Certified Unsolvability in Classical Planning

2. Applications

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Certificate Structure

First look

on Github: `https://github.com/salome-eriksson/helve`

A certificate consists of the following files:

- task description
  - limited to STRIPS
    → STRIPS with negation coming soon™
  - variable and action IDs (according to occurence in list)
- certificate
  - state sets: `e ID type description`
    `e 0 h p cnf 3 2 2 -1 0`
  - action sets: `a ID type description`
    `a 0 u 2 4 5 6`
  - statements: `k ID type set-ID(s) justification premises` `k 0 d 7 sd 5 4`
- (BDD descriptions)

(detailed explanation in README.md of github repository)

Certificate File

Example

what we have seen so far:

#	statement	justification
(0)	$\emptyset$ dead	**ED**
(1)	$\{\mathbf{I}\} \sqsubseteq \mathit{states}(\neg a \vee \neg b)$	**B1**
(2)	$S_{\neg a \vee \neg b}[\mathbf{A}] \sqsubseteq S_{\neg a \vee \neg b} \cup \emptyset$	**B2**
(3)	$\overline{S_{\neg a \vee \neg b}}$ dead	**PI** with (3),(1) and (2)

...

the corresponding certificate file:

```
e 0 c e
e 1 c i
a 0 a
k 0 d 0 ed
e 2 h p cnf 2 1 1 2 0
k 1 s 1 2 b1
e 3 p 2 0
e 4 u 2 0
k 2 s 3 4 b2
e 5 n 2
k 3 d 5 pi 2 0 1
...
```

→ Demo

Blind Search

High-Level Certificate

Blind search explores all reachable states $\mathcal{R}^\Pi$.
$\rightarrow$ Recall completeness proof:

Forward Blind Search Certificate

#	statement	justification
(0)	$\emptyset$ dead	**ED**
(1)	$\mathcal{R}^\Pi[\mathbf{A}] \sqsubseteq \mathcal{R}^\Pi \cup \emptyset$	**B2**
(2)	$\mathcal{R}^\Pi \cap \mathbf{S}_G \sqsubseteq \emptyset$	**B1**
(3)	$\mathcal{R}^\Pi \cap \mathbf{S}_G$ dead	**SD** with (0) and (2)
(4)	$\mathcal{R}^\Pi$ dead	**PG** with (1), (0) and (3)
(5)	$\{\mathbf{I}\} \sqsubseteq \mathcal{R}^\Pi$	**B1**
(6)	$\{\mathbf{I}\}$ dead	**SD** with (4) and (5)
(7)	unsolvable	**CI** with (6)

For backwards search, show $\{\mathbf{I}\} \sqsubseteq \overline{\mathcal{R}^\Pi_B}$ and $[\mathbf{A}]\mathcal{R}^\Pi_B \sqsubseteq \mathcal{R}^\Pi_B \cup \emptyset$, deduce $\mathcal{R}^\Pi_B$ dead (rule **RI**), and from $\mathbf{S}_G \sqsubseteq \mathcal{R}^\Pi_B$ show $\mathbf{S}_G$ dead.

Translation to Certificate File

#	statement	justification
(0)	$\emptyset$ dead	**ED**

1	e 0 c e		$S_0 = \emptyset$
2	e 1 c i		$S_1 = \{\mathbf{I}\}$
3	e 2 c g		$S_2 = \mathbf{S}_G$
4	a 0 a		$A_0 = \mathbf{A}$
5	k 0 d 0 ed	(0)	$S_0 (= \emptyset)$ dead

Translation to Certificate File

#	statement	justification
(1)	$\mathcal{R}^{\Pi}[\mathbf{A}] \sqsubseteq \mathcal{R}^{\Pi} \cup \emptyset$	**B2**

1	e 0 c e		$S_0 = \emptyset$
2	e 1 c i		$S_1 = \{\mathbf{I}\}$
3	e 2 c g		$S_2 = \mathbf{S}_G$
4	a 0 a		$A_0 = \mathbf{A}$
5	k 0 d 0 ed	(0)	$S_0 (= \emptyset)$ dead
6	e 3 . . .		$S_3 = \mathcal{R}^{\Pi}$
7	e 4 p 3 0		$S_4 = S_3[A_0] = \mathcal{R}^{\Pi}[\mathbf{A}]$
8	e 5 u 3 0		$S_5 = S_3 \cup S_0 = \mathcal{R}^{\Pi} \cup \emptyset$
9	k 1 s 4 5 b2	(1)	$S_4 (= \mathcal{R}^{\Pi}[\mathbf{A}]) \sqsubseteq S_5 (= \mathcal{R}^{\Pi} \cup \emptyset)$

Translation to Certificate File

#	statement	justification
(2)	$\mathcal{R}^{\Pi} \cap \mathbf{S}_G \sqsubseteq \emptyset$	**B1**

1	e 0 c e		$S_0 = \emptyset$
2	e 1 c i		$S_1 = \{\mathbf{I}\}$
3	e 2 c g		$S_2 = \mathbf{S}_G$
4	a 0 a		$A_0 = \mathbf{A}$
5	k 0 d 0 ed	(0)	$S_0 (= \emptyset)$ dead
6	e 3 . . .		$S_3 = \mathcal{R}^{\Pi}$
7	e 4 p 3 0		$S_4 = S_3[A_0] = \mathcal{R}^{\Pi}[\mathbf{A}]$
8	e 5 u 3 0		$S_5 = S_3 \cup S_0 = \mathcal{R}^{\Pi} \cup \emptyset$
9	k 1 s 4 5 b2	(1)	$S_4 (= \mathcal{R}^{\Pi}[\mathbf{A}]) \sqsubseteq S_5 (= \mathcal{R}^{\Pi} \cup \emptyset)$
10	e 6 i 3 2		$S_6 = S_3 \cap S_2 = \mathcal{R}^{\Pi} \cap \mathbf{S}_G$
11	k 2 s 6 0 b1	(2)	$S_6 (= \mathcal{R}^{\Pi} \cap \mathbf{S}_G) \sqsubseteq S_0 (= \emptyset)$

Translation to Certificate File

#	statement	justification
(3)	$\mathcal{R}^\Pi \cap \mathbf{S}_G$ dead	**SD** with (0) and (2)

1	e 0 c e		$S_0 = \emptyset$
2	e 1 c i		$S_1 = \{\mathbf{I}\}$
3	e 2 c g		$S_2 = \mathbf{S}_G$
4	a 0 a		$A_0 = \mathbf{A}$
5	k 0 d 0 ed	(0)	$S_0 (= \emptyset)$ dead
6	e 3 . . .		$S_3 = \mathcal{R}^\Pi$
7	e 4 p 3 0		$S_4 = S_3[A_0] = \mathcal{R}^\Pi[\mathbf{A}]$
8	e 5 u 3 0		$S_5 = S_3 \cup S_0 = \mathcal{R}^\Pi \cup \emptyset$
9	k 1 s 4 5 b2	(1)	$S_4 (= \mathcal{R}^\Pi[\mathbf{A}]) \sqsubseteq S_5 (= \mathcal{R}^\Pi \cup \emptyset)$
10	e 6 i 3 2		$S_6 = S_3 \cap S_2 = \mathcal{R}^\Pi \cap \mathbf{S}_G$
11	k 2 s 6 0 b1	(2)	$S_6 (= \mathcal{R}^\Pi \cap \mathbf{S}_G) \sqsubseteq S_0 (= \emptyset)$
12	k 3 d 6 sd 2 0	(3)	$S_6 (= \mathcal{R}^\Pi \cap \mathbf{S}_G)$ dead

Translation to Certificate File

#	statement	justification
(4)	$\mathcal{R}^{\Pi}$ dead	**PG** with (1), (0) and (3)

1	e 0 c e		$S_0 = \emptyset$
2	e 1 c i		$S_1 = \{\mathbf{I}\}$
3	e 2 c g		$S_2 = \mathbf{S}_G$
4	a 0 a		$A_0 = \mathbf{A}$
5	k 0 d 0 ed	(0)	$S_0 (= \emptyset)$ dead
6	e 3 . . .		$S_3 = \mathcal{R}^{\Pi}$
7	e 4 p 3 0		$S_4 = S_3[A_0] = \mathcal{R}^{\Pi}[\mathbf{A}]$
8	e 5 u 3 0		$S_5 = S_3 \cup S_0 = \mathcal{R}^{\Pi} \cup \emptyset$
9	k 1 s 4 5 b2	(1)	$S_4 (= \mathcal{R}^{\Pi}[\mathbf{A}]) \sqsubseteq S_5 (= \mathcal{R}^{\Pi} \cup \emptyset)$
10	e 6 i 3 2		$S_6 = S_3 \cap S_2 = \mathcal{R}^{\Pi} \cap \mathbf{S}_G$
11	k 2 s 6 0 b1	(2)	$S_6 (= \mathcal{R}^{\Pi} \cap \mathbf{S}_G) \sqsubseteq S_0 (= \emptyset)$
12	k 3 d 6 sd 2 0	(3)	$S_6 (= \mathcal{R}^{\Pi} \cap \mathbf{S}_G)$ dead
13	k 4 d 3 pg 1 0 3	(4)	$S_3 (= \mathcal{R}^{\Pi})$ dead

Translation to Certificate File

#	statement	justification
(5)	$\{\mathbf{I}\} \sqsubseteq \mathcal{R}^{\Pi}$	**B1**

1	e 0 c e		$S_0 = \emptyset$
2	e 1 c i		$S_1 = \{\mathbf{I}\}$
3	e 2 c g		$S_2 = \mathbf{S}_G$
4	a 0 a		$A_0 = \mathbf{A}$
5	k 0 d 0 ed	(0)	$S_0 (= \emptyset)$ dead
6	e 3 . . .		$S_3 = \mathcal{R}^{\Pi}$
7	e 4 p 3 0		$S_4 = S_3[A_0] = \mathcal{R}^{\Pi}[\mathbf{A}]$
8	e 5 u 3 0		$S_5 = S_3 \cup S_0 = \mathcal{R}^{\Pi} \cup \emptyset$
9	k 1 s 4 5 b2	(1)	$S_4 (= \mathcal{R}^{\Pi}[\mathbf{A}]) \sqsubseteq S_5 (= \mathcal{R}^{\Pi} \cup \emptyset)$
10	e 6 i 3 2		$S_6 = S_3 \cap S_2 = \mathcal{R}^{\Pi} \cap \mathbf{S}_G$
11	k 2 s 6 0 b1	(2)	$S_6 (= \mathcal{R}^{\Pi} \cap \mathbf{S}_G) \sqsubseteq S_0 (= \emptyset)$
12	k 3 d 6 sd 2 0	(3)	$S_6 (= \mathcal{R}^{\Pi} \cap \mathbf{S}_G)$ dead
13	k 4 d 3 pg 1 0 3	(4)	$S_3 (= \mathcal{R}^{\Pi})$ dead
14	k 5 s 1 3 b1	(5)	$S_1 (= \{\mathbf{I}\}) \sqsubseteq S_3 (= \mathcal{R}^{\Pi})$

Translation to Certificate File

#	statement	justification
(6)	$\{\mathbf{I}\}$ dead	**SD** with (4) and (5)

e 0 c e		$S_0 = \emptyset$
e 1 c i		$S_1 = \{\mathbf{I}\}$
e 2 c g		$S_2 = \mathbf{S}_G$
a 0 a		$A_0 = \mathbf{A}$
k 0 d 0 ed	(0)	$S_0 (= \emptyset)$ dead
e 3 . . .		$S_3 = \mathcal{R}^{\Pi}$
e 4 p 3 0		$S_4 = S_3[A_0] = \mathcal{R}^{\Pi}[\mathbf{A}]$
e 5 u 3 0		$S_5 = S_3 \cup S_0 = \mathcal{R}^{\Pi} \cup \emptyset$
k 1 s 4 5 b2	(1)	$S_4 (= \mathcal{R}^{\Pi}[\mathbf{A}]) \sqsubseteq S_5 (= \mathcal{R}^{\Pi} \cup \emptyset)$
e 6 i 3 2		$S_6 = S_3 \cap S_2 = \mathcal{R}^{\Pi} \cap \mathbf{S}_G$
k 2 s 6 0 b1	(2)	$S_6 (= \mathcal{R}^{\Pi} \cap \mathbf{S}_G) \sqsubseteq S_0 (= \emptyset)$
k 3 d 6 sd 2 0	(3)	$S_6 (= \mathcal{R}^{\Pi} \cap \mathbf{S}_G)$ dead
k 4 d 3 pg 1 0 3	(4)	$S_3 (= \mathcal{R}^{\Pi})$ dead
k 5 s 1 3 b1	(5)	$S_1 (= \{\mathbf{I}\}) \sqsubseteq S_3 (= \mathcal{R}^{\Pi})$
k 6 d 1 sd 5 4	(6)	$S_1 (= \{\mathbf{I}\})$ dead

Translation to Certificate File

#	statement	justification
(7)	unsolvable	**CI** with (6)

1	e 0 c e		$S_0 = \emptyset$
2	e 1 c i		$S_1 = \{\mathbf{I}\}$
3	e 2 c g		$S_2 = \mathbf{S}_G$
4	a 0 a		$A_0 = \mathbf{A}$
5	k 0 d 0 ed	(0)	$S_0 (= \emptyset)$ dead
6	e 3 . . .		$S_3 = \mathcal{R}^\Pi$
7	e 4 p 3 0		$S_4 = S_3[A_0] = \mathcal{R}^\Pi[\mathbf{A}]$
8	e 5 u 3 0		$S_5 = S_3 \cup S_0 = \mathcal{R}^\Pi \cup \emptyset$
9	k 1 s 4 5 b2	(1)	$S_4 (= \mathcal{R}^\Pi[\mathbf{A}]) \sqsubseteq S_5 (= \mathcal{R}^\Pi \cup \emptyset)$
10	e 6 i 3 2		$S_6 = S_3 \cap S_2 = \mathcal{R}^\Pi \cap \mathbf{S}_G$
11	k 2 s 6 0 b1	(2)	$S_6 (= \mathcal{R}^\Pi \cap \mathbf{S}_G) \sqsubseteq S_0 (= \emptyset)$
12	k 3 d 6 sd 2 0	(3)	$S_6 (= \mathcal{R}^\Pi \cap \mathbf{S}_G)$ dead
13	k 4 d 3 pg 1 0 3	(4)	$S_3 (= \mathcal{R}^\Pi)$ dead
14	k 5 s 1 3 b1	(5)	$S_1 (= \{\mathbf{I}\}) \sqsubseteq S_3 (= \mathcal{R}^\Pi)$
15	k 6 d 1 sd 5 4	(6)	$S_1 (= \{\mathbf{I}\})$ dead
16	k 7 u ci 6	(7)	unsolvable

Implementation Details

Depending on the concrete algorithm, some implementation details affect performance:

- formalism for $\mathcal{R}^\Pi$
  - symbolic search: BDD
    $\rightarrow$ overhead if no singular closed BDD!
  - explicit search: explicit enumeration or BDD
    $\rightarrow$ fast generation vs fast verification
- when to build the certificate
  - during search: unnecessary overhead for solvable problems
  - at the end: more overhead (iterate over entire closed list), but also more localized

Heuristic Search

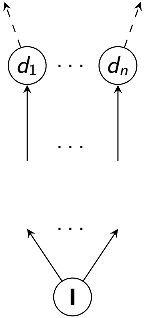
Idea

1. Each dead-end is dead.
2. The set of expanded states contains no goal state.
3. The set of expanded states can only reach itself and dead-ends.
4. $\rightarrow$ the set of expanded states is dead.
5. The initial state is in the set of expanded states.
6. $\rightarrow$ The initial state is dead and the task unsolvable.

High-Level Certificate

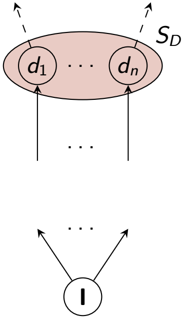
(1) $\emptyset$ dead

(2) $\{d_1\}$ dead (3) $\{d_2\}$ dead . . . (4) $\{d_n\}$ dead



High-Level Certificate

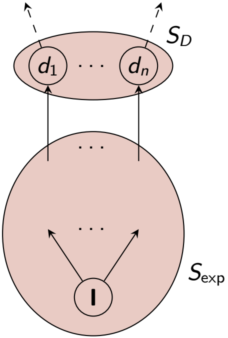
(1) $\emptyset$ dead
(2) $\{d_1\}$ dead (3) $\{d_2\}$ dead ... (4) $\{d_n\}$ dead



#	statement	justification
(5)	$\{d_1\} \cup \{d_2\}$ dead	**UD** with (2) and (3)
	...	
(6)	$\bigcup_{1 \le i \le n} d_i$ dead	**UD** with ...
(7)	$S_D \sqsubseteq \bigcup_{1 \le i \le n} d_i$	**B1**
(8)	S_D dead	**SD** with (6) and (7)

High-Level Certificate

(1) $\emptyset$ dead
(2) $\{d_1\}$ dead   (3) $\{d_2\}$ dead   . . .   (4) $\{d_n\}$ dead



#	statement	justification
(5)	$\{d_1\} \cup \{d_2\}$ dead	**UD** with (2) and (3)
	. . .	
(6)	$\bigcup_{1 \leq i \leq n} d_i$ dead	**UD** with . . .
(7)	$S_D \sqsubseteq \bigcup_{1 \leq i \leq n} d_i$	**B1**
(8)	S_D dead	**SD** with (6) and (7)
(9)	$S_{\text{exp}}[\mathbf{A}] \sqsubseteq S_{\text{exp}} \cup S_D$	**B2**
(10)	$S_{\text{exp}} \cap \mathbf{S}_G \sqsubseteq \emptyset$	**B1**
(11)	$S_{\text{exp}} \cap \mathbf{S}_G$ dead	**SD** with (1) and (10)
(12)	S_{exp} dead	**PG** with (9), (8) and (11)
(13)	$\{\mathbf{I}\} \sqsubseteq S_{\text{exp}}$	**B1**
(14)	$\{\mathbf{I}\}$ dead	**SD** with (12) and (13)
(15)	task unsolvable	**CI** with (14)

Bridging Representations

Statements "$\{d_i\}$ dead" might use different representations.

1 Show $\{d_i\}_{\mathbf{explicit}} \sqsubseteq \{d_i\}_{\mathbf{R}}$ (basic statement **B4**)

and then either

2a build $(S_{\text{exp}})_{\mathbf{explicit}}$, and

3a show $(S_{\text{exp}})_{\mathbf{explicit}} \sqsubseteq (S_{\text{exp}})_{\mathbf{explicit}} \cup \bigcup\{d_i\}_{\mathbf{explicit}}$ (**B2**).

or

2b build $(S_D)_{\mathbf{explicit}}$, $(S_D)_{\mathbf{BDD}}$ and $(S_{\text{exp}})_{\mathbf{BDD}}$,

3b show $(S_D)_{\mathbf{explicit}} \sqsubseteq \bigcup\{d_i\}_{\mathbf{explicit}}$ (**B2**),

4b show $(S_D)_{\mathbf{BDD}} \sqsubseteq (S_D)_{\mathbf{explicit}}$ (**B4**), and

5b show $(S_{\text{exp}})_{\mathbf{BDD}} \sqsubseteq (S_{\text{exp}})_{\mathbf{BDD}} \cup (S_D)_{\mathbf{BDD}}$ (**B2**).

$\rightarrow$ tradeoff efficient generation vs efficient verification

Delete Relaxation

h^{max} dead-end

$h^{max}(s) = \infty \leftrightarrow$ some $g \in \mathbf{G}$ relaxed unreachable

Consider $R_u^+(s) = \{v \mid v \text{ relaxed unreachable from } s\}$ and $\varphi = \bigwedge_{v \in R_u^+(s)} \neg v$.

- We can't reach any s' containing any $v \in R_u^+(s)$: $S_\varphi[\mathbf{A}] \subseteq S_\varphi$
- All states satisfying φ do not satisfy g: $S_\varphi \cap \mathbf{S}_G = \emptyset$
- State s satisfies φ: $\{s\} \subseteq S_\varphi$

$\rightarrow$ Show that S_φ is dead (**PG**) and thus s is dead (**SD**).

We can choose between different representations:
BDD, Horn formula, 2CNF formula, explicit (over $R_u^+(s)$)

h^m & Clause-Learning State Space Search

h^m dead-ends:

- same concept as h^{max}: $\varphi = \bigwedge_{t \in R_u^m(s)} \bigvee_{v \in t} \neg v$, where $R_u^m(s)$ are the tuples unreachable from s.
- representation: Horn formulas (or 2CNF formulas for $m = 2$)
  $\rightarrow$ BDDs not suited [Edelkamp & Kissmann 2011]

Clause-Learning State Space Search [Steinmetz & Hoffmann (2017)]:

- uses h^C $\rightarrow$ same concept (again)
- can be refined to detect **I** as dead-end $\rightarrow$ compact certificate
- uses additional source for mutexes
  $\rightarrow$ Integrate additional information into certificate!

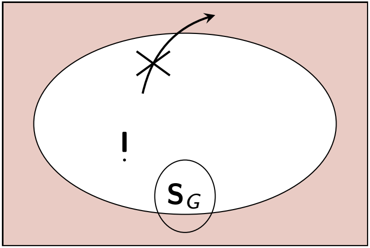
Other heuristics

- $h^{\max}$ approach covers all delete-relaxation heuristics ($h^{\text{LM-Cut}}$, landmarks based on delete relaxation, ...)
- Merge & Shrink:
  - transformation from Merge & Shrink representation to ADD [Helmert et al. 2014] and extract ∞-paths to BDD
    $\rightarrow$ limited to linear merge strategies [Helmert et al. 2015]
  - one set for all dead-ends
    $\rightarrow$ certificate more compact
  - implementation detail: unreachable and dead-end states merged
    $\rightarrow$ disable for certificate generation

h^2 Preprocessor

Algorithm Overview

- introduced in [Alcázar & Torralba (2015)]
- preprocessing step that simplifies planning task
- used in many IPC planners
- incremental h^2 reachability analysis, alternating between forward and backward
  $\rightarrow$ remove unreachable facts and actions



Algorithm Overview

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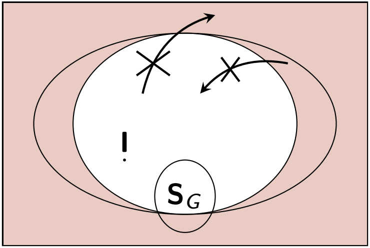

Algorithm Overview

- introduced in [Alcázar & Torralba (2015)]
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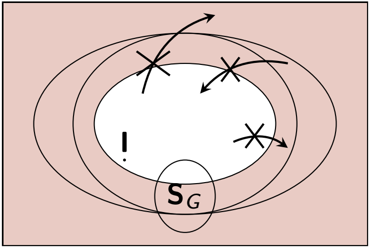
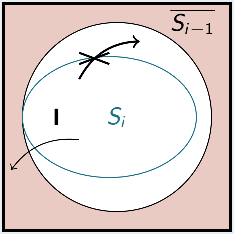


High-Level Certificate

- D_i: set of literal pairs shown dead before or in iteration i
- $S_i = \{s \mid \{p, q\} \not\subseteq s \text{ for all } \{p, q\} \in D_i\}$
- start with iteration 1 and $D_0 = \{\} \rightarrow \overline{S_0}(= \{\})$ dead

Forward iteration i



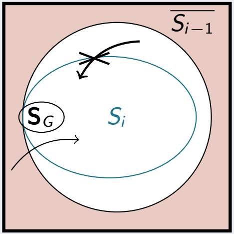
given: (1) $\overline{S_{i-1}}$ dead

#	statement	justification
(2)	$\{\mathbf{I}\} \sqsubseteq S_i$	**B1**
(3)	$S_i[\mathbf{A}] \sqsubseteq S_i \cup \overline{S_{i-1}}$	**B2**
(4)	$\overline{S_i}$ dead	**PI** with (3), (1) and (2)

High-Level Certificate

- D_i: set of literal pairs shown dead before or in iteration i
- $S_i = \{s \mid \{p,q\} \not\subseteq s \text{ for all } \{p,q\} \in D_i\}$
- start with iteration 1 and $D_0 = \{\} \rightarrow \overline{S_0}(= \{\})$ dead

Backward iteration i



given: (1) $\overline{S_{i-1}}$ dead

#	statement	justification
(2)	$\overline{S_i} \cap \mathbf{S}_G \sqsubseteq \overline{S_{i-1}}$	**B1**
(3)	$\overline{S_i} \cap \mathbf{S}_G$ dead	**SD** with (1) and (2)
(4)	$[\mathbf{A}]S_i \sqsubseteq S_i \cup \overline{S_{i-1}}$	**B2**
(5)	$\overline{S_i}$ dead	**RG** with (4), (1) and (3)

Remarks

- representation of S_i: $\bigwedge_{\{p,q\}\in D_i} \neg p \vee \neg q$
  $\rightarrow$ 2CNF (Horn not suitable since p and q can be negative)
- If the h^2 preprocessor detects the task unsolvable, we can extract a full proof:
  - ends in forward iteration: $\mathbf{S}_G \subseteq \overline{S_n}$ (all goal states dead)
  - ends in backward iteration: $\{\mathbf{I}\} \subseteq \overline{S_n}$ (initial state dead)
- Otherwise, we can use the statement "$\overline{S_n}$ dead" to explain why we pruned certain states.
- We can also extract more fine-grained statements such as "$S_{p\wedge q}$ dead" within the proof system.

Recap

Take-Home Messages

- We can verify algorithms on different levels (unit tests, certifying algorithms, theorem provers).
- The unsolvability proof system incrementally deduces knowledge about dead states.
- Its modularity enables us to combine different sources of information.
- Efficient verification depends on the representation of state sets, i.e. which operations are efficiently supported.
- Different representations can offer tradeoffs between efficient generation and verification.
- Generating certificates often involves reachability arguments.

Future Work

- cover more planning techniques, e.g.
  - dead-end potentials
  - partial order reduction
  - task transformations
- extend the verifier
  - more representations
    $\rightarrow$ talk in Session E2 next week about CNF
  - more inference rules
- verify the verifier!