

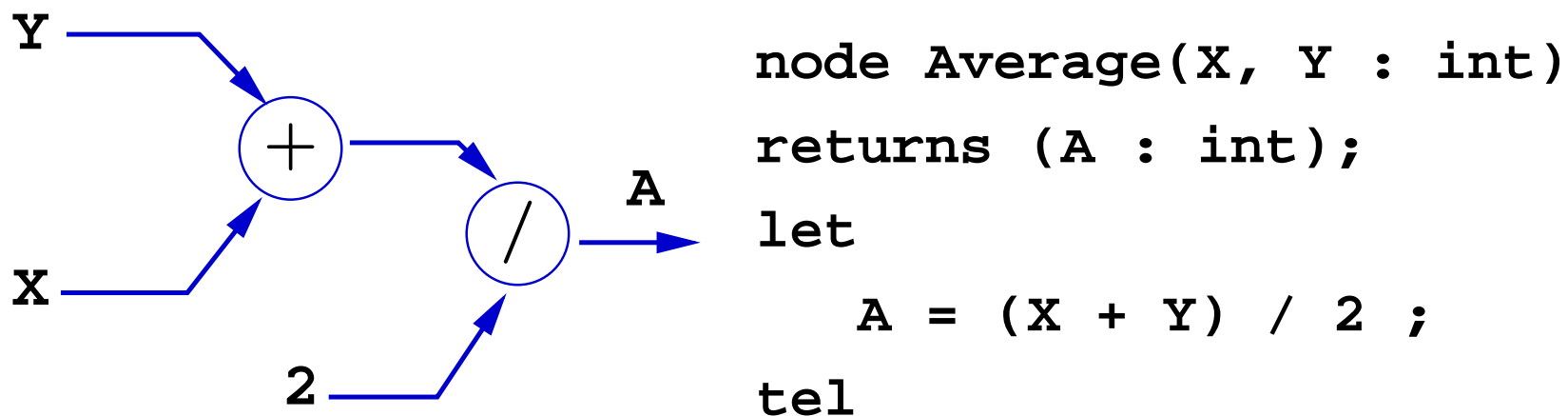
The Lustre Language

Synchronous Programming

Pascal Raymond, Nicolas Halbwachs
Verimag-CNRS

Data-flow approach

- A program = a network of operators connected by wires
- Rather classical (control theory, circuits)



- Synchronous: discrete time = \mathbb{N}
 $\forall t \in \mathbb{N} \quad A_t = (X_t + Y_t)/2$
- Full parallelism: nodes are running concurrently

Another version

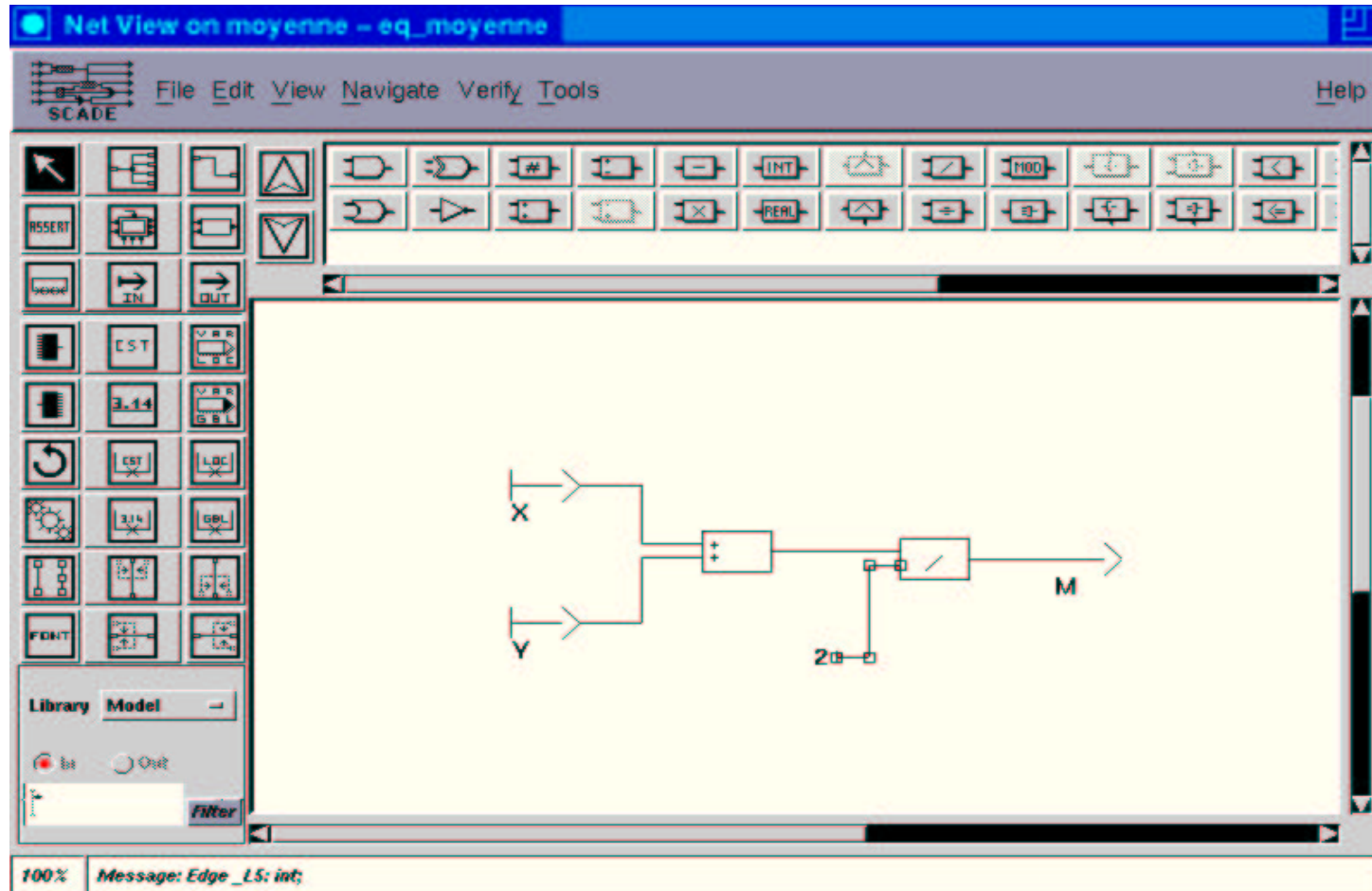
```

node Average(X, Y : int)
returns (A : int);
var S : int;           – local variable
let
    A = S / 2;          – equations
    S = X + Y;          – (order does not matter)
tel

```

- declarative: set of equations
- a single equation for each output/local
- variables are infinite sequences of values

Lustre (textual) and Scade (graphical)



Data-flow approach _____ Lustre (textual) and Scade (graphical)

Combinational programs

- Basic types: bool, int, real

- Constants:

$2 \equiv 2, 2, 2, \dots$

$\text{true} \equiv \text{true}, \text{true}, \text{true}, \dots$

- Pointwise operators:

$\mathbf{X} \equiv x_0, x_1, x_2, x_3 \dots \quad \mathbf{Y} \equiv y_0, y_1, y_2, y_3 \dots$

$\mathbf{X} + \mathbf{Y} \equiv x_0 + y_0, x_1 + y_1, x_2 + y_2, x_3 + y_3 \dots$

- All classical operators are provided

- **if operator**

```
node Max(A,B: real) returns (M: real);  
let  
    M = if (A >= B) then A else B;  
tel
```

Warning: functional “if then else”, not statement

```
let  
    if (A >= B) then M = A ;  
    else M = B ;  
tel
```

Memory programs

Delay operator

- Previous operator: **pre**

X	x_0	x_1	x_2	x_3	x_4	...
pre X	nil	x_0	x_1	x_2	x_3	...

Memory programs

Delay operator

- Previous operator: **pre**

X x_0 x_1 x_2 x_3 x_4 ...

pre X **nil** x_0 x_1 x_2 x_3 ...

i.e. $(\text{pre } X)_0$ undefined and $\forall i \neq 0 \ (\text{pre } X)_i = X_{i-1}$

Memory programs

Delay operator

- Previous operator: **pre**

X x_0 x_1 x_2 x_3 x_4 ...

pre X **nil** x_0 x_1 x_2 x_3 ...

i.e. $(\text{pre } X)_0$ undefined and $\forall i \neq 0 \ (\text{pre } X)_i = X_{i-1}$

- Initialization: **->**

X x_0 x_1 x_2 x_3 x_4 ...

Y y_0 y_1 y_2 y_3 y_4 ...

$X \rightarrow Y$ x_0 y_1 y_2 y_3 y_4 ...

Memory programs

Delay operator

- Previous operator: **pre**

X x_0 x_1 x_2 x_3 x_4 ...

pre X **nil** x_0 x_1 x_2 x_3 ...

i.e. $(\text{pre } X)_0$ undefined and $\forall i \neq 0 \ (\text{pre } X)_i = X_{i-1}$

- Initialization: **->**

X x_0 x_1 x_2 x_3 x_4 ...

Y y_0 y_1 y_2 y_3 y_4 ...

$X \rightarrow Y$ x_0 y_1 y_2 y_3 y_4 ...

i.e. $(X \rightarrow Y)_0 = X_0$ and $\forall i \neq 0 \ (X \rightarrow Y)_i = Y_i$

Nodes with memory

- Boolean example: raising edge

```
node Edge (X : bool) returns (E : bool);
let
    E = false -> X and not pre X ;
tel
```

- Numerical example: min and max of a sequence

```
node MinMax(X : int)
returns (min, max : int); – several outputs
let
    min = X -> if (X < pre min) then X else pre min;
    max = X -> if (X > pre max) then X else pre max;
tel
```

Recursive definition

Examples

- $N = 0 \rightarrow \text{pre } N + 1$

Recursive definition

Examples

- $N = 0 \rightarrow \text{pre } N + 1 \quad N = 0, 1, 2, 3, \dots$

Recursive definition

Examples

- $N = 0 \rightarrow \text{pre } N + 1$ $N = 0, 1, 2, 3, \dots$
- $A = \text{false} \rightarrow \text{not pre } A$

Recursive definition

Examples

- $N = 0 \rightarrow \text{pre } N + 1$ $N = 0, 1, 2, 3, \dots$
- $A = \text{false} \rightarrow \text{not pre } A$ $A = \text{false}, \text{true}, \text{false}, \text{true}, \dots$

Recursive definition

Examples

- $N = 0 \rightarrow \text{pre } N + 1 \quad N = 0, 1, 2, 3, \dots$
- $A = \text{false} \rightarrow \text{not pre } A \quad A = \text{false}, \text{true}, \text{false}, \text{true}, \dots$
- Correct \Rightarrow the sequence can be computed step by step

Counter-example

- $x = 1 / (2 - x)$
- unique (integer) solution: “X=1”
- but not computable step by step

Sufficient condition: **forbid combinational loops**

How to detect combinational loops?

Recursive definition _____ Counter-example

Syntactic vs semantic loop

- **Example:**

`X = if C then Y else A;`

`Y = if C then B else X;`

- **Syntactic loop**

- **But not semantic:** `X = Y = if C then B else A`

Correct definitions in Lustre

- **Choice:** syntactic loops are rejected
(even if they are “false” loops)

Exercices

- A flow $F = 1, 1, 2, 3, 5, 8, \dots$?
- A node `Switch(on, off: bool)` returns `(s: bool)`; such that:
 - ★ `s` raises (*false to true*) if `on`, and falls (*true to false*) if `off`
 - ★ everything behaves as if `s` was *false* at the origin
 - ★ must work properly even if `off` and `on` are the same
- A node `Count(reset, x: bool)` returns `(c: int)`; such that:
 - ★ `c` is reset to 0 if `reset`, otherwise it is incremented if `x`,
 - ★ everything behaves as if `c` was 0 at the origin

Solutions

- **Fibonacci:**

```
f = 1 -> pre( f + (0 -> pre f));
```

- **Bistable:**

```
node Switch(on,off: bool) returns (s: bool);
let s = if(false -> pre s) then not off else on; tel
```

- **Counter:**

```
node Count(reset,x: bool) returns (c: int);
let
  c = if reset then 0
      else if x then (0->pre c) + 1
      else (0->pre c);
tel
```

Modularity

Reuse

- Once defined, a user node can be used as a basic operator
- Instanciation is functional-like
- Example (exercice: what is the value?)

```
A = Count(true -> (pre A = 3), true)
```

- Several outputs:

```
node MinMaxAverage(x: bool) returns (a: int);  
var min,max: int;  
let  
    a = average(min,max);  
    min, max = MinMax(x);  
tel
```

A complete example: stopwatch

- 1 integer output: `displayed time`
- 3 input buttons: `on_off`, `reset`, `freeze`
 - ★ `on_off` starts and stops the stopwatch
 - ★ `reset` resets the stopwatch (if not running)
 - ★ `freeze` freezes the displayed time (if running)

A complete example: stopwatch

- 1 integer output: `displayed time`
- 3 input buttons: `on_off`, `reset`, `freeze`
 - ★ `on_off` starts and stops the stopwatch
 - ★ `reset` resets the stopwatch (if not running)
 - ★ `freeze` freezes the displayed time (if running)
- Find local variables (and how they are computed):
 - ★ `running`: `bool`, a *Switch* instance
 - ★ `frozen`: `bool`, a *Switch* instance
 - ★ `cpt`: `int`, a *Count* instance

```
node Stopwatch(on_off,reset,freeze: bool)
returns (time: int);
var running, freezed:bool; cpt:int;
let
    running = Switch(on_off, on_off);
    freezed = Switch(
        freeze and running,
        freeze or on_off);
    cpt = Count(reset and not running, running);
    time = if freezed then (0 -> pre time) else cpt;
tel
```

Clocks

Motivation

- Attempt to conciliate “control” with data-flow
- Express that some part of the program works *less often*
- \Rightarrow notion of data-flow clock (similar to clock-enabled in circuit)

Clocks

Motivation

- Attempt to conciliate “control” with data-flow
- Express that some part of the program works *less often*
- \Rightarrow notion of data-flow clock (similar to clock-enabled in circuit)

Sampling: when operator

X	4	1	-3	0	2	7	8
C	<i>true</i>	<i>false</i>	<i>false</i>	<i>true</i>	<i>true</i>	<i>false</i>	<i>true</i>
X when C	4			0	2		8

- whenever C is false, X when C **does not exist**

Projection: current operator

- One can operate only on flows with the same clock
- **projection** on a common clock is (sometime) necessary

X	4	1	-3	0	2	7	8
C	<i>true</i>	<i>false</i>	<i>false</i>	<i>true</i>	<i>true</i>	<i>false</i>	<i>true</i>
Y = X when C	4			0	2		8
Z = current(Y)	4	4	4	0	2	2	8

Nodes and clocks

- Clock of a node instance = clock of its effective inputs
- Sampling inputs = enforce the whole node to run slower
- In particular, sampling inputs \neq sampling outputs

C	<i>true</i>	<i>true</i>	<i>false</i>	<i>false</i>	<i>true</i>	<i>false</i>	<i>true</i>
<code>Count((r,true) when C)</code>	1	2			3		4
<code>Count(r,true) when C</code>	1	2			5		7

Example: stopwatch with clocks

```

node Stopwatch(on_off,reset,freeze: bool)
returns (time: int);
var running, freezed:bool;
    cpt_ena, tim_ena : bool;
    (cpt:int) when cpt_ena;
let
    running = Switch(on_off, on_off);
    freezed = Switch(
        freeze and running,
        freeze or on_off);
    cpt_ena = true -> reset or running;
    cpt = Count((not running, true) when cpt_ena);
    tim_ena = true -> not freezed;
    time = current(current(cpt) when tim_ena);
tel

```

Clock checking

- Similar to type checking
- Clocks must be named (clocks are equal iff they are the same var)
- The clock of each var must be declared (the default is the base clock)
- $clk(\text{exp when } C) = C \Leftrightarrow clk(\text{exp}) = C$
- $clk(\text{current exp}) = clk(clk(\text{exp}))$
- For any other op:
 $clk(e1 \text{ op } e2) = C \Leftrightarrow clk(e1) = C \wedge clk(e2) = C$

Programming with clocks

- Clocks **are** the right semantic solution
- However, using clocks is quite tricky (cf. stopwatch)
- Main problem: initialisation

`current(X when C)` exists, but is undefined until C becomes true for the first time
- Solution: *activation condition*
 - ★ not an operator, rather a *macro*
 - ★ `X = CONDUCT(OP, clk, args, dflt)` equivalent to:


```
X = if clk then current(OP(args when clk))
      else (dflt -> pre X)
```
 - ★ Provided by Scade (industrial)

Is that all there is? _____

Dedicated vs general purpose languages

- Synchronous languages are dedicated to *reactive kernel*
- Not suitable for complex data types manipulation
- Abstract types and functions are *imported* from the host language (typically C)

However ...

- Statically sized arrays are provided
- Static recursion (Lustre V4, dedicated to circuit)
- Modules and templates (Lustre V6, dedicated to software)

Is that all there is? _____ However ...