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Sudoku in Coq

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Abstract

This note presents a formalisation done in COQ of Sudoku. We formalise what is a Sudoku, a Sudoku checker and a Sudoku solver. The Sudoku solver uses a naive Davis-Putnam procedure.

1 The Grid

The grid is parametrised by two integers h and w . It is composed of hw subrectangles, each rectangle is composed of h lines and w columns. If we take $h = 3$ and $w = 3$, we get the usual grid composed of 9 subsquares.

We are going to formalize the grid as a list of integers. In order to express what rows, columns, subrectangles are, we first need to have some basic list operations. The function `take` takes the `n` first elements of a list `l`.

```
Fixpoint take (n: nat) (l: list A) : list A :=
match l with
  nil => nil
| a::l1 =>
  match n with
    0 => nil
  | S n1 => a:: take n1 l1
  end
end.
```

The function `jump` skips the first `n` elements of a list `l`.

```

Fixpoint jump (n: nat) (l: list A) : list A :=
match l with
  nil => nil
| a::l1 => match n with 0 => l | S n1 => jump n1 l1 end
end.

```

The function `take_and_jump` takes the `t` first elements then skips `j` elements and repeats this `n` times.

```

Fixpoint take_and_jump (t j n: nat) (l: list A) : list A :=
  match n with
    0 => nil
  | S n1 => take t l ++ take_and_jump t j n1 (jump j l)
  end.

```

Now we are ready to consider an arbitrary grid. We take `h` as the number of rows of a subrectangle and `w` as the number of columns of a subrectangle. So a subrectangle contains exactly `size` cells.

```

Variable h w: nat.
Definition size := h * w.

```

In a grid, there are `size` rows. The function `row` returns the row number `i`.

```

Definition row i (l: list nat) := take size (jump (i * size) l).

```

The function `column` returns the column number `i`.

```

Definition column i (l: list nat) :=
  take_and_jump 1 size size (jump i l).

```

The function `rect` returns the subrectangle number `i`.

```

Definition rect i (l: list nat) :=
  take_and_jump w size h
    (jump (w * (mod i h) + h * (div i h) * size) l).

```

In the list that represents the grid, we take the convention that the integer 0 indicates an empty cell. We define the list `ref_list` that contains all the possible values of a cell: 1, 2, ..., `size`.

```

Fixpoint progression (n m: nat) : list nat :=
  match n with 0 => nil | S n1 => m :: progression n1 (S m) end.

```

```

Definition ref_list := progression size 1.

```

2 The Sudoku

A way to define what is a Sudoku is to use the notion of `permutation`.

```
Inductive permutation : list A -> list A -> Prop :=
| permutation_nil: permutation nil nil
| permutation_skip: forall a l1 l2,
    permutation l2 l1 -> permutation (a :: l2) (a :: l1)
| permutation_swap: forall a b l,
    permutation (a :: b :: l) (b :: a :: l)
| permutation_trans: forall l1 l2 l3,
    permutation l1 l2 -> permutation l2 l3 -> permutation l1 l3.
```

A list of integers is a Sudoku if it has the right length, each of its rows is a permutation of `ref_list`, each of its columns is a permutation of `ref_list` and each of its subrectangles is a permutation of `ref_list`.

```
Definition sudoku l :=
  length l = size * size /\
  (forall i, i < size -> permutation (row i l) ref_list) /\
  (forall i, i < size -> permutation (column i l) ref_list) /\
  (forall i, i < size -> permutation (rect i l) ref_list).
```

3 The Sudoku checker

We can easily decide if a list is a permutation of another one with the function `permutation_dec1`.

```
Definition permutation_dec1 :
  (forall a b : A, {a = b} + {a <> b}) ->
  forall l1 l2, {permutation l1 l2} + {~ permutation l1 l2}.
```

It follows that we can define a Sudoku checker.

```
Definition check: forall l, {sudoku l} + {~sudoku l}.
```

4 The Sudoku solver

In order to solve Sudoku, we are going to translate the problem into a constraint problem and use a Davis-Putnam procedure [1] to solve it.

4.1 Positions, literals, clause and clauses

Positions

A literal represents the fact that a given cell contains a given value. We first define the type `pos` for positions.

```
Inductive pos: Set := Pos (x: nat) (y: nat).
```

Positions starts at (0,0) till (size-1, size-1). A position is valid if it is inside the grid.

```
Definition valid_pos (p: pos) := let (x,y) := p in  
  x < size /\ y < size.
```

To enumerate all the positions in a left-right top-down manner, we use the function `next`.

```
Definition next (p: pos) := let (x,y) := pos in  
  if eq_nat (S y) size then Pos (S x) 0 else Pos x (S y).
```

We can turn a position into its index in the list that represents the grid with the function `pos2n`

```
Definition pos2n (p: pos) := let (x,y) := p in x * size + y.
```

The function `get` retrieves from the list `s` that represents the grid the value inside the cell at position `p`

```
Definition get p l := nth 0 (jump (pos2n p) l) 0.
```

The function `update` puts inside the cell at position `p` the value `v`.

```
Fixpoint subst (n: nat) (v: A) (l: list A) : list A :=  
  match l with  
  | nil => nil  
  | a :: l1 =>  
    match n with 0 => L :: l1 | S n1 => a :: subst n1 L l1 end  
end.
```

```
Definition update p L (l: list nat) := subst (pos2n p) L l.
```

Literals

A literal is composed of a position and a value.

```
Inductive lit: Set := L (p: pos) (v: nat).
```

Clause

A clause is a disjunction of literals. It is represented as a list. A clause is satisfied if and only if at least one of its literals is satisfied,

Definition `clause := list lit`.

We provide some operations to manipulate clauses. The function `lit_is_in` checks if a literal is in a clause.

Definition `lit_is_in: lit -> clause -> bool`.

The function `lit_insert` adds a literal inside a clause.

Definition `lit_insert: lit -> clause -> clause`.

The function `lit_rm` removes from `c2` all the literals that occur in `c1`.

Definition `lit_rm (c1 c2: clause): clause`.

The function `clause_merge` appends all the literals in `c1` and `c2`.

Definition `clause_merge (c1 c2: clause): clause`.

Clauses

The problem to solve is a conjunction of clauses. The conjunction is represented as a list. To solve the problem, we need to satisfy each clause, i.e. we need to satisfy at least one literal in each clause.

Definition `clauses := list (nat * clause)`.

The integer associated to each clause represents the length of the clause, i.e. the number of literals in the clause. This integer is used to sort the list. Clauses with few literals are on top of the list. The function `clause_insert` adds a clause in the list of clauses.

Definition `clause_insert: clause -> clauses -> clauses`.

The function `clause_merge` appends two lists of clauses.

Definition `clauses_merge: clauses -> clauses -> clauses`.

The key function for manipulating clauses is the function `clauses_update`. It is used to update the list of clauses removing from the list all the clauses that contain the literal `l` and removing from each clause in the list all the literals that occur in `c`.

```

Fixpoint clauses_update (l: lit) (c: list lit) (cs: clauses)
{struct cs}: clauses :=
match cs with
nil => nil
| (n , c1) :: cs1 =>
  if lit_is_in l c1 then clauses_update l c cs1 else
  let res := lit_rm c c1 in
  clause_insert res (clauses_update l c cs1)
end.

```

This function is called to update the list of constraints when a new fact is known. The literal `l` is this new fact we know to hold (for example the cell (1, 2) contains 3). The list of literals `c` contains the facts we know not to hold (for example the cell (1, 2) does not contain 1, the cell (1, 2) does not contain 2, the cell (1, 2) does not contain 4, ...).

4.2 Generating problem constraints

In order to generate constraints, we need some list. The list `indexes` contains all the possible index for a position from 0 to `size`-1.

Definition `indexes := progression size 0`.

The list `cross` contains all the position (x,y) with $0 \leq x < h$ and $0 \leq y < w$.

```

Definition cross :=
  let p := progression h 0 in
  let q := progression w 0 in
  fold_right (fun x l => (map (fun y => (Pos x y)) q) ++ l) nil p.

```

The list `cross1` contains all the pairs (x,y) with $0 \leq x < \text{size}$ and $1 \leq y \leq \text{size}$.

```

Definition cross1 :=
  let p := indexes in
  let q := ref_list in
  fold_right (fun x l => (map (fun y => (x, y)) q) ++ l) nil p.

```

The function `gen_row` generates the constraints that the row number `i` contains the value `z`.

```

Definition gen_row i z :=
  fold_right (fun y l => lit_insert (L (Pos i y) z) l) nil indexes.

```

The function `gen_column` generates the constraints that the column number `i` contains the value `z`.

```
Definition gen_column i z :=
  fold_right (fun x l => lit_insert (L (Pos x i) z) l) nil indexes.
```

The function `gen_rect` generates the constraints that the subrectangle number `i` contains the value `z`.

```
Definition gen_rect i z :=
  let x := h * div i h in
  let y := w * mod i h in
  fold_right (fun p l => lit_insert (L (shift p x y) z) l)
    nil cross.
```

where `div` and `mod` are the division and the modulo respectively. The function `gen_cell` generates the constraints that the cell at position `p` contains a value.

```
Definition gen_cell p :=
  fold_right (fun z l => lit_insert (L p z) l) nil ref_list.
```

The function `all_cell` generates the constraint that all the cells of the grid contain a value.

```
Definition all_cell :=
  let c0 := cross2 in
  (fold_right (fun p l => let res := gen_cell p in
    clause_insert res l) nil c0).
```

5 Generating complement literals

To speed up the search, when we have a new fact, we not only remove all the clauses that contains the corresponding literals but we also simplify clauses removing the literals that cannot hold. Computing from a known fact the list of fact that cannot hold is done by the function `anti_literals`.

```
Definition anti_literals (l: lit) :=
  let c := l :: nil in
  let (p, v) := l in
  let (x, y) := p in
```



```

clause_merge (lit_rm c (gen_row x v))
  (clause_merge (lit_rm c (gen_column y v))
    (clause_merge (lit_rm c (gen_rect ((div x h) * h + (div y w)) v))
      (lit_rm c (gen_cell p))))).

```

6 Generating the initial constraints

To generate the initial constraints, we just accumulate the clauses that each number appears in each row, each number appears in each column, each number appears in each subrectangle and finally each cell contains a value.

```

Definition init_c :=
  let c1 := cross1 in
  fold_right
    (fun iz l => let res := gen_row (fst iz) (snd iz) in
      clause_insert res l)
  (fold_right
    (fun iz l => let res := gen_column (fst iz) (snd iz) in
      clause_insert res l)
  (fold_right
    (fun iz l => let res := gen_rect (fst iz) (snd iz) in
      clause_insert res l)
  all_cell c1) c1) c1.

```

These constraints are redundant but most importantly a list that satisfies these constraints is a Sudoku. Note that the initial constraint only ensures that the list `ref_list` is included in each row, each column and subrectangle. It is sufficient because the list `ref_list` is composed of unique elements.

```

Inductive uelist : list A -> Prop :=
  uelist_nil: uelist nil
  | uelist_cons: forall a l, ~ In a l -> uelist l -> uelist (a :: l) .

```

```

Theorem ref_list_uelist : uelist ref_list.

```

So we can apply a derived version of the pigeon-hole principle.

```

Theorem uelist_eq_permutation: forall (l1 l2 : list A), uelist l1 ->
  incl l1 l2 -> length l1 = length l2 -> permutation l1 l2.

```

where `incl` is the inclusion predicate.

Before starting the search, we first have to simplify the list of clauses with all the information that is present in the initial grid. This is done by the function `gen_init_clauses_aux` that walks through the initial grid `s` and updates the list of clauses `c`. The argument `p` contains the actual position of the element of the list `s` we are considering.

```
Fixpoint gen_init_clauses_aux (s: list nat) (p: pos) (c: clauses):
  clauses :=
  match s with
  | nil => c
  | a :: s1 =>
    let p1 := next p in
    let ll := L p a in
    if (In_dec eq_nat a ref_list) then
      let c1 := clauses_update ll (anti_literals ll) c in
      gen_init_clauses_aux s1 p1 c1
    else gen_init_clauses_aux s1 p1 c
  end.
```

The main function is `gen_init_clauses`.

```
Definition gen_init_clauses s :=
  gen_init_clauses_aux s (Pos 0 0) init_c.
```

7 Finding one solution

To organize the search for a solution, we have to deal with Coq's restriction that only structural recursive schemas can be used in function definitions. The first function we write is the function `try_one` that given the current state of the Sudoku and the list of constraints `cs` tries to satisfies the clause `c`. For this, it picks a literal of `c`, supposes it holds and calls the continuation `f` to check if the result is satisfiable. If so, it returns the solution, otherwise it tries the next literal.

```
Fixpoint try_one (s: list nat) (c: clause)
  (cs: clauses)
  (f: list nat -> clauses -> option (list nat))
  {struct c}:
  option (list nat) :=
  match c with
```

```

    nil => None
  | (L p v) as k:: c1 =>
    let s1 := update p v s in
    let cs1 := clauses_update k (anti_literals k) cs in
    match f s1 cs1 with
    | None => try_one s c1 cs f
    | Some c1 => Some c1
    end
  end.
end.

```

The function `find_one_aux` is the one that organizes the recursion.

```

Fixpoint find_one_aux (n: clauses) (s: list nat)
  (cs: clauses): option (list nat) :=
match cs with
| nil => Some s
| (_, nil) :: _ => None
| (_, p) :: cs1 =>
  match n with
  | nil => None
  | _ :: n1 => try_one s p cs1 (find_one_aux n1)
  end
end.
end.

```

It takes the current state of the Sudoku `s` and the corresponding list of clauses `cs`. It looks at the top of the list of clauses. As this list is ordered, clauses with few literals come first. If the list contains the empty clause, this clause is unsatisfiable so there is no solution. Otherwise it takes the first clause and tries to satisfy it using `try_one`. The argument `n` is a dummy argument added to ensure structural termination. As at each call of `try_one` we remove at least one clause from the list of clauses, taking the initial list of clauses can safely be given as dummy argument. The main function is then

```

Definition find_one s :=
  let cs := gen_init_clauses s in find_one_aux cs s cs.

```

To state the correctness of this algorithm, we need to define the predicate that indicates if a grid is a refinement of another grid

```

Definition refine s1 s2 :=
  length s1 = size * size /\
  length s2 = size * size /\
  forall p, valid_pos p ->
    In (get p s1) ref_list -> get p s1 = get p s2.

```

With this predicate, the correctness is expressed as

```
Theorem find_one_correct:
  forall s, length s = size * size ->
    match find_one s with
      None => forall s1, refine s s1 -> ~ sudoku s1
    | Some s1 => refine s s1 /\ sudoku s1
    end.
```

8 Finding all solutions

It is trivial to modify the previous algorithm so that it returns not the first solution but all the solutions. The function `try_all` accumulates all the solutions instead of stopping at the first one.

```
Fixpoint try_all (s: list nat) (c: clause) (cs: clauses)
  (f: list nat -> clauses -> list (list nat)):
  list (list nat) :=
  match c with
    nil => nil
  | (L p v) as k:: l1 =>
    let s1 := update p v s in
    let cs1 := clauses_update k (anti_literals k) cs in
    merges (f s1 cs1) (try_all s l1 cs f)
  end.
```

where the function

```
merges: list nat -> list (list nat) -> list (list nat)
```

inserts a solution in a list of solutions.

```
Fixpoint find_all_aux (n: clauses) (s: list nat) (cs: clauses):
  list (list nat) :=
  match cs with
    nil => s :: nil
  | (_, nil) :: _ => nil
  | (_, p) :: cs1 =>
    match n with
      nil => nil
    | _ :: n1 => try_all s p cs1 (find_all_aux n1)
    end
  end.
```

The main function is then

```
Definition find_all s :=  
  let cs := gen_init_clauses s in find_all_aux cs s cs.
```

The corresponding correctness statement is the following.

```
Theorem find_all_correct:  
  forall s s1, refine s s1 -> (sudoku s1 <-> In s1 (find_all s)).
```

9 Running example

To use the Sudoku contribution, we first need to load it.

Require Import Sudoku.

Suppose we want to solve 3x3 Sudoku, we first create the initial position taking the convention that zeros correspond to empty cells.

```
Definition test :=  
  5 :: 0 :: 0 :: 0 :: 0 :: 0 :: 0 :: 0 :: 0 :: 0 ::  
  0 :: 4 :: 0 :: 8 :: 1 :: 0 :: 0 :: 0 :: 0 :: 0 ::  
  0 :: 9 :: 3 :: 0 :: 0 :: 0 :: 0 :: 0 :: 0 :: 2 ::  
  0 :: 0 :: 0 :: 0 :: 0 :: 0 :: 0 :: 2 :: 0 :: 3 ::  
  9 :: 0 :: 0 :: 7 :: 0 :: 0 :: 0 :: 0 :: 0 :: 0 ::  
  2 :: 3 :: 0 :: 0 :: 0 :: 6 :: 0 :: 7 :: 0 :: 0 ::  
  3 :: 6 :: 5 :: 1 :: 0 :: 0 :: 0 :: 0 :: 0 :: 0 ::  
  0 :: 0 :: 0 :: 0 :: 5 :: 0 :: 8 :: 0 :: 0 :: 0 ::  
  0 :: 0 :: 1 :: 0 :: 7 :: 0 :: 6 :: 0 :: 0 :: 0 :: nil.
```

Doing

Eval compute in find_one 3 3 test.

returns

```
5 :: 8 :: 6 :: 2 :: 3 :: 7 :: 9 :: 1 :: 4 ::  
7 :: 4 :: 2 :: 8 :: 1 :: 9 :: 3 :: 5 :: 6 ::  
1 :: 9 :: 3 :: 4 :: 6 :: 5 :: 7 :: 8 :: 2 ::  
6 :: 5 :: 7 :: 9 :: 8 :: 1 :: 2 :: 4 :: 3 ::  
9 :: 1 :: 4 :: 7 :: 2 :: 3 :: 5 :: 6 :: 8 ::  
2 :: 3 :: 8 :: 5 :: 4 :: 6 :: 1 :: 7 :: 9 ::  
3 :: 6 :: 5 :: 1 :: 9 :: 8 :: 4 :: 2 :: 7 ::  
4 :: 7 :: 9 :: 6 :: 5 :: 2 :: 8 :: 3 :: 1 ::  
8 :: 2 :: 1 :: 3 :: 7 :: 4 :: 6 :: 9 :: 5 :: nil
```

Doing

```
Eval compute in length (find_all 3 3 test).
```

returns 1. We are then sure that there is a unique solution to this Sudoku
The source code is available at

<ftp://ftp-sop.inria.fr/marelle/Laurent.Thery/Sudoku.zip>

References

- [1] Martin Davis and Hilary Putnam. A computing procedure for quantification theory. *J. ACM*, 7(3):201–215, 1960.