MiniLustre mais il fait le Maximum !

or

Towards the Development of a Certified Compiler for Lustre

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A Certified compiler for SCADE/Lustre

Implement a verified compiler for a synchronous data-flow language with the help of the proof assistant Coq

Combines **certified compilation** and **translation validation**

Certified translation

- Write a compilation function $C : L_1 \rightarrow L_2$ in Coq with its proof of semantics preservation
- natural for local program transformation (e.g., data-flow to sequential code)

Translation validation

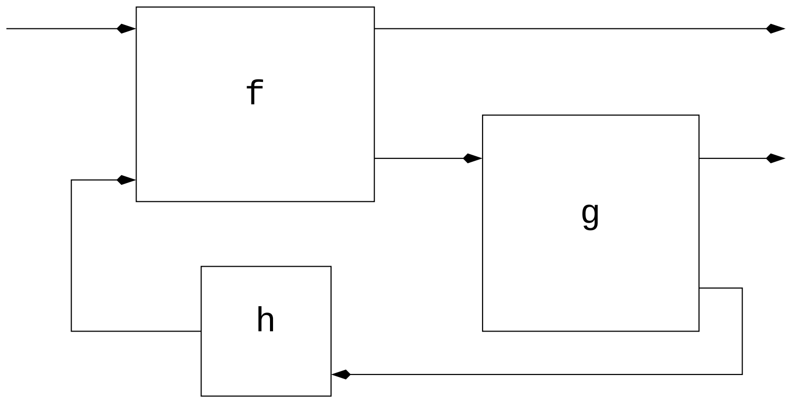
- Write C independently (e.g., in Caml) and a validation function $V : L_1 \times L_2 \rightarrow$ bool with its proof of semantics preservation
- easier for non local transformation (e.g., type or clock inference, find a clever scheduling of equation, memory optimization)

See Xavier Leroy's work for a discussion on pros and cons of both

Motivations (first step)

First build a reference compiler, as small as possible, purely functional (as much as possible) and based on local rewriting rules

Focus on synchronous block-diagrams as found in Lustre/SCADE or (a subset of) Simulink



- formalize the **code generation** into imperative sequential code (e.g., C)
- as **small** as possible but **realistic** (the code should be efficient)
- make it **modular**, i.e., the definition of a stream function is compiled once for all

as a way to:

- build a certified compiler inside a Proof assistant
- complement previous works on the extension/formalization of synchronous languages

Code Generation

Principle:

A stream function $f : \mathit{Stream}(T) \rightarrow \mathit{Stream}(T')$ is compiled into a pair:

- an initial state and a transition function: $\langle s_0 : S, f_t : S \times T \rightarrow T' \times S \rangle$

a stream equation $y = f(x)$ is computed sequentially by $y_n, s_{n+1} = f_t(s_n, x_n)$

An alternative (more general) solution:

- an initial state: $s_0 : S$
- a value function: $f_v : S \times T \rightarrow T'$
- a state modification ("commit") function: $f_s : S \times T \rightarrow S'$

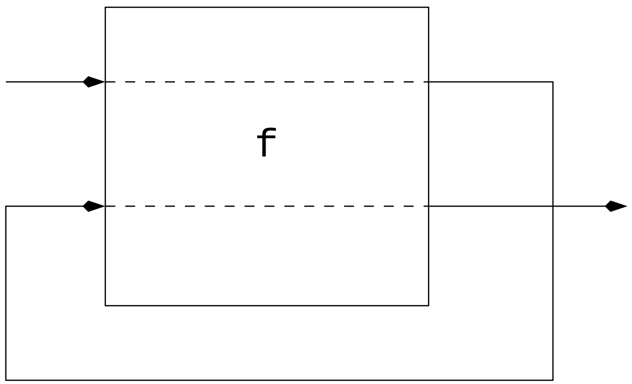
Final remarks:

- this generalises to MIMO systems
- in actual implementations, states are modified in place
- synchrony finds a very practicle justification here: a data-flow can be implemented as a single scalar variable

Modular Code Generation

- produce a transition function for each block definition
- compose them together to produce the main transition function
- static scheduling following data-dependences

But modular code generation is not always feasible even in the absence of causality loops



$$(y, z) = f(t, y)$$

This observation has led to two different approaches to the compilation problem

Two Traditional Approaches

Non Modular Code Generation

- full static inlining before code generation starts
- enumeration techniques into (very efficient) automata ([Halbwachs et all., Raymond PhD. thesis, POPL 87, PLILP 91])
- keeps maximal expressiveness but at the price of modular compilation and the size of the code may explode
- finding the adequate boolean variables to get efficient code in both code and size is difficult

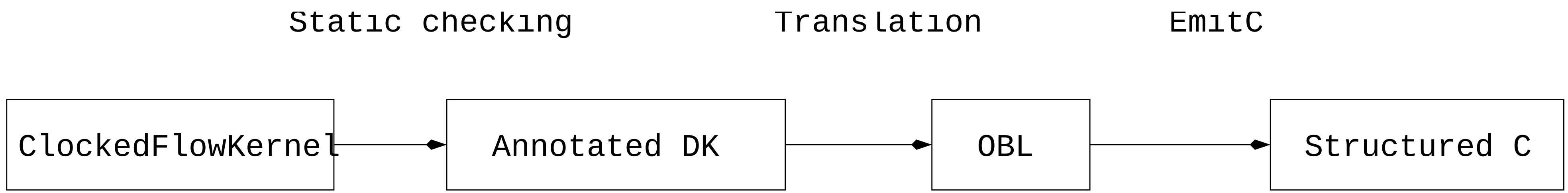
Modular code generation

- mandatory in industrial compilers
- no preliminary inlining (unless requested by the user)
- imposes stronger causality constraints: every feedback loop must cross an explicit delay
- well accepted by SCADE users and justified by the need for *tracability*

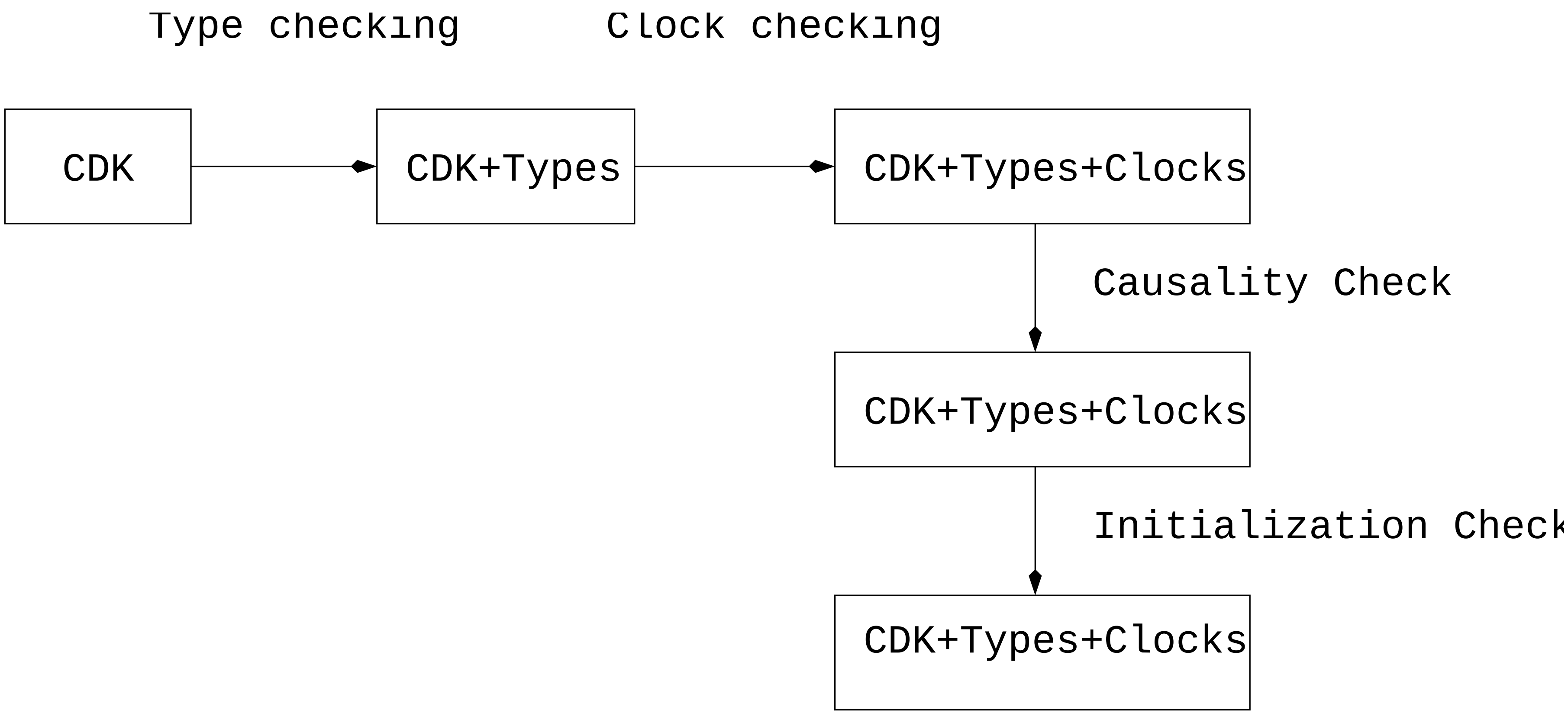
Proposal

- a compiler where everything can be "traced" with a precise semantics for every intermediate language
- introduce a basic **clocked** data-flow language as the input language
- general enough to be used as a input language for Lustre
- be a "good" input language for modern ones (e.g., mix of automata and data-flow as found in SCADE 6 or Simulink/StateFlow)
- provides a slightly more general notion of clocks
- and a reset construct
- compilation through an intermediate "object based" intermediate language to represent transition function
- provide a translation into imperative code (e.g., structured C, Java)

Organisation of the Compiler



Static Checking



A Clocked Data-flow Basic Language

A data-flow kernel where every expression is explicitely annotated with its clock

$$
\begin{array}{lcl}
a & ::= & e^{ct} \\
e & ::= & v \mid x \mid v \ \texttt{fby}\ a \mid a \ \texttt{when}\ C(x) \mid (as) \\
 & & \quad \mid op\,(a, ..., a) \mid f\,(a, ..., a)\ \texttt{every}\, a \\
 & & \quad \mid \texttt{merge}\ x\ (C \rightarrow a)\ ...\ (C \rightarrow a)
\end{array}
$$

$$
\begin{array}{lcl}
D & ::= & pat = a \mid D \,\texttt{and}\, D \\
pat & ::= & x \mid (pat, ..., pat) \\
d & ::= & \texttt{node}\ f(p) = p \,\texttt{with}\,\texttt{var}\ p\ \texttt{in}\ D \\
p & ::= & x : bt; ...; x : bt \\
td & ::= & \texttt{type}\, bt \mid \texttt{type}\, bt = C + ... + C \\
v & ::= & C \mid i \\
ck & ::= & \mathbf{base} \mid ck\ \mathbf{on}\ C(x) \\
ct & ::= & ck \mid ct \times ... \times ct
\end{array}
$$

Informal Semantics

h	`True`	`False`	`True`	`False`	...
x	x_0	x_1	x_2	x_3	...
y	y_0	y_1	y_2	y_3	...
v `fby` x	v	x_0	x_1	x_2	...
$x + y$	$x_0 + y_0$	$x_1 + y_1$	$x_2 + y_2$	$x_3 + y_3$	...
$z = x$ `when` `True`(h)	x_0		x_2		...
$t = y$ `when` `False`(h)		y_1		y_3	...
`merge` h (`True` $\rightarrow z$) (`False` $\rightarrow t$)	x_0	y_1	x_2	y_3	...

- z is at a slower rate than x. We say its clock is ck `on` `True`(h)
- the `merge` constructs needs its two arguments to be on complementary clocks
- statically checked through a dedicated type system (clock calculus)

Derived Operators

$$\begin{aligned}
\texttt{if}\ x\ \texttt{then}\ e_2\ \texttt{else}\ e_3 &= \texttt{merge}\ x \\
&\qquad (\texttt{True} \rightarrow e_2\ \texttt{when}\ \texttt{True}(x)) \\
&\qquad (\texttt{False} \rightarrow e_3\ \texttt{when}\ \texttt{False}(x))
\end{aligned}$$

$$\begin{aligned}
y = e_1\ \texttt{->}\ e_2 &= y = \texttt{if}\ init\ \texttt{then}\ e_1 \texttt{else}\ e_2 \\
&\quad \texttt{and}\ init = \texttt{True}\ \texttt{fby}\ \texttt{False}
\end{aligned}$$

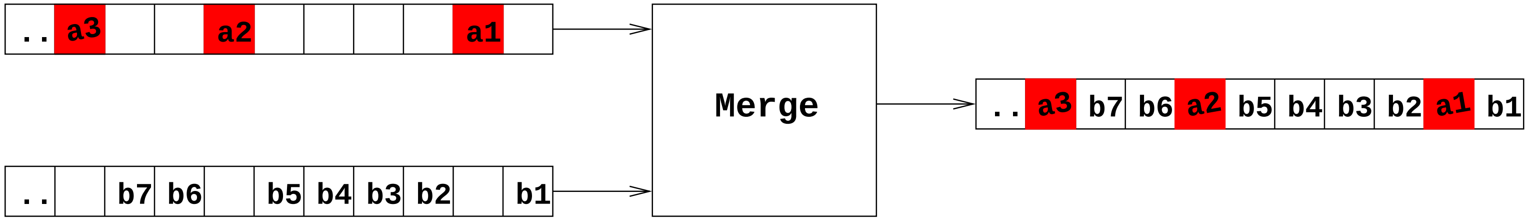
$$\texttt{pre}\,(e) = nil\ \texttt{fby}\ e$$

Example (counter)

```
node counting (tick:bool; top:bool) = (o:int) with
var v: int in
    o = if tick then v else 0 -> pre o + v
and v = if top then 1 else 0
```

N-ary Merge

`merge` combines two complementary flows (flows on complementary clocks) to produce a faster one:



introduced in Lucid Synchrone V1 (1996), input language of ReLuC

Example: `merge c (a when c) (b whenot c)`

Generalization:

- can be generalized to n inputs with a specific extension of clocks with enumerated types
- the sampling e `when` c is now written e `when` $\texttt{True}(c)$
- the semantics extends naturally and we know how to compile it efficiently
- thus, **a good basic for compilation**

Reseting a behavior

- in SCADE/Lustre, the “reset” behavior of an operator must be explicitely designed with a specific reset input

```
node count() returns (s:int);
let
 s = 0 fby s + 1
tel;

node resetable_counter(r:bool) returns (s:int);
let
  s = if r then 0 else 0 fby s + 1;
tel;
```

- painful to apply on large model
- propose a primitive that applies on node instance and allow to reset any node (no specific design condition)

Modularity and reset

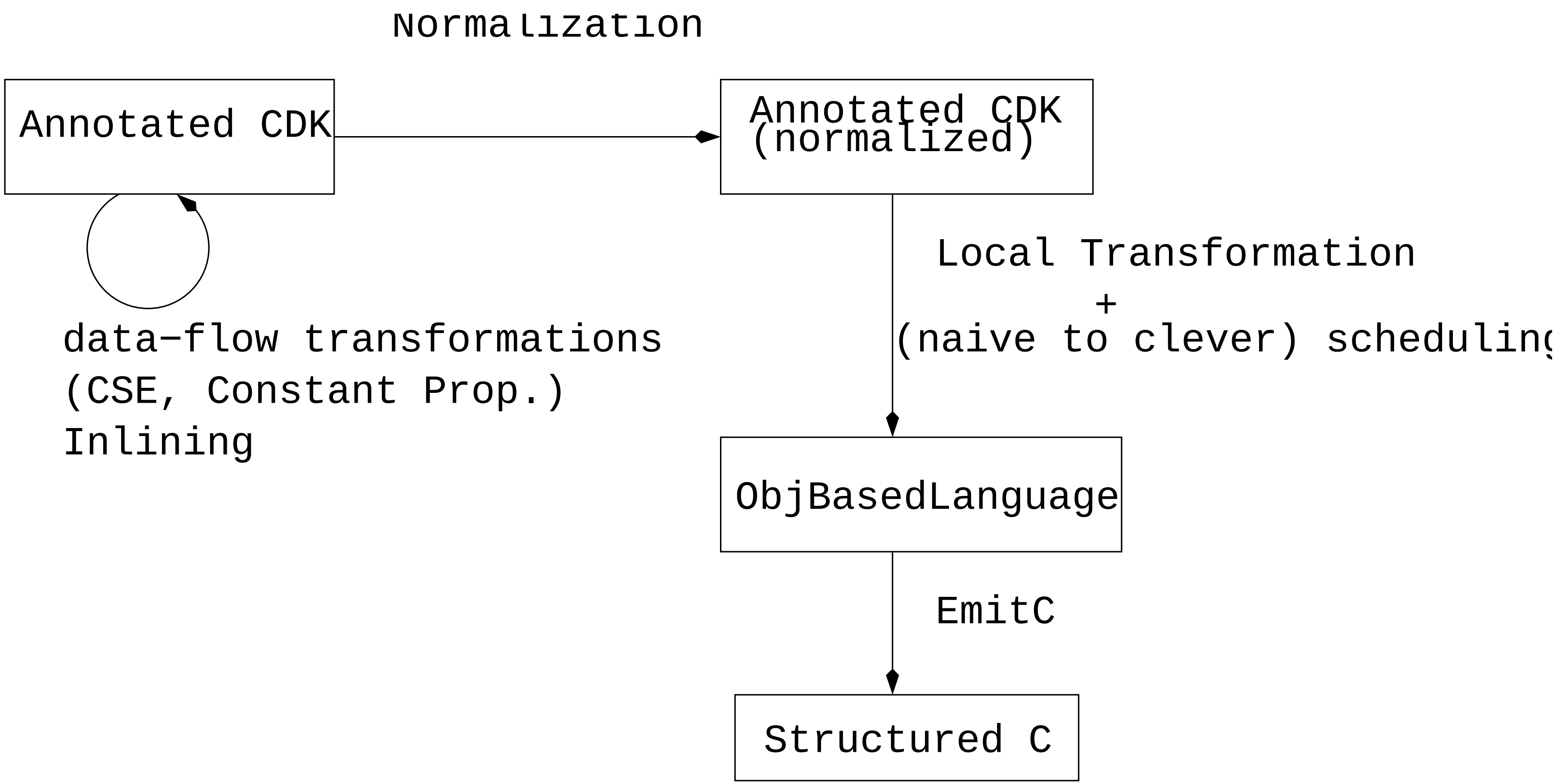
Specific notation in the basic calculus: $f\ (a_1, ..., a_n)\ \texttt{every}\ c$

- all the node instances used in the definition of node x are reseted when the boolean c is true
- the reset is "asynchronous": no clock constraint between the condition c and the clock of the node instance

is-it a primitive construct? yes and no

- modular translation of the basic language with reset into the basic language without reset ([PPDP00], with G. Hamon)
- essentially a translation of the initialization operator $\texttt{->}$
- $e_1\ \texttt{->}\ e_2$ becomes $\texttt{if}\ c\ \texttt{then}\ e_1\ \texttt{else}\ e_2$
- very demanding to the code generator whereas it is trivial to compile!
- useful translation for verification tools, basic for compilation
- thus, **a good basic for compilation**

Translation



Syntactic Dependences and Scheduling

Programs which cannot be statically scheduled are rejected during the causality analysis

- we define $Left\ (e)$ for the list of variables from e which are free in e and not as an argument of a delay `fby`
- $Left\ (D)$ is the union of such variables for any expression of D
- for any $pat = a$ from D, any variable from pat depends on $Left\ (D)$
- the transitive closure defines the notion of static dependence (Halbwachs et al, [PLILP 91])
- the program can be statically scheduled if there is no cycle
- simple inductive definitions (see [APGES 07] paper)
- an equation $x = v\ \texttt{fby}\ y + 2$ is executed after every equations using x

Remark: several classical "graph based" optimization can be applied on this data-flow kernel

- Common Sub-expression Elimination, Constant Propagation, Inlining

Putting Equations in Normal Form

- prepare equations before the translation
- extract delays from nested expressions by a linear traversal
- Equations are transformed such that delays are extracted from nested computation.

Normal Form:

$$
\begin{array}{lcl}
a & ::= & e^{ck} \\
e & ::= & a \texttt{ when } C(x) \mid op\,(a, ..., a) \mid x \mid v \\
ce & ::= & \texttt{merge}\; x\; (C \to ca)\; ...\; (C \to ca) \mid e \\
ca & ::= & ce^{ck} \\
eq & ::= & x = ca \mid x = (v \texttt{ fby } a)^{ck} \\
 & & \quad\quad \mid (x, ..., x) = (f\;(a, ..., a) \texttt{ every } x)^{ck} \\
D & ::= & D \texttt{ and } D \mid eq
\end{array}
$$

Example

$$z = ((((4 \texttt{ fby } o) * 3) \texttt{ when } \mathtt{True}(c)) + k)^{ck \texttt{ on } \mathtt{True}(c)}$$

$$\texttt{and } o = (\texttt{merge } c \ (\mathtt{True} \rightarrow (5 \texttt{ fby } (z+1)) + 2)$$

$$(\mathtt{False} \rightarrow ((6 \texttt{ fby } x)) \texttt{ when } \mathtt{False}(c)))^{ck}$$

is rewritten into:

$$z = (((t_1 * 3) \texttt{ when } \mathtt{True}(c)) + k)^{ck \texttt{ on } \mathtt{True}(c)}$$

$$\texttt{and } o = (\texttt{merge } c \ (\mathtt{True} \rightarrow t_2 + 2)$$

$$(\mathtt{False} \rightarrow t_3 \texttt{ when } \mathtt{False}(c)))^{ck}$$

$$\texttt{and } t_1 = (4 \texttt{ fby } o)^{ck}$$

$$\texttt{and } t_2 = (5 \texttt{ fby } (z+1))^{ck \texttt{ on } \mathtt{True}(c)}$$

$$\texttt{and } t_3 = (6 \texttt{ fby } x)^{ck}$$

Intermediate Language

$$
\begin{array}{rcl}
d & ::= & \texttt{class}\ f = \\
& & \langle \texttt{memory}\ m, \\
& & \quad \texttt{instances}\ j, \\
& & \quad \texttt{reset}()\ \texttt{returns}\ () \ = \ S, \\
& & \quad \texttt{step}\ (p)\ \texttt{returns}\ (p) = \texttt{var}\ p\ \texttt{in}\ S \rangle \\
S & ::= & x \ := \ c \mid \texttt{state}\ (x) \ := \ c \mid S\ ;\ S \mid \texttt{skip} \\
& & \qquad \mid o.\texttt{reset} \mid (x, ..., x) = o.\texttt{step}\ (c, ..., c) \\
& & \qquad \mid \texttt{case}\ (x)\ \{C : S; ...; C : S\} \\
c & ::= & x \mid v \mid \texttt{state}\ (x) \mid op(c, ..., c) \\
v & ::= & C \mid i \\
j & ::= & o : f, ..., o : f \\
p, m & ::= & x : t, ..., x : t
\end{array}
$$

Intermediate Language

- the minimal need to represent transition functions
- we introduce an ad-hoc intermediate language to represent them
- it has an “object-based” flavor (with minimal expressiveness nonetheless)
- static allocation of states only
- it can be trivially translated into a imperative language
- we only need a subset set of C (functions and static allocation of structures, very simple pointer manipulation)

Principles of the translation

- Hierarchical memory model which corresponds to the call graph: one local memory for each function call
- Control-structure (invariant): a computation on clock ck is executed when ck is true
- a guarded equations $x = e^{ck}$ translates into a control-structure

E.g., the equation:

$$x = (y+2)^{\texttt{base on } C_1(x_1) \texttt{ on } C_2(x_2)}$$

is translated into a piece of control-structure:

$$\texttt{case } (x_1)\ \{C_1 : \texttt{case } (x_2)\ \{C_2 : x = y + 2\}\}$$

- local generation of a control-structure from a clock

$$
\begin{array}{lcl}
Control(\texttt{base}, S) & = & S \\
Control(ck \ \texttt{on} \ C(x), S) & = & Control(ck, \texttt{case} \ (x) \ \{C : S\})
\end{array}
$$

- merge them locally

$$
\begin{array}{l}
Join(\texttt{case} \ (x) \ \{C_1 : S_1; ...; C_n : S_n\}, \\
\qquad \texttt{case} \ (x) \ \{C_1 : S_1'; ...; C_n : S_n'\}) \\
\quad = \texttt{case} \ (x) \ \{C_1 : Join(S_1, S_1'); ...; C_n : Join(S_n, S_n')\} \\
Join(S_1, S_2) = S_1; S_2
\end{array}
$$

- the translation is made on a linear traversal of the sequence of normalized and scheduled equations

- every function defines a machine (a “class”)

- control-optimization: find a static schedule which gather equations guarded by related clocks

Translation

A context (m, si, j, d, s):

- m is the state memory $[v_1/x_1, ..., v_n/x_n]$
- si is the initialization code (reset method)
- j is the instance memory $[f_1/o_1, ..., f_m/o_m]$
- d is the set of local variables
- s is a sequence of instructions

A few mutually recursive functions:

- $TE_{(m,si,j,d,s)}\,(e)$ translates an expression in context (m, si, j, d, s)
- $TA_{(m,si,j,d,s)}\,(x, e^{ck})$ translates an expression storing the result in x
- $TEq_{(m,si,j,d,s)}\,(eq)$ for equations
- $TEqList_{(m,si,j,d,s)}\,(eqlist)$ for a list of equations

Translation

A few definitions (see paper [APGES07] for details)

$$TA_{(m,si,j,d,s)}\,(x, e^{ck}) = (m, si, j, d, Control(ck, x\ :=\ TE_{(m,si,j,d,s)}\,(e)))$$

$$TEq_{(m,si,j,d,s)}\,(x = ca) = TA_{(m,si,j,d,s)}\,(x, ca)$$

$$\begin{aligned} TEq_{(m,si,j,d+[x:t],s)}\,(x = (v\ \texttt{fby}\ a)^{ck}) = let\ c = TE_{(m,si,j,d,s)}\,(a)\ in\ & \\ & (m + [x : t], [\texttt{state}\,(x)\ :=\ v]@si, \\ & j, d, \\ & [Control(ck, \texttt{state}\,(x)\ :=\ c)]@s) \end{aligned}$$

Example

```
node count (x : int; z : bool) returns (o : int);
var
  i : bool; o2:int;
let
   i = true fby false;
   o = merge i (true -> (x + o2) when true(i))
               (false -> (0 fby o + 1) when false(i));
   o2 = merge i (true -> (42 fby (o when true(i))) + 1)
                (false -> 0);
 tel;
```

```
class count {
  x_1 : bool; x_3 : int; x_2 : int;

  reset() { mem x_1 = true; mem x_3 = 42; mem x_2 = 0; }

  step(x : int; z : bool) returns (o : int) {
    i : bool; o2 : int;

    i = mem(x_1);
    mem x_1 = false;
    switch (i) {
      case false :
        o2 = 0;
        o = mem(x_2) + 1;
      case true :
        o2 = mem(x_3) + 1;
        o = x + o2;
        mem x_3 = o;
    };
    mem x_2 = o; }
```

Example (modularity)

- each function is compiled separately
- a function call needs a local memory

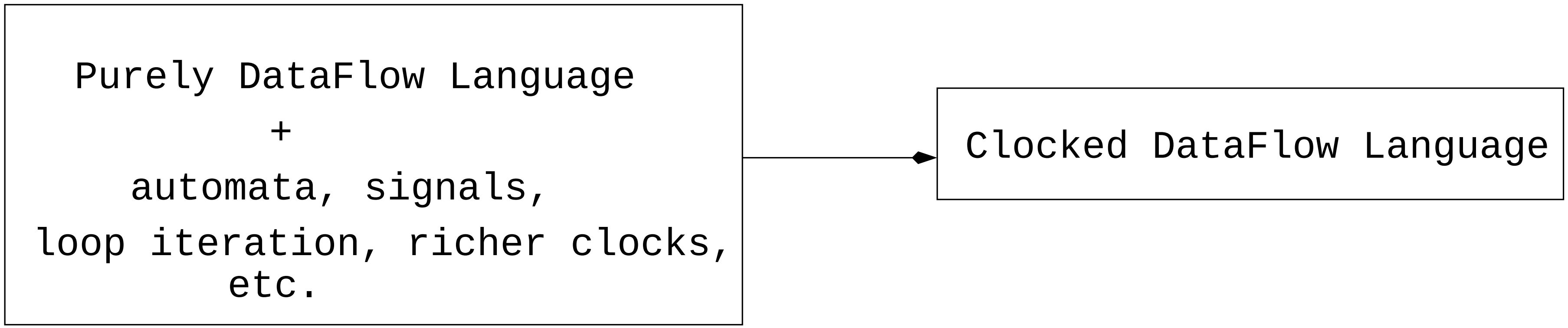
```
node count(x:int) returns (o:int);
let
  o = 0 fby o + x;
tel;

node condact(c:bool;input:int) returns (o:int);
let
  o = merge c (true -> count(input when true(c)))
              (false -> (0 fby o) when false(c));
tel;
```

```
class condact {
  x_2 : int; x_4 : count;

  reset() {
    x_4.reset();
    mem x_2 = 0;
  }

  step(c : bool; input : int) returns (o : int) {
    x_3 : int;

    switch (c) {
      case true :
        (x_3) = x_4.step(input);
        o = x_3;
      case false :
        o = mem(x_2);
    };
    mem x_2 = o; }
```

MiniLustre in Numbers

Administrative code	Abstract syntax + printers	335
	Lexer&Parser	546
	main (misc, symbol tables, loader)	285
Basis	graph	74
	scheduling	67
	type checking	269
	clock checking	190
	causality check	30
	normalization	95
	translate (to ob)	132
Emitters to concrete languages	(C, Java and Caml)	arround 300 each
Optimizations	Inline + reset	250
	Dead-code Removal	42
	Data-flow network minimization	162

Extensions (towards a full language)



- extend the source language with new programming constructs
- translation semantics into the basic data-flow language
- this is essentially the approach we have followed previously (Lucid Synchrone, ReLuC compiler of SCADE)
- clocks play a central role
- simple and gives very good code
- reuse of the existing code generator (adequate in the context of a certification process)

Question: What about polymorphism and higher-order?

Formal Certification (Coq programming)

In parallel, we have done:

- an implementation of MiniLustre in the programming language of Coq (1500 loc)
- extracted caml code + hand-coded caml code to get the compiler
- type and clock inference also done

We are currently working on the semantics and proof of equivalence between the source language and the intermediate language

Semantics

We (finally) choose a "reaction semantics" (in SOS style) for the source language

$$
\begin{array}{llll}
\text{Values:} & w+ & ::= & w \mid (w+, ..., w+) \\
 & w & ::= & abs \mid v \\
\text{Reaction Environnement:} & R & ::= & [w_1/x_1, ..., w_n/x_n] \quad (i \neq j \Rightarrow x_i \neq x_j) \\
\text{Reaction:} & & & R \underset{ck}{\vdash} e_1 \xrightarrow{w+} e_2 \quad R \vdash D \xrightarrow{R'} D'
\end{array}
$$

Lemma 1 (Normalization) *if* $D_N \in Norm(D)$ *then* $R \vdash D \xrightarrow{R'} D'$ *then*
$R \vdash D_N \xrightarrow{R'} D'_N \wedge D'_N \in Norm(D')$

Lemma 2 (Scheduling) *if* $D_S \in Sch\,(D)$ *then* $R \vdash D \xrightarrow{R'} D'$ *then*
$R \vdash D_S \xrightarrow{R'} D'_S \wedge D'_S \in Sch\,(D)$

We define the predicate $R \underset{seq}{\vdash} D \xrightarrow{R'} D'$ for normalized and scheduled equations; $Init(D)$ gives the initial state (left part of `fby`).

Lemma 3 (Sequential computation) *If* $D_S \in Sch\,(Norm(D))$ *then* $R, R' \vdash D \xrightarrow{R'} D'$ *iff*
$R, Init(D) \underset{seq}{\vdash} D_S \xrightarrow{R_0} D'_S \wedge D'_S \in Sch\,(Norm(D')) \wedge R' = Init(D_S), R_0$

Semantics for the Intermediate Language

An operational one (in SOS style two). No fix-point.

$$\rho \quad ::= \quad [v_1/x_1; ...; v_m/xn] \text{ where } x_i \neq x_j \text{ for all } i \neq j$$

and

$$\begin{array}{lcl} m & ::= & [v_1/x_1; ...; v_n/x_n] \\ j & ::= & [O_1/o_1; ...; O_m/o_m] \\ M & ::= & \langle m, j \rangle \\ O & ::= & \langle M, reset = S, step = \lambda p.q \;\texttt{with}\; S \rangle \end{array}$$

Two predicate:

- $M, \rho \vdash e \Downarrow v$: e evaluates to v in M and ρ
- $M, \rho \vdash S \Downarrow \rho', M'$ for instructions

Prove the preservation of semantics for the translation function.

Conclusion

Current

- a reference (small) MiniLustre compiler has been implemented
- semantics "on paper" (source and intermediate language) and semantics preservation of the translation

Future (relatively close)

- Coq development of the semantics preservation
- finish the Coq programming of the reference compiler (combines **translation validation** (e.g., scheduling) and **certified compilation**)

Future (longer term)

- mixed systems (data-flow systems + mode-automata)
- source-to-source transformation into the data-flow system
- translation semantics (as done in ReLuC [EMSOFT'05, EMSOFT'06])
- the reference implementation MiniLustre has been done accordingly (about 300 extra lines of Caml code)