# Effective Heuristics and Belief Tracking for Planning with Incomplete Information


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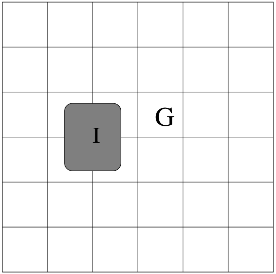
# Incomplete Information: Conformant Planning

**Task**

Robot must move from **uncertain** *I* into *G* with **certainty**.




- Similar to classical planning except for **uncertain** *I*
- **Plans**, however, quite **different**: best **conformant** plan **must move the robot to a corner first (localization)**

# Motivation

Conformant planning is **special case** of contingent planning

Ideas provide the **basis** for

- Planning with Sensing (Brafman & Hoffmann, 2005)
- Derivation of Finite–State Controllers (Bonet, Palacios, Geffner, 2009)

Obtaining conformant planners that **scale up** well is critical.

# Conformant Planning: Belief State Formulation

- **Belief state**: **set** of possible states
- Actions map belief state $b$ into belief state $b_a$

$$b_a = \{s' | s' \in F(a,s) \ \& s \in b\}$$

- Conformant planning is path–finding in **belief space**

**Challenges:** # of belief states is **doubly exponential** in # of vars.

- **Effective representation** of belief states $b$
- **Effective heuristic** $h(b)$ for estimating cost to $G$ in belief space

**Recent alternative:** translation into classical planning (Palacios & Geffner 2007).

# Basic Translation: Move to the “knowledge level”

**conformant problem $P = \langle F, O, I, G \rangle$**

1. $F$ fluents in $P$
2. $O$ actions with effects $C \rightarrow L$
3. $I$ initial situation, CNF **clauses** over $F$-literals
4. $G$ goal situation, **conjuction** of $F$-literals

**classical problem $K_0(P) = \langle F', O', I', G' \rangle$**

1. $F' = \{KL, K\neg L \mid L \in F\}$
2. $O' = O$ **but** preconditions $L$ replaced by $KL$, effects $C \rightarrow L$ replaced by rules
   - **Support** $KC \rightarrow KL$
   - **Cancellation** $\neg K\neg C \rightarrow \neg K\neg L$
3. $I' = \{KL \mid \text{clause } L \in I\}$
4. $G' = \{KL \mid L \in G\}$

# Basic Translation: Properties

$K_0(P)$ is **sound** but **incomplete**:

- **Soundness**: every classical plan for $K_0(P)$ is a conformant plan for $P$
- **Completeness**: all plans for $P$ are classical plans for $K_0(P)$.

# Key Elements in General Translation $K_{T,M}(P)$

1. A set $T$ of **tags** $t$
   - consistent sets of **assumptions** (literals) about initial situation $I$:

$$I \not\models \neg t$$

2. A set $M$ of **merges** $m$
   - **valid subsets of tags** (DNF)

$$I \models \bigvee_{t \in m} t$$

3. Tagged literals $KL/t$ meaning that $L$ true **if** $t$ **initially** true

# General Translation: $K_{T,M}(P)$

**conformant problem** $P = \langle F, O, I, G \rangle$

$\ldots$

**classical problem** $K_{T,M}(P) = \langle F', O', I', G' \rangle$

- $F' = \{KL/t \, , K\neg L/t \mid L \in F \; \& \; t \in T\}$
- $O' = O$ **but** preconditions $L$ replaced by $KL$, effects $C \rightarrow L$ replaced by rules
  - **Support** $KC/t \rightarrow KL/t$
  - **Cancellation** $\neg K\neg C/t \rightarrow \neg K\neg L/t$
  - Plus **merge actions**

$$\bigwedge_{t \in m, m \in M} KL/t \;\rightarrow\; KL$$

- $I' = \{KL/t \mid \text{if } I \models t \supset L\}$
- $G' = \{KL \mid L \in G\}$

# Compiling Uncertainty Away: Properties

- Translation $K_{T,M}(P)$ **always sound**, for suitable choice of sets of **tags** and **merges**, it is **complete**
- **Conformant width** is roughly the **max # of relevant uncertain** variables that interact in $P$
- $K_i(P)$ is **polynomial instance** of $K_{T,M}(P)$ that is **complete** for problems with conformant width **bounded** by $i$
- Most benchmarks have **bounded** width and **equal** to 1!
- $K_i(P)$ with $i = 1$, is basis for conformant planner $T0$ (Palacios & Geffner, 2009)

# Shortcomings of the Translation–based Approach

1. For problems with high width, **complete translation** unfeasible
2. **Incomplete** yet **tractable** translations may
   - render a solvable problem **unsolvable**
   - result in **infinite** heuristic values for solvable beliefs
3. Relevant information like **cardinality of beliefs**, seems to get **lost in translation**

# Contributions of this work

1. **New translation** $K_S^i(P)$
   - Exponential in $i$, always **complete**, not always **sound**
   - $K_S^i(P)$ **sound** for problems with conformant width $\leq i$
2. **New planner** $T1$ based on $K_S^1(P)$ **improves** upon $T0$ planner based on $K_1(P)$
   - **Belief space** planner
   - Two heuristics
     - **Reachability** heuristic $h_C$ derived from $K_S^1(P)$
     - **Certainty** heuristic $h_K$

# Outline for the rest of the talk

1. **Translation** $K_S^i(P)$
2. **Planner** $T1$
3. Experimental **Results**

# Idea for the $K_S^i(P)$ translation

$K_{S0}(P)$ is $K_{T,M}(P)$ with $T = S_0$.

- $K_{S0}(P)$ sound and complete, but **exponential** on $|F|$

Define $K_S$ to be like $K_{S0}$, **but** $T = S \subseteq S_0$

- $S$ **set of samples** of $S_0$
- $K_S(P)$ is **complete** but not necessarily **sound.**

$K_S^i(P)$ like $K_S(P)$ but with a **specific** sample set $S$

- **Sound** when width of problem $P$ **bounded** by $i$
- $|S|$ **exponential** on $i$

# Bases for Conformant Problems

## Definition

A **set of states** $S$, $S \subseteq S_0$ is a **basis for problem** $P$, iff any conformant plan that conforms with $S$ also conforms with $S_0$

## Theorem (Palacios & Geffner, JAIR 2009)

If problem $P$ has width $i$, then there exists a basis $S$ for $P$ of size **exponential in** $i$**.**

# The $K_S^i(P)$ translation

$K_S^i(P)$ is $K_S(P)$ with **sample set** $S \subseteq S_0$ s.t. $S$ guaranteed to be a basis for $P$ if width$(P) \leq i$

$K_S^i(P)$ is **always** complete and **sound** if width$(P) \leq i$,

**Computation** of sample sets $S$ **exponential** in $i$, provided that $I$ compiled into $d$–DNNF (Darwiche, 2002)

See paper for details

# $T1$ planner

Belief space planner $T1$ **implicitly** represents **beliefs.**

Search **node** $n = \langle \pi,\ S_n,\ R \rangle$

- $\pi$ is the **plan prefix** to reach $n$ from **root node** $\langle \emptyset,\ S^1,\ R_0 \rangle$
- $S_n$ is sample set $S^1$ progressed through $\pi$
- $R$ set of **known** literals

SAT solver used to check literals true in $R$

Two heuristics:

- $h_C(n) = h(K_S(P))$, where $S = S_n$
- $h_K(n)$ ... in next slide

# Certainty heuristic $h_K$

Given node $n = \langle \pi,\ S_n,\ R \rangle$, $h_K(n)$ defined as:

# of literals $L$ in *oneof* **invariants** overlapping $G$ s.t. $\neg L \notin R$

Related to

- **Landmark** heuristic (Richter, Helmert & Westphal, 2008)
- **Belief cardinality** heuristic (Bertoli & Cimatti, 2002)

## $T1$ planner: Search Engine

- Multi-queue best first search algorithm (Helmert, 2004)
- 3 open lists Q1,Q2, Q3:
  - **Q1**: nodes for helpful actions or that decrease certainty heuristic $h_K$, ordered with $h_C$
  - **Q2**: nodes for helpful actions or that decrease certainty heuristic $h_K$, ordered with $h_K$
  - **Q3**: nodes for non-helpful actions, ordered with $h_C$
- We alternate expansion from Q1 and Q2, ${}^{1}/_{10}$ of the expansions are from Q3.

# Experimental Evaluation

| | | *T0* | | | *DNF* | | | *T1* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Domain* | *I* | *S* | *avg T* | *avg L* | *S* | *avg T* | *avg L* | *S* | *avg T* | *avg L* |
| bomb | 8 | **8** | 1.7 | 111 | **8** | 4.0 | 93 | 7 | 0.6 | 93 |
| coins | 8 | 7 | 0.1 | 83 | 7 | 0.8 | 81 | **8** | 0.7 | 142 |
| comm | 8 | **8** | 0.2 | 155 | 7 | 255.3 | 170 | **8** | 48.4 | 162 |
| corners-cube | 10 | 8 | 4.4 | 303 | **10** | 1.4 | 184 | **10** | 95.8 | 432 |
| cube | 6 | 3 | 19.6 | 216 | **6** | 959.7 | 1346 | **6** | 6.0 | 223 |
| square-ctr | 5 | 2 | 18.4 | 171 | **5** | 1209.4 | 2111 | **5** | 17.0 | 258 |
| logistics | 3 | **3** | 0.0 | 24 | 1 | 7.5 | 160 | **3** | 0.1 | 41 |
| look-and-grab | 18 | 11 | 0.4 | 31 | 7 | 5.2 | 9 | **15** | 0.1 | 11 |
| push-to | 9 | 6 | 180.2 | 227 | 7 | 67.8 | 89 | **8** | 65.1 | 219 |
| Raos-keys | 3 | **2** | 0.0 | 16 | **2** | 0.5 | 22 | 1 | 0.7 | 21 |
| ring | 3 | **3** | 0.1 | 55 | 1 | 1546.3 | 39 | **3** | 0.6 | 41 |
| Uts-k | 6 | **6** | 4.8 | 82 | **6** | 9.6 | 92 | 4 | 13.1 | 100 |

*T1* compared with conf. planners *T0* and DNF (To, Son & Pontelli, 2010)

*T1* has a **higher coverage** than both *T0* and DNF.

# Heuristics comparison: $h_C(b)$ vs. $h_K(b)$

| | | $h_C$ | | | | $h_K$ | | | | T1 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Domain | I | S | T | E | L | S | T | E | L | S | T | E | L |
| Bomb | 9 | 7 | 71 | 4k | 101 | 7 | 11 | 773 | 101 | **8** | 2 | 100 | 101 |
| Cube(Ctr) | 12 | 6 | 84 | 32k | 188 | 10 | 1 | 890 | 61 | **12** | 0.1 | 61 | 58 |
| Cube(Cor) | 11 | 8 | 92 | 219k | 271 | 10 | 4 | 26k | 88 | **11** | 12 | 15k | 269 |
| Dispose | 11 | 7 | 664 | 8k | 349 | **9** | 57 | 2k | 190 | 8 | 134 | 1k | 491 |
| Logistics | 4 | 2 | 0.2 | 546 | 30 | 2 | 544 | 1613k | 30 | **4** | 0.1 | 554 | 78 |
| Ring | 7 | 6 | 1 | 1k | 17 | 5 | 571 | 58k | 17 | **8** | 0.2 | 214 | 31 |
| UTS-k | 15 | **15** | 0.06 | 26 | 7 | 2 | 0.05 | 154 | 7 | 13 | 0.04 | 10 | 9 |

- The **combination** of $h_C$ and $h_K$ in T1 performs generally better

# Summary

1. A method to define and compute a **sample set** $S \subseteq S_o$ s.t.
   - $|S|$ is exponential in $i$
   - translation $K^i_S(P)$ based on $S$ is sound and complete if $width(P) \leq i$
2. A **Planner** $T1$ based on new translation, extended with certainty heuristic, **competitive** with state–of–the–art.

# All good things come to an End

Thank you!