

A Tabled Prolog Program for Solving Sokoban

Neng-Fa Zhou Agostino Dovier

Department of Computer and Information Science,
CUNY Brooklyn College & Graduate Center, USA

Department of Mathematics and Computer Science,
University of Udine, Italy

Pescara, September 2nd, 2011

Summary

- 1 Introduction
- 2 Sokoban as a Planning Problem
- 3 Tabling
- 4 Sokoban as a Prolog Program
- 5 Computational Results
- 6 Conclusions

History

- Sokoban is a type of transport puzzle invented by *Hiroyuki Imabayashi* in 1980
- Published by the Japanese company **Thinking Rabbit, Inc.** in 1982.
- Sokoban means “warehouse-keeper” (**magazziniere**) in Japanese.
- Thinking Rabbit joined **Square Co., Ltd.**

Sokoban Rules

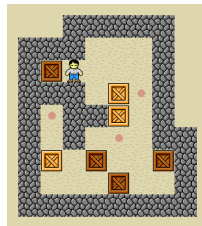
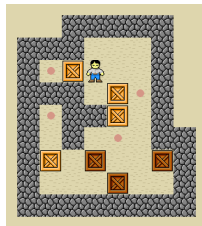
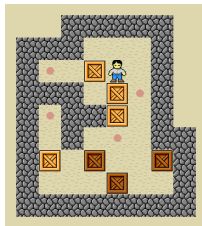
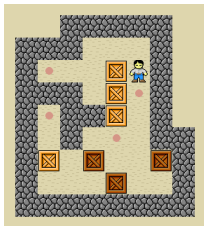
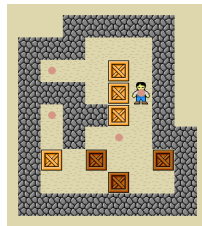
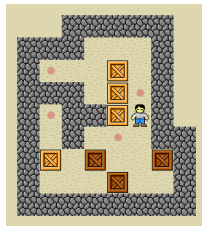
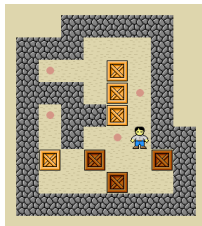
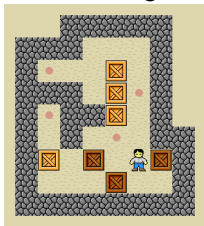
(from <http://www.sokoban.jp/>)



Sokoban @ work

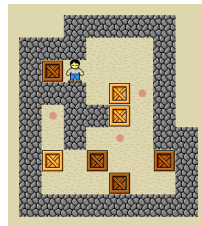
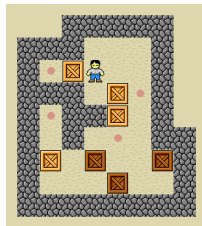
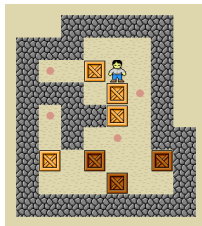
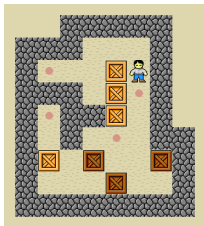
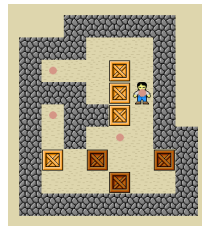
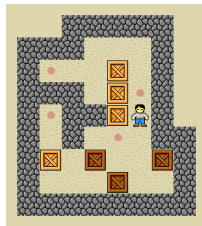
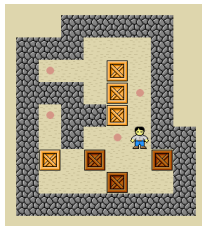
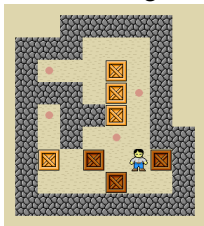
Macro-actions

The following sequence of 8 actions



Macro-actions

The following sequence of 8 actions



is counted as a single (macro) action.

The genesis of this work

- With Andrea Formisano and Enrico Pontelli we developed a CLP(FD) solver for the action description language \mathcal{B} (and a compiler in ASP) [ICLP07–MG65]

The genesis of this work

- With Andrea Formisano and Enrico Pontelli we developed a CLP(FD) solver for the action description language \mathcal{B} (and a compiler in ASP) [ICLP07–MG65]
- Neng-Fa Zhou is the main developer (actually, the **father**) of B-Prolog that includes a fast solver of constraints on finite domains

The genesis of this work

- With Andrea Formisano and Enrico Pontelli we developed a CLP(FD) solver for the action description language \mathcal{B} (and a compiler in ASP) [ICLP07–MG65]
- Neng-Fa Zhou is the main developer (actually, the **father**) of B-Prolog that includes a fast solver of constraints on finite domains
- In the 2009 ASP competition we wrote with him some \mathcal{B} domains that, once interpreted with the B-Prolog solver behaved very well (in particular peg-solitaire).

The genesis of this work

- With Andrea Formisano and Enrico Pontelli we developed a CLP(FD) solver for the action description language \mathcal{B} (and a compiler in ASP) [ICLP07–MG65]
- Neng-Fa Zhou is the main developer (actually, the **father**) of B-Prolog that includes a fast solver of constraints on finite domains
- In the 2009 ASP competition we wrote with him some \mathcal{B} domains that, once interpreted with the B-Prolog solver behaved very well (in particular peg-solitaire).
- Neng-Fa asked us to do the same for the 2011 competition.

The genesis of this work

- With Andrea Formisano and Enrico Pontelli we developed a CLP(FD) solver for the action description language \mathcal{B} (and a compiler in ASP) [ICLP07–MG65]
- Neng-Fa Zhou is the main developer (actually, the **father**) of B-Prolog that includes a fast solver of constraints on finite domains
- In the 2009 ASP competition we wrote with him some \mathcal{B} domains that, once interpreted with the B-Prolog solver behaved very well (in particular peg-solitaire).
- Neng-Fa asked us to do the same for the 2011 competition.
- This approach for Sokoban was un-successful, but this forced us to look for another declarative approach.

Representation

1	2			10	11	15
3	4	7	8	11	12	16
5	6			13	14	17

```
location(1). ... location(17).
```

Representation

1	2			10	11	15
3	4	7	8	11	12	16
5	6			13	14	17

```
location(1). ... location(17).
```

```
step(1, right, 2). step(10, right, 11). step(11, right, 15).
```

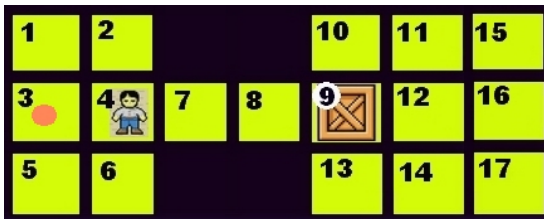
```
step(2, left, 1). step(11, left, 10). step(15, left, 11).
```

```
step(1, down, 3). step(2, down, 4).
```

```
step(3, up, 1). step(4, up, 2).
```

```
...
```

Representation



Encoding in B

Fluents

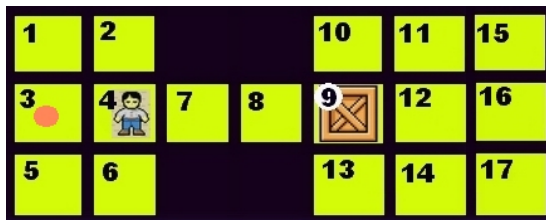
```
fluent (free (L) ) :-  
    location (L) .  
fluent (box_in (L) ) :-  
    location (L) .  
fluent (sokoban_in (L) ) :-  
    location (L) .
```


Encoding in B

Fluents

```
fluent (free(L) ) :-  
    location(L) .  
fluent (box_in(L) ) :-  
    location(L) .  
fluent (sokoban_in(L) ) :-  
    location(L) .  
  
fluent (reachable(A) ) :-  
    location(A) .
```

Representation

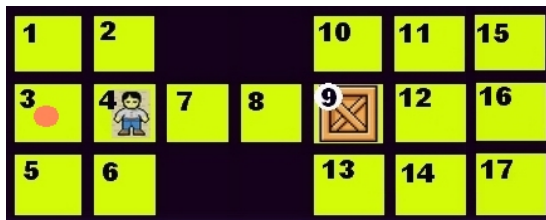


```
free(1). free(2). free(10). free(11). free(15).
free(3). free(7). free(8). free(12). free(16).
free(5). free(6). free(13). free(14). free(17).
```

```
box_in(9).
```

```
sokoban_in(4).
```

Representation



```
free(1). free(2). free(10). free(11). free(15).
free(3). free(7). free(8). free(12). free(16).
free(5). free(6). free(13). free(14). free(17).
```

```
box_in(9).
```

```
sokoban_in(4).
```

```
goal(box_in(3)).
```

Input from ASP competition

```
top(col4row4,col4row3). top(col4row3,col4row2).  
right(col4row2,col5row2). right(col5row2,col6row2).  
....
```

Input from ASP competition

```
top(col4row4,col4row3). top(col4row3,col4row2).  
right(col4row2,col5row2). right(col5row2,col6row2).  
....  
  
box(col8row2). box(col3row4).  
sokoban(col4row4).
```

Input from ASP competition

```
top(col4row4,col4row3). top(col4row3,col4row2).  
right(col4row2,col5row2). right(col5row2,col6row2).  
....
```

```
box(col8row2). box(col3row4).  
sokoban(col4row4).
```

```
solution(col3row2). solution(col2row2).
```

Encoding in B

Actions (help from Andrea Formisano)

```
action(push(From,D,To)) :-  
    location(From), location(To), neq(From,To),  
    direction(D), % D = left, right, up, down  
    step(_Sokoban,D,From),  
    straight_connection(From,To,D,_).
```

Encoding in B

Actions (help from Andrea Formisano)

```

action(push(From,D,To)) :-
    location(From), location(To), neq(From,To),
    direction(D), % D = left, right, up, down
    step(_Sokoban,D,From),
    straight_connection(From,To,D,_).

executable(push(From,D,To), [sokoban_in(S0), reachable(S1),
                             box_in(From) | Free_LIST ]) :-
    action(push(From,D,To)),
    location(S0), location(S1),
    step(S1,D,From),
    straight_connection(From,To,D, [From|PATH]),
    empty_path(PATH, Free_LIST ).

empty_path([], []).
empty_path([L|R], [free(L) | S]) :-
    empty_path(R, S).

```


Encoding in B

Actions Effects

```
causes(push(From,D,To), box_in(To) , []) :-
    action(push(From,D,To)) .
```

```
causes(push(From,D,To), neg(box_in(From)) , []) :-
    action(push(From,D,To)) .
```

```
causes(push(From,D,To), sokoban_in(S), []) :-
    action(push(From,D,To)) ,
    location(S), step(S,D,To) .
```

```
causes(push(From,D,To), free(S) , [sokoban_in(S)]) :-
    action(push(From,D,To)) ,
    location(S), \+ step(S,D,To) .
```

```
causes(push(From,D,To), free(From) , []) :-
    action(push(From,D,To)) ,
    \+ step(From,D,To) .
```

Encoding in B

Basic Static Causal Laws

```
caused([free(L)],neg(box_in(L))) :- location(L).
```

```
caused([free(L)],neg(sokoban_in(L))) :- location(L).
```

```
caused([sokoban_in(L)],neg(free(L))) :- location(L).
```

```
caused([sokoban_in(L)],neg(box(L))) :- location(L).
```

```
caused([sokoban_in(L1)],neg(sokoban_in(L2))) :-  
    location(L1), location(L2), neq(L1,L2).
```

```
caused([box_in(L)],neg(free(L))) :- location(L).
```

```
caused([box_in(L)],neg(sokoban_in(L))) :- location(L).
```

Encoding in B

Static Causal Laws: reachability

```
caused([sokoban_in(A)], reachable(A)) :-  
    location(A).
```

```
caused([reachable(B), free(C)], reachable(C)) :-  
    location(B), location(C),  
    neq(B, C),  
    step(B, D, C), direction(D).
```

The results

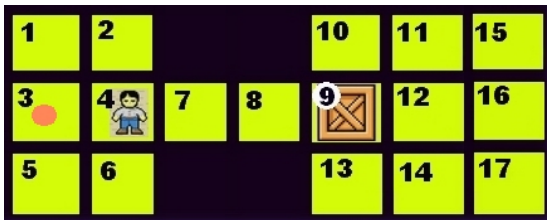
- This B encoding, compiled in ASP and run using clingo run rather fast on the proposed examples.
- We later discovered that the running time is comparable to that of the direct ASP solution of the Sokoban (also run using clingo)

The results

- This B encoding, compiled in ASP and run using clingo run rather fast on the proposed examples.
- We later discovered that the running time is comparable to that of the direct ASP solution of the Sokoban (also run using clingo)
- Unfortunately, the same **did not holds** for the CLP(FD) encoding (even if speed was not the real problem) which was our overall goal

Static Causal Laws as a (simple) constraint

`push(9, left, 3)` is forbidden (12 is not reachable from 4).

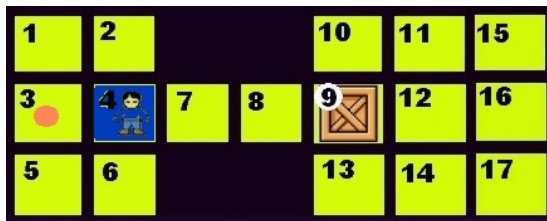


```
caused([sokoban_in(A)], reachable(A)) :-
    location(A).
```

```
caused([reachable(B), free(C)], reachable(C)) :-
    location(B), location(C),
    neq(B, C),
    step(B, D, C), direction(D).
```

Static Causal Laws as a (simple) constraint

`push(9, left, 3)` is forbidden (12 is not reachable from 4).

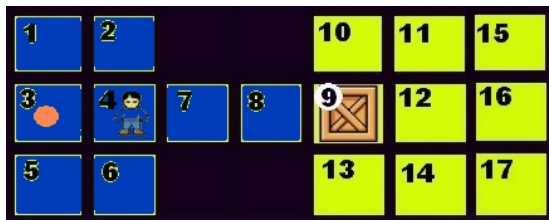


```
caused([sokoban_in(A)], reachable(A)) :-
    location(A).
```

```
caused([reachable(B), free(C)], reachable(C)) :-
    location(B), location(C),
    neq(B, C),
    step(B, D, C), direction(D).
```

Static Causal Laws as a (simple) constraint

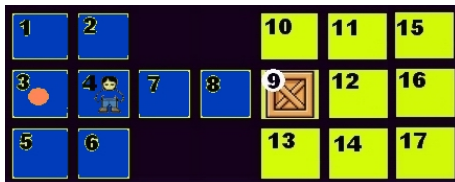
`push(9, left, 3)` is forbidden (12 is not reachable from 4).



```
caused([sokoban_in(A)], reachable(A)) :-
    location(A).
```

```
caused([reachable(B), free(C)], reachable(C)) :-
    location(B), location(C),
    neq(B, C),
    step(B, D, C), direction(D).
```

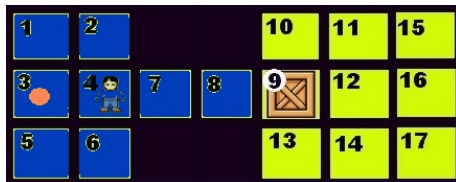

Static Causal Laws as a (simple) constraint



```
caused([reachable(B), free(C)], reachable(C)) :-
    location(B), location(C), neq(B, C),
    step(B, D, C), direction(D).
```

```
reachable(11) ∧ free(12) → reachable(12).
reachable(12) ∧ free(11) → reachable(11).
```

Static Causal Laws as a (simple) constraint

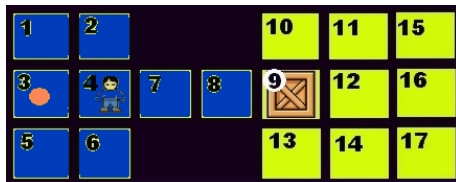


```

caused([reachable(B), free(C)], reachable(C)) :-
    location(B), location(C), neq(B, C),
    step(B, D, C), direction(D).
  
```

$\text{reachable}(11) \wedge \underline{\text{free}(12)} \rightarrow \text{reachable}(12).$
 $\text{reachable}(12) \wedge \underline{\text{free}(11)} \rightarrow \text{reachable}(11).$
 $\text{reachable}(11)$ and $\text{reachable}(12)$ both true is a solution (of the constraint).

Static Causal Laws as a (simple) constraint

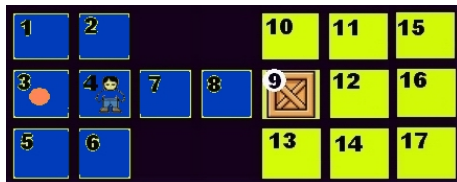


```
caused([reachable(B), free(C)], reachable(C)) :-
    location(B), location(C), neq(B, C),
    step(B, D, C), direction(D).
```

$\text{reachable}(11) \wedge \underline{\text{free}(12)} \rightarrow \text{reachable}(12).$
 $\text{reachable}(12) \wedge \underline{\text{free}(11)} \rightarrow \text{reachable}(11).$
 $\text{reachable}(11)$ and $\text{reachable}(12)$ both true is a solution (of the constraint).

This (loop) problem is correctly addressed by the ASP encoding.

Static Causal Laws as a (simple) constraint



```
caused([reachable(B), free(C)], reachable(C)) :-
    location(B), location(C), neq(B, C),
    step(B, D, C), direction(D).
```

$\text{reachable}(11) \wedge \underline{\text{free}(12)} \rightarrow \text{reachable}(12).$
 $\text{reachable}(12) \wedge \underline{\text{free}(11)} \rightarrow \text{reachable}(11).$
 $\text{reachable}(11)$ and $\text{reachable}(12)$ both true is a solution (of the constraint).

This (loop) problem is correctly addressed by the ASP encoding.
 A correct constraint encoding would introduce too many constraints
 (making the CLP(FD) interpreter too slow).

A solution (in B^{MV})

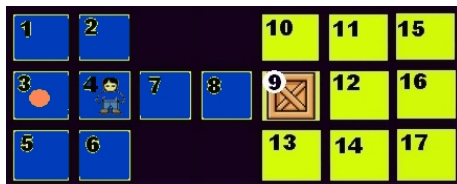
- Add the multivalued fluent `occupation(L)` with three values: 0 for free, 1 for sokoban, and 2 for a box
- For each location L , let L_1, \dots, L_{N_L} be the neighbor locations of L .
- M is a “big” number
- Post the constraints:

$$\text{occupation}(L) = 1 \rightarrow \text{reachable}(L) = 0$$

$$\text{occupation}(L) = 2 \rightarrow \text{reachable}(L) = M$$

$$\text{reachable}(L) = \min\{\text{reachable}(L_1) + 1, \dots, \text{reachable}(L_{N_L}) + 1, M\}$$

A solution



$\text{reachable}(4) = 0$

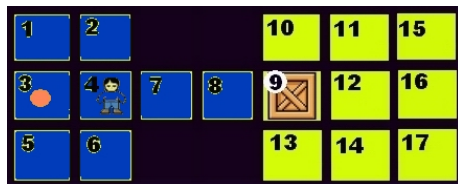
$\text{reachable}(2) = \text{reachable}(3) =$

$\text{reachable}(6) = \text{reachable}(7) = 1$

$\text{reachable}(1) = \text{reachable}(5) = \text{reachable}(8) = 2$

$\text{reachable}(9) = \text{reachable}(10) = \dots = \text{reachable}(17) = 20$

A solution



$\text{reachable}(4) = 0$

$\text{reachable}(2) = \text{reachable}(3) =$

$\text{reachable}(6) = \text{reachable}(7) = 1$

$\text{reachable}(1) = \text{reachable}(5) = \text{reachable}(8) = 2$

$\text{reachable}(9) = \text{reachable}(10) = \dots = \text{reachable}(17) = 20$

Unfortunately, this solution generates slow code.

Tabling

- Tabling has become a well-known and useful feature of many Prolog systems.
- The idea of tabling is to memorize answers to tabled subgoals and use the answers to resolve subsequent variant or subsumed subgoals.
- This idea resembles the dynamic programming idea of reusing solutions to overlapping sub-problems.

Tabling

- Tabling has become a well-known and useful feature of many Prolog systems.
- The idea of tabling is to memorize answers to tabled subgoals and use the answers to resolve subsequent variant or subsumed subgoals.
- This idea resembles the dynamic programming idea of reusing solutions to overlapping sub-problems.
- B-Prolog is a tabled Prolog system based on **linear tabling**, allows variant subgoals to share answers, and uses the local (lazy) strategy to return answers.

Tabling in B-Prolog

Fibonacci numbers

```
:-table fib/2.  
fib(0, 1).  
fib(1, 1).  
fib(N, F):-  
    N>1, N1 is N-1, N2 is N-2,  
    fib(N1, F1),    fib(N2, F2),  
    F is F1+F2.
```

Tabling in B-Prolog

Fibonacci numbers

```
:-table fib/2.  
fib(0, 1).  
fib(1, 1).  
fib(N, F):-  
    N>1, N1 is N-1, N2 is N-2,  
    fib(N1, F1),    fib(N2, F2),  
    F is F1+F2.
```

- **Without** tabling, the subgoal `fib(N, X)` would spawn 2^N subgoals, many of which are variants.

Tabling in B-Prolog

Fibonacci numbers

```
:-table fib/2.  
fib(0, 1).  
fib(1, 1).  
fib(N, F):-  
    N>1, N1 is N-1, N2 is N-2,  
    fib(N1, F1),    fib(N2, F2),  
    F is F1+F2.
```

- **Without** tabling, the subgoal `fib(N, X)` would spawn 2^N subgoals, many of which are variants.
- **With** tabling, the time complexity drops to linear since the same variant subgoal is resolved only once.

Tabling in B-Prolog

Modes

- B-Prolog allows **Mode-directed tabling**

`:-table p(M1, ..., Mn) : C.`

- C (optional), the *cardinality limit*, bounds the number of answers to be tabled for p ,
- Each M_i is a **mode**:
 - $+$ (input \longrightarrow usually ground)
 - $-$ (output \longrightarrow usually a variable)
 - `min` or `max` (optimized \longrightarrow output)
- Only one argument in a tabled predicate can have the mode `min` or `max`.

Tabling in B-Prolog

Shortest path (`sp`) in a weighted directed graph $X \xrightarrow{W} Y$

```
:-table sp(+,+,-,min) .
sp(X,Y,[(X,Y)],W) :-
    edge(X,Y,W) .
sp(X,Y,[(X,Z)|Path],W) :-
    edge(X,Z,W1),
    sp(Z,Y,Path,W2),
    W is W1+W2.
```

The predicate `sp(X,Y,Path,W)` states that `Path` is a path from `X` to `Y` with the smallest weight `W`.

Tabling in B-Prolog

Shortest path (`sp`) in a weighted directed graph $X \xrightarrow{W} Y$

```
:-table sp(+,+,-,min) .
sp(X,Y,[ (X,Y) ],W) :-
    edge(X,Y,W) .
sp(X,Y,[ (X,Z) |Path],W) :-
    edge(X,Z,W1) ,
    sp(Z,Y,Path,W2) ,
    W is W1+W2.
```

The predicate `sp(X,Y,Path,W)` states that `Path` is a path from `X` to `Y` with the smallest weight `W`.

For each pair of nodes, only one (shortest) answer is tabled!

The Sokoban program

- Neng-Fa's implementation of the Sokoban program is based on the just seen tabled definition of shortest path
- The overall code is very short and simple (as one might expect from Prolog programming)
- A little (actually very little) domain knowledge is added

The Sokoban program

```
:-table plan_sokoban(+,+,-,min).
plan_sokoban(_SokobanLoc,BoxLocs,Plan,Len):-
    goal_reached(BoxLocs),!,    Plan=[],Len=0.
plan_sokoban(SokobanLoc,BoxLocs,
    [push(BoxLoc,Dir,DestLoc)|Plan],Len):-
    select(BoxLoc,BoxLocs,BoxLocs1),
    step(PrevNeibLoc,Dir,BoxLoc),
    \+ member(PrevNeibLoc,BoxLocs1),
    step(BoxLoc,Dir,NextNeibLoc),
    good_dest(NextNeibLoc,BoxLocs1),
    reachable_by_sokoban(SokobanLoc,PrevNeibLoc,BoxLocs),
    choose_dest(BoxLoc,NextNeibLoc,Dir,
        DestLoc,NewSokobanLoc,BoxLocs1),
    insert_ordered(DestLoc,BoxLocs1,NewBoxLocs),
    plan_sokoban(NewSokobanLoc,NewBoxLocs,Plan,Len1),
    Len is Len1+1.
```

The Sokoban program

```
:-table reachable_by_sokoban/3.
reachable_by_sokoban(Loc, Loc, _BoxLocs) .
reachable_by_sokoban(Loc1, Loc2, BoxLocs) :-
    step(Loc1, _, Loc3) ,
    \+ member(Loc3, BoxLocs) ,
    reachable_by_sokoban(Loc3, Loc2, BoxLocs) .
```

```
choose_dest(Loc, NextLoc, _Dir, Dest, NewSokobanLoc, _BoxLocs) :-
    Dest=NextLoc, NewSokobanLoc=BoxLoc.
choose_dest(Loc, NextLoc, Dir, Dest, NewSokobanLoc, BoxLocs) :-
    step(NextLoc, Dir, NextNextLoc) ,
    good_dest(NextNextLoc, BoxLocs) ,
    choose_dest(NextLoc, NextNextLoc, Dir,
                Dest, NewSokobanLoc, BoxLocs) .
```

The Sokoban program

Domain Knowledge

```

good_dest (Loc, BoxLocs) :-
    \+ member (Loc, BoxLocs),
    (corner (Loc) -> storage (Loc); true),
    foreach (BoxLoc in BoxLocs, \+ stuck (BoxLoc, Loc)).
:-table stuck/2.
stuck (X, Y) :- (right (X, Y); right (Y, X)),
    (\+ storage (X); \+ storage (Y)),
    (\+ top (X, _), \+ top (Y, _);
    \+ top (_, X), \+ top (_, Y)), !.
stuck (X, Y) :- (top (X, Y); top (Y, X)),
    (\+ storage (X); \+ storage (Y)),
    (\+ right (X, _), \+ right (Y, _);
    \+ right (_, X), \+ right (_, Y)), !.

```

Two boxes constitute a deadlock if they are next to each other and both adjacent to a wall, unless both their locations are storage squares.

Competition results

CPU time, seconds

Instance	BPSolver	Clasp
1-sokoban-optimization-0-0.asp	0.58	0.06
13-sokoban-optimization-0-0.asp	0.06	0.74
18-sokoban-optimization-0-0.asp	0.00	9.80
20-sokoban-optimization-0-0.asp	33.57	13.24
24-sokoban-optimization-0-0.asp	2.66	3.52
27-sokoban-optimization-0-0.asp	0.78	1.16
29-sokoban-optimization-0-0.asp	0.78	2.92
33-sokoban-optimization-0-0.asp	1.96	26.74
37-sokoban-optimization-0-0.asp	0.38	8.52
4-sokoban-optimization-0-0.asp	Mem Out	0.62
43-sokoban-optimization-0-0.asp	Mem Out	35.67
45-sokoban-optimization-0-0.asp	Mem Out	9.30
47-sokoban-optimization-0-0.asp	Mem Out	18.66
5-sokoban-optimization-0-0.asp	0.00	0.16
9-sokoban-optimization-0-0.asp	0.00	2.12

Conclusions

- We have played with the Sokoban game using several Logic Programming tools

Conclusions

- We have played with the Sokoban game using several Logic Programming tools
- It was funny

Conclusions

- We have played with the Sokoban game using several Logic Programming tools
- It was funny
- Direct ASP (or B translated to ASP) works
- B interpreted by CLP(FD) does not work correctly (but we are now developing and exploiting a special **reachability** global constraint)

Conclusions

- We have played with the Sokoban game using several Logic Programming tools
- It was funny
- Direct ASP (or B translated to ASP) works
- B interpreted by CLP(FD) does not work correctly (but we are now developing and exploiting a special **reachability** global constraint)
- Tabled B-Prolog works (even if there are still some memory problems to cope with)
- Adding knowledge, of course, helps