NUXMV: Planning as Model Checking *

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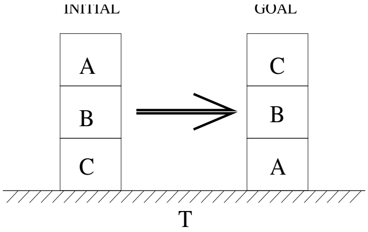
Planning Problem

- **Planning Problem:** given $\langle I, G, T \rangle$, where
  - **I**: (representation of) initial state
  - **G**: (representation of) goal state
  - **T**: transition relation

  find a sequence of transitions $t_1, ..., t_n$ leading from the initial state to the goal state.
- Idea: encode planning problem as model checking problem



$$
\begin{array}{ll}
Init: & On(A,B), On(B,C), On(C,T), Clear(A) \\
Goal: & On(C,B), On(B,A), On(A,T) \\
Move(a,b,c) & \\
\quad Precond: & Block(a) \land Clear(a) \land On(a,b) \land \\
 & (Clear(c) \lor Table(c)) \land \\
 & a \neq b \land a \neq c \land b \neq c \\
\quad Effect: & Clear(b) \land \neg On(a,b) \land \\
 & On(a,c) \land \neg Clear(c)
\end{array}
$$

Example: blocks [2/8]

```
MODULE block(id, ab, bl)
VAR
  above : {none, a, b, c}; -- the block above this one
  below : {none, a, b, c}; -- the block below this one
DEFINE
  clear := (above = none);
INIT
  above = ab &
  below = bl
INVAR
  below != id & above != id -- a block can't be above or below itself


MODULE main
VAR
  move : {move_a, move_b, move_c}; -- at each step only one block moves
  block_a : block(a, none, b);
  block_b : block(b, a, c);
  block_c : block(c, b, none);
...
```

Example: blocks [3/8]

- a block can not move only if it has some block above itself

```
...
TRANS
  (!block_a.clear -> move != move_a) &
  (!block_b.clear -> move != move_b) &
  (!block_c.clear -> move != move_c)
...
```

Example: blocks [3/8]

- a block can not move only if it has some block above itself

```
...
TRANS
  (!block_a.clear -> move != move_a) &
  (!block_b.clear -> move != move_b) &
  (!block_c.clear -> move != move_c)
...
```

- **Q:** what's wrong with following formulation?

```
...
TRANS
  (block_a.clear -> move = move_a) &
  (block_b.clear -> move = move_b) &
  (block_c.clear -> move = move_c)
...
```

Example: blocks [3/8]

- a block can not move only if it has some block above itself

```
...
TRANS
  (!block_a.clear -> move != move_a) &
  (!block_b.clear -> move != move_b) &
  (!block_c.clear -> move != move_c)
...
```

- **Q:** what's wrong with following formulation?

```
...
TRANS
  (block_a.clear -> move = move_a) &
  (block_b.clear -> move = move_b) &
  (block_c.clear -> move = move_c)
...
```

A:

- any `non-clear` `block` would still be able to `move`
- `move` can only have **one** valid value $\Longrightarrow$ inconsistency whenever there are two clear blocks at the same time

Example: blocks [4/8]

- a `moving` `block` changes location and remains clear

```
TRANS
  (move = move_a -> next(block_a.clear) &
                    next(block_a.below) != block_a.below) &
  (move = move_b -> next(block_b.clear) &
                    next(block_b.below) != block_b.below) &
  (move = move_c -> next(block_c.clear) &
                    next(block_c.below) != block_c.below)
```

- a `non-moving` `block` does not change its location

```
TRANS
  (move != move_a -> next(block_a.below) = block_a.below) &
  (move != move_b -> next(block_b.below) = block_b.below) &
  (move != move_c -> next(block_c.below) = block_c.below)
```

Example: blocks [5/8]

- a `block` remains connected to any `non-moving` block

```
TRANS
  (move != move_a & block_b.above = a
                  -> next(block_b.above) = a) &
  (move != move_a & block_c.above = a
                  -> next(block_c.above) = a) &
  (move != move_b & block_a.above = b
                  -> next(block_a.above) = b) &
  (move != move_b & block_c.above = b
                  -> next(block_c.above) = b) &
  (move != move_c & block_a.above = c
                  -> next(block_a.above) = c) &
  (move != move_c & block_b.above = c
                  -> next(block_b.above) = c)
```

Example: blocks [5/8]

- a `block` remains connected to any `non-moving` block

```
TRANS
  (move != move_a & block_b.above = a
                    -> next(block_b.above) = a) &
  (move != move_a & block_c.above = a
                    -> next(block_c.above) = a) &
  (move != move_b & block_a.above = b
                    -> next(block_a.above) = b) &
  (move != move_b & block_c.above = b
                    -> next(block_c.above) = b) &
  (move != move_c & block_a.above = c
                    -> next(block_a.above) = c) &
  (move != move_c & block_b.above = c
                    -> next(block_b.above) = c)
```

- **Q:** what about “below block”?

Example: blocks [5/8]

- a `block` remains connected to any `non-moving` block

```
TRANS
  (move != move_a & block_b.above = a
                    -> next(block_b.above) = a) &
  (move != move_a & block_c.above = a
                    -> next(block_c.above) = a) &
  (move != move_b & block_a.above = b
                    -> next(block_a.above) = b) &
  (move != move_b & block_c.above = b
                    -> next(block_c.above) = b) &
  (move != move_c & block_a.above = c
                    -> next(block_a.above) = c) &
  (move != move_c & block_b.above = c
                    -> next(block_b.above) = c)
```

- **Q:** what about "below block"?
  A: covered in previous slide!

Example: blocks [6/8]

- positioning of blocks is simmetric

```
INVAR
  (block_a.above = b <-> block_b.below = a)
& (block_a.above = c <-> block_c.below = a)
& (block_b.above = a <-> block_a.below = b)
& (block_b.above = c <-> block_c.below = b)
& (block_c.above = a <-> block_a.below = c)
& (block_c.above = b <-> block_b.below = c)

& (block_a.above = none -> (block_b.below != a & block_c.below != a))
& (block_b.above = none -> (block_a.below != b & block_c.below != b))
& (block_c.above = none -> (block_a.below != c & block_b.below != c))

& (block_a.below = none -> (block_b.above != a & block_c.above != a))
& (block_b.below = none -> (block_a.above != b & block_c.above != b))
& (block_c.below = none -> (block_a.above != c & block_b.above != c))
```

Example: blocks [7/8]

Remark: a **plan** is a sequence of transition leading the initial state to an accepting state

Idea:

- assert property *p*: "goal state is not reachable"
- if a plan exists, NUXMV produces a counterexample for *p*
- the counterexample for *p* is a plan to reach the goal

Example: blocks [7/8]

Remark: a **plan** is a sequence of transition leading the initial state to an accepting state

Idea:

- assert property p: "goal state is not reachable"
- if a plan exists, NUXMV produces a counterexample for p
- the counterexample for p is a plan to reach the goal

Examples:

- get a plan for reaching "goal state"

```
SPEC
  !EF(block_a.below = none & block_a.above = b & block_b.below = a &
      block_b.above = c & block_c.below = b & block_c.above = none)
```

Example: blocks [7/8]

Remark: a **plan** is a sequence of transition leading the initial state to an accepting state

Idea:

- assert property p: "goal state is not reachable"
- if a plan exists, nuXmv produces a counterexample for p
- the counterexample for p is a plan to reach the goal

Examples:

- get a plan for reaching "goal state"

```
SPEC
  !EF(block_a.below = none & block_a.above = b & block_b.below = a &
      block_b.above = c & block_c.below = b & block_c.above = none)
```

- get a plan for reaching a configuration in which all blocks are placed on the table

```
SPEC
  !EF(block_a.below = none & block_b.below = none &
      block_c.below = none)
```

Example: blocks [8/8]

- at any given time, at least one block is placed on the table

```
INVARSPEC
  block_a.below = none | block_b.below = none | block_c.below = none
```

Example: blocks [8/8]

- at any given time, at least one block is placed on the table

```
INVARSPEC
  block_a.below = none | block_b.below = none | block_c.below = none
```

- at any given time, at least one block has nothing above

```
INVARSPEC
  block_a.above = none | block_b.above = none | block_c.above = none
```

Example: blocks [8/8]

- at any given time, at least one block is placed on the table

```
INVARSPEC
  block_a.below = none | block_b.below = none | block_c.below = none
```

- at any given time, at least one block has nothing above

```
INVARSPEC
  block_a.above = none | block_b.above = none | block_c.above = none
```

- we can always reach a configuration in which all nodes are placed on the table

```
SPEC
  AG EF (block_a.below = none & block_b.below = none &
         block_c.below = none)
```

Example: blocks [8/8]

- at any given time, at least one block is placed on the table

```
INVARSPEC
  block_a.below = none | block_b.below = none | block_c.below = none
```

- at any given time, at least one block has nothing above

```
INVARSPEC
  block_a.above = none | block_b.above = none | block_c.above = none
```

- we can always reach a configuration in which all nodes are placed on the table

```
SPEC
  AG EF (block_a.below = none & block_b.below = none &
         block_c.below = none)
```

- we can always reach the goal state

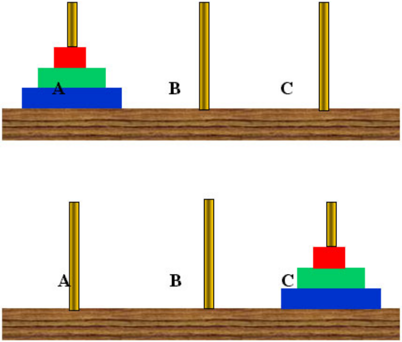
```
SPEC
  AG EF(block_a.below = none & block_a.above = b &
        block_b.below = a & block_b.above = c &
        block_c.below = b & block_c.above = none)
```

Contents

Example: tower of hanoi [1/4]

Game with 3 `poles` and N `disks` of different sizes:

- **initial state:** stack of disks with decreasing size on pole A
- **goal state:** move stack on pole C
- **rules:**
  - only one disk may be moved at each transition
  - only the upper disk can be moved
  - a disk can not be placed on top of a smaller disk



Example: tower of hanoi [2/4]

- base system model

```
MODULE main
VAR
  d1 : {left,middle,right}; -- largest
  d2 : {left,middle,right};
  d3 : {left,middle,right};
  d4 : {left,middle,right}; -- smallest
  move : 1..4; -- possible moves
```

Example: tower of hanoi [2/4]

- base system model

```
MODULE main
VAR
  d1 : {left,middle,right}; -- largest
  d2 : {left,middle,right};
  d3 : {left,middle,right};
  d4 : {left,middle,right}; -- smallest
  move : 1..4; -- possible moves
```

- disk *i* is moving

```
DEFINE
  move_d1 := (move = 1);
  move_d2 := (move = 2);
  move_d3 := (move = 3);
  move_d4 := (move = 4);
...
```

Example: tower of hanoi [2/4]

- base system model

```
MODULE main
VAR
  d1 : {left,middle,right}; -- largest
  d2 : {left,middle,right};
  d3 : {left,middle,right};
  d4 : {left,middle,right}; -- smallest
  move : 1..4; -- possible moves
```

- disk i is moving

```
DEFINE
  move_d1 := (move = 1);
  move_d2 := (move = 2);
  move_d3 := (move = 3);
  move_d4 := (move = 4);
...
```

- disk d_i can move iff $\forall j > i . d_i \neq d_j$

```
  clear_d1 := (d1!=d2 & d1!=d3 & d1!=d4);
  clear_d2 := (d2!=d3 & d2!=d4);
  clear_d3 := (d3!=d4);
  clear_d4 := TRUE;
```

Example: tower of hanoi [3/4]

- initial state

```
INIT
  d1 = left &
  d2 = left &
  d3 = left &
  d4 = left;
```

Example: tower of hanoi [3/4]

- initial state

```
INIT
  d1 = left &
  d2 = left &
  d3 = left &
  d4 = left;
```

- move description for disk 1

```
TRANS
  move_d1 ->
    -- disks location changes
    next(d1) != d1 &
    next(d2) = d2 &
    next(d3) = d3 &
    next(d4) = d4 &
    -- d1 can move only if it is clear
    clear_d1 &
    -- d1 can not move on top of smaller disks
    next(d1) != d2 &
    next(d1) != d3 &
    next(d1) != d4
```

Example: tower of hanoi [4/4]

- get a plan for reaching "goal state"

```
SPEC
  ! EF (d1=right & d2=right & d3=right & d4=right)
```

Example: tower of hanoi [4/4]

- get a plan for reaching “goal state”

```
SPEC
  ! EF (d1=right & d2=right & d3=right & d4=right)
```

- NUXMV execution:

```
nuXmv > read_model -i hanoi.smv
nuXmv > go
nuXmv > check_ctlspec
-- specification !(EF (((d1 = right & d2 = right) & d3 = right)
                        & d4 = right))  is false
-- as demonstrated by the following execution sequence
Trace Description: CTL Counterexample
  -> State: 2.1 <-
    d1 = left
    d2 = left
    d3 = left
    d4 = left
...
```

Example: ferryman [1/4]

A ferryman has to bring a sheep, a cabbage, and a wolf safely across a river.

- **initial state:** all animals are on the right side
- **goal state:** all animals are on the left side
- **rules:**
  - the ferryman can cross the river with at most one passenger on his boat
  - the cabbage and the sheep can not be left unattended on the same side of the river
  - the sheep and the wolf can not be left unattended on the same side of the river

Q: can the ferryman transport all the goods to the other side safely?

Example: ferryman [2/4]

- base system model

```
MODULE main
VAR
  cabbage : {right,left};
  sheep   : {right,left};
  wolf    : {right,left};
  man     : {right,left};
  move    : {c, s, w, e}; -- possible moves

DEFINE
  carry_cabbage := (move = c);
  carry_sheep   := (move = s);
  carry_wolf    := (move = w);
  no_carry      := (move = e);
```

Example: ferryman [2/4]

- base system model

```
MODULE main
VAR
  cabbage : {right,left};
  sheep   : {right,left};
  wolf    : {right,left};
  man     : {right,left};
  move    : {c, s, w, e}; -- possible moves

DEFINE
  carry_cabbage := (move = c);
  carry_sheep   := (move = s);
  carry_wolf    := (move = w);
  no_carry      := (move = e);
```

- initial state

```
ASSIGN
  init(cabbage) := right;
  init(sheep)   := right;
  init(wolf)    := right;
  init(man)     := right;
```

Example: ferryman [3/4]

- ferryman carries cabbage

```
TRANS
  carry_cabbage ->
    cabbage = man &
    next(cabbage) != cabbage &
    next(man) != man &
    next(sheep) = sheep &
    next(wolf) = wolf
```

Example: ferryman [3/4]

- ferryman carries cabbage

```
TRANS
  carry_cabbage ->
    cabbage = man &
    next(cabbage) != cabbage &
    next(man) != man &
    next(sheep) = sheep &
    next(wolf) = wolf
```

- ferryman carries sheep

```
TRANS
  carry_sheep ->
    sheep = man &
    next(sheep) != sheep &
    next(man) != man &
    next(cabbage) = cabbage &
    next(wolf) = wolf
```

Example: ferryman [3/4]

- ferryman carries cabbage

```
TRANS
  carry_cabbage ->
    cabbage = man &
    next(cabbage) != cabbage &
    next(man) != man &
    next(sheep) = sheep &
    next(wolf) = wolf
```

- ferryman carries sheep

```
TRANS
  carry_sheep ->
    sheep = man &
    next(sheep) != sheep &
    next(man) != man &
    next(cabbage) = cabbage &
    next(wolf) = wolf
```

- ferryman carries wolf

```
TRANS
  carry_wolf ->
    wolf = man &
    next(wolf) != wolf &
    next(man) != man &
    next(sheep) = sheep &
    next(cabbage) = cabbage
```

Example: ferryman [3/4]

- ferryman carries cabbage

```
TRANS
  carry_cabbage ->
    cabbage = man &
    next(cabbage) != cabbage &
    next(man) != man &
    next(sheep) = sheep &
    next(wolf) = wolf
```

- ferryman carries sheep

```
TRANS
  carry_sheep ->
    sheep = man &
    next(sheep) != sheep &
    next(man) != man &
    next(cabbage) = cabbage &
    next(wolf) = wolf
```

- ferryman carries wolf

```
TRANS
  carry_wolf ->
    wolf = man &
    next(wolf) != wolf &
    next(man) != man &
    next(sheep) = sheep &
    next(cabbage) = cabbage
```

- ferryman carries nothing

```
TRANS
  no_carry ->
    next(man) != man &
    next(sheep) = sheep &
    next(cabbage) = cabbage &
    next(wolf) = wolf
```

Example: ferryman [4/4]

- get a plan for reaching "goal state"

```
DEFINE
  safe_state := (sheep = wolf | sheep = cabbage) -> sheep = man;
  goal := cabbage = left & sheep = left & wolf = left;

SPEC
  ! E[safe_state U goal]
```

Example: ferryman [4/4]

- get a plan for reaching "goal state"

```
DEFINE
  safe_state := (sheep = wolf | sheep = cabbage) -> sheep = man;
  goal := cabbage = left & sheep = left & wolf = left;

SPEC
  ! E[safe_state U goal]
```

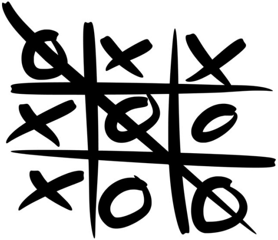
- NUXMV execution:

```
nuXmv > read_model -i ferryman.smv
nuXmv > go
nuXmv > check_ctlspec
-- specification !E [ safe_state U goal ]   is false
-- as demonstrated by the following execution sequence
  -> State: 1.1 <-
    cabbage = right
    sheep = right
    wolf = right
    man = right
...
```

Example: tic-tac-toe [1/5]

Tic-tac-toe is a turn-based game for two adversarial players (X and O) marking the squares of a board ($\rightarrow$ a 3×3 grid). The player who succeeds in placing three respective marks in a horizontal, vertical or diagonal row wins the game.

- Example: `O` wins



- we model tic-tac-toe puzzle as an array of size nine

```
  1 | 2 | 3
____|___|____
  4 | 5 | 6
____|___|____
  7 | 8 | 9
    |   |
```

Example: tic-tac-toe [2/5]

- base system model

```
MODULE main
VAR
  B : array 1..9 of {0,1,2};
  player : 1..2;
  move : 0..9;
```

Example: tic-tac-toe [2/5]

- base system model

```
MODULE main
VAR
  B : array 1..9 of {0,1,2};
  player : 1..2;
  move : 0..9;
```

- initial state

```
INIT
  B[1] = 0 &
  B[2] = 0 &
  B[3] = 0 &
  B[4] = 0 &
  B[5] = 0 &
  B[6] = 0 &
  B[7] = 0 &
  B[8] = 0 &
  B[9] = 0;
INIT
  move = 0;
```

Example: tic-tac-toe [3/5]

- turns modeling

```
ASSIGN
  init(player) := 1;
  next(player) :=
    case
      player = 1 : 2;
      player = 2 : 1;
    esac;
```

Example: tic-tac-toe [3/5]

- turns modeling

```
ASSIGN
  init(player) := 1;
  next(player) :=
    case
      player = 1 : 2;
      player = 2 : 1;
    esac;
```

- move modeling

```
TRANS
  next(move=1) ->
    B[1] = 0 & next(B[1]) = player &
    next(B[2])=B[2] &
    next(B[3])=B[3] &
    next(B[4])=B[4] &
    next(B[5])=B[5] &
    next(B[6])=B[6] &
    next(B[7])=B[7] &
    next(B[8])=B[8] &
    next(B[9])=B[9]
```

Example: tic-tac-toe [4/5]

- "end" state

```
DEFINE
  win1 := (B[1]=1 & B[2]=1 & B[3]=1) | (B[4]=1 & B[5]=1 & B[6]=1) |
          (B[7]=1 & B[8]=1 & B[9]=1) | (B[1]=1 & B[4]=1 & B[7]=1) |
          (B[2]=1 & B[5]=1 & B[8]=1) | (B[3]=1 & B[6]=1 & B[9]=1) |
          (B[1]=1 & B[5]=1 & B[9]=1) | (B[3]=1 & B[5]=1 & B[7]=1);

  win2 := (B[1]=2 & B[2]=2 & B[3]=2) | (B[4]=2 & B[5]=2 & B[6]=2) |
          (B[7]=2 & B[8]=2 & B[9]=2) | (B[1]=2 & B[4]=2 & B[7]=2) |
          (B[2]=2 & B[5]=2 & B[8]=2) | (B[3]=2 & B[6]=2 & B[9]=2) |
          (B[1]=2 & B[5]=2 & B[9]=2) | (B[3]=2 & B[5]=2 & B[7]=2);

  draw := !win1 & !win2 &
          B[1]!=0 & B[2]!=0 & B[3]!=0 & B[4]!=0 &
          B[5]!=0 & B[6]!=0 & B[7]!=0 & B[8]!=0 & B[9]!=0;

TRANS
  (win1 | win2 | draw) <-> next(move)=0
```

Example: tic-tac-toe [5/5]

A **strategy** is a plan that need to be accomplished for winning the game "if the opponent has two in a row, play the third to block them"

- player 2 does not have a "winning" strategy
  ```
  SPEC
    ! (AX (EX (AX (EX (AX (EX (AX (EX (AX win2)))))))))
  ```
- player 2 has a "non-losing" strategy
  ```
  SPEC
    AX (EX (AX (EX (AX (EX (AX (EX (AX !win1))))))))
  ```

Verification:

```
nuXmv > read_model -i tictactoe.smv
nuXmv > go
nuXmv > check_ctlspec
-- specification !(AX (EX (AX (EX (AX (EX
                  (AX (EX (AX win2)))))))))  is true
-- specification AX (EX (AX (EX (AX (EX
                  (AX (EX (AX !win1))))))))  is true
```

Exercises [1/2]

- Tower of Hanoi: extend the tower of hanoi to handle five disks, and check that the goal state is reachable.

- Ferryman: another ferryman has to bring a fox, a chicken, a caterpillar and a crop of lettuce safely across a river.
  - **initial state:** all goods are on the right side
  - **goal state:** all goods are on the left side
  - **rules:**
    - the ferryman can cross the river with at most **two** passengers on his boat
    - the fox eats the chicken if left unattended on the same side of the river
    - the chicken eats the caterpillar if left unattended on the same side of the river
    - the caterpillar eats the lettuce if left unattended on the same side of the river

Can the ferryman bring every item safely on the other side?

Exercises [2/2]

- Tic-Tac-Toe: encode and verify the following properties
  - player 2 has also a "non-winning" strategy
  - player 2 does not have a "losing" strategy
  - player 2 does not have a "drawing" strategy
  - player 2 has a "non-drawing" strategy
  - player 1 does not have a "winning" strategy
  - player 1 has a "non-losing" strategy
  - player 1 has also a "non-winning" strategy
  - player 1 does not have a "losing" strategy
  - player 1 does not have a "drawing" strategy
  - player 1 has a "non-drawing" strategy