A Lustre V6 tutorial

Verimag

December 4, 2008 - Synchron'08 - Aussois

Outline

- Lustre
- Lustre V6
- The Lustre V6 compiler

Outline

- Lustre
- Lustre V6

  P. Raymond & the Synchronous group et al.
- The Lustre V6 compiler

  P. Raymond, J. Ballet, E. Jahier

Lustre

a Data-flow Synchronous Language

- Generalised synchronous circuits: wires hold numerics
- Operators + wires structured into nodes
- Pre-defined operators
  - Boolean: and, not, ...
  - Arithmetic: +, -, ...
  - Temporal: pre, when, current

Lustre

Targetting reactive critical systems

- Time constraints

  → we want a predictable bound on execution time
- Memory constraints

  → we want a predictable bound on memory usage

  → (we want that bound to be as small as possible)

⇒ No loops, first-order

Lustre

a loop-free first-order language

But Can those limitations be overlooked ?

Lustre

a loop-free first-order language

But Can those limitations be overlooked ?

→ Yes: loops and genericity were introduced in V4

Lustre

Example of loops and genericity in V4

```
node add(const n:int; t1,t2 : int ^ n)
returns (res:int ^ n);
let
  res = t1 + t2; -- for i=0..n-1, res[i] = t1[i] + t2[i];
tel
```

Lustre

Example of loops and genericity in V4

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Lustre

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Lustre

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- this is legal as long as n is a ground constant which value is known at compile time ⟶ static genericity
- Pushing that idea further ⇒ Lustre V6

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- Lustre
- Lustre V6

  a statically generic (1.5-order) Lustre

- The Lustre V6 compiler

Lustre V6

What's new (compared to V4)

- Structure and enumerated types
- Package mechanism (Ada-like)
  - ⟶ Name space
  - ⟶ Encapsulation
- (Static) Genericity
  - ⟶ Parametric packages
  - ⟶ Parametric nodes (well-typed macros)
  - ⟶ Static recursion
  - ⟶ Array iterators (versus homomorphic extension – not new; different)

Lustre V6

Structures

```
type complex = struct {
   re : real = 0.;
   im : real = 0.
};
```

Lustre V6

Structures

```
type complex = struct {
   re : real = 0.;
   im : real = 0.
};

node plus (a, b : complex) returns (c : complex);
let
  c = complex { re = a.re+b.re ; im = a.im+b.im };
tel
```


Lustre V6

Enumerated type

```
type trival = enum { Pile, Face, Tranche };
```


Lustre V6

Enumerated clocks + merge (© *Pouzet*)

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Lustre V6

Enumerated clocks + merge (© *Pouzet*)

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type trival = enum { Pile, Face, Tranche };
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```

Lustre V6

Enumerated clocks + merge (©*Pouzet*)

```
type trival = enum { Pile, Face, Tranche };
node merge_node(clk: trival;
   i1 when Pile(clk); i2 when Face(clk);
   i3 when Tranche(clk))
returns (y: int);
```

Lustre V6

Enumerated clocks + merge (©*Pouzet*)

```
type trival = enum { Pile, Face, Tranche };
node merge_node(clk: trival;
   i1 when Pile(clk); i2 when Face(clk);
   i3 when Tranche(clk))
returns (y: int);
let
    y = merge clk
        (Pile:    i1)
        (Face:    i2)
        (Tranche: i3);
tel
```


Lustre V6

Packages

```
package complex
provides
  type t; -- Encapsulation
  const i:t;
  node re(c: t) returns (r:real);
```

Lustre V6

Packages

```
package complex
provides
  type t; -- Encapsulation
  const i:t;
  node re(c: t) returns (r:real);
body
  type t = struct { re :  real ; im :  real };
  const i:t = t { re = 0. ; im = 1. };
  node re(c: t) returns (re:real);
  let re = c.re; tel;
end
```


Lustre V6

Generic packages

```
model modSimple
  needs type t;
  provides
        node fby1(init, fb: t) returns (next: t);
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Lustre V6

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model modSimple
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  node fby1(init, fb: t) returns (next: t);
  let next = init -> pre fb; tel
end
```

Lustre V6

Generic packages

```
model modSimple
  needs type t;
  provides
        node fby1(init, fb: t) returns (next: t);
body
  node fby1(init, fb: t) returns (next: t);
  let next = init -> pre fb; tel
end
package pint is modSimple(t=int);
```


Lustre V6

Generic nodes

```
node mk_tab<<type t; const init: t; const size: int>>
       (a:t) returns (res: t^size);
let
  res =  init ^ size;
tel
```

Lustre V6

Generic nodes

```
node mk_tab<<type t; const init: t; const size: int>>
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let
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tel
node tab_int3 = mk_tab<<int, 0, 3>>;
```

Lustre V6

Generic nodes

```
node mk_tab<<type t; const init: t; const size: int>>
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let
  res =  init ^ size;
tel
node tab_int3 = mk_tab<<int, 0, 3>>;
node tab_bool4 = mk_tab<<bool, true, 4>>;
```


Lustre V6

Generic nodes

```
node toto_n<<
   node f(a, b: int) returns (x: int);
   const n : int
  >>(a: int) returns (x: int^n);
var v : int;
let
  v = f(a, 1);
  x =  v ^ n;
tel
```

Lustre V6

Generic nodes

```
node toto_n<<
   node f(a, b: int) returns (x: int);
   const n : int
  >>(a: int) returns (x: int^n);
var v : int;
let
  v = f(a, 1);
  x =  v ^ n;
tel
node toto_3 = toto_n<<Lustre::iplus, 3>>;
```


Lustre V6

Static recursion

```
node consensus<<const n : int>>(T: bool^n)
returns (a: bool);
let
  a =  with (n = 1)  then T[0]
      else T[0] and consensus << n-1 >> (T[1 .. n-1]);
tel

node main = consensus<<8>>;
```


Lustre V6

Are parametric nodes necessary?

- **Indeed, parametric nodes could be emulated with the package mechanism**

  → **but we keep them to keep the syntax ligth**

  → **we didn't really want to have recursive packages**

Lustre V6

Arrays

- **As in Lustre V4**

  → **The array size is static (`var mat23: int ^ 2 ^ 3;`)**

  → **Array slices (`T1[3..5] = T2[0..2];`)**

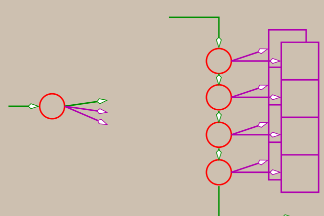
- **But no more homomorphic extension**

  where $t1 + t2$ **means** $\forall i \in \{0, .., size - 1\},\ t1[i] + t2[i]$

  ⇒ **operate on arrays via iterators**

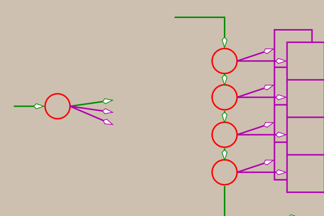
Lustre V6

The fill iterator



Lustre V6

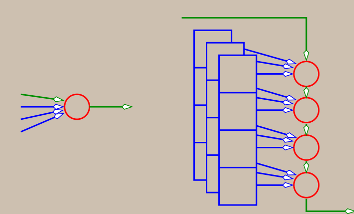
The fill iterator



```
node incr (acc : int) returns (acc', res : int);
fill<<incr; 4>>(0) ⇝(4, [0,1,2,3])
```

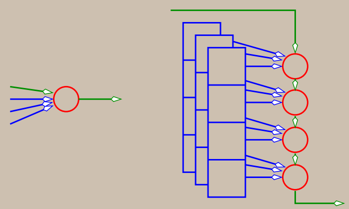

Lustre V6

The red iterator



Lustre V6

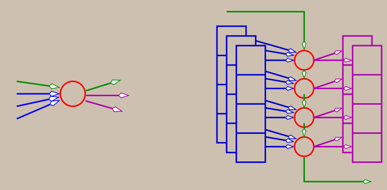
The red iterator



```
red<<+; 3>>(0, [1,2,3]) ⤳6
```

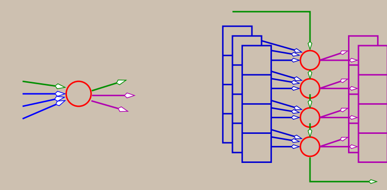

Lustre V6

fill+red=~~mapred~~, ~~fillred~~, fold



Lustre V6

fill+red=~~mapred~~, ~~fillred~~, fold

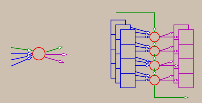


```
fill<<incr; 4>>(0) ≡ fold<<incr; 4>>(0)
red<<+; 3>>(0, [1,2,3]) ≡ fold<<+; 3>>(0, [1,2,3])
```


Lustre V6

The fold iterator

```
node cumul(acc_in,x:int) returns (acc_out,y:int)
let
   y = acc_in+x;
   acc_out = y;
tel
```



```
  fold<<cumul>>(0, [1,2,3])
```

Lustre V6

The fold iterator

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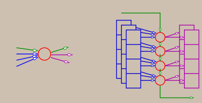

```
  fold<<cumul>>(0, [1,2,3])⤳(6, [1,3,6])
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Lustre V6

The fold iterator

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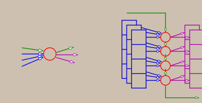
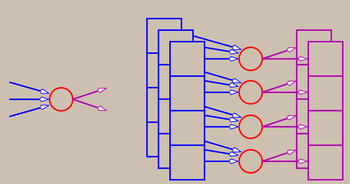


```
  fold<<cumul>>(0, [1,2,3])⤳(6, [1,3,6])

  fold<<fold<<fold<<full_adder; n>>; m>>; p>>
                      (false, x, y) ⤳(r,''x+y'')
```


Lustre V6

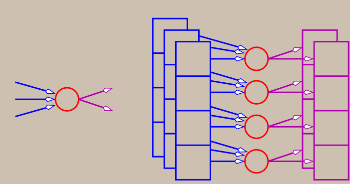
The map iterator



```
map <<+; 3>>([1,0,2],[3,6,-1]) ⤳[4,6,1]
```

Lustre V6

The map iterator



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Lustre V6

About Lustre V6 array iterators

More general that usual iterators:

their are of variable arity

Outline

- Lustre
- Lustre V6
- The Lustre V6 compiler
  - The front-end
  - The back-end (J. Ballet)
  - The back-back-end (J. Ballet)

The Lustre V6 compiler

The Front-end: LUS2LIC

- Perform usual checks
  - ⟶ Syntax, Types, Clocks
  - ⟶ Unique definition of outputs
  - ⟶ Combinational cycles detection

The Lustre V6 compiler

The Front-end: LUS2LIC

- Perform usual checks
  - ⟶ Syntax, Types, Clocks
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  - ⟶ Combinational cycles detection
- Perform some static evaluation
  - ⟶ arrays size
  - ⟶ parametric packages and nodes
  - ⟶ recursive nodes

The Lustre V6 compiler

The Front-end: LUS2LIC

- Perform usual checks
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- Perform some static evaluation
  - ⟶ arrays size
  - ⟶ parametric packages and nodes
  - ⟶ recursive nodes
- Generate intermediate code: LIC (Lustre internal code)

Lustre Internal Code (LIC)

was: expanded code (ec)

- LIC ≡ core Lustre
  - No more packages
  - Parametric constructs are instanciated
    - ⟶ constants
    - ⟶ types
    - ⟶ nodes

Lustre Internal Code (LIC)

was: expanded code (ec)

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Lustre Internal Code (LIC)

was: expanded code (ec) cont.

- LIC versus ec
  - ⟶ Nodes are not (necessarily) expanded
  - ⟶ Arrays are not (necessarily) expanded

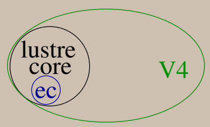
Lustre Internal Code (LIC)

was: expanded code (ec) cont.

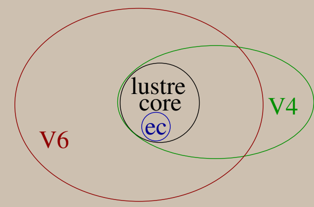
- LIC versus ec
  - ⟶ Nodes are not (necessarily) expanded
  - ⟶ Arrays are not (necessarily) expanded
- LIC versus Lustre v4
  - ⟶ Structures and enums
  - ⟶ array iterators

Lustre potatoes

Lustre potatoes



Lustre potatoes



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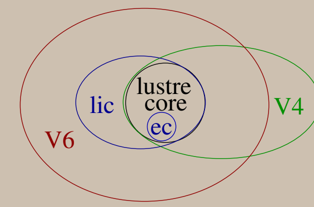

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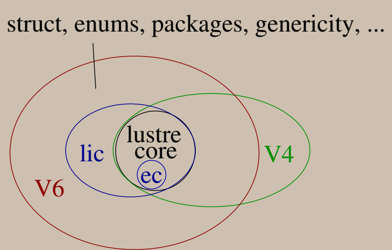

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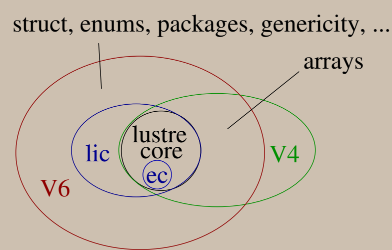

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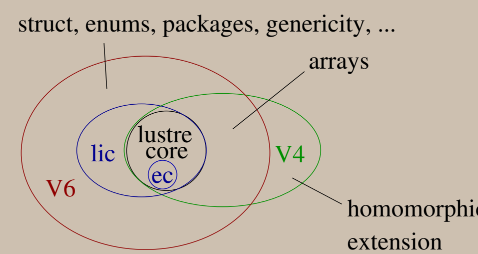

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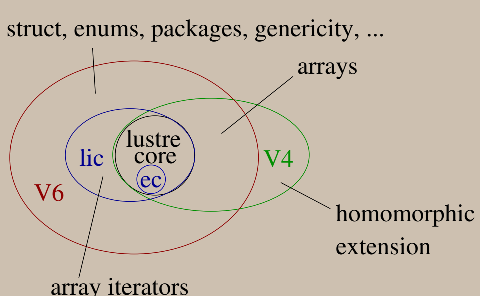

The Lustre V6 compiler

The back-end

The role of the backend is to generate sequential code

We defined (yet) another intermediary format to represent sequential code: SOC (Synchronous Object Code)

The idea is that translating this format into any sequential language is easy, and done at the very end

The back-end

maps each node to a Synchronous Object Component (SOC)

- **A SOC is made of:**
  - a set of memories
  - a set of methods: typically, an init and a step method

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The back-end

maps each node to a Synchronous Object Component (SOC)

- **A SOC is made of:**
  - **a set of memories**
  - **a set of methods: typically, an init and a step method**
- **each method is made of a sequence of guarded atomic operations**

- **atomic operation (named actions) can be**
  - **another SOC method call**
  - **an assignment (a wire)**

The back-end

From node to SOC

For each node, we:

- **Identify memories**
- **Explicitely separate the control (clocks) from the computations**

  $\longrightarrow$ **set of guarded equations**
- **Split equations into more finer-grained steps: actions**

  $\longrightarrow$ **a set of guarded actions (a wire or a call)**
- **Find a correct ordering for actions (sheduling)**

  $\longrightarrow$ **a sequence of guarded actions**

The back-back-end

From SOC to C

- **pretty-print the SOC into, let's say, C**
- **provide a C implementation of every predefined (non-temporal) operators**

Lustre V6 compiler

An alpha release is available

http://www-verimag.imag.fr/∼synchron/lustre-v6/

- **The front-end `lus2lic` seems ok**

Lustre V6 compiler

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- **The front-end `lus2lic` seems ok**

- `lus2lic --lustre-v4`**: added last friday; seems to work**

Lustre V6 compiler

An alpha release is available

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- **The front-end `lus2lic` seems ok**
- `lus2lic --lustre-v4`**: added last friday; seems to work**

- **The back-back: generates C code... But its not finished.**

Thanks for your attention

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Verimag

December 5, 2008 -

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Lustre

a Data-flow Synchronous Language

- Generalised synchronous circuits: wires hold numerics
- Operators + wires structured into nodes
- Pre-defined operators
    - Boolean: and, not, ...
    - Arithmetic: +, -, ...
    - Temporal: pre, when, current

Lustre

Targetting reactive critical systems

- Time constraints

    → we want a predictable bound on execution time

- Memory constraints

    → we want a predictable bound on memory usage

    → (we want that bound to be as small as possible)

⇒ No loops, first-order

Lustre

a loop-free first-order language

But Can those limitations be overlooked ?

→ Yes: loops and genericity were introduced in V4

Lustre

Example of loops and genericity in V4

```
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- this is legal as long as n is a ground constant which value is known at compile time → static genericity
- Pushing that idea further ⇒ Lustre V6

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    a statically generic (1.5-order) Lustre

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Lustre V6

What's new (compared to V4)

- Structure and enumerated types
- Package mechanism (Ada-like)
    - → Name space
    - → Encapsulation
- (Static) Genericity
    - → Parametric packages
    - → Parametric nodes (well-typed macros)
    - → Static recursion
    - → Array iterators (versus homomorphic extension – not new; different)

Lustre V6

Structures

```
type complex = struct {
   re : real = 0.;
   im : real = 0.
};

node plus (a, b : complex) returns (c : complex);
let
  c = complex { re = a.re+b.re ; im = a.im+b.im };
tel
```


Lustre V6

Enumerated type

```
type trival = enum { Pile, Face, Tranche };
```


Lustre V6

Enumerated clocks + merge (© *Pouzet*)

```
type trival = enum { Pile, Face, Tranche };
node merge_node(clk: trival;
   i1 when Pile(clk); i2 when Face(clk);
   i3 when Tranche(clk))
returns (y: int);
let
    y = merge clk
        (Pile:    i1)
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Lustre V6

Packages

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package complex
provides
  type t; -- Encapsulation
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Lustre V6

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Lustre V6

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Lustre V6

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node toto_3 = toto_n<<Lustre::iplus, 3>>;
```


Lustre V6

Static recursion

```
node consensus<<const n : int>>(T: bool^n)
returns (a: bool);
let
  a =  with (n = 1)  then T[0]
      else T[0] and consensus << n-1 >> (T[1 .. n-1]);
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node main = consensus<<8>>;
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Lustre V6

Are parametric nodes necessary?

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  → we didn't really want to have recursive packages

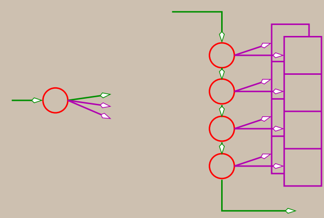
Lustre V6

Arrays

- **As in Lustre V4**
  - ⟶ The array size is static (`var mat23: int ^ 2 ^ 3;`)
  - ⟶ Array slices (`T1[3..5] = T2[0..2];`)
- **But no more homomorphic extension**
  - where $t1 + t2$ means $\forall i \in \{0, .., size - 1\},\ t1[i] + t2[i]$
  - ⇒ operate on arrays via iterators

Lustre V6

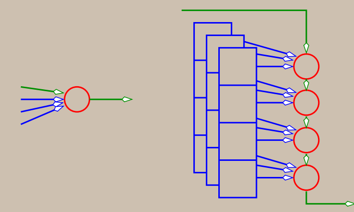
The fill iterator



```
node incr (acc : int) returns (acc', res : int);
fill<<incr; 4>>(0) ⇝(4, [0,1,2,3])
```


Lustre V6

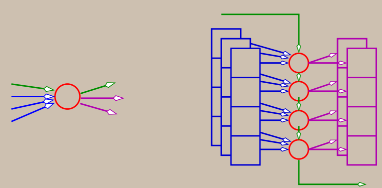
The red iterator



```
red<<+; 3>>(0, [1,2,3]) ⇝6
```


Lustre V6

fill+red=~~mapred~~, ~~fillred~~, fold

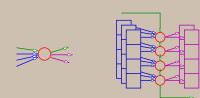


```
fill<<incr; 4>>(0) ≡ fold<<incr; 4>>(0)
red<<+; 3>>(0, [1,2,3]) ≡ fold<<+; 3>>(0, [1,2,3])
```


Lustre V6

The fold iterator

```
node cumul(acc_in,x:int) returns (acc_out,y:int)
let
   y = acc_in+x;
   acc_out = y;
tel
```

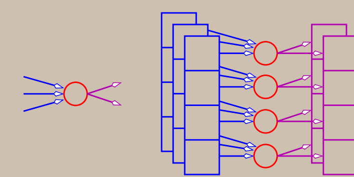


```
fold<<cumul>>(0, [1,2,3])⇝(6, [1,3,6])

fold<<fold<<fold<<full_adder; n>>; m>>; p>>
                    (false, x, y) ⇝(r,''x+y'')
```


Lustre V6

The map iterator



```
map <<+; 3>>([1,0,2],[3,6,-1]) ⇝[4,6,1]
```


Lustre V6

About Lustre V6 array iterators

More general that usual iterators:

their are of variable arity

Outline

- Lustre
- Lustre V6
- The Lustre V6 compiler
  - The front-end
  - The back-end (J. Ballet)
  - The back-back-end (J. Ballet)

The Lustre V6 compiler

The Front-end: LUS2LIC

- **Perform usual checks**
  - ⟶ Syntax, Types, Clocks
  - ⟶ Unique definition of outputs
  - ⟶ Combinational cycles detection
- **Perform some static evaluation**
  - ⟶ arrays size
  - ⟶ parametric packages and nodes
  - ⟶ recursive nodes
- **Generate intermediate code: LIC (Lustre internal code)**

Lustre Internal Code (LIC)

was: expanded code (ec)

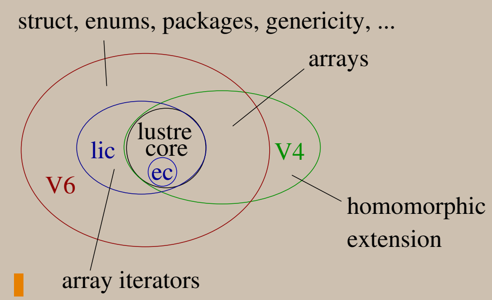
- LIC ≡ core Lustre
  - No more packages
  - Parametric constructs are instanciated
    - ⟶ constants
    - ⟶ types
    - ⟶ nodes

Lustre Internal Code (LIC)

was: expanded code (ec) cont.

- LIC versus ec
  - ⟶ Nodes are not (necessarily) expanded
  - ⟶ Arrays are not (necessarily) expanded
- LIC versus Lustre v4
  - ⟶ Structures and enums
  - ⟶ array iterators

Lustre potatoes



The Lustre V6 compiler

The back-end

The role of the backend is to generate sequential code

We defined (yet) another intermediary format to represent sequential code: SOC (Synchronous Object Code)

The idea is that translating this format into any sequential language is easy, and done at the very end

The back-end

maps each node to a Synchronous Object Component (SOC)

- A SOC is made of:
  - a set of memories
  - a set of methods: typically, an init and a step method
- each method is made of a sequence of guarded atomic operations
- atomic operation (named actions) can be
  - another SOC method call
  - an assignment (a wire)

The back-end

From node to SOC

For each node, we:

- Identify memories
- Explicitely separate the control (clocks) from the computations
  - ⟶ set of guarded equations
- Split equations into more finer-grained steps: actions
  - ⟶ a set of guarded actions (a wire or a call)
- Find a correct ordering for actions (sheduling)
  - ⟶ a sequence of guarded actions

The back-back-end

From SOC to C

- pretty-print the SOC into, let's say, C
- provide a C implementation of every predefined (non-temporal) operators

Lustre V6 compiler

An alpha release is available

`http://www-verimag.imag.fr/~synchron/lustre-v6/`

- The front-end `lus2lic` seems ok
- `lus2lic --lustre-v4`: added last friday; seems to work
- The back-back: generates C code... But its not finished.

Thanks for your attention

A Lustre V6 tutorial

Verimag

December 5, 2008 -

Outline

- Lustre
- Lustre V6
- The Lustre V6 compiler

Outline

- Lustre
- Lustre V6

  P. Raymond & the Synchronous group et al.

- The Lustre V6 compiler

  P. Raymond, J. Ballet, E. Jahier

Lustre

a Data-flow Synchronous Language

- Generalised synchronous circuits: wires hold numerics
- Operators + wires structured into nodes
- Pre-defined operators
  - Boolean: and, not, ...
  - Arithmetic: +, -, ...
  - Temporal: pre, when, current

Lustre

Targetting reactive critical systems

- **Time constraints**

  ⟶ we want a predictable bound on execution time

- **Memory constraints**

  ⟶ we want a predictable bound on memory usage

  ⟶ (we want that bound to be as small as possible)

⇒ **No loops, first-order**

Lustre

a loop-free first-order language

But Can those limitations be overlooked ?

⟶ **Yes: loops and genericity were introduced in V4**

Lustre

Example of loops and genericity in V4

```
node add(const n:int; t1,t2 : int ^ n)
returns (res:int ^ n);
let
  res = t1 + t2; -- for i=0..n-1, res[i] = t1[i] + t2[i];
tel
```

- **this is legal as long as n is a ground constant which value is known at compile time ⟼ static genericity**
- **Pushing that idea further ⇒ Lustre V6**

Outline

- **Lustre**
- **Lustre V6**

  a statically generic (1.5-order) Lustre

- **The Lustre V6 compiler**

Lustre V6

What's new (compared to V4)

- Structure and enumerated types
- Package mechanism (Ada-like)
  - → Name space
  - → Encapsulation
- (Static) Genericity
  - → Parametric packages
  - → Parametric nodes (well-typed macros)
  - → Static recursion
  - → Array iterators (versus homomorphic extension – not new; different)

Lustre V6

Structures

```
type complex = struct {
   re : real = 0.;
   im : real = 0.
};

node plus (a, b : complex) returns (c : complex);
let
  c = complex { re = a.re+b.re ; im = a.im+b.im };
tel
```


Lustre V6

Enumerated type

```
type trival = enum { Pile, Face, Tranche };
```


Lustre V6

Enumerated clocks + merge (©*Pouzet*)

```
type trival = enum { Pile, Face, Tranche };
node merge_node(clk: trival;
   i1 when Pile(clk); i2 when Face(clk);
   i3 when Tranche(clk))
returns (y: int);
let
    y = merge clk
        (Pile:    i1)
        (Face:    i2)
        (Tranche: i3);
tel
```

Lustre V6

Packages

```
package complex
provides
  type t; -- Encapsulation
  const i:t;
  node re(c: t) returns (r:real);
body
  type t = struct { re : real ; im : real };
  const i:t = t { re = 0. ; im = 1. };
  node re(c: t) returns (re:real);
  let re = c.re; tel;
end
```


Lustre V6

Generic packages

```
model modSimple
  needs type t;
  provides
        node fby1(init, fb: t) returns (next: t);
body
  node fby1(init, fb: t) returns (next: t);
  let next = init -> pre fb; tel
end
package pint is modSimple(t=int);
```


Lustre V6

Generic nodes

```
node mk_tab<<type t; const init: t; const size: int>>
       (a:t) returns (res: t^size);
let
  res =  init ^ size;
tel
node tab_int3 = mk_tab<<int, 0, 3>>;
node tab_bool4 = mk_tab<<bool, true, 4>>;
```


Lustre V6

Generic nodes

```
node toto_n<<
   node f(a, b: int) returns (x: int);
   const n : int
  >>(a: int) returns (x: int^n);
var v : int;
let
  v = f(a, 1);
  x =  v ^ n;
tel
node toto_3 = toto_n<<Lustre::iplus, 3>>;
```

Lustre V6

Static recursion

```
node consensus<<const n : int>>(T: bool^n)
returns (a: bool);
let
  a =  with (n = 1)  then T[0]
     else T[0] and consensus << n-1 >> (T[1 .. n-1]);
tel

node main = consensus<<8>>;
```


Lustre V6

Are parametric nodes necessary?

- **Indeed, parametric nodes could be emulated with the package mechanism**

  → **but we keep them to keep the syntax ligth**

  → **we didn't really want to have recursive packages**

Lustre V6

Arrays

- **As in Lustre V4**

  → **The array size is static (**`var mat23:  int ^ 2 ^ 3;`**)**

  → **Array slices (**`T1[3..5] = T2[0..2];`**)**

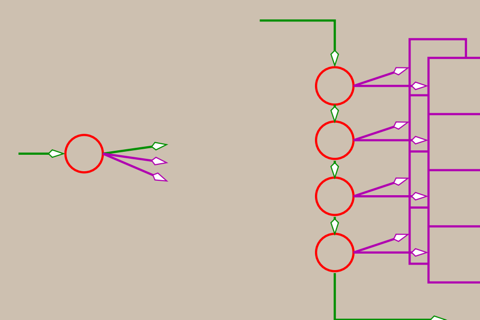
- **But no more homomorphic extension**

  where $t1 + t2$ **means** $\forall i \in \{0, .., size - 1\},\ t1[i] + t2[i]$

  ⇒ **operate on arrays via iterators**

Lustre V6

The fill iterator



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Lustre V6

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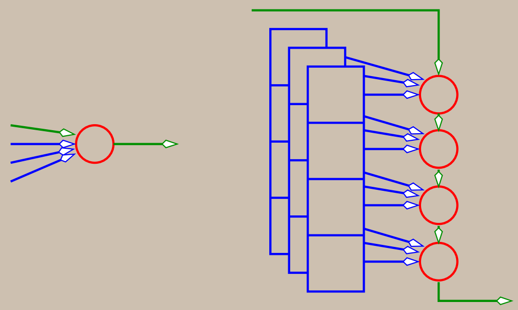

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Lustre V6

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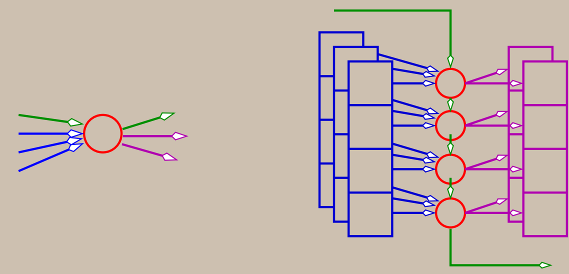

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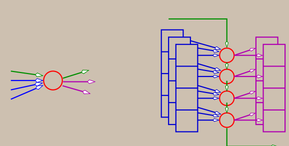

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Lustre V6

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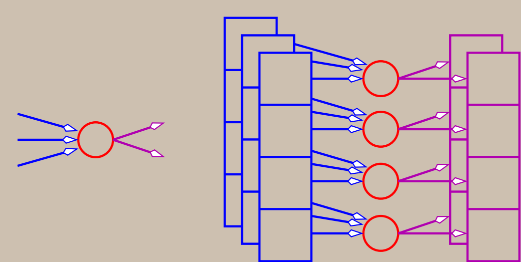

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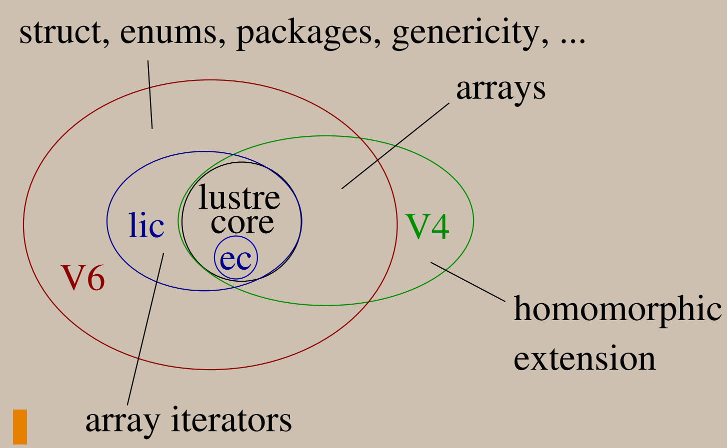

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