# Lustre and Scade: modelling and verifying reactive systems

# Reactive system

- In the course introduction, we have emphasised the "model-driven design" for ESs.
- In this lecture we will review Scade and Lustre: a tool and a modelling language that implement this approach

# Lustre - Scade

- Lustre is a synchronous language to specify reactive systems
- Scade is a tool to manipulate Lustre models

# Reactive system

- Computer system that reacts to the inputs it receives
- The sequence of inputs is not known by the system before its execution begins

# Reactive system

- Example: plane autopilot
  - The inputs are provided by the sensors (speed, attitude,...)
  - The system must keep the plane flying safely whatever the inputs
- To contrast: a compiler is not a reactive system
  - Input = File to compile (does not change during the execution)

# Synchronous language

- In a synchronous language, the following hypothesis is made on the system:
- It boasts a clock that ticks regularly
- In a synchronous model, it is assumed that all the computations are carried out simultaneously at each tick

# Synchronous language

- Example: Assume two variables d and x
  - At each tick they are updated:
    - d' = -d if x=0 ; d otherwise
    - x' = x + d

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- Example: Assume two variables d and x
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    - d' = -d if x=0 ; d otherwise
    - x' = x + d

x:

d:

# Synchronous language

- Example: Assume two variables d and x
  - At each tick they are updated:
    - $d' = -d$ if $x=0$ ; $d$ otherwise
    - $x' = x + d$

x: 0

d: -1

# Synchronous language

- Example: Assume two variables d and x
  - At each tick they are updated:
    - d' = -d if x=0 ; d otherwise
    - x' = x + d

| | | |
|---|---|---|
| x: | 0 | -1 |
| d: | -1 | 1 |

# Synchronous language

- Example: Assume two variables d and x
  - At each tick they are updated:
    - d’ = -d if x=0 ; d otherwise
    - x’ = x + d

| | | | |
|---|---|---|---|
| x: | 0 | -1 | 0 |
| d: | -1 | 1 | 1 |

# Synchronous language

- Example: Assume two variables d and x
  - At each tick they are updated:
    - d' = -d if x=0 ; d otherwise
    - x' = x + d

| | | | | |
|---|---|---|---|---|
| x: | 0 | -1 | 0 | 1 |
| d: | -1 | 1 | 1 | -1 |

# Synchronous language

- Example: Assume two variables d and x
  - At each tick they are updated:
    - d’ = -d if x=0 ; d otherwise
    - x’ = x + d

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| x: | 0 | -1 | 0 | 1 | 0 | -1 | 0 | 1 |
| d: | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 |

# Synchronous language

- Example: Assume two variables d and x
  - At each tick they are updated:
    - d' = -d if x=0 ; d otherwise
    - x' = x + d

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| x: | 0 | -1 | 0 | 1 | 0 | -1 | 0 | 1 | |
| d: | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | ... |

# Synchronous language

- Variable updates are done in parallel. Each step consists in:
  - reading inputs: x and d
  - writing outputs: x' and d'

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| x: | 0 | -1 | 0 | 1 | 0 | -1 | 0 | 1 | |
| d: | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | ... |

# Historical background

- Lustre = research project started in the '80s in Grenoble.
  - Motivation: reliable development of critical systems:
    - aerospace
    - trains without drivers
    - nuclear power plants

# Historical background

- In the ‘90s, these ideas slowly transferred from the academic world to the industry:
  - Airbus A320 (fly-by-wire)
  - Framatom power plants 1450MW

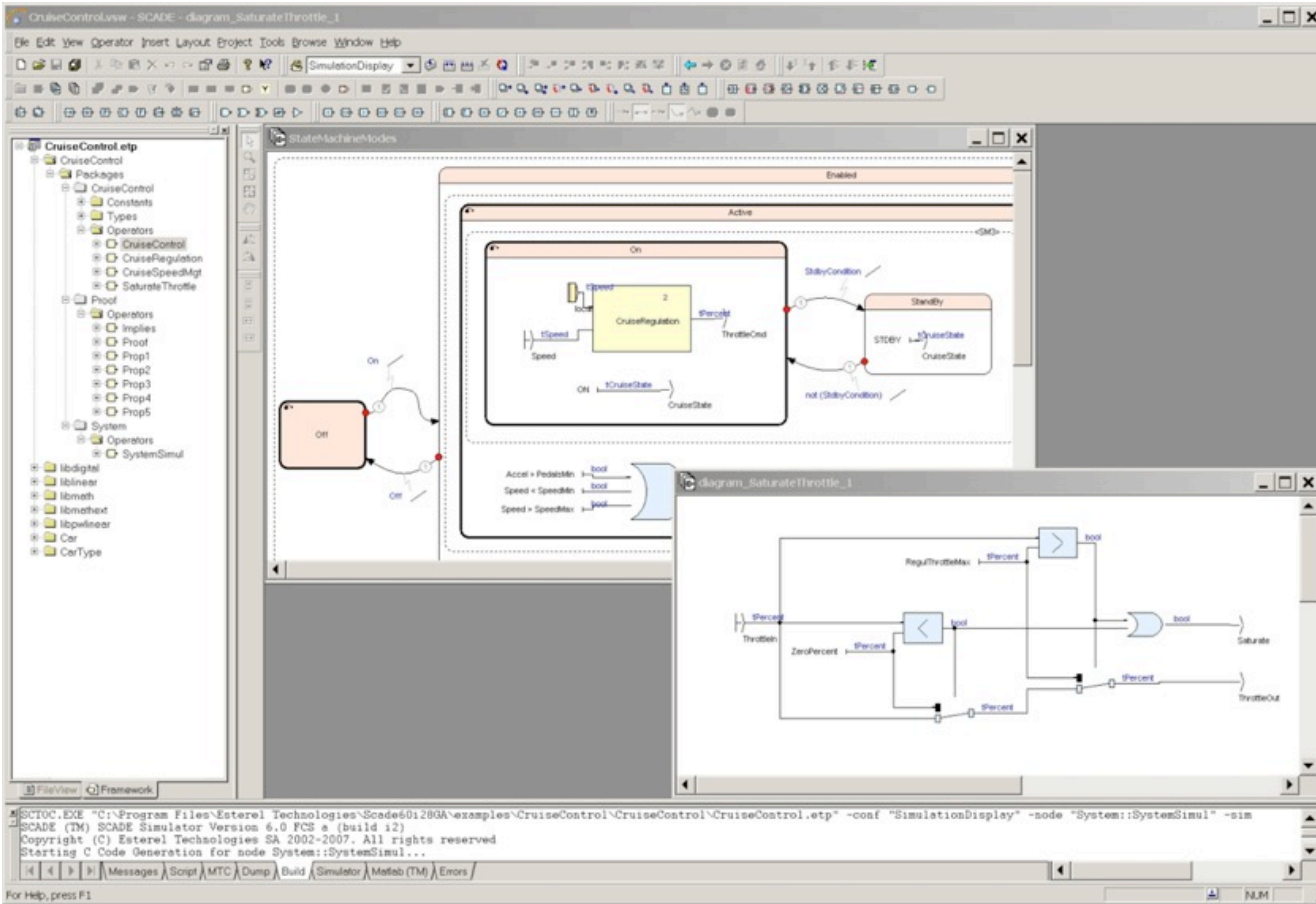
# Historical background

- In 1993, the Verimag laboratory is founded at Grenoble University by academics and industrial partners
- Verimag develops SCADE a commercial tool to model, test and verify synchronous systems using Lustre

# Historical background

- SCADE quickly replaces similar internal projects at Airbus, Merlin-Gerin, etc... and becomes a de facto European standard
- SCADE is afterwards sold to Esterel Technologies that develops and maintains it since then

# Scade


CruiseControl.vsw - SCADE - diagram_SaturateThrottle_1
File Edit View Operator Insert Layout Project Tools Browse Window Help
SimulationDisplay
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Types
Operators
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CruiseSpeedMgt
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System
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libpwlinear
Car
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FileView
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SCADE (TM) SCADE Simulator Version 6.0 FCS a (build i2)
Copyright (C) Esterel Technologies SA 2002-2007. All rights reserved
Starting C Code Generation for node System::SystemSimul...
Messages
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MTC
Dump
Build
Simulator
Matlab (TM)
Errors
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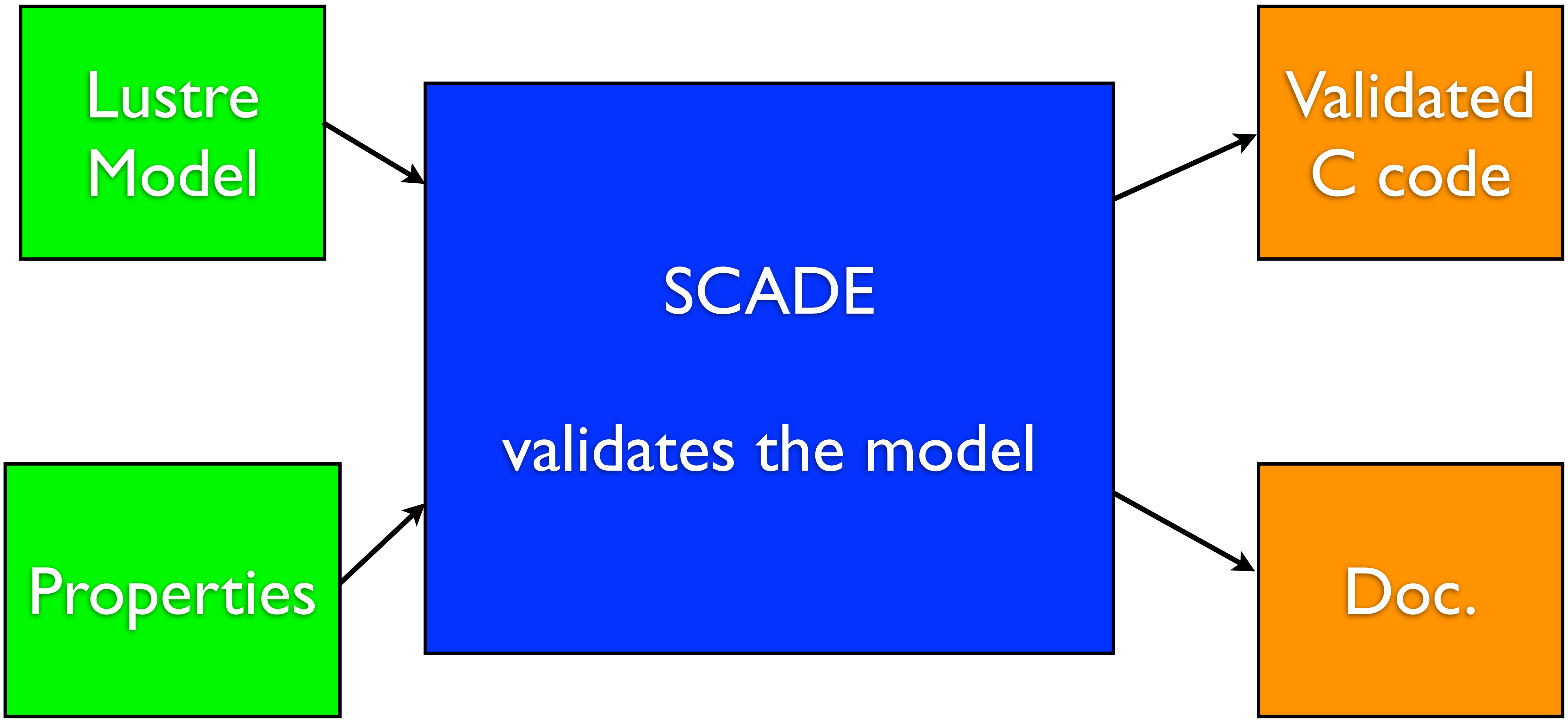
# Scade

- SCADE is a complete software suite running under Windows. It contains:
  - a GUI to manipulate LUSTRE models graphically
  - a simulator
  - a verification tool
  - a code generator
  - a reporting tool

# Developing with scade



# Lustre - 3 basic concepts

- flow = data
- node = code (how to update flows)
- cycle = one step of execution (allows to precisely define the dynamics of the program)

# Lustre - flow

- Data are sequences of values called flows
  - All the values in a flow have the same type (it is the type of the flow)
  - Example: integer flow: 0,1,2,3,....

# Lustre - nodes

- Nodes update the flows and are the basic bricks of any Lustre program
- Lustre is a functional language: each node defines a function that receives input flows and produces output flows

# Lustre - nodes

- Example:

input flow

output flow

```
node EDGE (X:bool) returns (Y:bool) ;
```

constraint linking X and Y

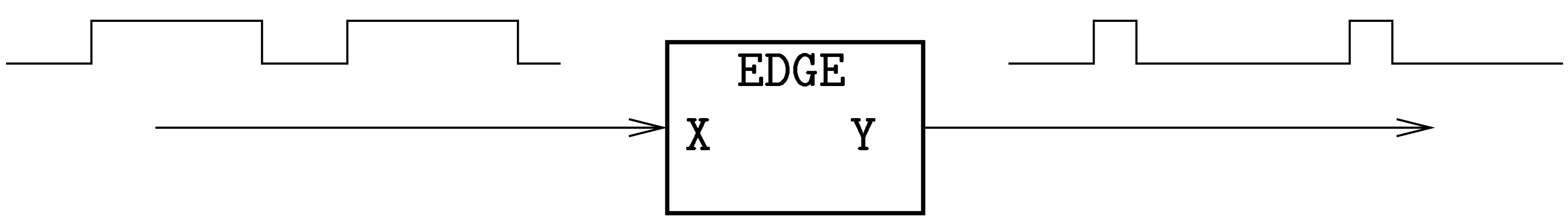
```
let
   Y = false -> X and not pre(X) ;
tel
```

# Lustre - cycles

- One cycle = one execution step of the Lustre program
- At each cycle, a new value is computed and added to each flow
  - Each cycle corresponds to a clock tick

# Lustre - cycles

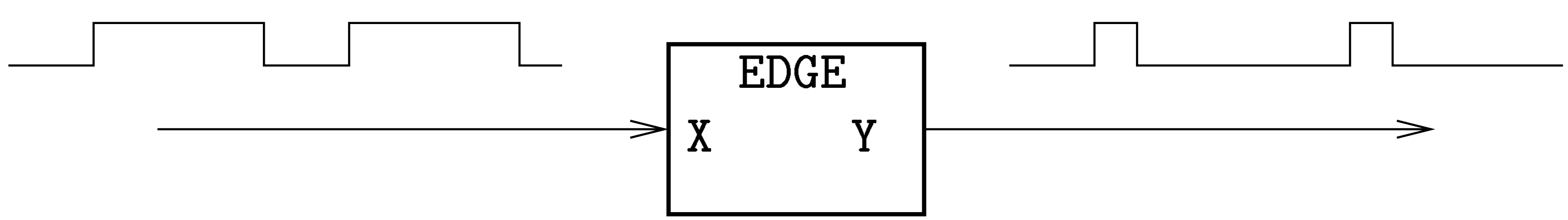
```
Y = false -> X and not pre(X)
```



# Lustre - cycles

init.
value

```
Y = false -> X and not pre(X)
```

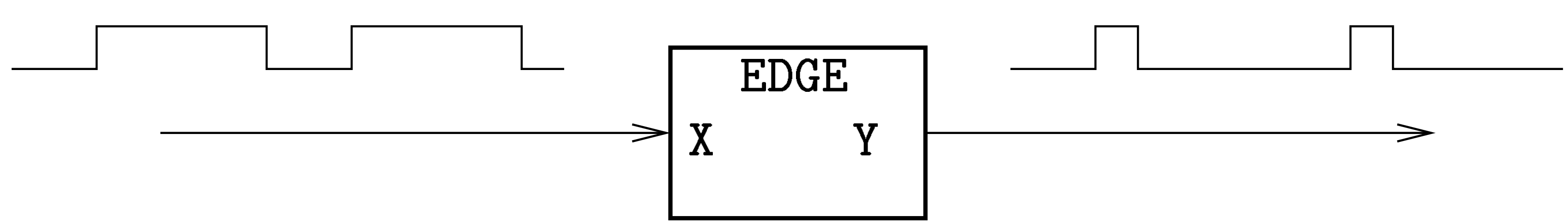


# Lustre - cycles

init.
value

previous
value of X

```
Y = false -> X and not pre(X)
```



# Lustre - cycles

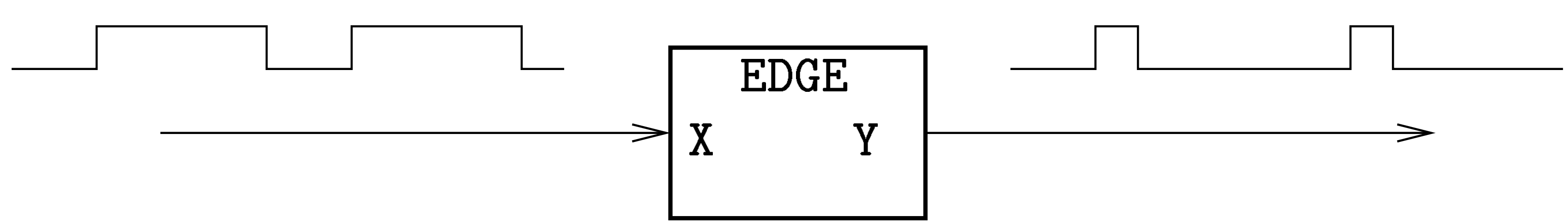
init. value

previous value of X

```
Y = false -> X and not pre(X)
```

Y

X F T T T F F T T



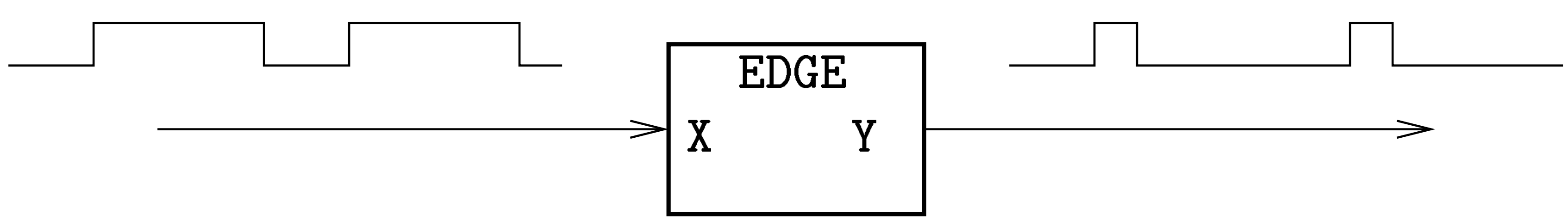
# Lustre - cycles

init.
value

previous
value of X

```
Y = false -> X and not pre(X)
```

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Y | | | | | | | | |
| X | F | T | T | T | F | F | T | T |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |



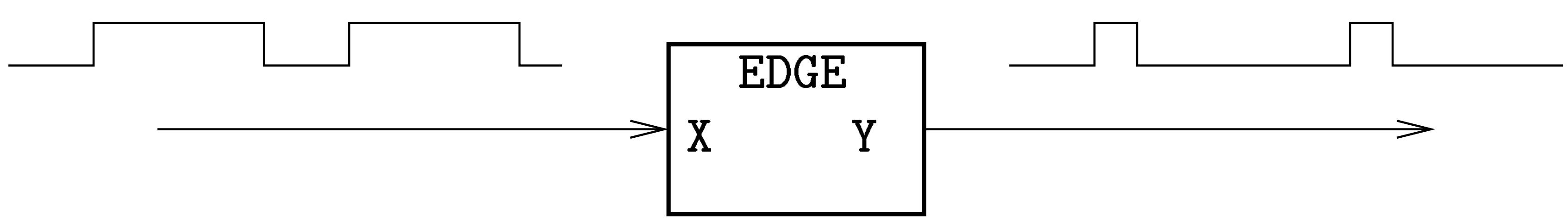
# Lustre - cycles

init.
value

previous
value of X

```
Y = false -> X and not pre(X)
```

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Y | F | | | | | | | |
| X | F | T | T | T | F | F | T | T |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |



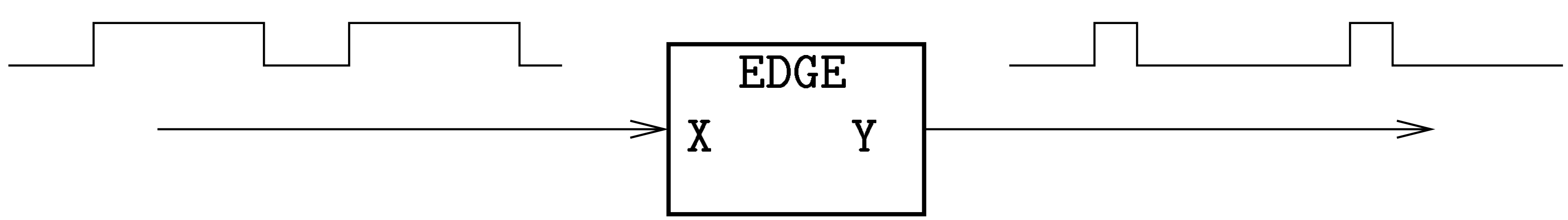
# Lustre - cycles

init.
value

previous
value of X

```
Y = false -> X and not pre(X)
```

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Y | F | T | | | | | | |
| X | F | T | T | T | F | F | T | T |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |



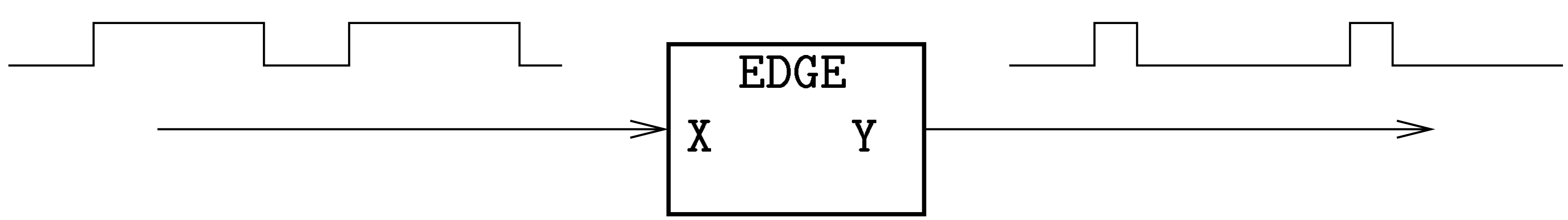
# Lustre - cycles

init. value

previous value of X

```
Y = false -> X and not pre(X)
```

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Y | F | T | F | | | | | |
| X | F | T | T | T | F | F | T | T |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |



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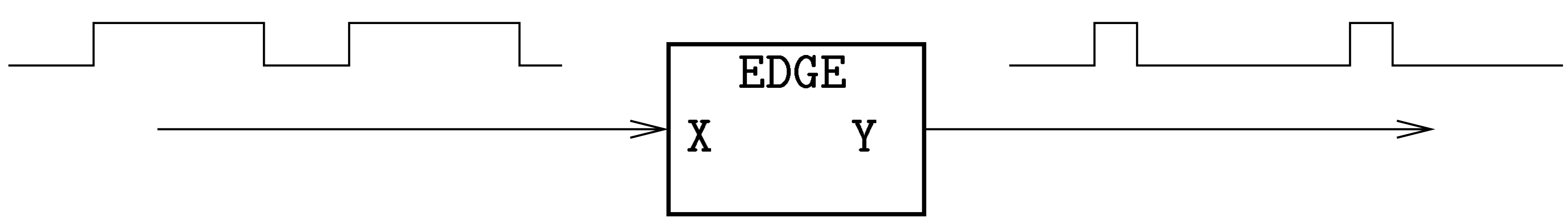
init.
value

previous
value of X

```
Y = false -> X and not pre(X)
```

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Y | F | T | F | F | | | | |
| X | F | T | T | T | F | F | T | T |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |



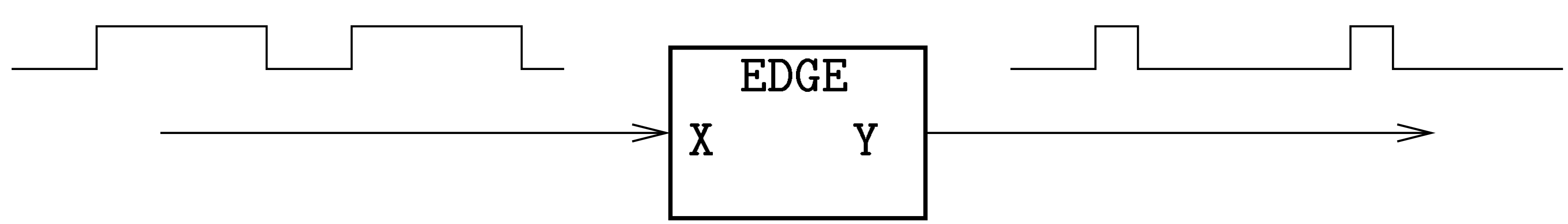
# Lustre - cycles

init. value

previous value of X

```
Y = false -> X and not pre(X)
```

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Y | F | T | F | F | F | | | |
| X | F | T | T | T | F | F | T | T |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |



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init. value

previous value of X

```
Y = false -> X and not pre(X)
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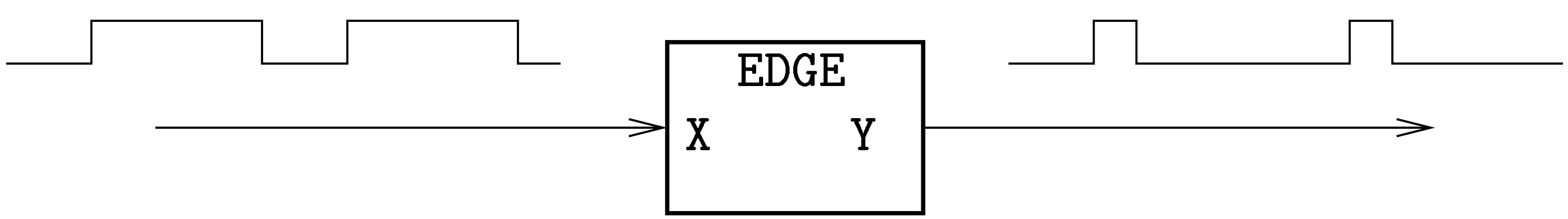
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Y | F | T | F | F | F | F | | |
| X | F | T | T | T | F | F | T | T |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |



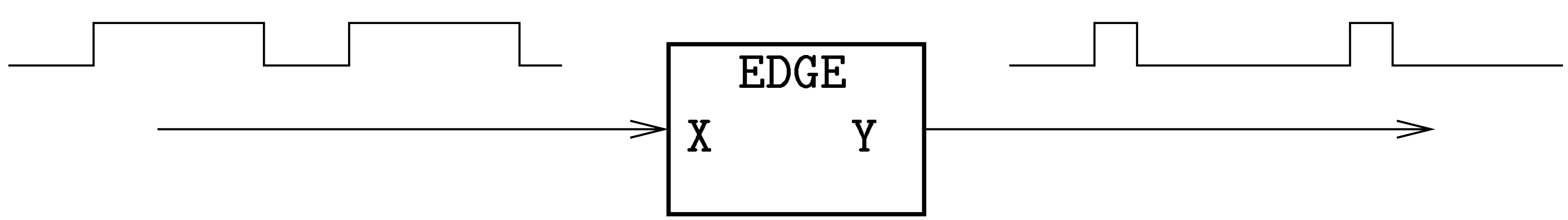
# Lustre - cycles

init. value

previous value of X

```
Y = false -> X and not pre(X)
```

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Y | F | T | F | F | F | F | T | |
| X | F | T | T | T | F | F | T | T |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |



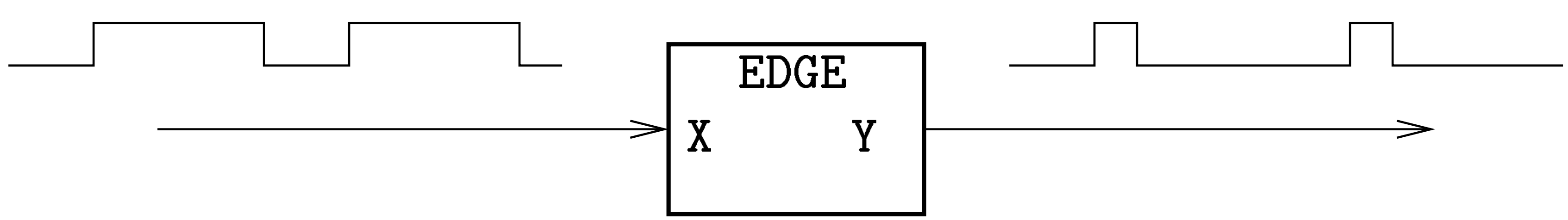
# Lustre - cycles

init. value

previous value of X

```
Y = false -> X and not pre(X)
```

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Y | F | T | F | F | F | F | T | F |
| X | F | T | T | T | F | F | T | T |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |



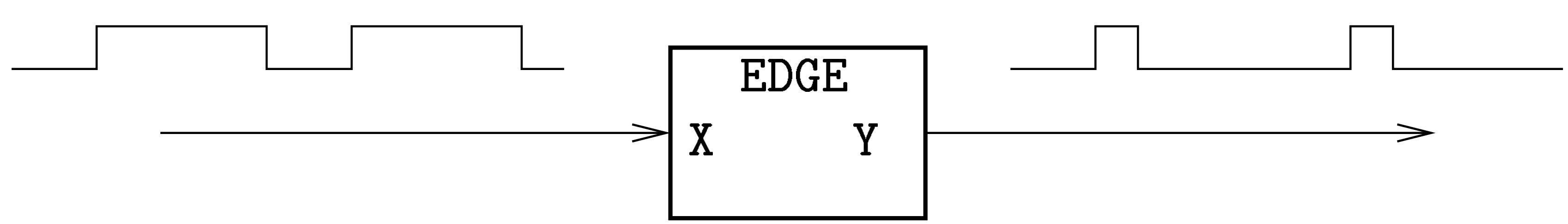
# Lustre - cycles

init. value

previous value of X

```
Y = false -> X and not pre(X)
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Y | F | T | F | F | F | F | T | F | |
| X | F | T | T | T | F | F | T | T | ..... |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |



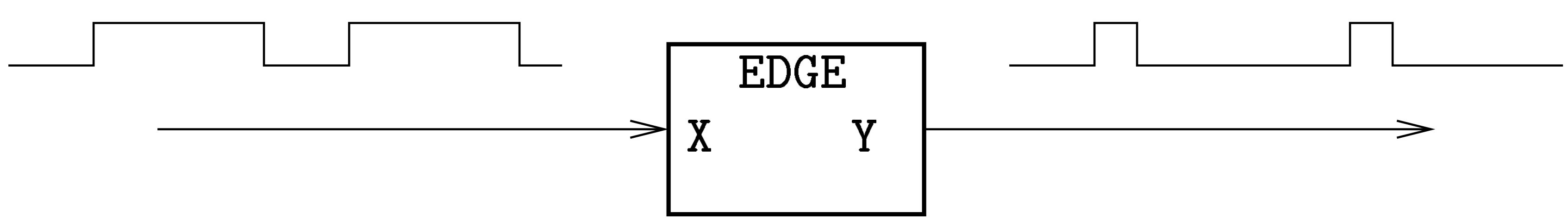
# Lustre - cycles

This node detects rising edges

of X

```
Y = false -> X and not pre(X)
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Y | F | T | F | F | F | F | T | F | |
| X | F | T | T | T | F | F | T | T | ..... |
| cycle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |



# Lustre - constants

- Boolean constants: `true`, `false`
- Arithmetic constants
- Constants represent constant flows:
  - eg: `false` represents (`false`, `false`, `false`,...)

# Lustre - operators

- **Boolean**: `and`, `or`, `xor`, `not`
- **Arithmetic**: +, -, *, /, `div`, `mod`
- **Comparison**: <, >, <=, >=, =, <>
- `if...then...else`

# Lustre - operators

- `pre`: previous value
  If $A = (a_1, a_2, a_3, \ldots, a_n, \ldots)$
  then `pre`$(A) = (nil, a_1, a_2, a_3, \ldots, a_{n-1}, \ldots)$

- `->`: initialisation of a flow
  if $A = (a_1, a_2, a_3, \ldots, a_n, \ldots)$
  and $B = (b_1, b_2, b_3, \ldots, b_n, \ldots)$
  then $A \texttt{->} B = (a_1, b_2, b_3, \ldots, b_n, \ldots)$

# Lustre - Example

```
Y = false -> X and not pre(X)
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| X | : | F | T | T | T | F | F | T | T |
| | : | | | | | | | | |
| | : | | | | | | | | |
| | : | | | | | | | | |
| | : | | | | | | | | |
| | : | | | | | | | | |
| Y | : | F | T | F | F | F | F | T | F |

# Lustre - Example

```
Y = false -> X and not pre(X)
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| X | : | F | T | T | T | F | F | T | T |
| pre(X) | : | nil | F | T | T | T | F | F | T |
| | : | | | | | | | | |
| | : | | | | | | | | |
| | : | | | | | | | | |
| | : | | | | | | | | |
| Y | : | F | T | F | F | F | F | T | F |

# Lustre - Example

```
Y = false -> X and not pre(X)
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| X | : | F | T | T | T | F | F | T | T |
| pre(X) | : | nil | F | T | T | T | F | F | T |
| not pre(X) | : | nil | T | F | F | F | T | T | F |
| | : | | | | | | | | |
| | : | | | | | | | | |
| | : | | | | | | | | |
| Y | : | F | T | F | F | F | F | T | F |

# Lustre - Example

```
Y = false -> X and not pre(X)
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| X | : | F | T | T | T | F | F | T | T |
| pre(X) | : | nil | F | T | T | T | F | F | T |
| not pre(X) | : | nil | T | F | F | F | T | T | F |
| X and not pre(X) | : | nil | T | F | F | F | F | T | F |
| | : | | | | | | | | |
| | : | | | | | | | | |
| Y | : | F | T | F | F | F | F | T | F |

# Lustre - Example

```
Y = false -> X and not pre(X)
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| X | : | F | T | T | T | F | F | T | T |
| pre(X) | : | nil | F | T | T | T | F | F | T |
| not pre(X) | : | nil | T | F | F | F | T | T | F |
| X and not pre(X) | : | nil | T | F | F | F | F | T | F |
| false | : | F | F | F | F | F | F | F | F |
| | : | | | | | | | | |
| Y | : | F | T | F | F | F | F | T | F |

# Lustre - Example

```
Y = false -> X and not pre(X)
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| X | : | F | T | T | T | F | F | T | T |
| pre(X) | : | nil | F | T | T | T | F | F | T |
| not pre(X) | : | nil | T | F | F | F | T | T | F |
| X and not pre(X) | : | nil | T | F | F | F | F | T | F |
| false | : | F | F | F | F | F | F | F | F |
| false -> X and not pre(X) | : | F | T | F | F | F | F | T | F |
| Y | : | F | T | F | F | F | F | T | F |

# Lustre and SCADE

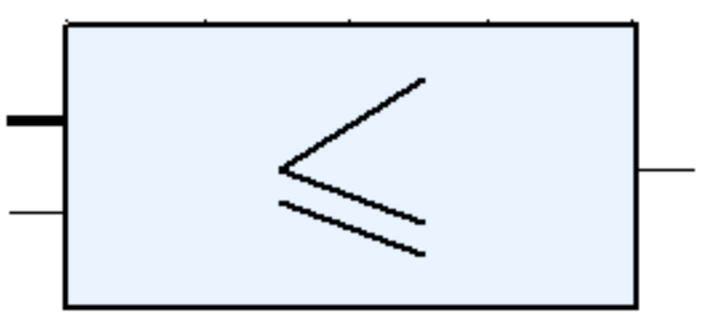
- In SCADE, models are represented graphically
- Scade operators correspond to Lustre operators

# Operators in SCADE

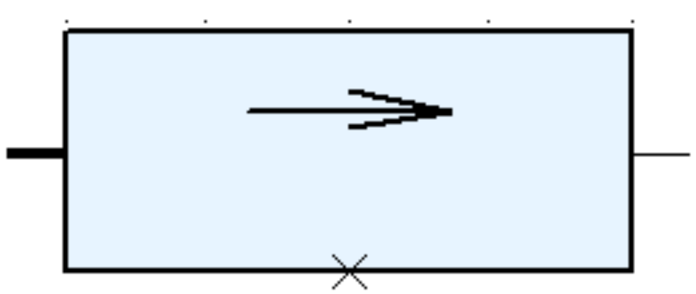

Constant flow


Input flow


Output flow



Comparison

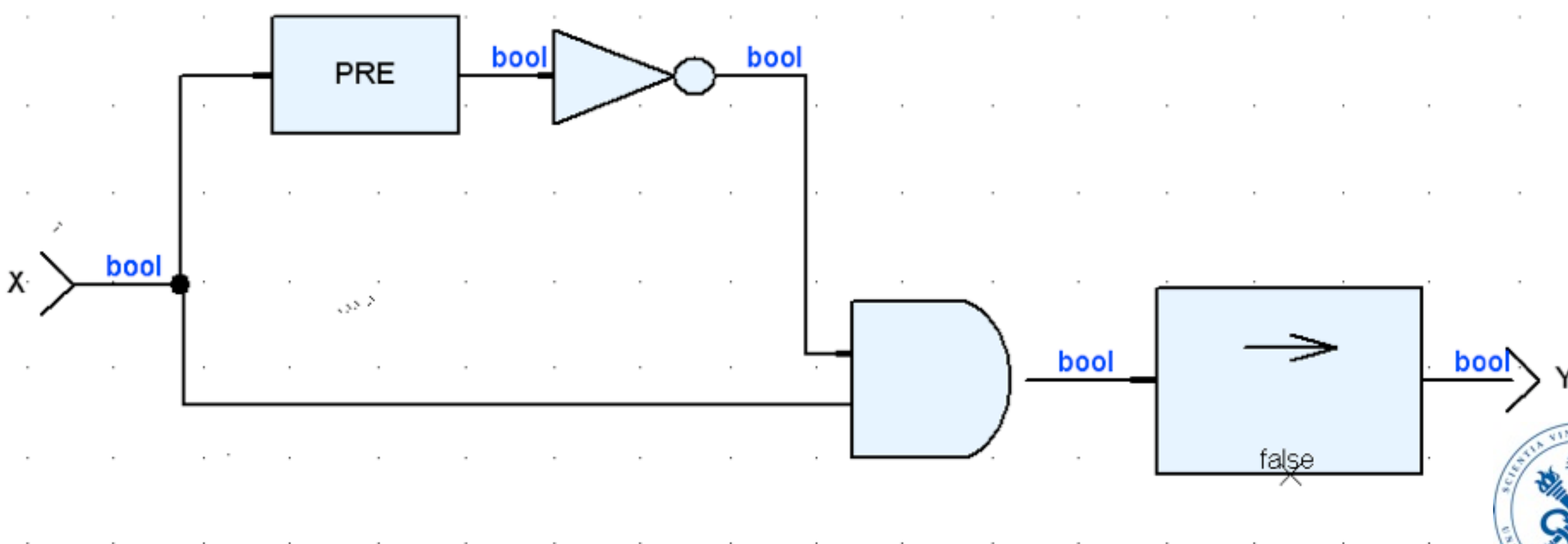


Initialisation

# Operators in SCADE

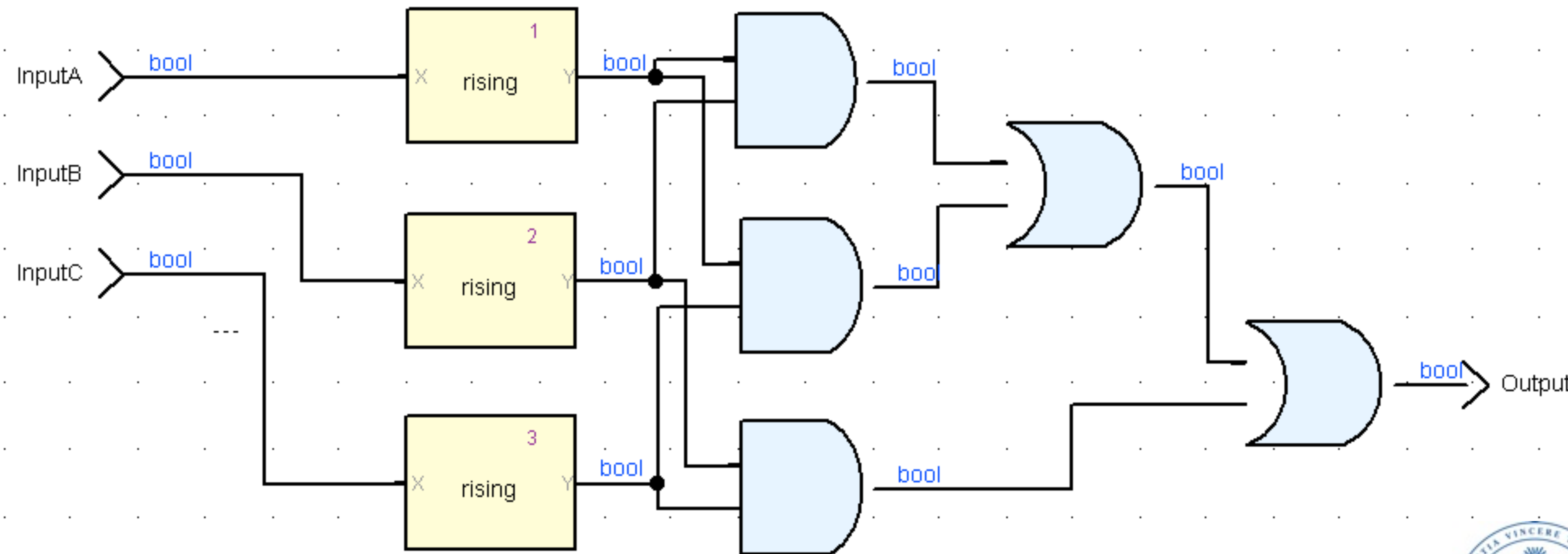
- Operators are combined to create nodes by linking them

```
Y = false -> X and not pre(X)
```



# Operators in SCADE

- Once a node is defined, it becomes an operator that can be invoked in other nodes



# SCADE - Simulator

- Models can be simulated in Scade
- The simulator computes the value of each flow at each cycle.
- The user can enter values for the input flows and observe the output flows (values can be plotted)

# SCADE - Simulator

- Demo... (fichier “operateurs”)

# SCADE - Verification

- Once the model has been debugged thanks to the simulator, it can be formally validated.
- SCADE allows to prove that a Boolean flow chosen by the user is always `true`.

# SCADE - Verification

- One thus has to design a flow (called a monitor) which is true iff a given property is verified
- This produces a proof of the property

$\Phi$ holds on the model

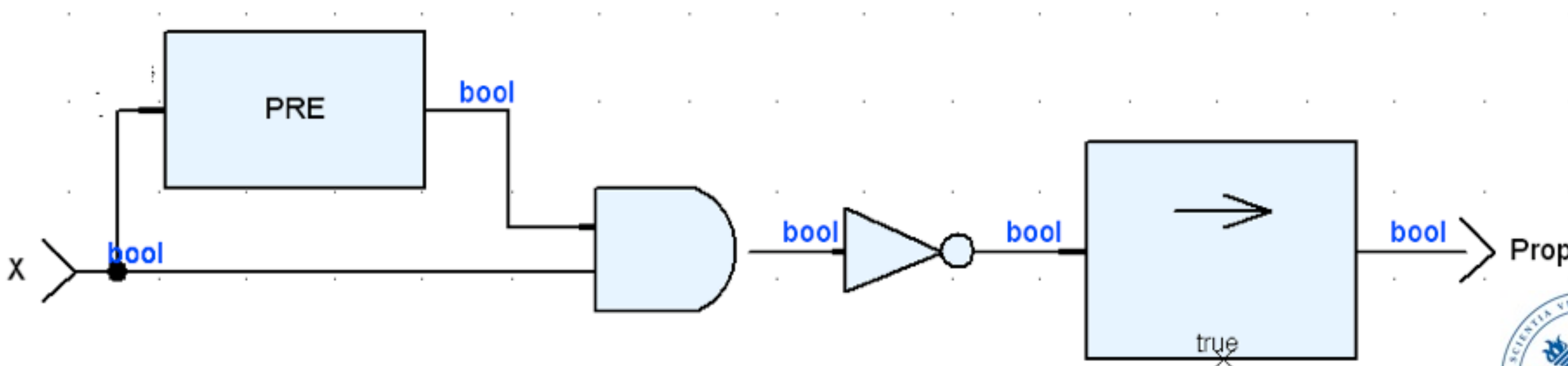
iff

`F = true`

proved by SCADE

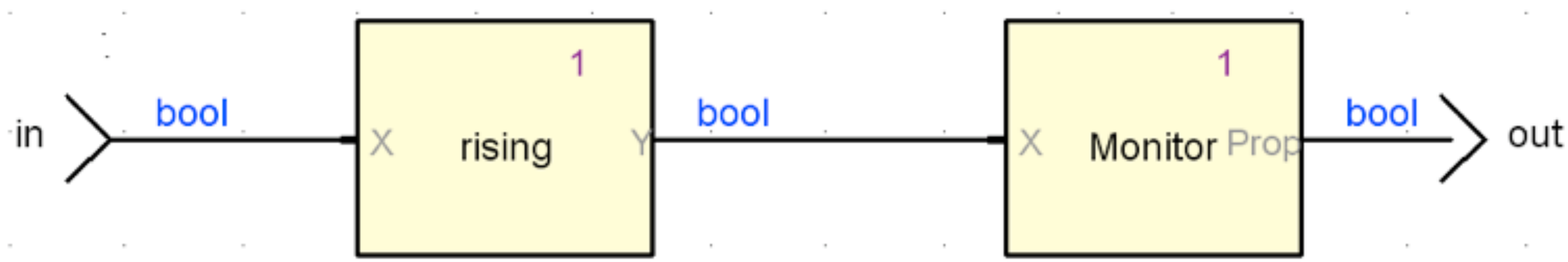
# SCADE - Verification

- Example: for the rising edge node, we want to make sure that we never have `true` as output during two consecutive cycles.
- `prop = true -> not(x and pre(x))`



# SCADE - Verification

- The monitor is then composed with the node to observe



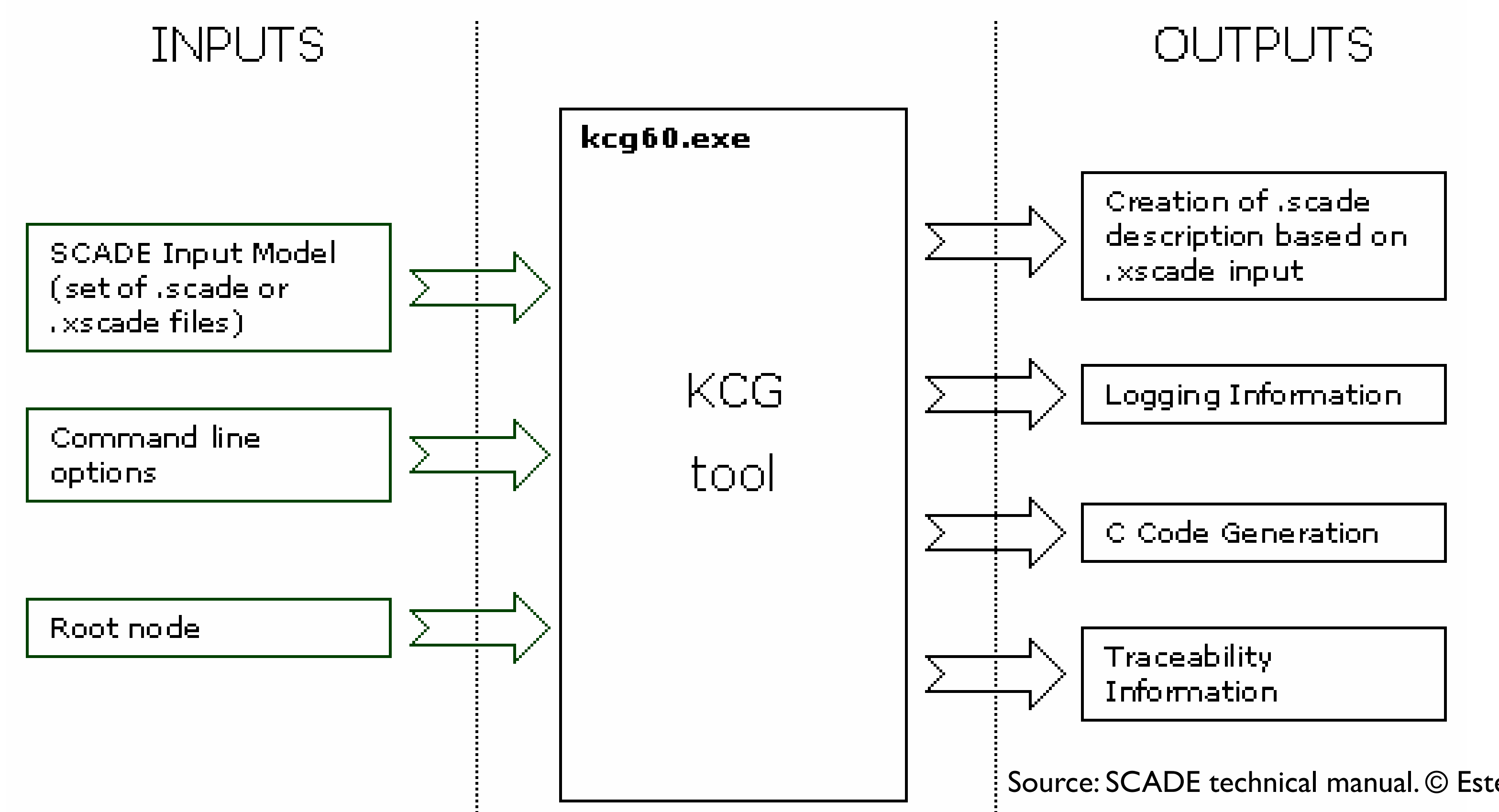

- And we check that the output of the monitor is always true

# SCADE - Verification

- Démo... (fichier “operateurs”)

# SCADE - Generation

- SCADE can generate C code from a given model
- Each node is translated as a function whose input and output parameters correspond to the input and outputs of the node

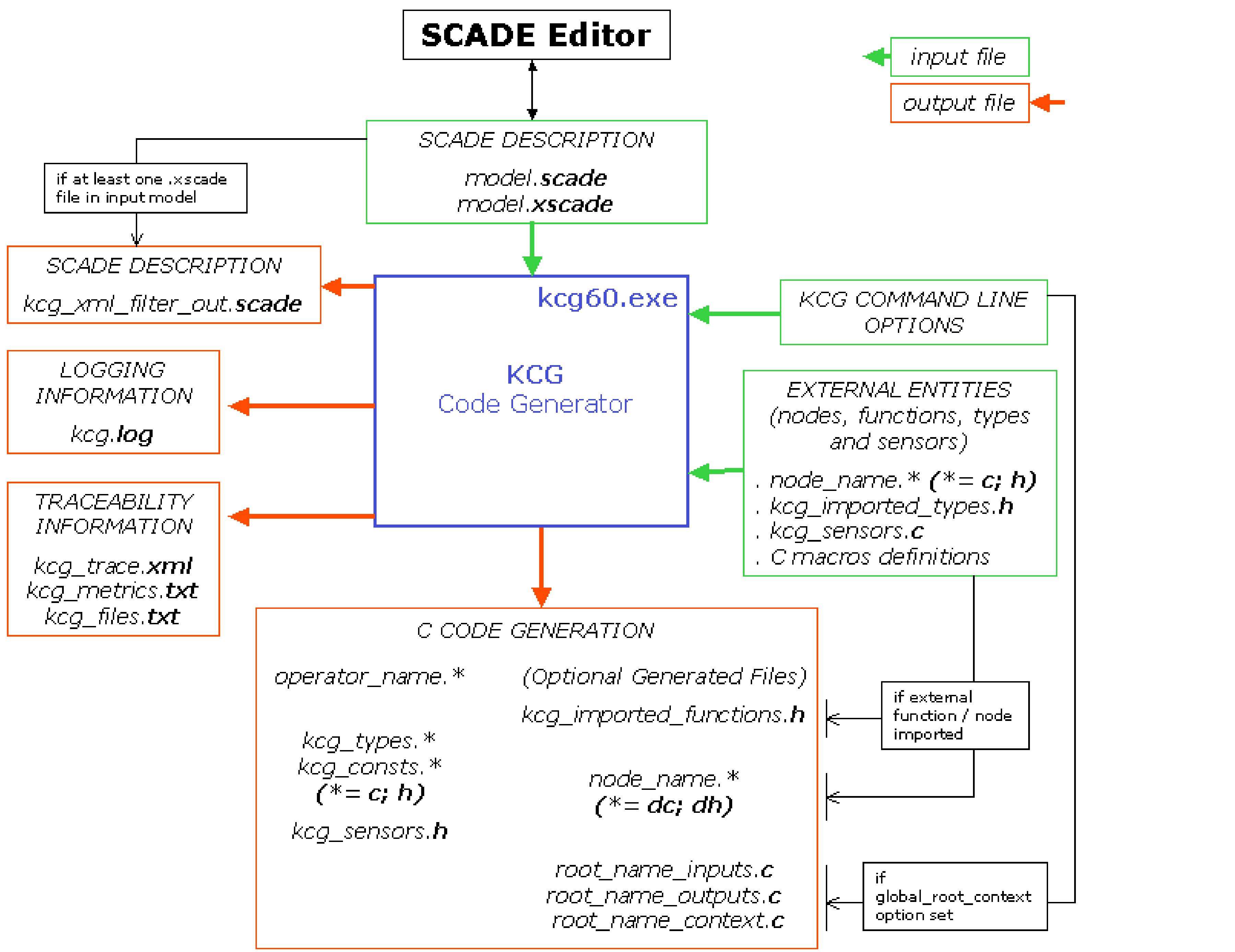



Source: SCADE technical manual. © Esterel Technologies

# SCADE - Generation

- Generated code enjoys the following characteristics:
  - It is deterministic (so is the model)
  - It contains no dynamic memory allocation (no "*out of memory*" at runtime on `malloc`...)
  - The mapping between the code and the model is (quite) clear
    - This allows to trace problems in the code back to the model

# SCADE - Generation



# SCADE - Generation

```
Y = false -> X and not pre(X)
```

## Generated code (rising.c):

```
/* $**************  KCG Version 6.0.0b (build i19) **************
** Command: s2c -config C:/Documents and Settings/Gilles/Bureau/operateurs/KCG 6.0\kcg_s2
** Generation date: 2008-12-09T17:05:12
*************************************************************$ */
#include "kcg_consts.h"
#include "kcg_sensors.h"
#include "rising.h"
void rising_reset(outC_rising *outC /* rising */)
{
  outC->init = kcg_true;
}
void rising(inC_rising *inC /* rising */, outC_rising *outC /* rising */)
{
  outC->Y = ((kcg_true ^outC->init)) & (((kcg_true ^outC->M_pre_)) & (inC->X));
  outC->M_pre_ = inC->X;
  outC->init = kcg_false;
}

/* $**************  KCG Version 6.0.0b (build i19) **************
** rising.c
** Generation date: 2008-12-09T17:05:12
*************************************************************$ */
```

# SCADE - Generation

```
Y = false -> X and not pre(X)
```

## Generated code (rising.h - part):

```
typedef struct { kcg_bool X /* rising::X */; } inC_rising;
/* rising */
/*   ========================== context type  ==========================   */

typedef struct {
  /*    ---------------------------  outputs  ---------------------------    */

  kcg_bool Y /* rising::Y */;
  /*    -----------------------  no local probes  -----------------------    */

  /*    -------------------  initialisation variables  -------------------    */

  kcg_bool init;
  /*    -------------------------  local memories  -----------------------    */

  kcg_bool M_pre_;
  /*    --------------------  no sub nodes' contexts  --------------------    */

} outC_rising;
/* rising */
/*   =======================  state vector type  =======================
```

# SCADE - Generation

```
Y = false -> X and not pre(X)
```

## Genrated Lustre Code (part):

```
/* $**************  KCG Version 6.0.0b (build i19) *************
** -
** Generation date: 2008-12-09T17:05:12
*************************************************************$ */
/* $**************  KCG Version 6.0.0b (build i19) *************
** Command: x2s C:/Documents and Settings/Gilles/Bureau/operateurs/rising.xscade
** Generation date: 2008-12-09T17:05:12
*************************************************************$ */

/* xscade source: C:/Documents and Settings/Gilles/Bureau/operateurs/rising.xscade */
node rising(X : bool) returns (Y : bool)
var
  _L1 : bool;
  _L3 : bool;
  _L4 : bool;
  _L5 : bool;
  _L6 : bool;
let
  _L1= X;
  Y= _L3;
  _L3= false -> _L4;
  _L4= _L6 and _L1;
  _L5= pre _L1;
  _L6= not _L5;
tel;
```

# SCADE - Generation

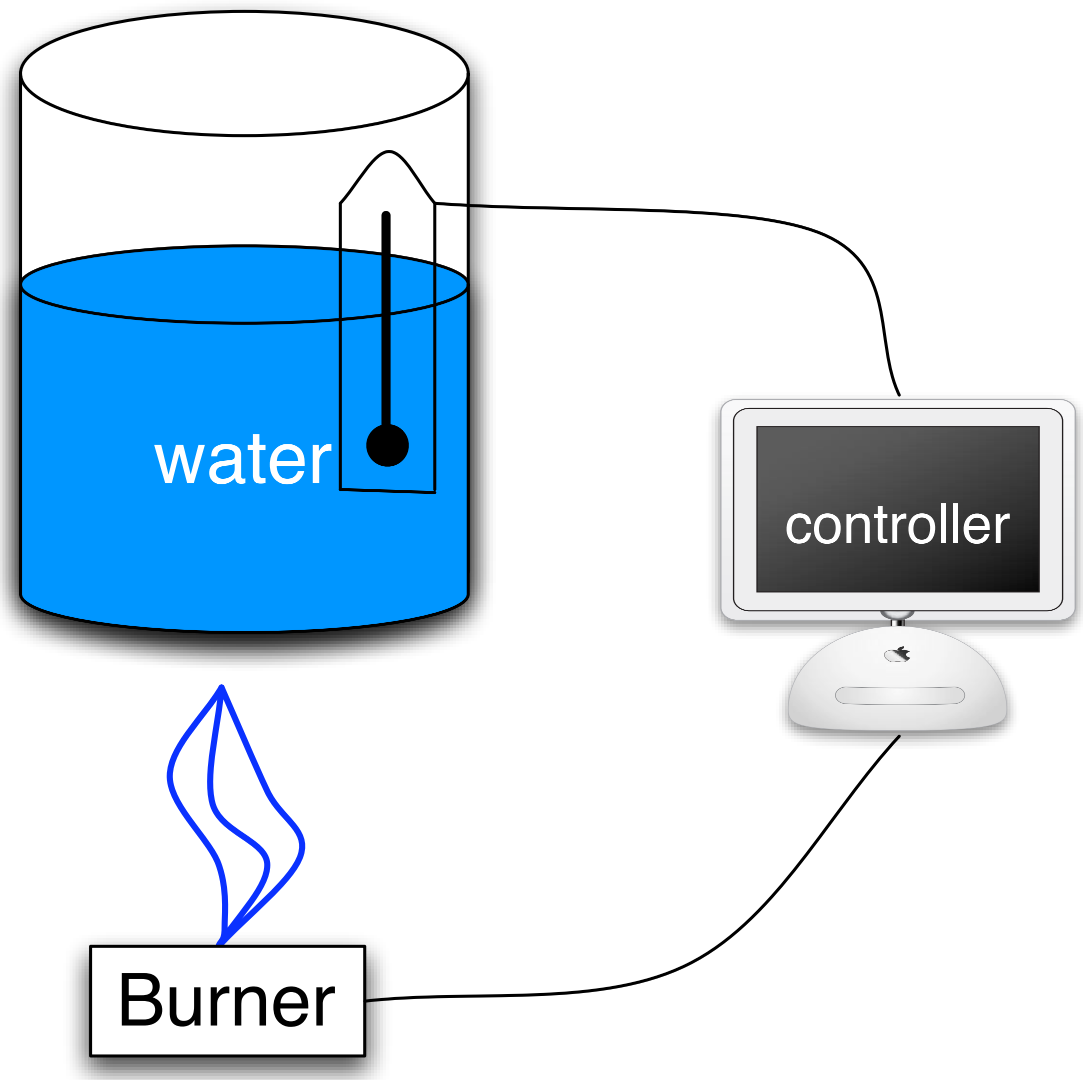
```
Y = false -> X and not pre(X)
```

## Traceability (kcg_trace.xml)


```
<?xml version="1.0" encoding="ISO-8859-1"?>
<!-- $*************** KCG Version 6.0.0b (build i19) ***************
** Command: s2c -config C:/Documents and Settings/Gilles/Bureau/operateurs/KCG 6.0\kcg_s2c_config
** Generation date: 2008-12-09T17:05:12
*************************************************************$ -->
<Model date="2008-12-09T17:05:12" commandLine="s2c -config C:/Documents and Settings/Gilles/Bureau
<RootNode scadeName="rising" targetCycleFct="rising" targetInitFct="rising_reset" headerFile="r
  <InCtxType targetName="inC_rising"/>
  <OutCtxType targetName="outC_rising"/>
  <StateVector targetName="rising_SV"/>
  <Input scadeName="X" scadeType="bool" targetName="X" targetType="kcg_bool"/>
  <Output scadeName="Y" scadeType="bool" targetName="Y" targetType="kcg_bool" inCtx="true"/>
</RootNode>
<PredefType scadeName="char" targetName="kcg_char"/>
<PredefType scadeName="bool" targetName="kcg_bool"/>
<PredefType scadeName="real" targetName="kcg_real"/>
<PredefType scadeName="int" targetName="kcg_int"/>
<Package scadeName="truthtables">
  <EnumType targetName="TruthTableValues_truthtables">
    <EnumVal scadeName="T" targetName="T_truthtables"/>
    <EnumVal scadeName="F" targetName="F_truthtables"/>
    <EnumVal scadeName="X" targetName="X_truthtables"/>
  </EnumType>
</Package>
</Model>
```

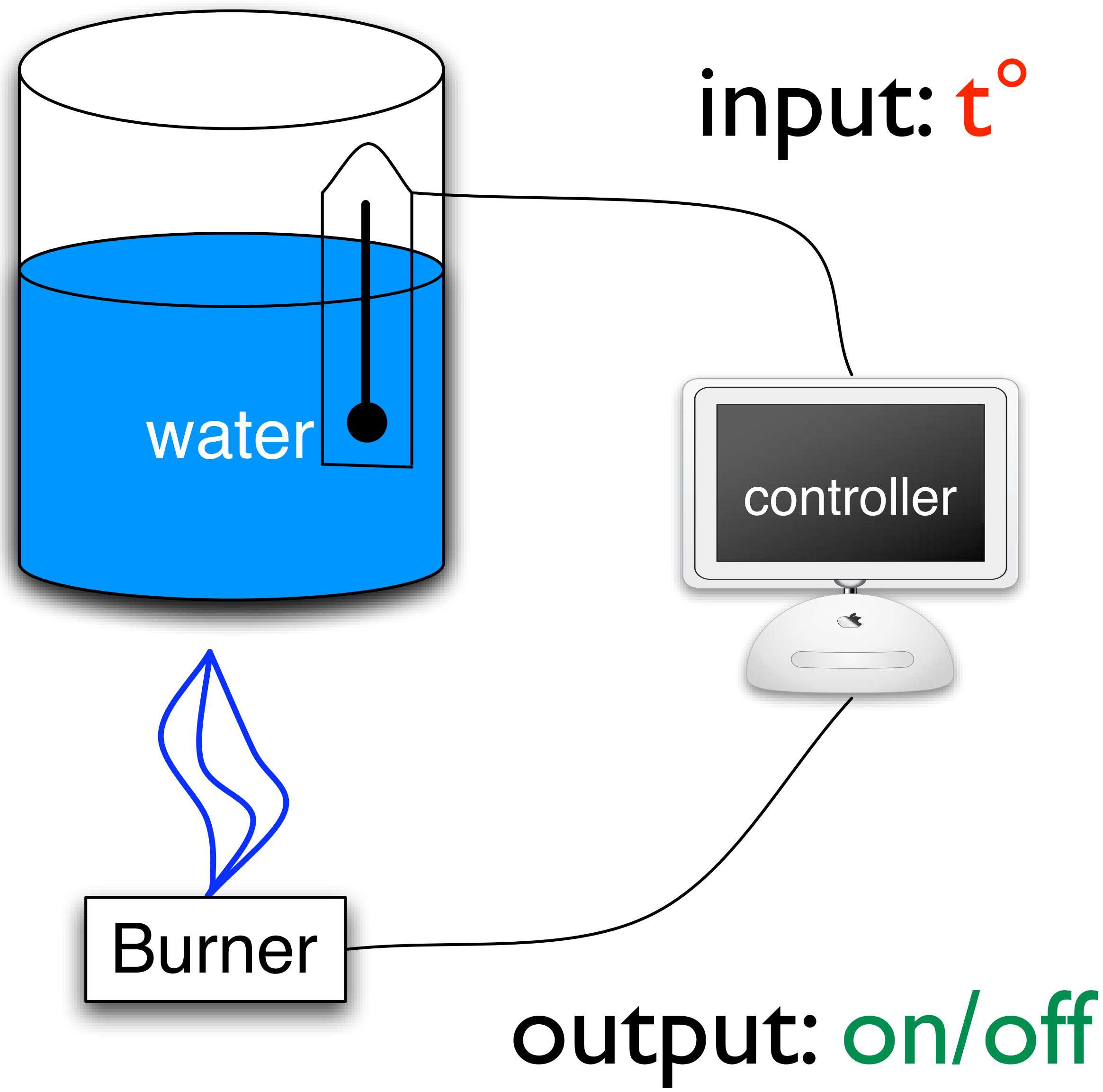
# Example - gas burner

- The controller must keep the temperature within a given interval
- Example: between 50 and 60 degrees (included)
- Initially, the temp. is in the interval



# Example - gas burner

- The controller turns the input flow (t°) into an output flow (Boolean)



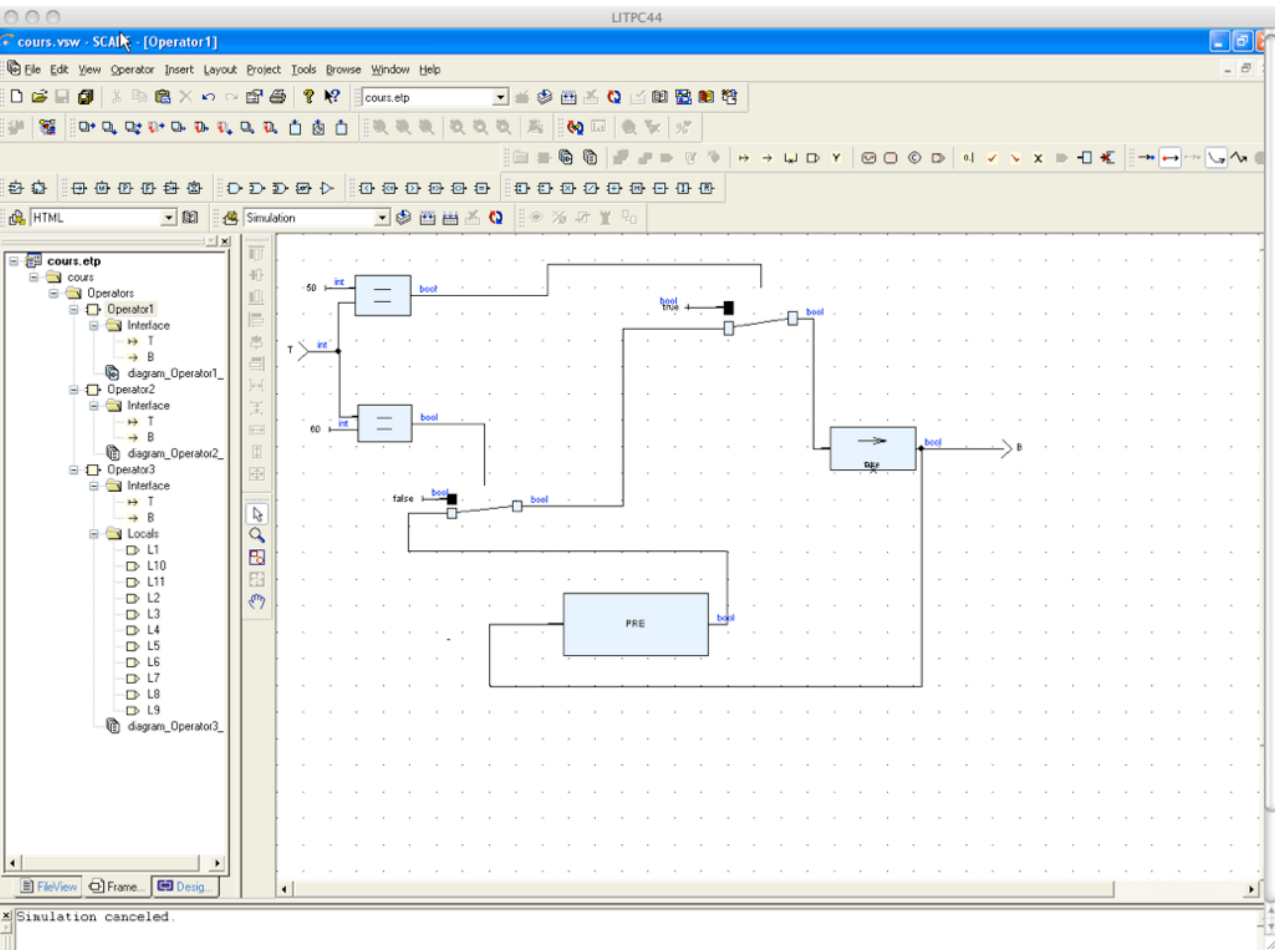
# Example - gas burner

- To find a proper model of the controller, we need hypothesis on the environment (= what has to be controlled)
  - When the burner switches on, temperature rises
  - When the burner switches off, temperature goes down

# Example - gas burner

- We propose the following control strategy:
  - When temperature reaches 50 °c, turn on the burner
  - When it reaches 60 °c, turn off the burner.

```
B = false -> (
     if T=50 then true
     else if T=60 then false
     else pre(B)
    )
```




vendredi 2 mars 2012

# Example - gas burner

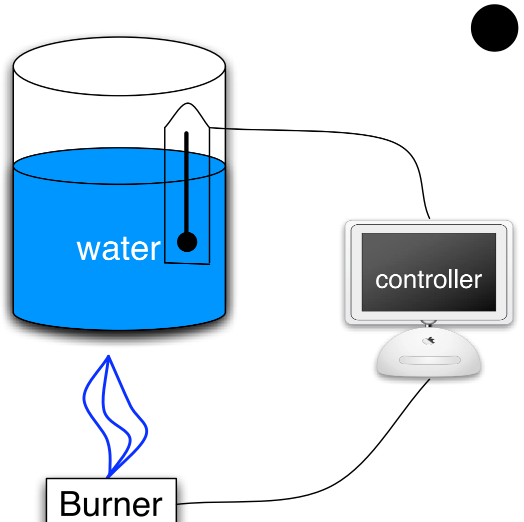
- To check that model of the controller we need a model of the environment
    - environment = burner + thermometer + tank
- This allow to simulate & verify the whole system

# Example - gas burner

- Hypothesis
  - Burner switches instantaneously
  - When heated, the temp. in the tank grows by 3°/time unit
  - When not heated, the temp. goes down by 1°/tu
  - Thermometer is precise

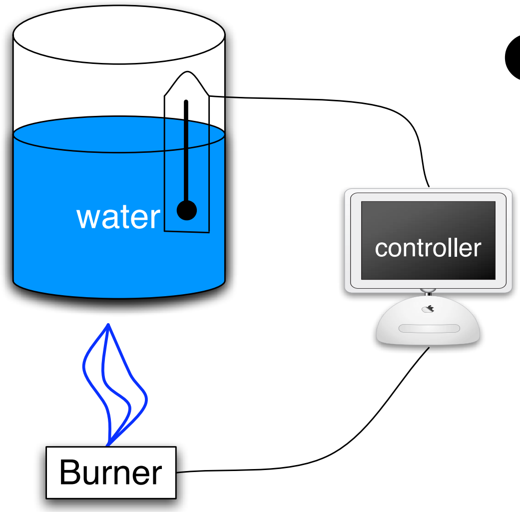
# Example - gas burner

- Thermometer:
  - 1 input: the temperature (real) of the tank: `temp`
  - 1 output: the reading: `reading`
  - equation:
    `temp = reading`



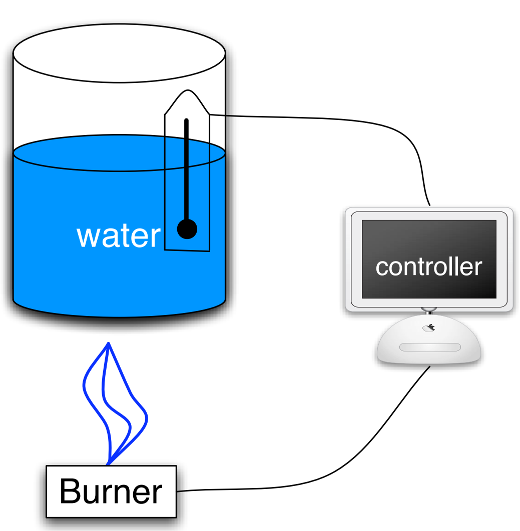
# Example - gas burner

- Burner:
  - 1 input: the command from the controller: `switch`
  - 1 output: the "flame" (Boolean): `heating`
  - equation: `heating = switch`

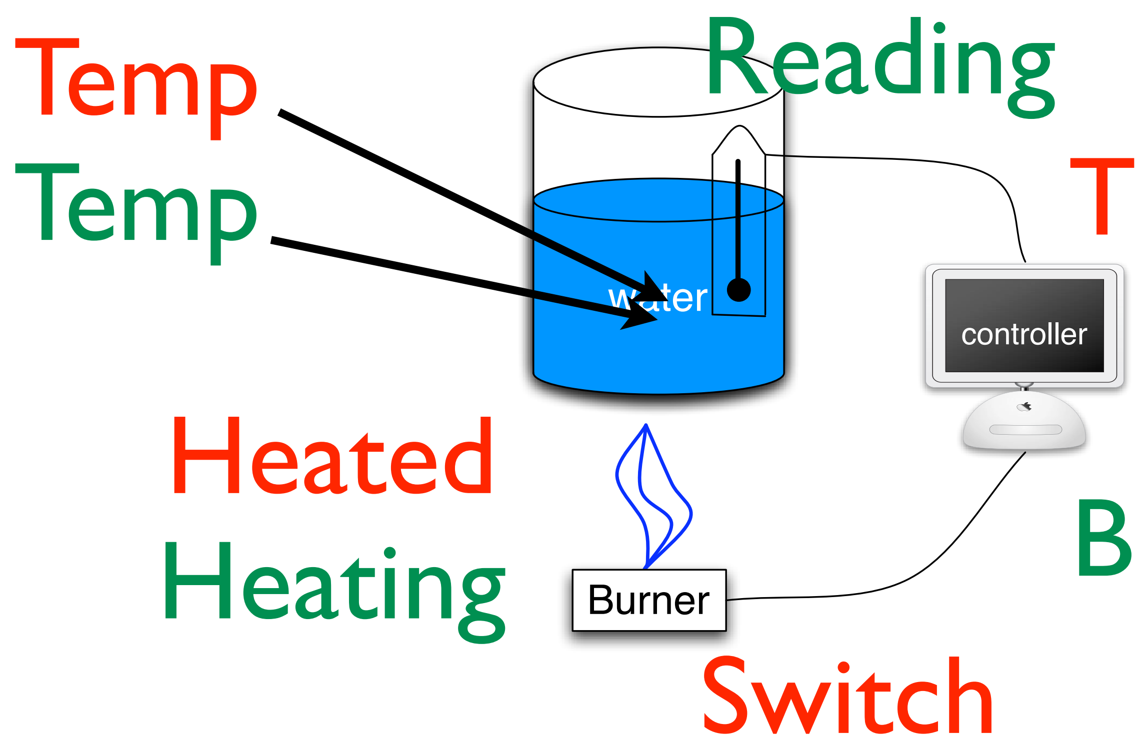


# Example - gas burner

- Tank:
  - 1 input: a Boolean indicating if the tank is being heated or not: `heated`
  - 1 output: the temperature: `temp`
  - equation:
    `temp = 55 -> (if heated then pre(temp)+3 else pre (temp)-1)`

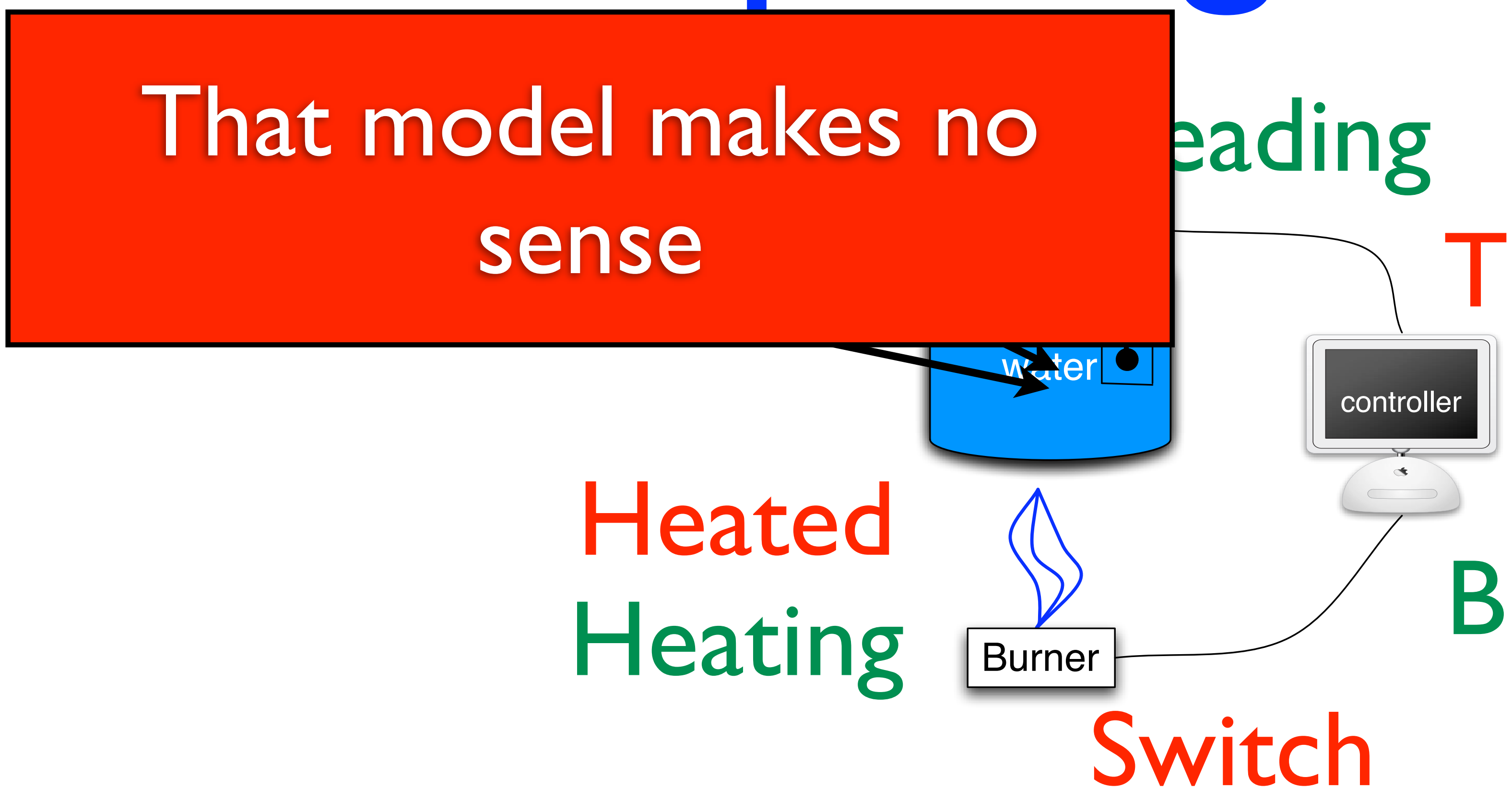


# Example - gas burner




```
Tank/Heated = Burner/Heating ;
CNTL/T = Thermo/Reading ;
Thermo/Temp = Tank/Temp ;
Burner/Switch = CNTL/B ;
```

# Example - gas burner




```
Tank/Heated = Burner/Heating ;
CNTL/T = Thermo/Reading ;
Thermo/Temp = Tank/Temp ;
Burner/Switch = CNTL/B ;
```

# Example - gas burner

That model makes no sense

eading

T

Equations are constraints, not instructions

Switch

```
Tank/Heated = Burner/Heating ;
CNTL/T = Thermo/Reading ;
Thermo/Temp = Tank/Temp ;
Burner/Switch = CNTL/B ;
```

# Example - gas burner

That model makes no sense

eading

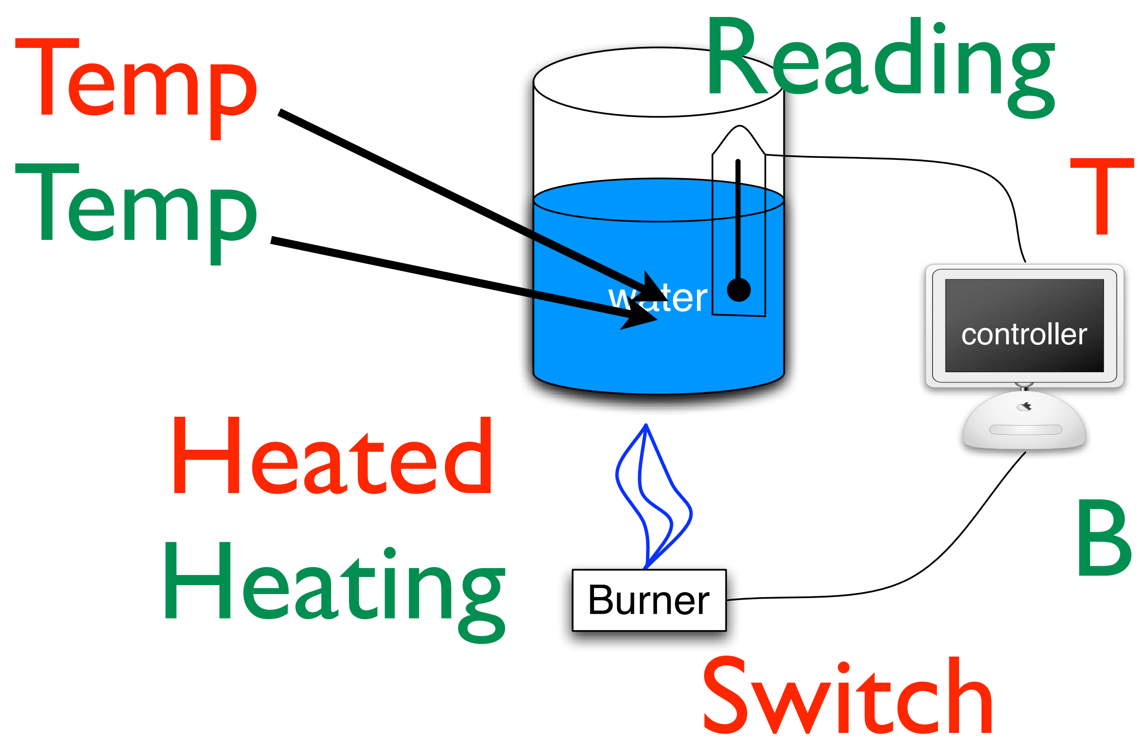
T

Equations are constraints, not instructions

There are cyclic dependencies !

```
Tank/Heated = B
CNTL/T = Thermo/Reading ;
Thermo/Temp = Tank/Temp ;
Burner/Switch = CNTL/B ;
```

# Example - gas burner




```
Tank/Heated = Burner/Heating ;
CNTL/T = Pre (Thermo/Reading) ;
Thermo/Temp = Tank/Temp ;
Burner/Switch = CNTL/B ;
```

# Example - gas burner

- Démo... (fichier “cours”)

# Example - gas burner

- The simulator in SCADE allows us to find a *bug* in our controller
  - For some initial temperatures, we never reach exactly 60 °c, and the burner will never switch off

# Example - gas burner

```
B = false -> (
     if T=50 then true
     else if T=60 then false
     else pre(B)
    )
```

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| T: | 55 | ... | 56 | 59 | 62 | 63 | ... |
| B: | False | | True | True | True | True | |

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

| | | | |
|---|---|---|---|
| T: | 55 | ... | 56 |
| B: | False | | True |

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

T: 55 ... 56

B: False True

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

| | | | | |
|---|---|---|---|---|
| T: | 55 | ... | 56 | 59 |
| B: | False | | True | True |

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

| | | | | |
|---|---|---|---|---|
| T: | 55 | | 56 | 59 |
| B: | False | ... | True | True |

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

| | | | | |
|---|---|---|---|---|
| T: | 55 | ... | 56 | 59 |
| B: | False | | True | True |

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

| | | | | | |
|---|---|---|---|---|---|
| T: | 55 | ... | 56 | 59 | 58 |
| B: | False | | True | True | False |

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

| | | | | | |
|---|---|---|---|---|---|
| T: | 55 | ... | 56 | 59 | 58 |
| B: | False | | True | True | False |

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

| | | | | | |
|---|---|---|---|---|---|
| T: | 55 | | 56 | 59 | 58 |
| B: | False | … | True | True | False |

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| T: | 55 | ... | 56 | 59 | 58 | 57 |
| B: | False | | True | True | False | False |

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

| | | | | | | |
|---|---|---|---|---|---|---|
| T: | 55 | ... | 56 | 59 | 58 | 57 |
| B: | False | | True | True | False | False |

# Example - gas burner

- This can be seen as a limit on the *sampling rate* of the CPU.
- We need to widen the conditions

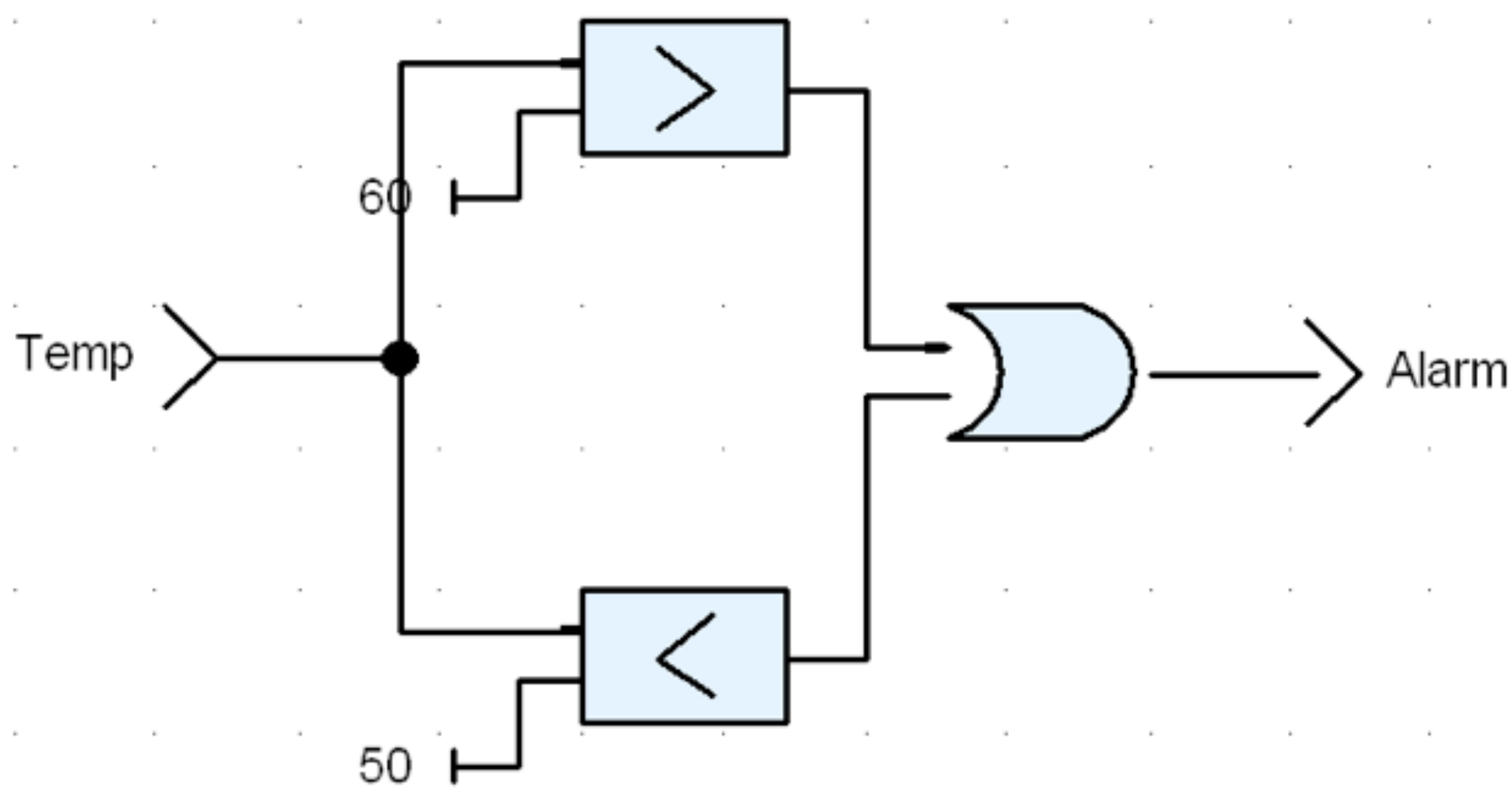
```
if T>=57 then false
```

Remind: `T` is the temperature computed at the previous cycle

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| T: | 55 | … | 56 | 59 | 58 | 57 | … |
| B: | False | | True | True | False | False | |

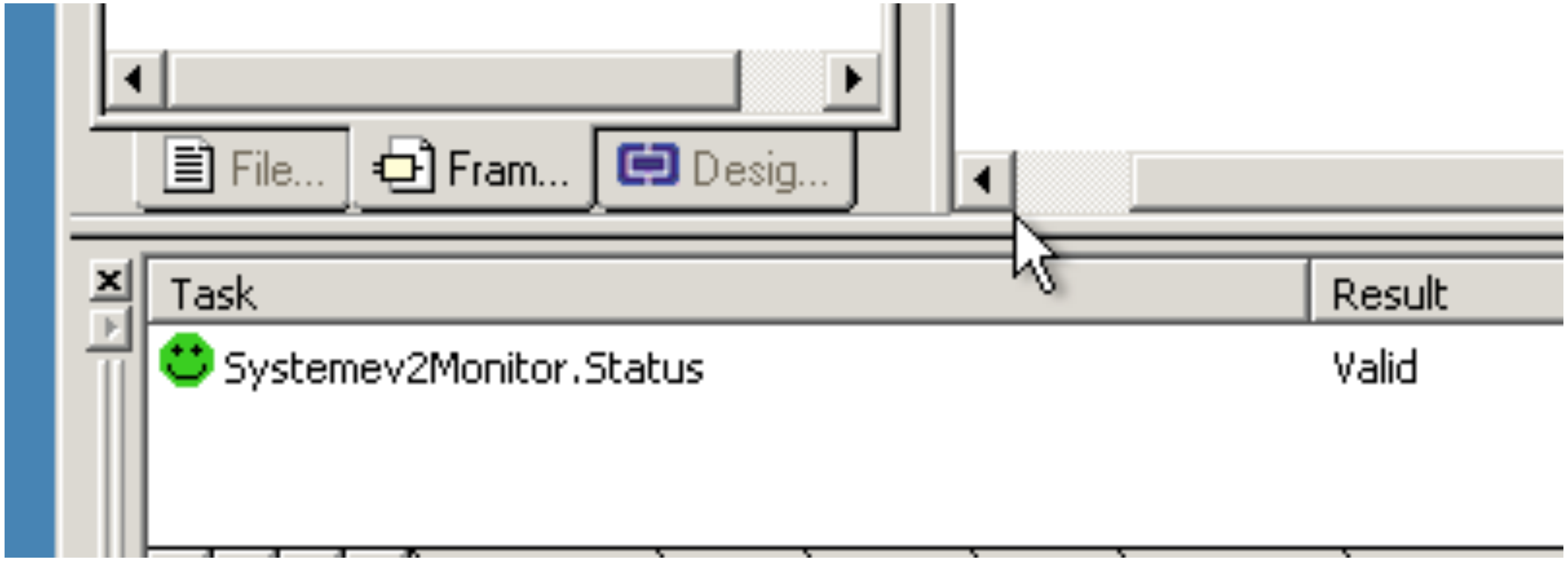
# Example - gas burner

- Let us now validate our controller by defining a monitor that will raise an alarm if the temperature goes off limits



# Example - gas burner

- Scade can prove that the property is valid...



# Example - gas burner

- Démo... (fichier system-moniteur.avi)

# Scade - State machines

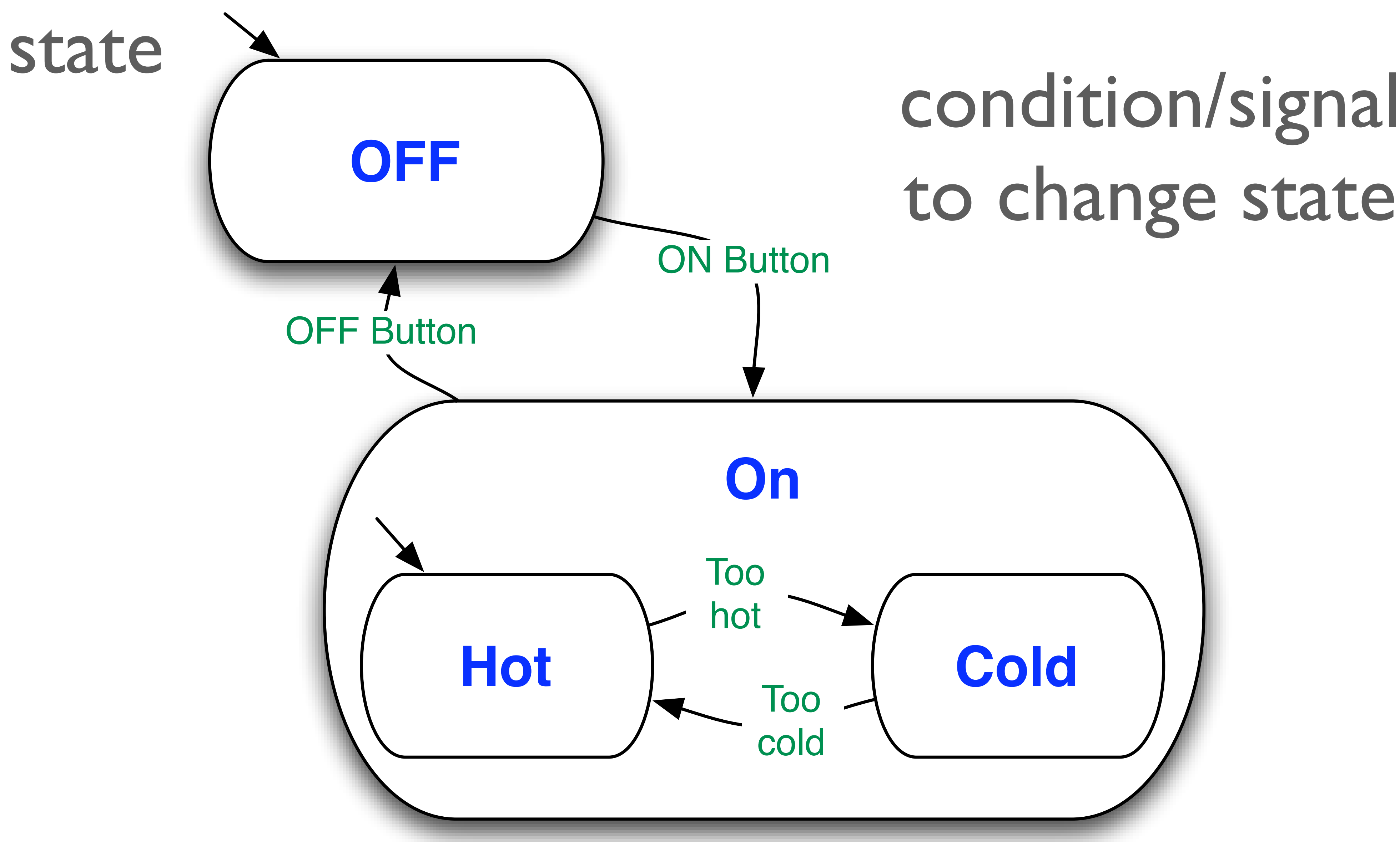
- The operators described so far manipulate data through flows
- In a realistic application, the way we manipulate date depends on the running mode

# Scade - State machines

- Example: air-co in a car
  - It can be on or off
  - When on, it can heat or refresh
  - There are thus three running modes
  - Outside *stimuli* (events) change the current running mode

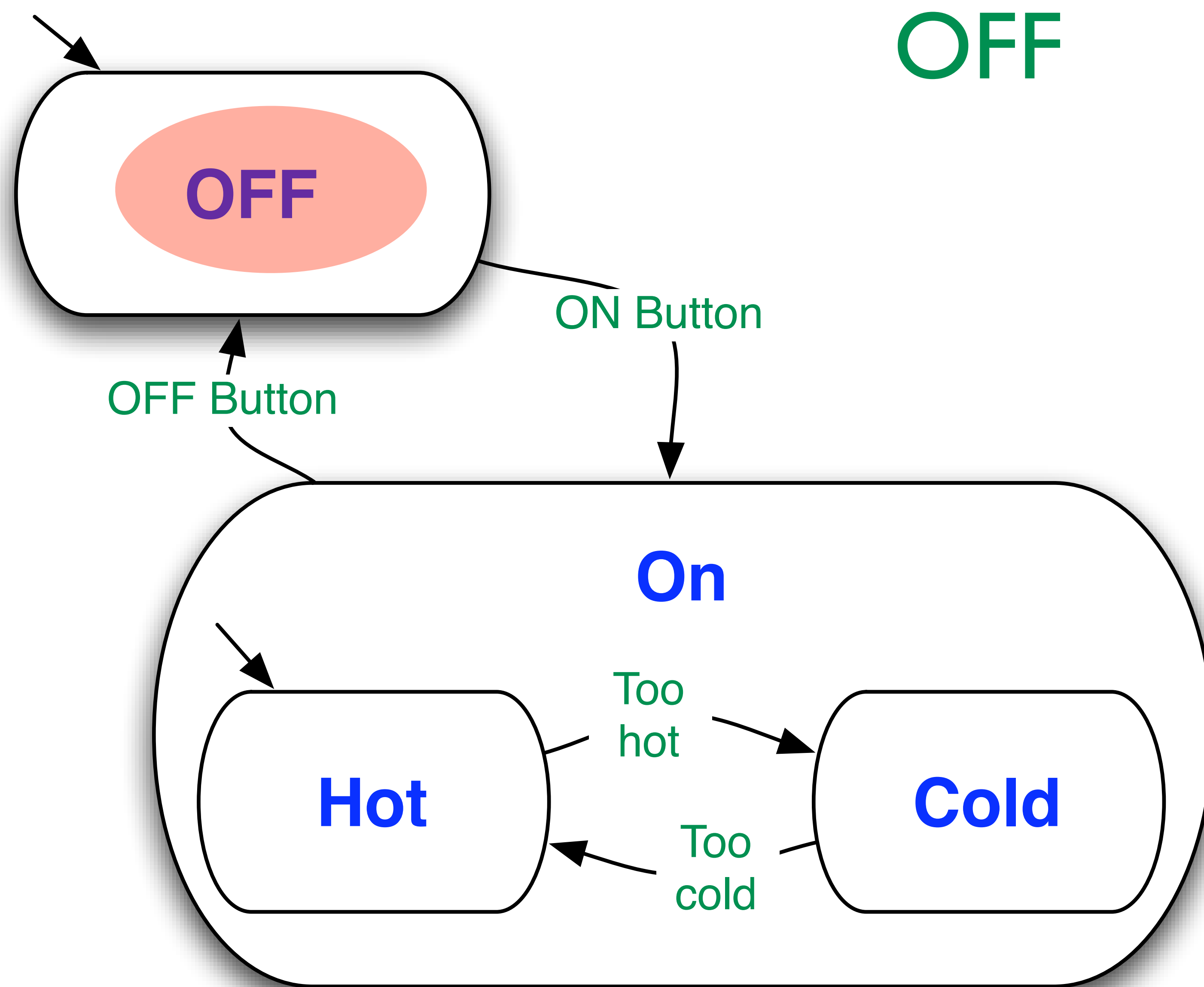
# Scade - State machines

- Example: car air-co



# Scade - State machines

- Example: car air-co

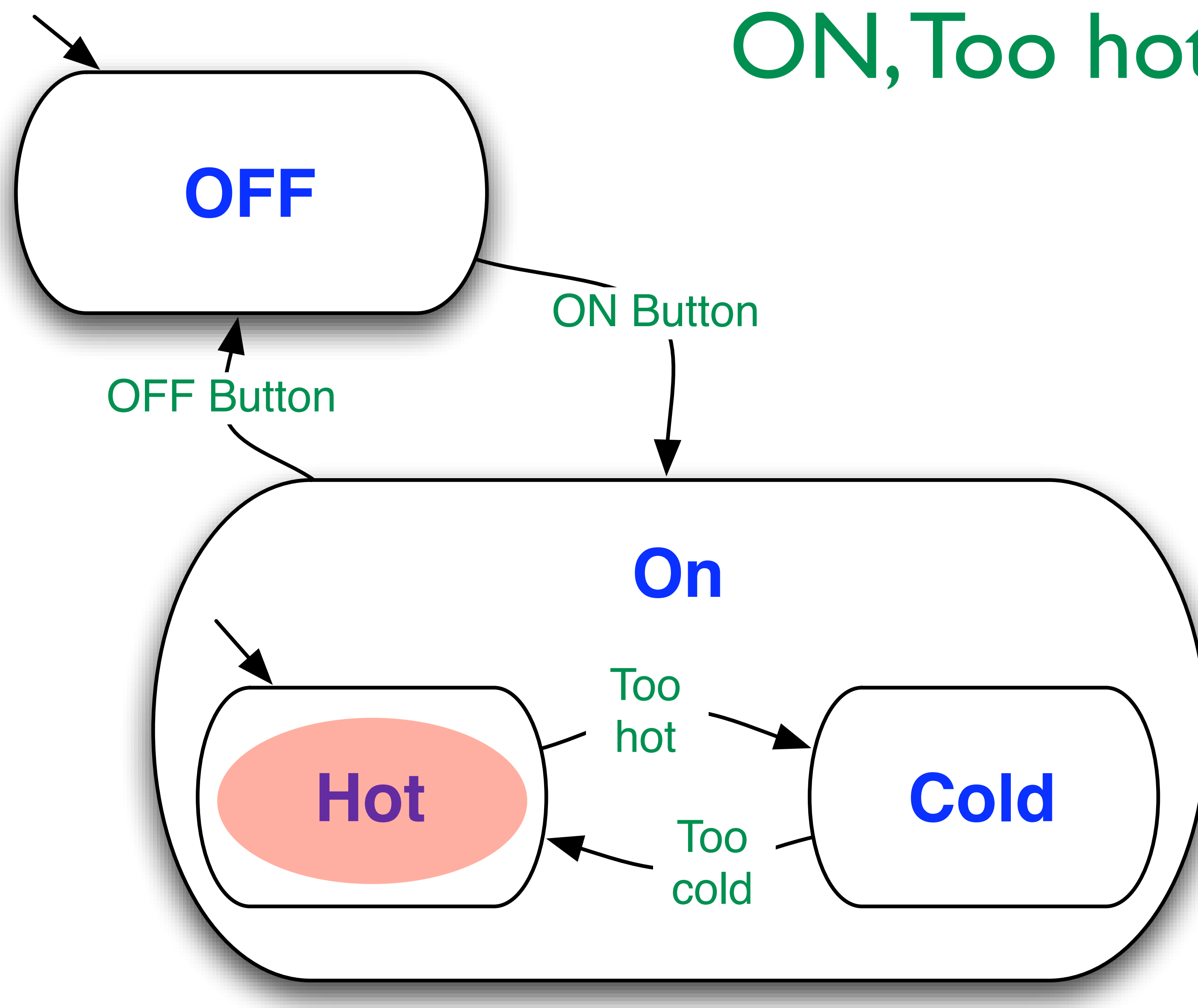



OFF

# Scade - State machines

- Example: car air-co

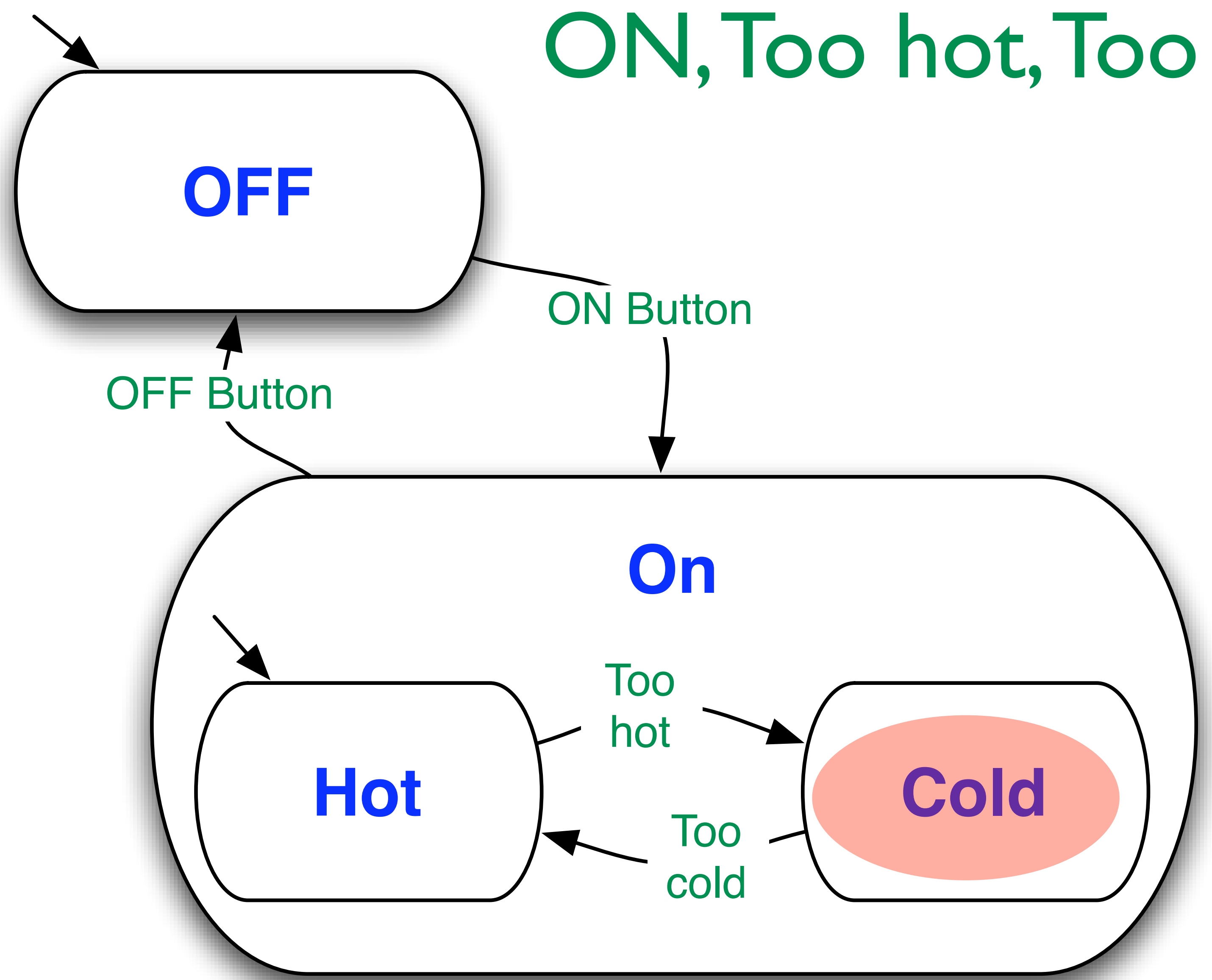
ON, Too hot



# Scade - State machines

- Example: car air-co

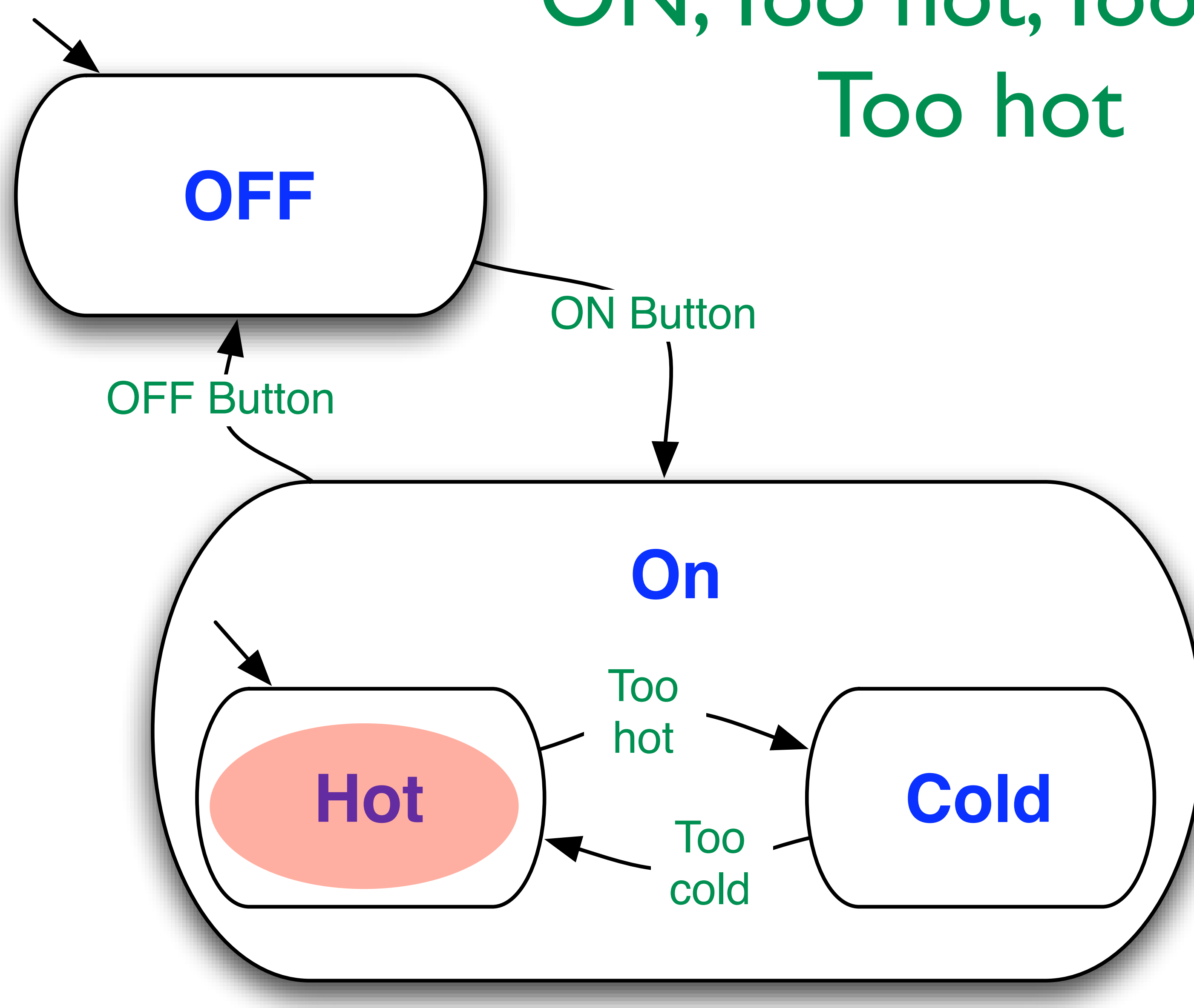
ON, Too hot, Too cold



# Scade - State machines

- Example: car air-co

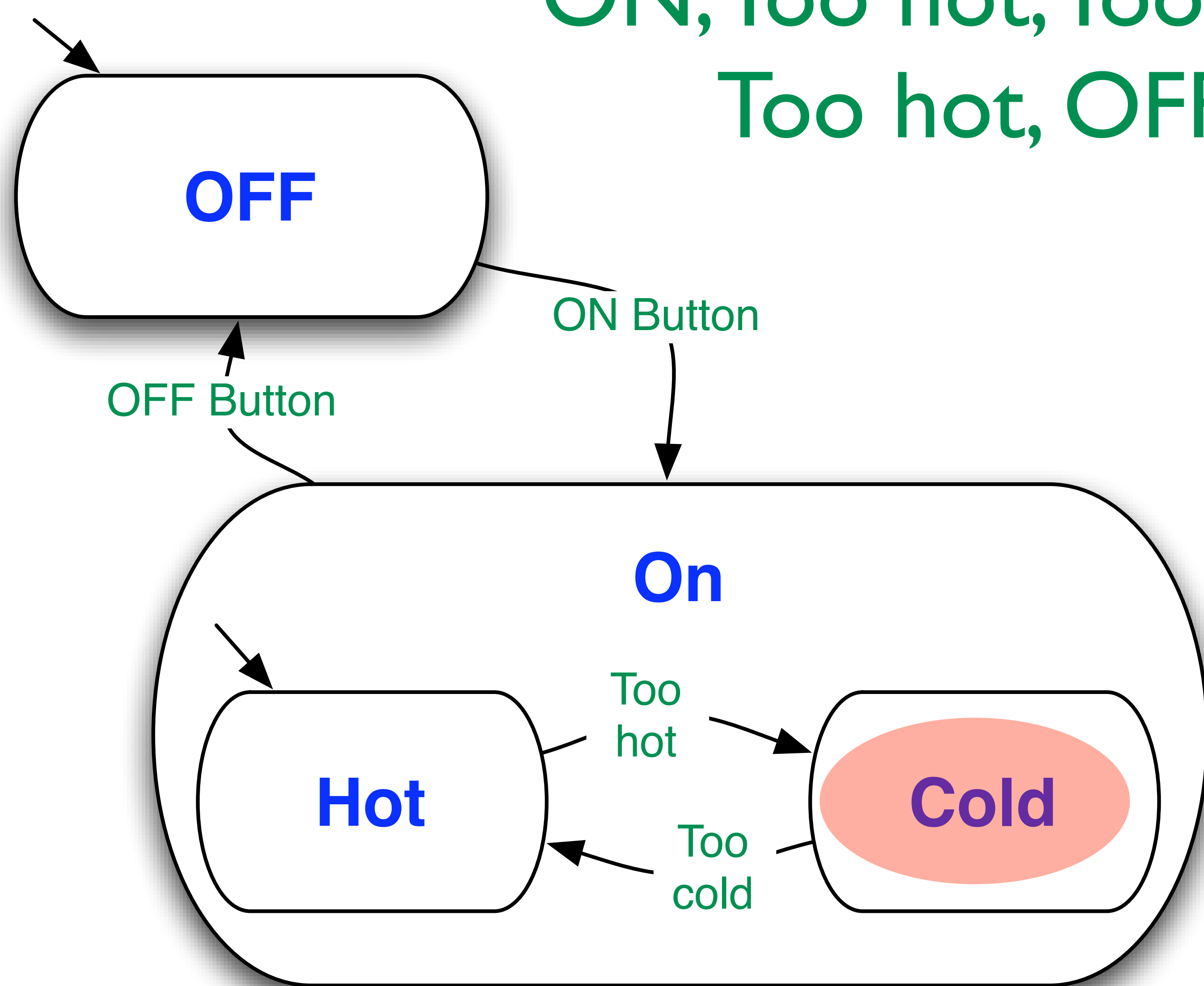
ON, Too hot, Too cold,
Too hot



# Scade - State machines

- Example: car air-co

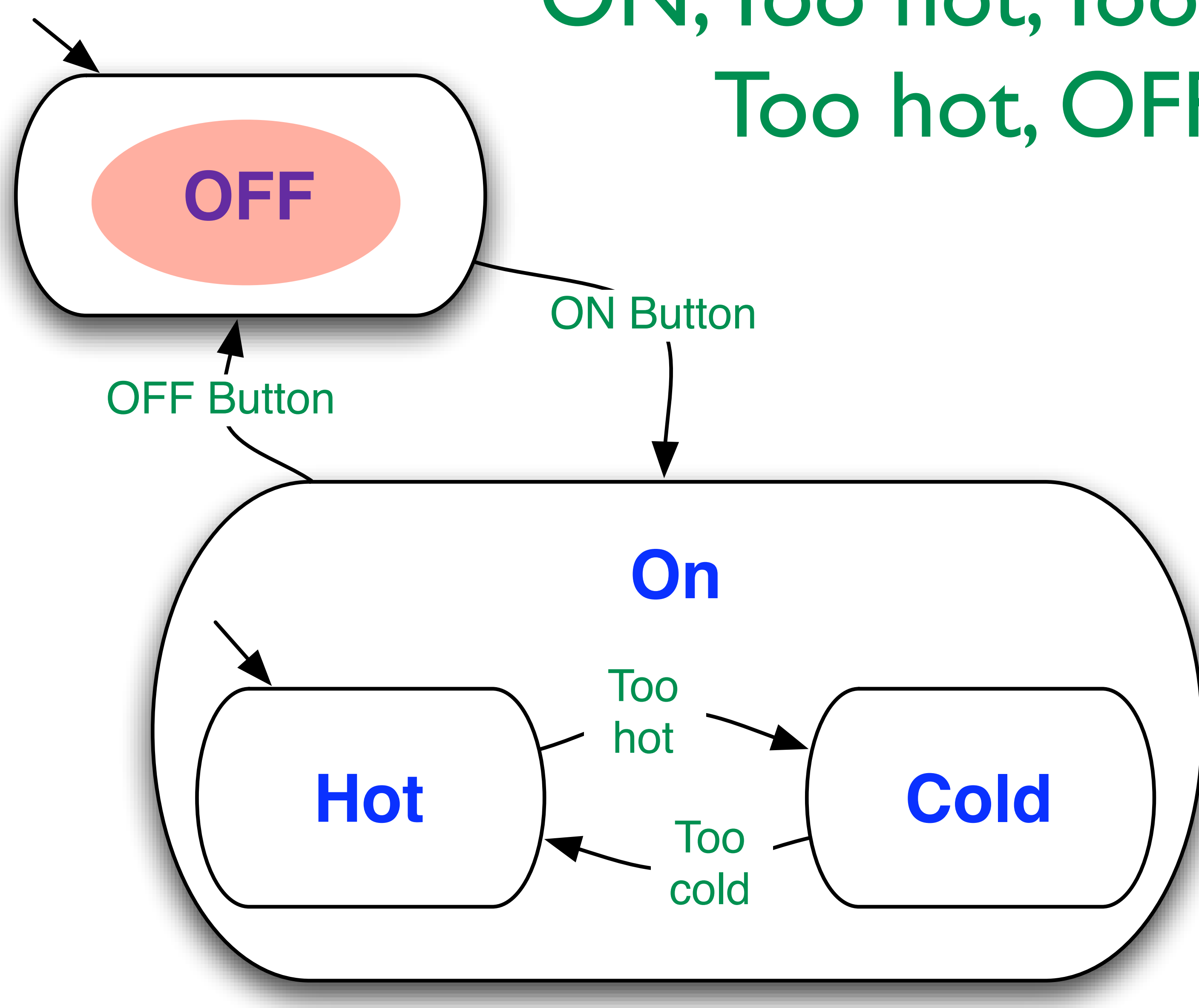
ON, Too hot, Too cold,
Too hot, OFF



# Scade - State machines

- Example: car air-co

ON, Too hot, Too cold,
Too hot, OFF



# State machines

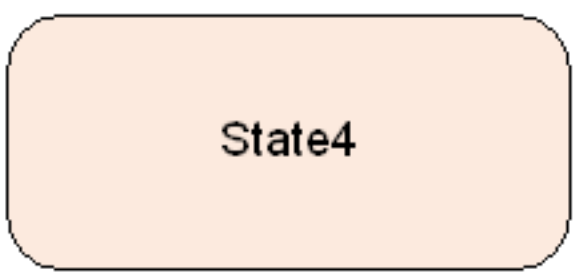
- State machines thus allow to combine two classical concepts:
  - data flows (via LUSTRE flows)
  - control flows (control depends upon the state of the state machine)

# Scade - State machines

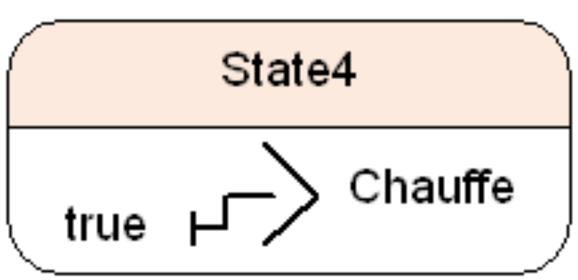
- Remark: We could do without state machines. We can encode them through flows:
  - a flow S encodes the current state.
  - the equations of the other flows contained `if` to test the value of S and determine the effect to apply.
- But state machines are more practical !

# Scade - State machines


One state machine




One state (w/o equation)




One state with one equation

# Scade - State machines

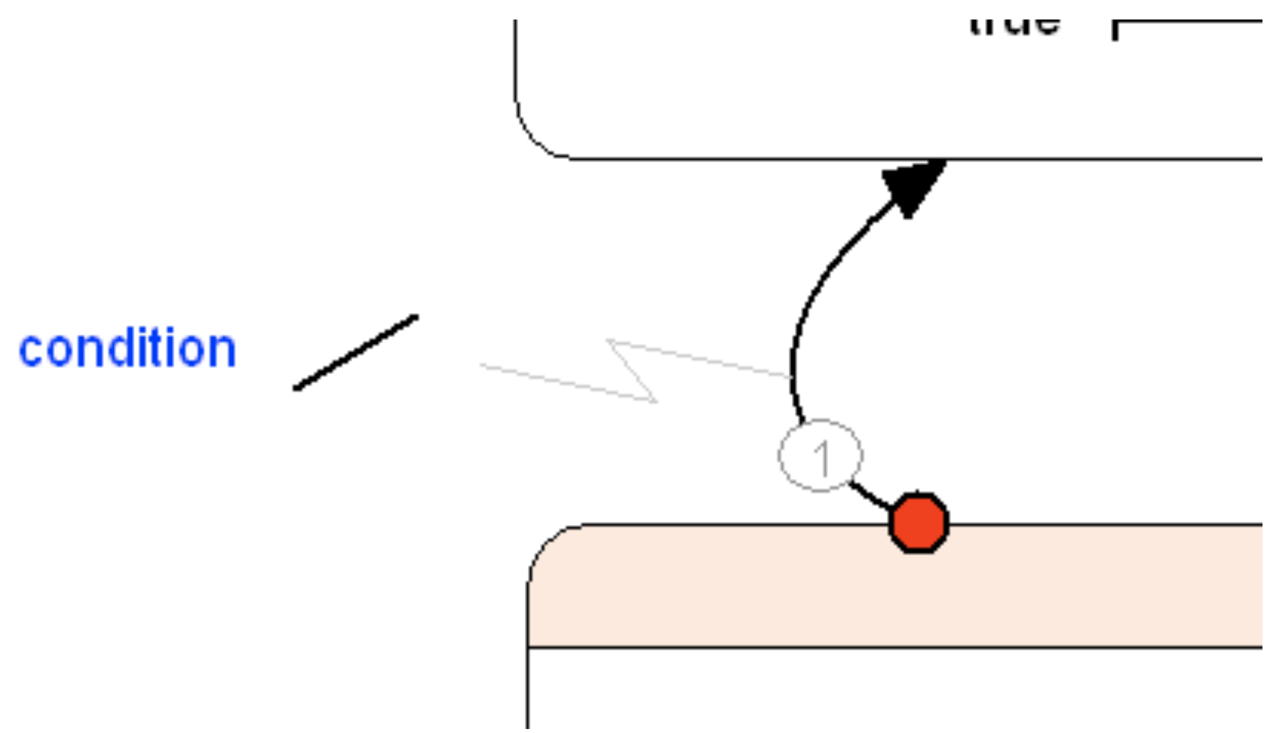
- Notion of signal:
  - Signals allow communications between state machines and:
    - other state machines
    - equations
    - the environment

# Scade - State machines

- Notion of signal:
  - A signal has a name.
  - It can be seen as a Boolean flow which is always `false`, except when the signal is sent.

# Scade - State Machines

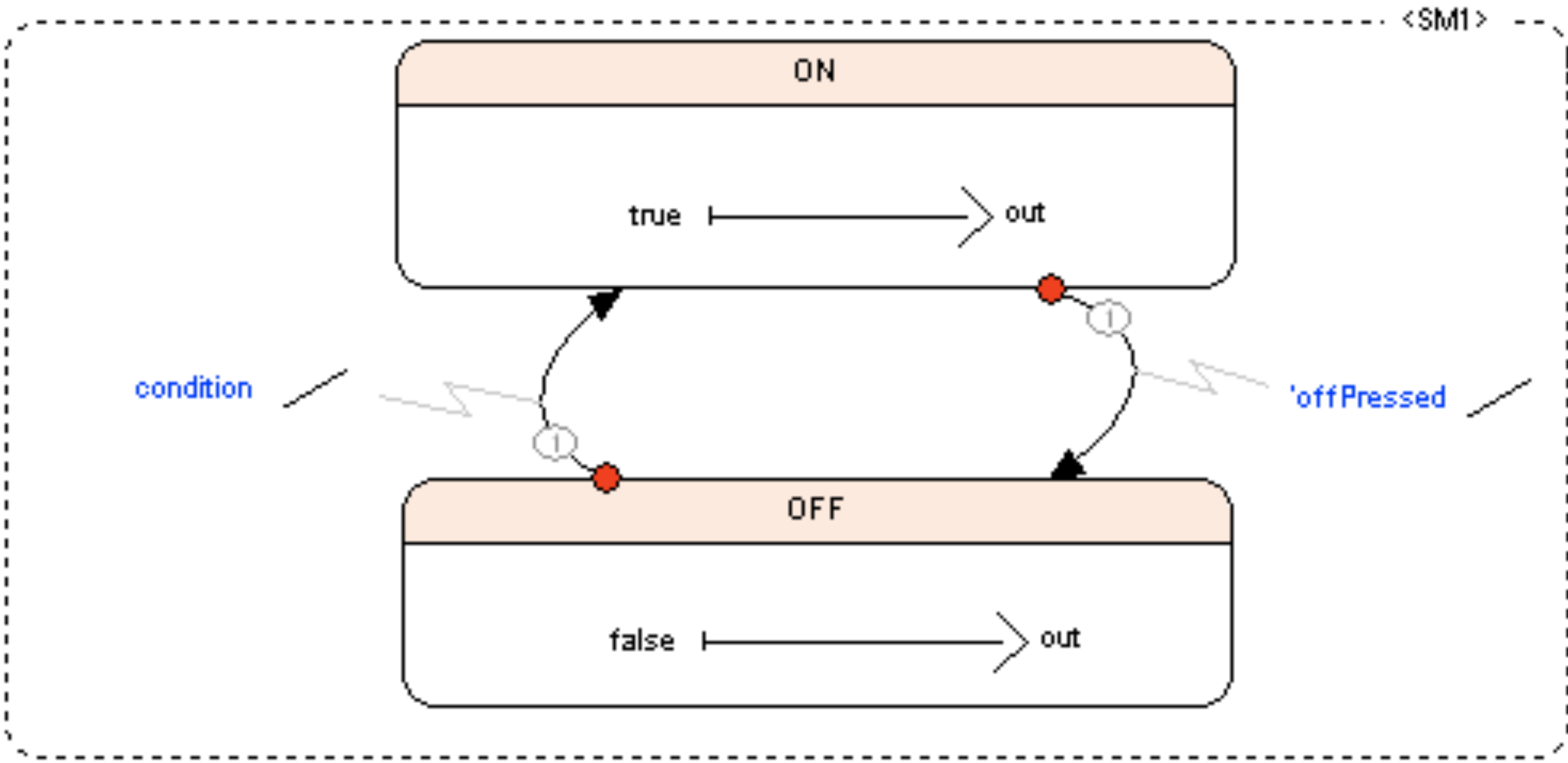
- Semantics of the state machines (summary):
  - At each time there is an active state per state machine
  - Edges allow to change the active state



# Scade - State machines

- Conditions can be added to the edges:
  - Boolean guards
  - signals: `'s` tests that `s` is sent.
- We can send a signal when a transition is taken

# Scade - State machines

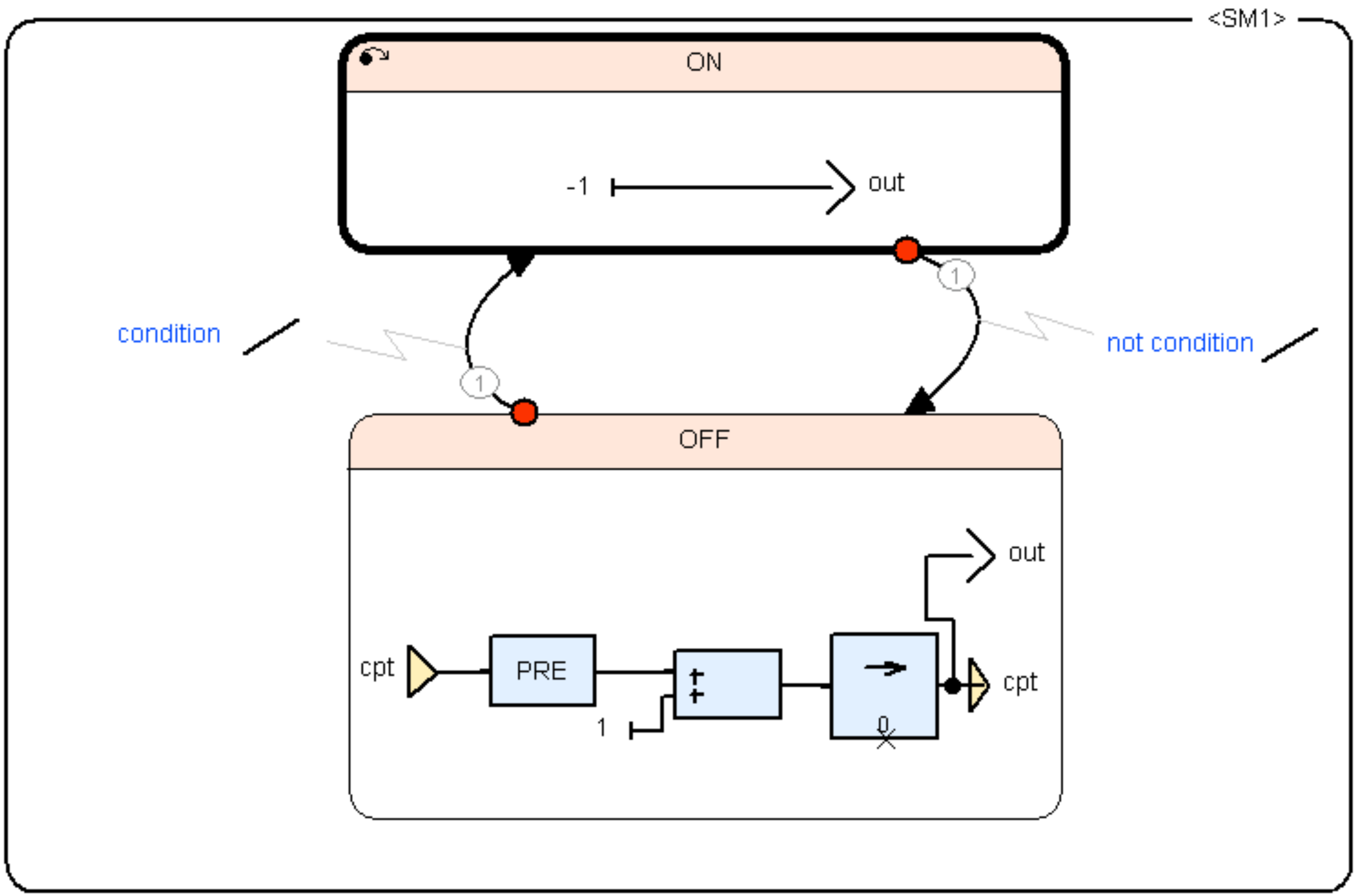


# Scade - State machines

- How to the flows inside a state behave when that state is reached ?
  - Depends on the incoming edge:
    - By default: "*restart*" edge: flows are reset
    - Otherwise: "*resume*" edge: flows keep their last values

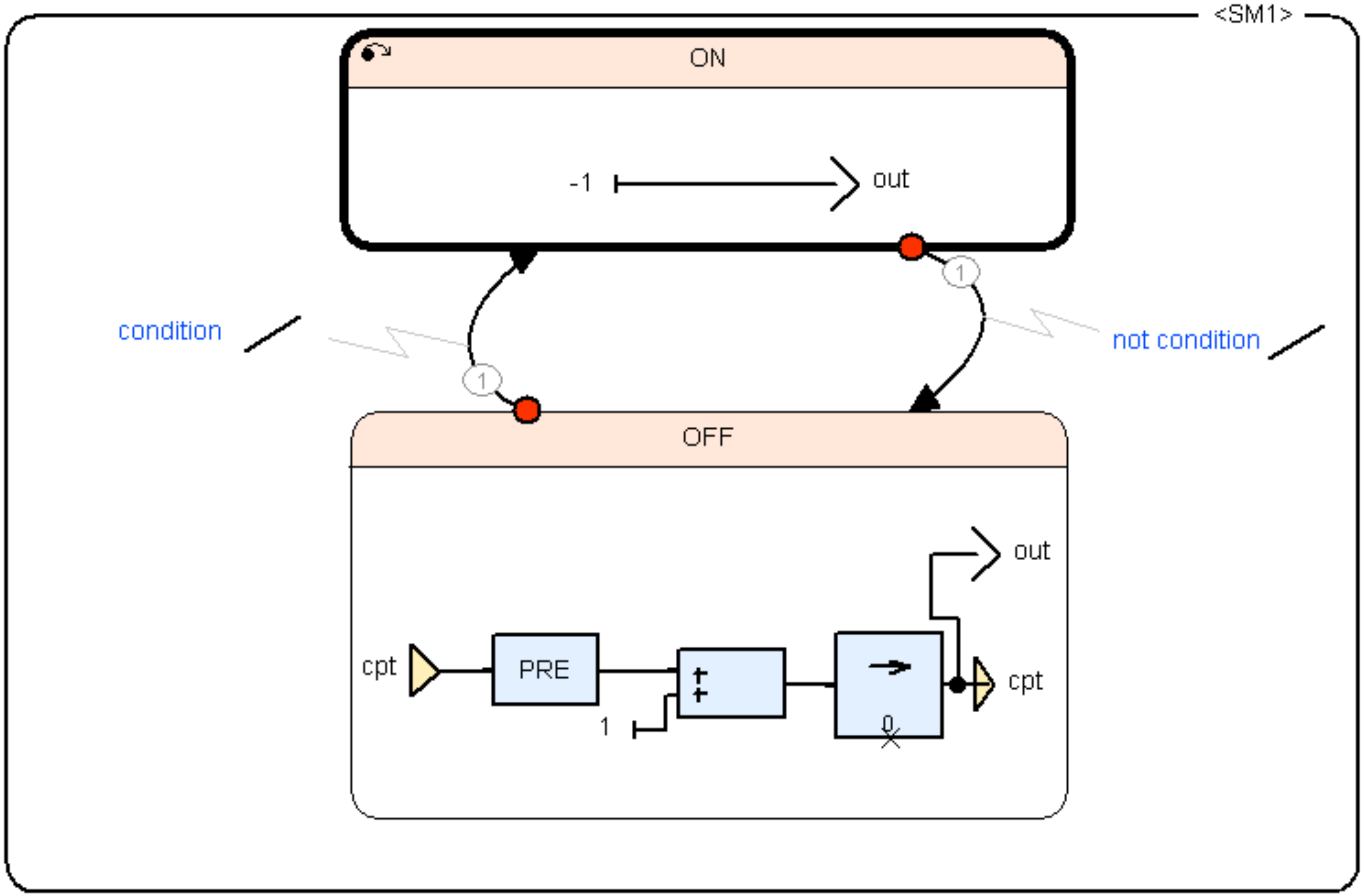
# Scade - State machines

- Example: state with a counter



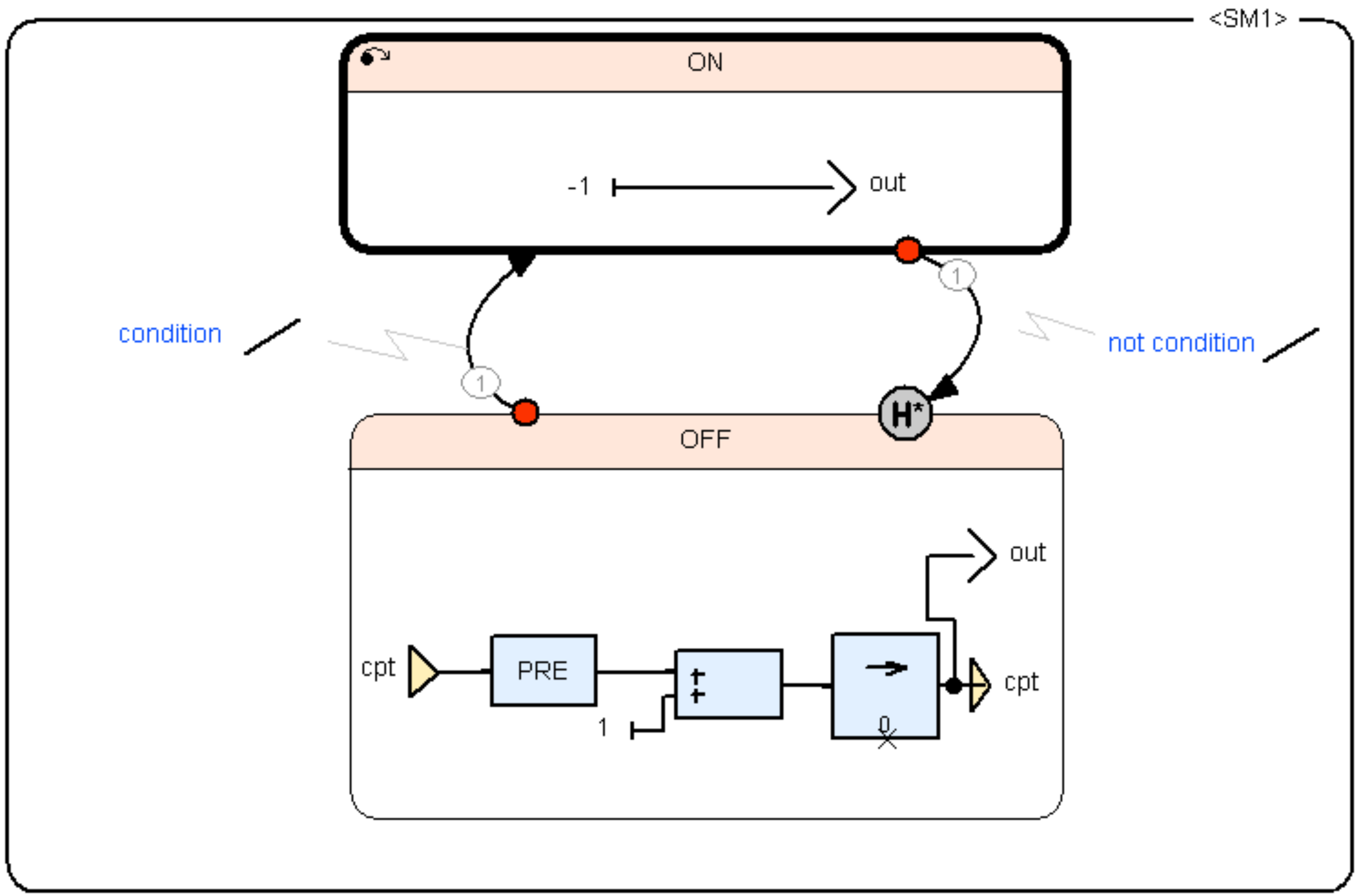
# Scade - State machines

- If the transition entering OFF is a *restart*, the counter is reset each time we enter the state



# Scade - State Machines

- If the transition entering OFF is a *resume*, the counter will keep its last value



# Scade - State Machines

- Démo... (fichier "DiffRestartResume")

# Example - gas burner

- Let us assume to the burner takes some delay before actually switching on, and stays in a transitory «ignition» state before moving to ON

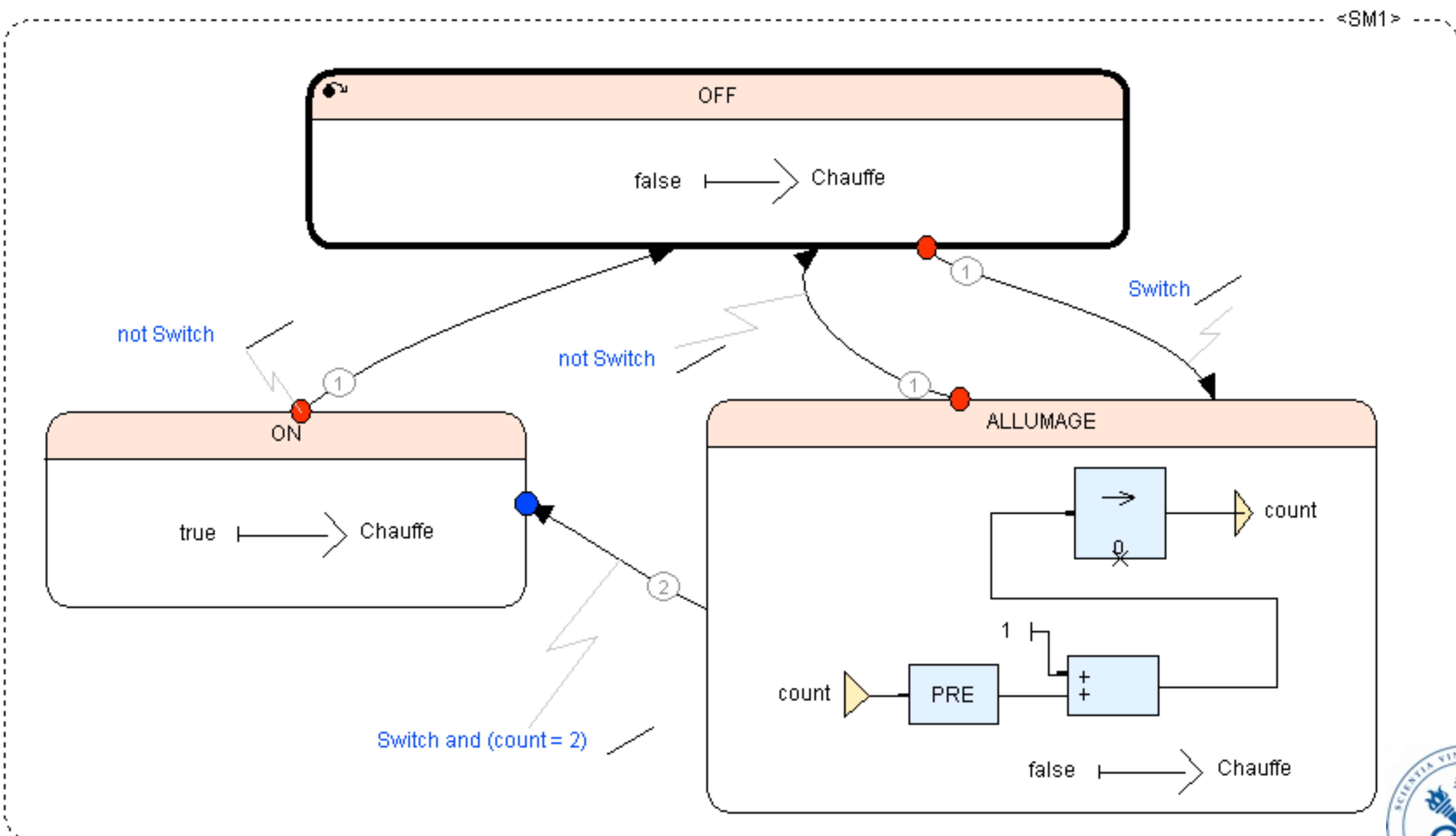
# Example - gas burner

- We can use a 3 states machine:
  - OFF (initial)
  - ignition: the burner does not heat. This state is left after a fixed number of cycles and the machine moves to:
  - ON: burner heats the tank

# Example - gas burner

- In states ON and OFF, we set the output flow to the right value (`true/false`)
- In the transitory state «ignition», a counter, allows to jump to ON after a given number of cycles, to simulate ignition time.

# Example - gas burner



# Example - gas burner

- As expected, this delay introduces a flaw in the control:
  - One cannot guarantee anymore that the temperature stays $\geq$ 50 °c if one switches the burner on at 50 °c
  - During the delay the temperature falls under 50°c

# Example - gas burner

- The verification step allows to detect this problem, and creates a scenario (execution trace).
- Demo (file bruleur-state.avi)

# Example - gas burner

- The controller is modified to switch on the burner when the temperature reaches 53°c
    - Remarks: the initial value of the counter is 0, we thus need three cycles to reach value 2.
- With this new control policy, SCADE can prove the property.

# Example - gas burner

- Demo.... (fichier “cours”)

# Scade - more...

- Advanced datatypes can be defined
    - struct-like datatypes
    - enum-like datatypes
- Scade also provides several libraries of operators
- ...