An Introduction to Lustre

Monday Oct 06, 2014

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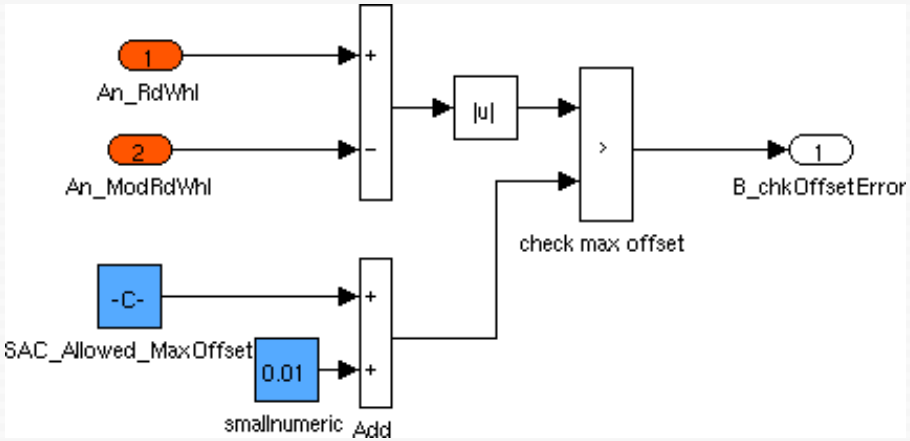
ES Programming languages

- **Which language to write embedded software in?**
- Traditional: low-level languages,C
- Trends: **high-level, declarative, model-based, component-based** languages

C

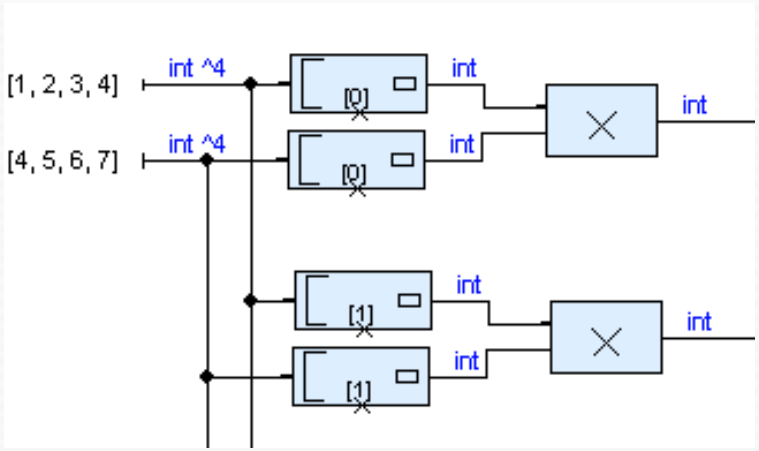
```
void setupActuatorModule() {
  TIM_TimeBaseInitTypeDef timInit;

  /* Setup timer TIM3 for pulse-width modulation:
     100kHz, periodically counting from 0 to 9999
  RCC_APB1PeriphClockCmd( RCC_APB1Periph_TIM3, ENA

  TIM_DeInit( TIM3 );
  TIM_TimeBaseStructInit( &timInit );

  timInit.TIM_Period = (unsigned portSHORT)0x270F;
  timInit.TIM_Prescaler = 720;

  timInit.TIM_ClockDivision = TIM_CKD_DIV1;
  timInit.TIM_CounterMode = TIM_CounterMode_Up;
```

Simulink



Lustre, synchronous prog.

- **Lustre**, Esterel, Signal
- Execution governed by a global clock, static scheduling
- Determinism is guaranteed (despite concurrency)
- Same language used for specification, modelling, prototyping, implementation



Lecture outline

- History of Lustre
- Overview of syntax + semantics
- Tutorial; Lustre by example

- *Next lecture: verification*

- Borrowed some material from slides by Pascal Raymond, Nicolas Halbwachs, Cesare Tinelli

History of Lustre

- Invented in 1980’s at Verimag (Fr)
- Continuously developed since then
- Currently:
    - Academic versions + compilers (Lustre V4, Lustre V6)
    - Commercial version (SCADE, Esterel Technologies)

Early applications

- 1979-1984: first versions of Lustre
- 1986: tool Saga (based on Lustre) to develop the monitoring and emergency stop system of a nuclear plant
- At the same time, a similar tool (SAO) was used to develop the fly-by-wire and flight control of the Airbus A320
- Both approaches were later combined by company Verilog → SCADE

History of Lustre/SCADE

- Nowadays, one of the standard languages for safety-critical systems
  - Avionics, automotive, etc.
  - Certified tools
    (SCADE compiler was one of the first commercial certified compilers)
- E.g., significant portion of A380 code is written in SCADE

Ideas that led to Lustre

- Embedded software replaces previous technologies
    - analogue systems, switching networks, hardware...
- Most embedded software is not developed by computer scientists, but rather by control engineers used with previous technologies
(and this is still true!)

Ideas that led to Lustre (2)

- These people are used to specific formalisms:
  - differential or finite-difference equations, analogue diagrams, “block-diagrams”...
- These data-flow formalisms enjoy some nice properties:
  - simple formal (functional and temporal) semantics, implicit parallelism

Ideas that led to Lustre (3)

- Idea: specialize our formalism into a programming language
    - (discrete time, executable semantics)

  → **Lustre**

- First versions of Simulink were developed at the same time
  → similar concepts

Lustre paradigms

- **Dataflow** language
  - similar to Simulink, but textual + time-discrete
  - changes force propagation
- **Synchronous**
  - program can have concurrent tasks, but all tasks run on the same clock; static scheduling (similar to synchronous hardware circuits)
  - good for quick reactions to environment

Lustre paradigms (2)

- **Declarative**
  - similar to functional languages
  - definitions instead of assignments
- Simple + modular language

Synchronous language family

- **Lustre**
  - Synchronous + dataflow
- **Esterel**
  - Synchronous + imperative
- **Signal**
  - “Polychronous” → multiple top-level clocks possible

Tool chains

- Lustre programs can be compiled to different target languages
  - C
  - VHDL → hardware
  - ...
- Good V&V support
  - automatic testing
  - static verification, model checking

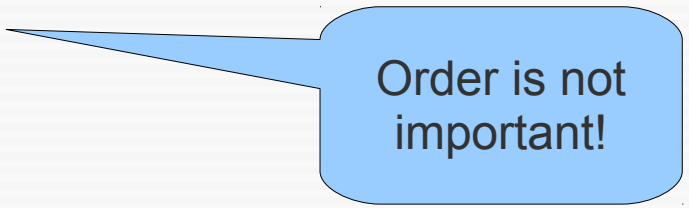
Main concepts

- **Nodes**
  - programs or sub-programs
  - collections of flow definitions
- **Flows**/streams
  - infinite sequence of values
    → e.g. stream of inputs or outputs
  - represented using variables
  - defined equationally (acyclic)

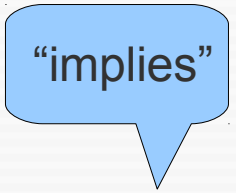
- Ignored here: **Clocks**

Node syntax

```
node name(parameters) returns(vals);
[var local_variable_list;]
let
   flow definition;
   flow definition;
   ...
tel
```



Basic types



- **`bool`**
  - `true, false, and, or, not, xor, =>`
  - `if ... then ... else ...`
- **`int`**, **`real`**
  - machine integers, floating-point num.
  - `+, -, *, /, div, mod, <>, <, <=, >, >=`
- Tuples
  - Arbitrary combinations of bool, int, real, & tuple terms
  - Used to return multiple values

Variable declarations, comments

```
X : int;
A, B : bool;
C : bool; D : int;



-- Comments!
```

The Luke tool

- Command line simulator & verifier
- Fragment of Lustre (v4) language
  - does not support arrays, const, assert, #, when, current, real
  - allows non-standard structures: nodes with no inputs; =, <> can be used on type bool
- Outputs simulations & counterexamples to Javascript webpage

Examples ...

- Luke binaries:
  - Linux: http://bit.ly/1n79Bnc
  - Windows: http://bit.ly/1rcufh3
  - Solaris: http://bit.ly/1EhG6Vc

Lustre is a
declarative
language!

Consequences of declarativeness

- Definitions of flows are **equations**, not assignments!
- Order is irrelevant:

```
y = x + 1;
z = y + 1;
```

is the same as

```
z = y + 1;
y = x + 1;
```

- No side effects

Consequences of declarat. (2)

- **Cyclic** definitions are not allowed:

```
y = x + 1;
z = y + 1;
x = z + 1;
```

  (this gives an error message during compilation/simulation)

- Also across multiple nodes!

Warning: functional if-then-else

- Never write something like this:

```
node Abs (x :  int) returns (y : int);
let
  if x >= 0 then y = x else y = -x;
tel
```

- Correct version:

```
node Abs (x :  int) returns (y : int);
let
  y = if x >= 0 then x else -x;
tel
```

Similar to ? : in C

The `pre` operator

- Access values of variables in the previous cycle:

$$\begin{aligned} X &= (X_0, X_1, X_2, X_3, \ldots) \\ pre\ X &= (nil, X_0, X_1, X_2, \ldots) \end{aligned}$$

The followed-by operator `->`

- Choose the initial element of a flow:

$$\begin{aligned} X &= (X_0, X_1, X_2, X_3, \ldots) \\ Y &= (Y_0, Y_1, Y_2, Y_3, \ldots) \\ X \rightarrow Y &= (X_0, Y_1, Y_2, Y_3, \ldots) \end{aligned}$$

- Typical use: `0 -> pre (…)`
- Be careful: `->` binds very weakly:

```
X and false -> pre Y
```

means

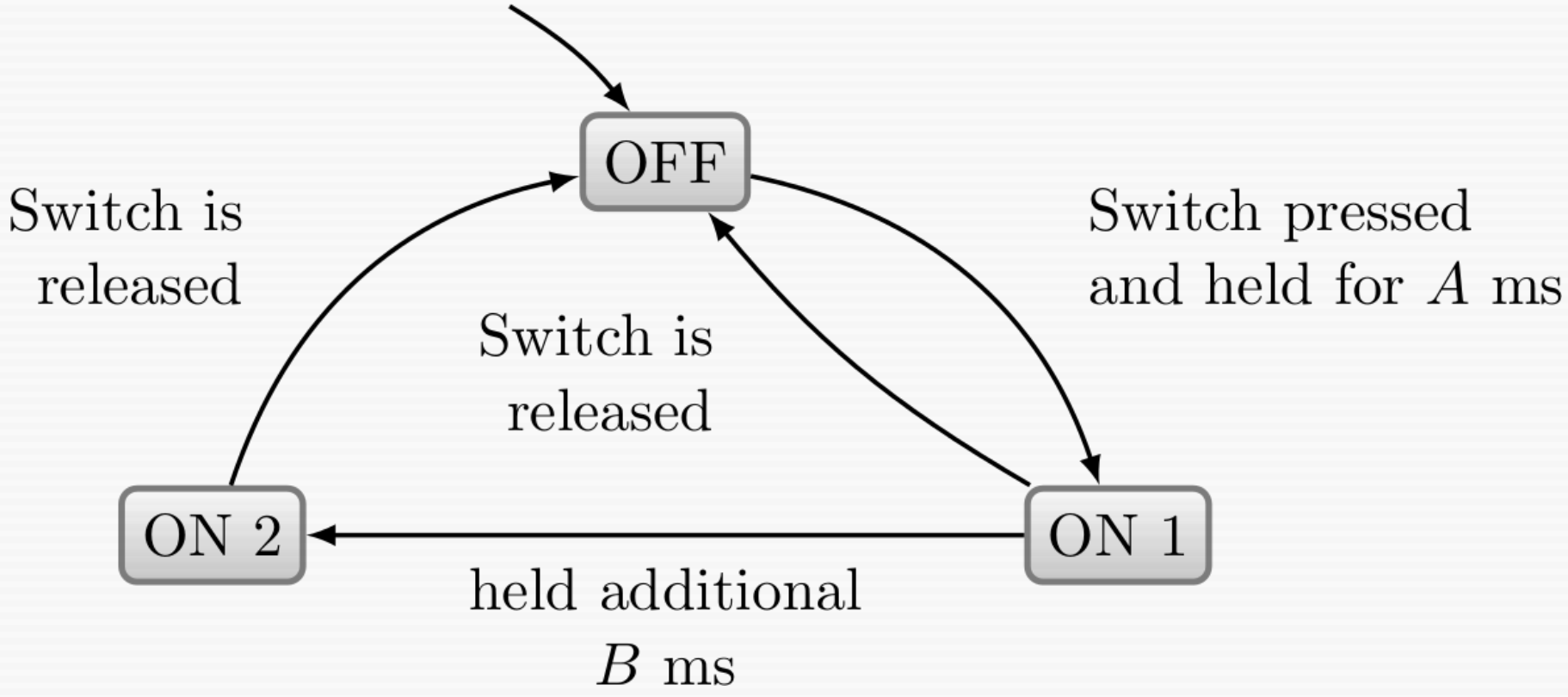
```
(X and false) -> pre Y
```

Use of -> and pre

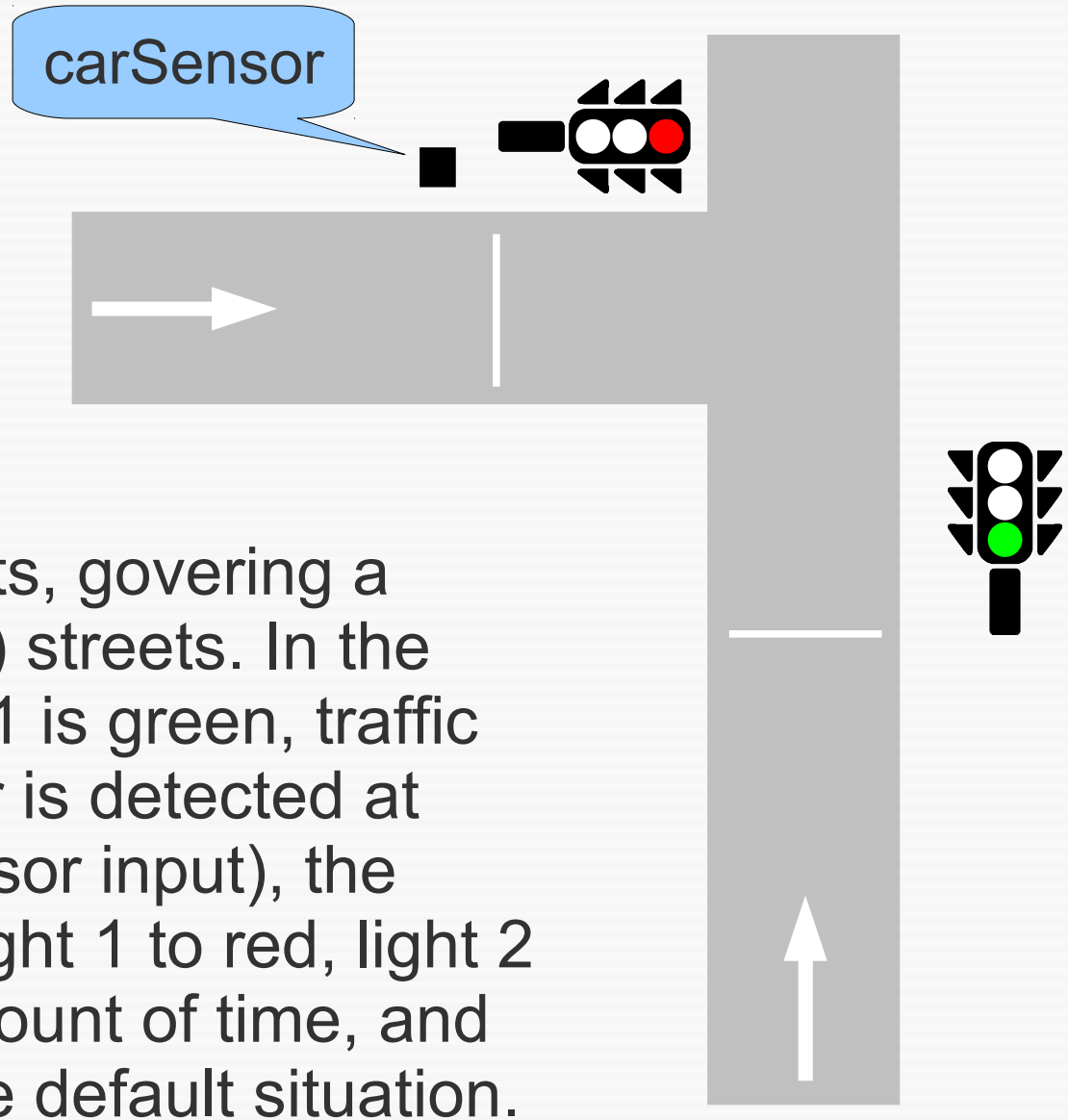
- -> and pre are commonly used to implement **iteration**
- The two operators replace loops

Examples ...

MultiStateSwitch



Traffic lights



System of two traffic lights, govering a junction of two (one-way) streets. In the default case, traffic light 1 is green, traffic light 2 is red. When a car is detected at traffic light 2 (the carSensor input), the system switches traffic light 1 to red, light 2 to green, waits some amount of time, and then switches back to the default situation.

Luke usage

- **Simulation**:

```
luke --node top_node filename
```

- **Verification**:

```
luke --node top_node --verify filename
```

  - returns either “Valid. All checks succeeded. Maximal depth was n” or “Falsified output ‘X’ in node ‘Y' at depth n” along with a counterexample.

Further Lustre features not supported in Luke

- Clocks
  - Used to delay sampling, execution
  - Operators: `when`, `current`
- `assert, const, #`
- Invocation of external functions
- Arrays, recursion, higher-order functions

SCADE features not supported in Luke

- `case :: switching`
- `fby(x, n, i)`: n-fold followed-by + pre
  - Guarded delay
  - `i -> pre (i -> pre ...)`
- `condact`
  - Guarded clock change

Further reading

- N. Halbwachs, P. Caspi, P. Raymond, and D. Pilaud. “The synchronous dataflow programming language LUSTRE”
- A tutorial of Lustre:
  http://www-verimag.imag.fr/~halbwach/PS/tutorial.ps
- Slides by Pascal Raymond, Nicolas Halbwachs:
  http://www-verimag.imag.fr/~raymond/edu/eng/lustre-a.pdf
  http://pop-art.inrialpes.fr/~girault/Synchron06/Slides/halbwachs
- Nicolas Halbwachs. “A Synchronous Language at Work: the Story of Lustre”

Next lecture

- How to **specify** and **analyse** Lustre programs