NUXMV: Introduction*

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Introduction

- nuXmv is a new symbolic model checker developed by **FBK-IRST**.
  - based on the NuSMV model checker
  - project url: `https://nuxmv.fbk.eu/`
  - *the binary of* nuXmv *is available for non-commercial or academic purposes only!*

- nuXmv allows for verifying
  - *finite-state systems* through state-of-the-art SAT-based algorithms;
  - *infinite-state systems* (e.g. systems with *real* and *integer* variables) through SMT-based techniques running on top of **MathSAT5**;

- nuXmv supports *synchronous* systems;
  asynchronous systems are no longer supported!

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Interactive shell [1/3]

- `nuXmv -int` (or `NuSMV -int`) activates an interactive shell
- `help` shows the list of all commands (if a command name is given as argument, detailed information for that command will be provided). note: option `-h` prints the command line help for each command.
- `reset` resets the whole system (in order to read in another model and to perform verification on it).
- `read_model [-i filename]` sets the input model and reads it.
- `go`, `go_bmc`, `go_msat` initialize NUXMV for verification or simulation with a specific backend engine.

Interactive shell [2/3]

- `pick_state [-v] [-a] [-r | -i]` picks a state from the set of initial states.
  - `-v` prints the chosen state.
  - `-r` picks a state from the set of the initial states randomly.
  - `-i` picks a state from the set of the initial states interactively.
  - `-a` displays all state variables (requires `-i`).
- `simulate [-p | -v] [-a] [-r | -i] -k N` generates a sequence of at most `N` transitions starting from the `current state`.
  - `-p` prints the changing variables in the generated trace;
  - `-v` prints changed and unchanged variables in the generated trace;
  - `-a` prints all state variables (requires `-i`);
  - `-r` at every step picks the next state randomly.
  - `-i` at every step picks the next state interactively.
- `print_current_state [-h] [-v]` prints out the current state.
  - `-v` prints all the variables.

Interacting Shell [2/3] - Output Example

```
nuXmv > reset; read_model -i example01.smv ; go ; pick_state -v; simulate -v
Trace Description: Simulation Trace
Trace Type: Simulation
  -> State: 1.1 <-
    b0 = FALSE
********  Simulation Starting From State 1.1   ********
Trace Description: Simulation Trace
Trace Type: Simulation
  -> State: 1.1 <-
    b0 = FALSE
  -> State: 1.2 <-
    b0 = TRUE
  -> State: 1.3 <-
    b0 = FALSE
  -> State: 1.4 <-
    b0 = TRUE
  -> State: 1.5 <-
    b0 = FALSE
  -> State: 1.6 <-
    b0 = TRUE
  ...
```

Interacting Shell [3/3]

- `goto_state state_label` makes `state_label` the `current state` (it is used to navigate along traces).
- `show_traces [-t] [-v] [-a | TN[.FS[:[TS]]]` prints the trace *TN* starting from state *FS* up to state *TS*
  - `-t` prints the total number of stored traces
  - `-v` verbosely prints traces content;
  - `-a` prints all the currently stored traces
- `show_vars [-s] [-f] [-i] [-t] [-v]` prints the variables content and type
  - `-s` print state variables;
  - `-f` print frozen variables;
  - `-i` print input variables;
  - `-t` prints the number of variables;
  - `-v` prints verbosely;
- `quit` stops the program.

Contents

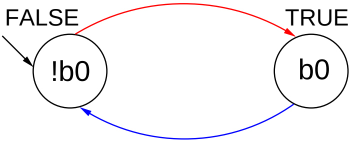
The first SMV program

- an SMV program is composed by a number of **modules**;
- each **module**, contains:
  - state variable declarations;
  - assignments defining the valid *initial states*;
  - assignments defining the *transition relation*;

Example:

```
MODULE main
VAR
    b0 : boolean;

ASSIGN
    init(b0) := FALSE;
    next(b0) := !b0;
```



Basic Types [1/2]

boolean: TRUE, FALSE, ...

```
x : boolean;
```

enumerative:

```
s : {ready, busy, waiting, stopped};
```

bounded integers (intervals):

```
n : 1..8;
```

integers*: -1, 0, 1, ...

```
n : integer;
```

rationals: 1.66, f'2/3, 2e3, 10e-1, ...

```
r : real;
```

words: used to model arrays of bits supporting bitwise logical and arithmetic operations.

- `unsigned word[3];`
- `signed word[7];`

*: integer numbers must be within C/C++ INT_MIN and INT_MAX bounds

Basic Types [2/2]

arrays:
declared with a couple of lower/upper bounds for the index and a type

```
VAR
  x : array 0..10 of boolean; -- array of 11 elements
  y : array -1..1 of {red, green, orange}; -- array of 3 elements
  z : array 1..10 of array 1..5 of boolean; -- array of array
ASSIGN
  init(x[5]) := bool(1);
  init(y[0]) := {red, green}; -- any value in the set
  init(z[3][2]) := TRUE;
```

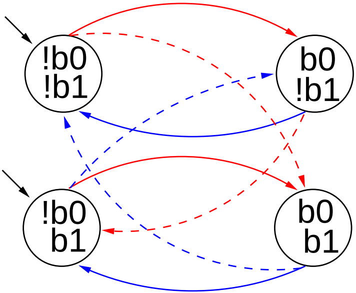
Remarks:

- Array indexes *must be constants*;

Adding a state variable

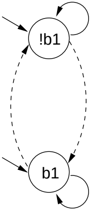
```
MODULE main
VAR
  b0 : boolean;
  b1 : boolean;

ASSIGN
  init(b0) := FALSE;
  next(b0) := !b0;
```



Remarks:

- the FSM is the result of the synchronous composition of the "subsystems" for b0 and b1
- the new state space is the cartesian product of the ranges of the variables.



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Initial States [1/2]

Example:

```
init(x) := FALSE; -- x must be FALSE
init(y) := {1, 2, 3}; -- y can be either 1, 2 or 3
```

`init(<variable>) := <simple_expression>;`

- constrains the initial value of `<variable>` to satisfy the `<simple_expression>`;
- the **initial** value of an unconstrained variable can be any of those allowed by its domain;

set of initial states

is given by the set of states whose variables satisfy all the `init()` constraints in a module.

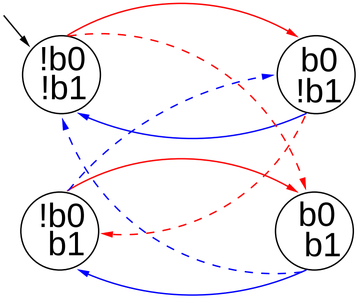
Initial States [2/2]

Example:

```
MODULE main
 VAR
   b0 : boolean;
   b1 : boolean;

 ASSIGN
   init(b0) := FALSE;
   next(b0) := !b0;

   init(b1) := FALSE;
```



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Expressions [1/3]

- arithmetic operators:
  `+` `-` `*` `/` `mod` `-` (unary)
- comparison operators:
  `=` `!=` `>` `<` `<=` `>=`
- logic operators:
  `&` `|` `xor` `!` (not) `->` `<->`
- bitwise operators:
  `<<` `>>`
- set operators: `{v1,v2,...,vn}`
  - `in`: tests a value for membership in a set *(set inclusion)*
  - `union`: takes the union of 2 sets *(set union)*
- count operator: counts number of true *boolean* expressions
  `count(b1 + b2 + ... + bn)`

Expressions [2/3]

- case expression:

```
case
  c1   : e1;
  c2   : e2;
  ...
  TRUE : en;
esac
```

C/C++ equivalent:

```
if (c1) then e1;
else if (c2) then e2;
  ...
else en;
```

- if-then-else expression:

  `cond_expr ? basic_epxr 1 : basic_expr2`

- conversion operators: `toint`, `bool`, `floor`, and
  - `swconst`, `uwconst`: convert an integer to a signed and an unsigned word respectively.
  - `word1` converts boolean to a single word bit.
  - `unsigned` and `signed` convert signed word to unsigned word and vice-versa.

Expressions [3/3]

- expressions in SMV do not necessarily evaluate to one value. In general, they can represent a set of possible values.

```
init(var) := {a,b,c} union {x,y,z} ;
```

- The meaning of `:=` in assignments is that the lhs can non-deterministically be assigned to any value in the set of values represented by the rhs.
- A constant `c` is considered as a syntactic abbreviation for {`c`} (the singleton containing `c`).

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Transition Relation [1/2]

Transition Relation

specifies a constraint on the values that a variable can assume in the *next state*, given the value of variables in the *current state*.

```
next(<variable>) := <next_expression>;
```

- `<next_expression>` can depend both on "current" and "next" variables:

```
next(a) := { a, a+1 } ;
next(b) := b + (next(a) - a) ;
```

- `<next_expression>` must evaluate to values in the domain of `<variable>`;
- the **next** value of an unconstrained variable evolves non-deterministically;

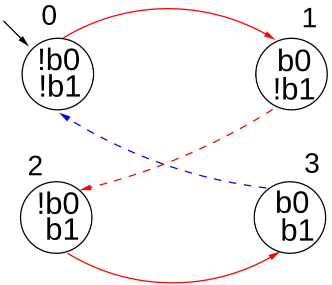
Example:

modulo-4 counter

```
MODULE main
 VAR
   b0 : boolean;
   b1 : boolean;

 ASSIGN
   init(b0) := FALSE;
   next(b0) := !b0;

   init(b1) := FALSE;
   next(b1) := case
       b0   : !b1;
       TRUE : b1;
     esac;
```



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Output Variable [1/2]

output variable

is a variable whose value deterministically depends on the value of other "current" state variables and for which no `init()` or `next()` are defined.

```
<variable> := <simple_expression>;
```

- <simple_expression> must evaluate to values in the domain of the <variable>.
- used to model *outputs* of a system;

Output Variable [2/2]

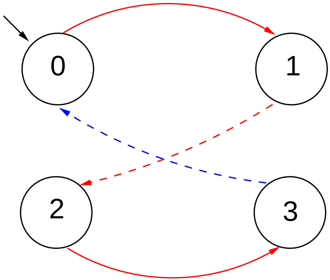
Example:

```
MODULE main
 VAR
   b0 : boolean;
   b1 : boolean;
   out : 0..3;

 ASSIGN
   init(b0) := FALSE;
   next(b0) := !b0;

   init(b1) := FALSE;
   next(b1) := ((!b0 & b1) | (b0 & !b1));

   out := toint(b0) + 2*toint(b1);
```



Assignment Rules (:=)

- **single assignment rule** – each variable may be assigned only once;
  Illegal examples:

```
init(var) := ready;      var := ready;         next(var) := ready;
init(var) := busy;       var := busy;          var := busy;

next(var) := ready;      init(var) := ready;
next(var) := busy;       var := busy;
```

Assignment Rules (:=)

- **single assignment rule** – each variable may be assigned only once;
  Illegal examples:

```
init(var) := ready;       var := ready;         next(var) := ready;
init(var) := busy;        var := busy;          var := busy;

next(var) := ready;       init(var) := ready;
next(var) := busy;        var := busy;
```

- **circular dependency rule** – a set of equations must not have "cycles" in its dependency graph, unless broken by delays;
  Illegal examples:

```
next(x) := next(y);       x := (x + 1) mod 2;   next(x) := x & next(x);
next(y) := next(x);
```

  Legal example:

```
next(x) := next(y);
next(y) := y & x;
```

DEFINE declarations

`DEFINE <id> := <simple_expression>;`

- similar to *C/C++ macro* definitions: each occurrence of the defined symbol is replaced with the body of the definition
- provide an alternative way of defining *output variables*;

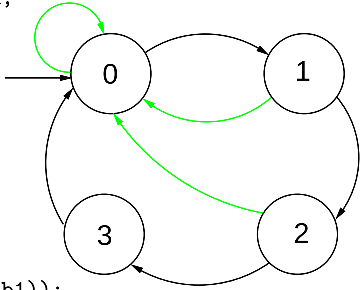
Example:

```
MODULE main
 VAR
   b0 : boolean;
   b1 : boolean;
 ASSIGN
   init(b0) := FALSE;
   next(b0) := !b0;
   init(b1) := FALSE;
   next(b1) := ((!b0 & b1) | (b0 & !b1));
 DEFINE
   out := toint(b0) + 2*toint(b1);
```

Example: modulo 4 counter with reset

The counter can be reset by an external "uncontrollable" signal.

```
MODULE main
VAR
  b0 : boolean; b1 : boolean; reset : boolean;
ASSIGN
  init(b0) := FALSE;
  init(b1) := FALSE;
  next(b0) := case
                reset = TRUE  : FALSE;
                reset = FALSE : !b0;
               esac;
  next(b1) := case
                reset : FALSE;
                TRUE  : ((!b0 & b1) | (b0 & !b1));
              esac;
DEFINE
  out := toint(b0) + 2*toint(b1);
```



Exercise 1

Exercise:

simulate the system with nuXmv and draw the FSM.

```
MODULE main
VAR
  request : boolean;
  state   : { ready, busy };

ASSIGN
  init(state) := ready;
  next(state) :=
    case
      state = ready & request : busy;
      TRUE                    : { ready, busy };
    esac;
```

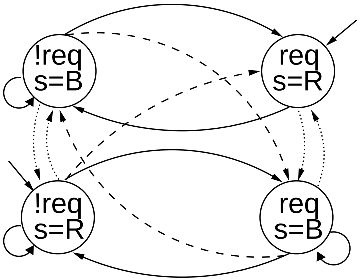
Exercise 1

Exercise:

simulate the system with NUXMV and draw the FSM.

```
MODULE main
VAR
  request : boolean;
  state   : { ready, busy };

ASSIGN
  init(state) := ready;
  next(state) :=
    case
      state = ready & request : busy;
      TRUE                    : { ready, busy };
    esac;
```



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Constraint Style Modeling [1/3]

```
MODULE main
VAR
request : boolean;  state : {ready,busy};
ASSIGN
  init(state) := ready;
  next(state) := case
      state = ready & request : busy;
      TRUE                   : {ready,busy};
  esac;
```

Every program can be alternatively defined in a *constraint style*:

```
MODULE main
VAR
  request : boolean;
  state   : {ready,busy};
INIT
  state = ready
TRANS
  (state = ready & request) -> next(state) = busy
```

Constraint Style Modeling [2/3]

- a model can be specified by zero or more constraints on:
  - *invariant states*:
    `INVAR <simple_expression>`
  - *initial states*:
    `INIT <simple_expression>`
  - *transitions*:
    `TRANS <next_expression>`
- constraints can be mixed with assignments;
- any propositional formula is allowed as constraint;
- not all **constraints** can be easily rewritten in terms of assignments!

```
TRANS
  next(b0) + 2*next(b1) + 4*next(b2) =
                  (b0 + 2*b1 + 4*b2 + tick) mod 8
```

Constraint Style Modeling [3/3]

- Models written in **assignment style**:
  - by construction, there is always *at least one initial state*;
  - by construction, all states have *at least one next state*;
  - *non-determinism is apparent* (unassigned variables, set assignments...).

- Models written in **constraint style**:
  - `INIT` constraints *can be inconsistent* $\Longrightarrow$ no initial state!
    - any specification (also `SPEC 0`) is vacuously true.
  - `TRANS` constraints *can be inconsistent*: $\Longrightarrow$ deadlock state!

    Example:

    ```
    MODULE main
    VAR b : boolean;
    TRANS b -> FALSE;
    ```

    - **tip:** use `check_fsm` to detect deadlock states
  - *non-determinism is hidden*:

    ```
    TRANS (state = ready & request) -> next(state) = busy
    ```

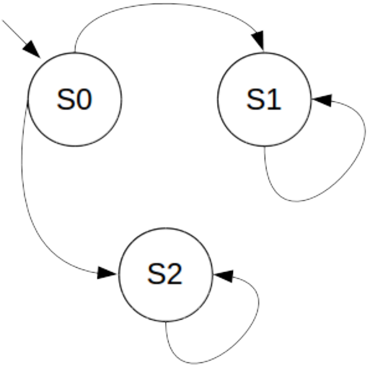
Example: Constraint Style & Case

```
MODULE main()
VAR
  state : {S0, S1, S2};

DEFINE
  go_s1 := state != S2;
  go_s2 := state != S1;

INIT
  state = S0;

TRANS
case
  go_s1 : next(state) = S1;
  go_s2 : next(state) = S2;
esac;
```



- **Q:** does it correspond to the FSM?

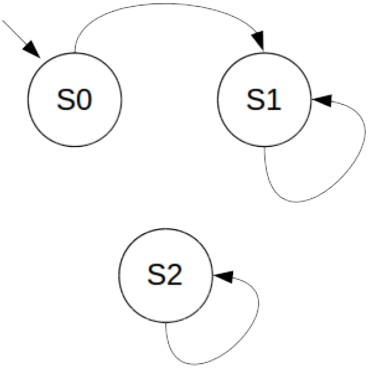
Example: Constraint Style & Case

```
MODULE main()
VAR
  state : {S0, S1, S2};

DEFINE
  go_s1 := state != S2;
  go_s2 := state != S1;

INIT
  state = S0;

TRANS
case
  go_s1 : next(state) = S1;
  go_s2 : next(state) = S2;
esac;
```



- **Q:** does it correspond to the FSM? No: cases are evaluated in order!

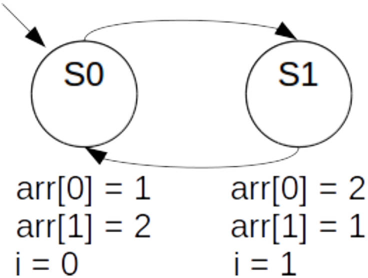
Example: Constraint Style & Swap

```
MODULE main()
VAR
   arr: array 0..1 of {1,2};
   i  : 0..1;

ASSIGN
  init(arr[0]) := 1;
  init(arr[1]) := 2;

  init(i) := 0;
  next(i) := 1-i;

TRANS
  next(arr[i]) = arr[1-i] &
  next(arr[1-i]) = arr[i];
```



- **Q:** does it correspond to the FSM?

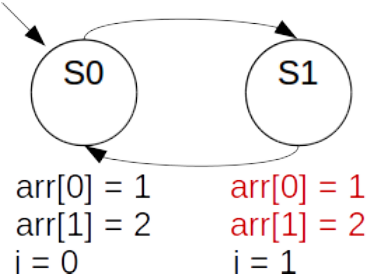
Example: Constraint Style & Swap

```
MODULE main()
VAR
   arr: array 0..1 of {1,2};
   i  : 0..1;

ASSIGN
  init(arr[0]) := 1;
  init(arr[1]) := 2;

  init(i) := 0;
  next(i) := 1-i;

TRANS
  next(arr[i]) = arr[1-i] &
  next(arr[1-i]) = arr[i];
```



- **Q:** does it correspond to the FSM? No: everything inside the **next()** operator is evaluated within the next state, indexes included!

Contents

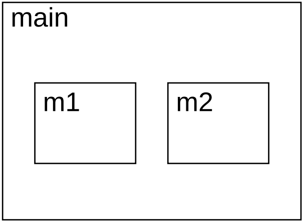
Modules [1/3]

SMV program = `main` module + 0 or *more* `other` modules

- a module can be instantiated as a VAR in `other` modules
- `dot notation` for accessing variables that are **local** to a module instance (e.g., `m1.out`, `m2.out`).

Example:

```
MODULE counter
  VAR out: 0..9;
  ASSIGN next(out) :=
              (out + 1) mod 10;
MODULE main
  VAR m1 : counter; m2 : counter;
      sum: 0..18;
  ASSIGN sum := m1.out + m2.out;
```



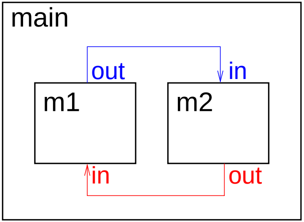
Modules [2/3]

A module declaration can be *parametric*:

- a parameter is passed by reference;
- any expression can be used as parameter;

Example:

```
MODULE counter(in)
  VAR out: 0..9;
  ...
MODULE main
  VAR m1 : counter(m2.out);
      m2 : counter(m1.out);
  ...
```



Modules [3/3]

- modules can be **composed**
- modules *without parameters and assignments* can be seen as simple **records**

Example:

```
MODULE point
VAR
  x: -10..10;
  y: -10..10;

MODULE circle
VAR
  center: point;
  radius: 0..10;
```

```
MODULE main
VAR c: circle;
ASSIGN
  init(c.center.x) := 0;
  init(c.center.y) := 0;
  init(c.radius)   := 5;
```

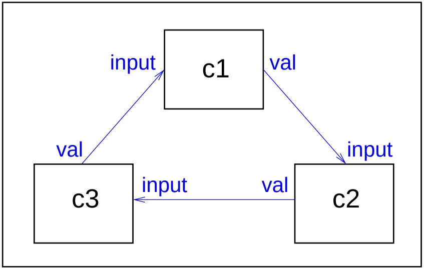
Contents

Synchronous composition [1/2]

The composition of modules is **synchronous** by default:
all modules move at each step.

```
MODULE cell(input)
VAR
  val : {red, green, blue};
ASSIGN
  next(val) := input;

MODULE main
VAR
  c1 : cell(c3.val);
  c2 : cell(c1.val);
  c3 : cell(c2.val);
```



Synchronous composition [2/2]

A possible execution:

step	*c1.val*	*c2.val*	*c3.val*
0	red	green	blue
1	blue	red	green
2	green	blue	red
3	red	green	blue
4	...	...	...
5	red	green	blue

Asynchronous composition [1/2]

Asynchronous composition can be obtained using keyword `process`:
one process moves at each step.

```
MODULE cell(input)
VAR
  val : {red, green, blue};
ASSIGN  next(val) := input;
FAIRNESS running

MODULE main
VAR
  c1 : process cell(c3.val);
  c2 : process cell(c1.val);
  c3 : process cell(c2.val);
```

Each process has a boolean `running` variable:

- true iff the process is selected for execution;
- can be used to guarantee a fair scheduling of processes.

Asynchronous composition [2/2]

A possible execution:

step	*running*	*c1.val*	*c2.val*	*c3.val*
0	-	**red**	**green**	**blue**
1	c2	red	**red**	blue
2	c1	**blue**	red	blue
3	c1	blue	red	blue
4	c3	blue	red	**red**
5	c2	blue	**blue**	red
6	c3	blue	blue	**blue**
...	...	blue	blue	blue

Warning: in NUXMV processes are deprecated!

Contents

Exercise: Adder [1/3]

```
MODULE bit-adder(in1, in2, cin)
VAR
  sum : boolean;
  cout : boolean;
ASSIGN
  next(sum) := (in1 xor in2) xor cin;
  next(cout) := (in1 & in2) | ((in1 | in2) & cin);

MODULE adder(in1, in2)
VAR
  bit[0] : bit-adder(in1[0], in2[0], bool(0));
  bit[1] : bit-adder(in1[1], in2[1], bit[0].cout);
  bit[2] : bit-adder(in1[2], in2[2], bit[1].cout);
  bit[3] : bit-adder(in1[3], in2[3], bit[2].cout);
DEFINE
  sum[0] := bit[0].sum;
  sum[1] := bit[1].sum;
  sum[2] := bit[2].sum;
  sum[3] := bit[3].sum;
  overflow := bit[3].cout;
```

```
MODULE main
VAR
  in1 : array 0..3 of boolean;
  in2 : array 0..3 of boolean;
  a : adder(in1, in2);
ASSIGN
  next(in1[0]) := in1[0]; next(in1[1]) := in1[1];
  next(in1[2]) := in1[2]; next(in1[3]) := in1[3];
  next(in2[0]) := in2[0]; next(in2[1]) := in2[1];
  next(in2[2]) := in2[2]; next(in2[3]) := in2[3];
DEFINE
  op1 := toint(in1[0]) + 2*toint(in1[1]) + 4*toint(in1[2]) +
         8*toint(in1[3]);
  op2 := toint(in2[0]) + 2*toint(in2[1]) + 4*toint(in2[2]) +
         8*toint(in2[3]);
  sum := toint(a.sum[0]) + 2*toint(a.sum[1]) + 4*toint(a.sum[2]) +
         8*toint(a.sum[3]) + 16*toint(a.overflow);
```

Exercise: Adder [3/3]

Exercise:

- simulate a random execution of the "adder" system;
- after how many steps the adder stores the computes the final `sum` value?
- add a `reset` control which changes the values of the operands and restarts the computation of the sum

Exercises Solutions

- will be uploaded on course website within a couple of days
- send me an email if you need help or you just want to propose your own solution for a review

- learning programming languages requires practice: try to come up with your own solutions first!