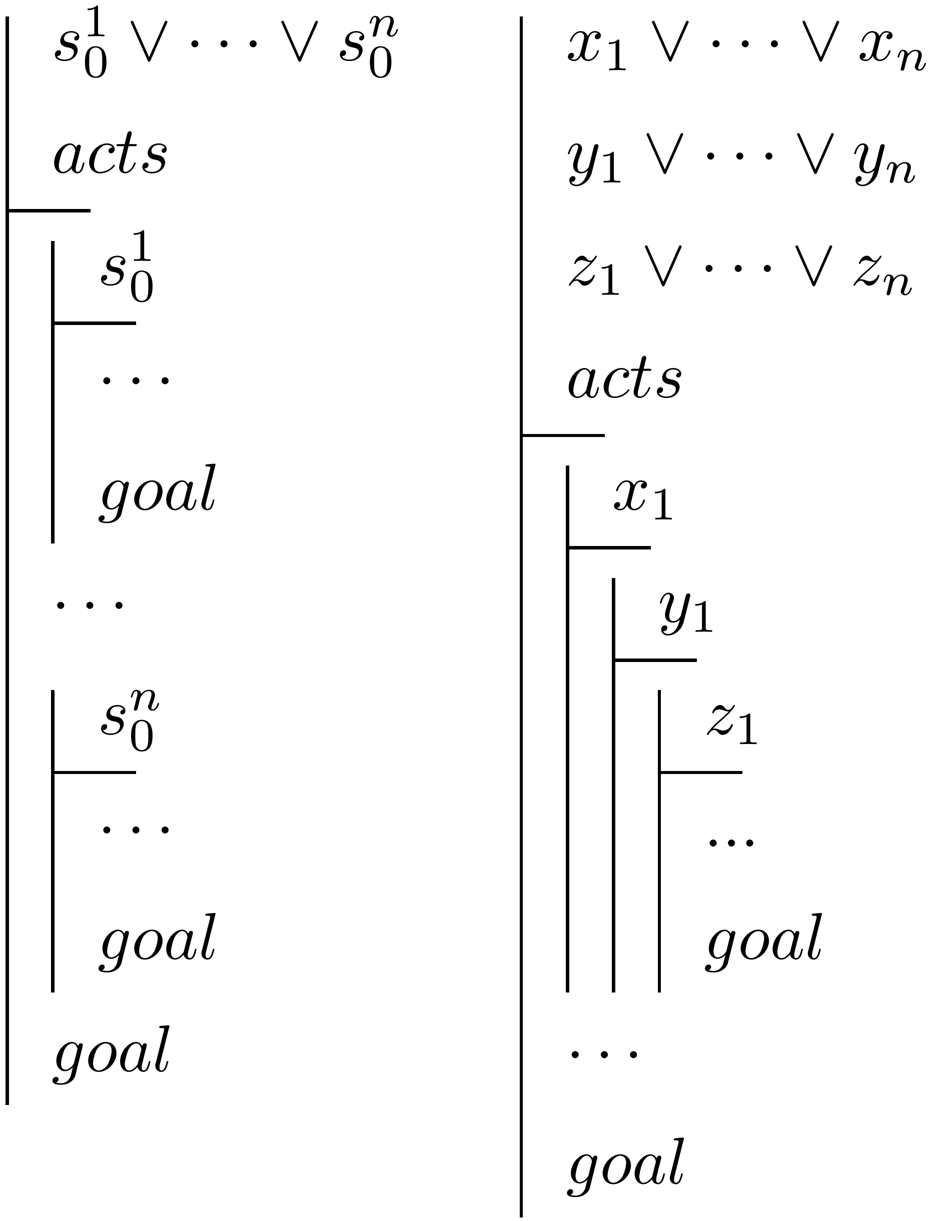
1	true $\xrightarrow{a} g/p$	
2	true $\xrightarrow{b} g/q$	
3	$g/p \wedge g/q \xrightarrow{merge} Kg$	
4	g/p	(MP 2)
5	g/q	(MP 3)
6	Kg	(MP 5,6,4)

Summary

- Mapping from conformant planning into classical planning that **solves efficiently a wide range of non-trivial conformant problems**
- **Idea**: to capture conformant plans requiring **polynomial verification**
- Done by accommodating in the **translation** a *limited* form of **’disjunctive reasoning’** and **’epistemic reasoning’**
- **Clear semantic** with many possible further extensions

Future Work

- Can be made **complete without:**
  - Explicit enumerate all s_0?
  - Nested subproofs?
- Relevant concepts:
  - Decomposition
  - Asymptotically Complete



$s_0^1 \vee \cdots \vee s_0^n$

$acts$

s_0^1

$\cdots$

$goal$

$\cdots$

s_0^n

$\cdots$

$goal$

$goal$

$x_1 \vee \cdots \vee x_n$

$y_1 \vee \cdots \vee y_n$

$z_1 \vee \cdots \vee z_n$

$acts$

x_1

y_1

z_1

$\ldots$

$goal$

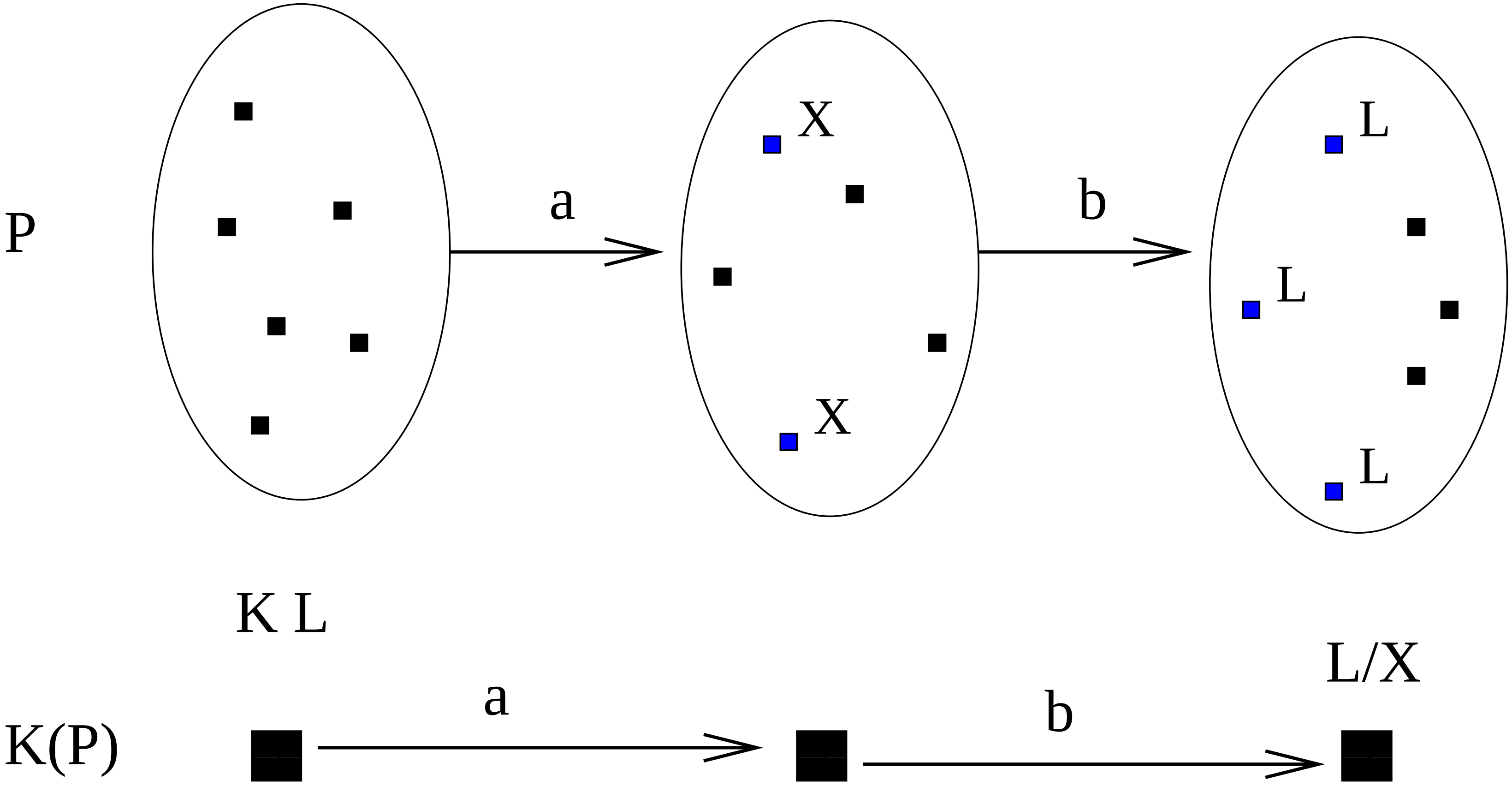
$\cdots$

$goal$

- $a : C \wedge X \rightarrow L$ translated to $a : KC \rightarrow L/X$
- $L/X \equiv$ If X then $L \equiv X \supset L \equiv \neg X \vee L$
- we want to avoid:

  $X \wedge \neg L \equiv$

  X is true but L is not


P
a
X
X
b
L
L
L
K L
K(P)
a
b
L/X