Compilation of Lustre

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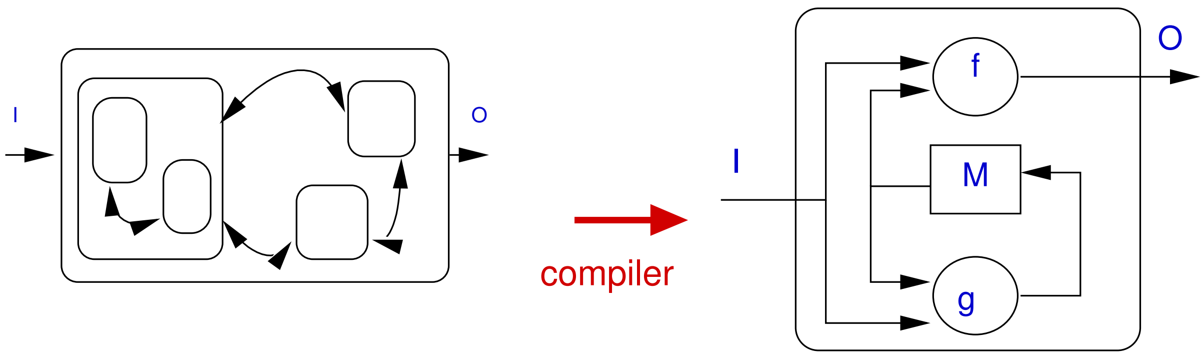
Compilation of synchronous programs

General problem

Transform a (hierarchic) parallel program into a (simple) sequential program.



Whole implementation of a reactive program P

```
var I, O, M;
M := m0; proc P_step() ...;
foreach step do
   read(I);
   P_step();  // combines: O := f(M, I); M := g(M, I);
   write(O);
end foreach
```

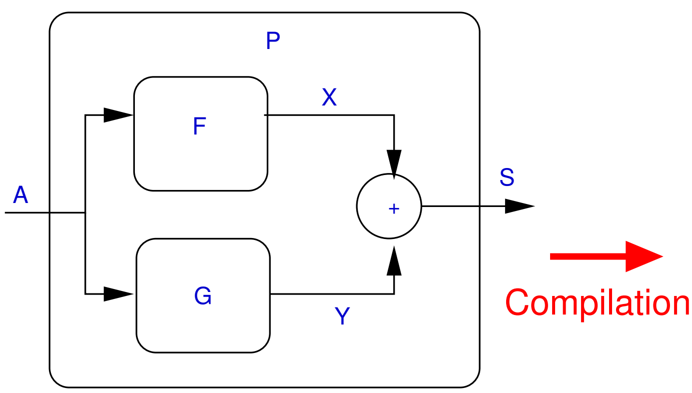
Job of the compiler

- Find the memory M and its initial value m0
- Build the core of the loop (the P_step procedure)
- As far as possible, generate efficient code

Modular compilation problem

The "obvious" way of compiling

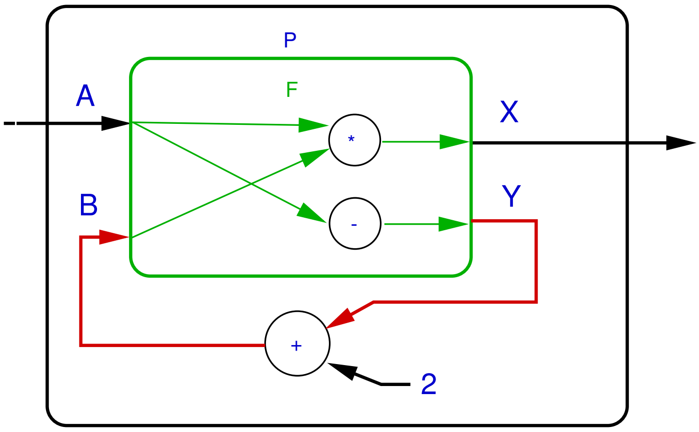
A Lustre node → a step procedure.




```
var A, X, Y, S;
proc F_step() begin X := ... end
proc G_step() begin Y := ... end
proc P_step()
begin
  F_step();
  G_step();
  S := X + Y;
end
```

Problem

What about feed-back loops ?



combinationnal loop ?

not when inlined ! $\Rightarrow$

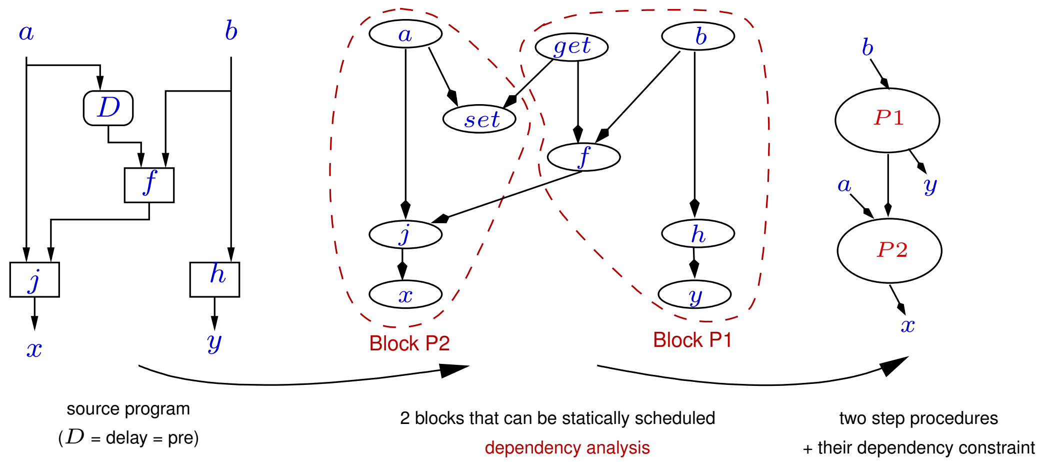
`X = A * (2 - A)`

- The program "is" correct (in a "parallel" world),
- but no `F_step` procedure can work!

Solution(s)

- Lustre (academic): expansion (i.e. inlining) of node calls
  - ↪ Strictly compliant with the principle of substitution.
  - ↪ Forbids modular compilation.
- Scade: feedback loops (without `pre`) are forbidden.
  - ↪ Reject correct parallel programs.
  - ↪ Allow modular compilation.
  - ↪ Reasonable choice in a industrial framework.
- Compilation into ordered blocks aka Modular Static Scheduling
  - ↪ Intermediate solution
  - ↪ Split the step into a minimal set of (sequential) blocks,
  - ↪ Only expand this simplified structure.

An example of Modular Static Scheduling



- Interesting theoretical result.
- Not (yet ?) used in industry.

Compilation of Lustre

Example : a filtered counter

- count rising edges of X (F),
- reset with a delay (R).

```
node CptF(X,reset: bool) returns (cpt: int);
var F, R : bool;
let
  cpt = if R then 0
    else if F then pre cpt + 1
    else pre cpt;
  R = true -> pre reset;
  F = X -> (X and not pre X);
tel
```

Simple loop compilation

Intuitively, do what is necessary to make definitions equivalent to assignments, i.e.:

- translate classical operators (trivial),
- replace `pre`'s and `->`'s with memory constructs,
- sequentialize according to data-dependencies (i.e. static scheduling).

Identify the memory

- Introduce a explicit variable for each **pre**:

```
pcpt = pre cpt;
preset = pre reset;
pX = pre X;
```

- Introduce a special memory

```
init = true -> false;
```

and replace each:

```
x -> y
```

with

```
if init then x else y
```

New version of the Lustre program

```
cpt = if R then 0
  else if F then pcpt + 1
  else pcpt;
R = if init then true else preset;
F = if init then X else (X and not pX);
pcpt = pre cpt;
preset = pre reset;
pX = pre X;
init = true -> false;
```


Sequentialization

Must take into account:

- Instantaneous dependences between values,
  - ↪ an (partial) order MUST exist (no combinational loop), example: `R` before `cpt` and `F` before `cpt`
  - ↪ chose a compatible complete order (schedule), example `R`, then `F` then `cpt`.
- Memorisations
  - ↪ Must be done at the end of the step, in any order.

Simple loop implementation (C-like code)

- Arithmetic and logic are translated "asit"
  (ex. **and** becomes **&&**, **if**..**then**..**else** becomes ..**?**..**:**..)
- `pre`'s are replaced with memories
- `->`'s are replaced with **init?**...**:**...
- Inputs/outputs are stores in global variables (for instance)

Simple loop implementation (C-like code)

```
int cpt; bool X, reset; /* I/O global vars */
int pcpt; bool pX, preset; /* non initialized memories */
bool init = true; /* the only necessary initialization */
void CptFiltre_step() {
    bool R, F;/* local vars */
    R = init ?  true :  preset;
    F = init ?  X : (X && !  pX);
    cpt = R ? 0 :  F ? pcpt + 1 :  pcpt;
    pcpt = cpt; pX = X; preset = reset;
    init = false;
}
```

Optimizations

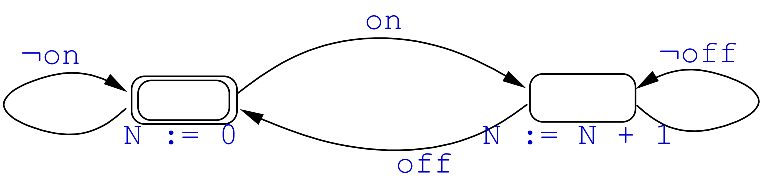
- Control structure: **?** becomes **if**
- Factorize conditions
- Eliminate useless local vars

```
if (init) {
    cpt = 0;
    init = false;
} else {
    F = (X && !  pX);
    cpt = preset ?  0 :  F ? (pcpt+1) :  pcpt;
}
pcpt = cpt; pX = X; preset = reset;
```


Compilation into automaton

Idea

The following reactive automaton:



is exactly equivalent to a Lustre program:

```
node Chrono(on, off :  bool) returns (N : int);
var R : bool;
let
   R = false -> pre(if R then not off else on);
   N = if R then (pre N + 1) else 0;
tel
```

Problem: how to build the automaton from the Lustre code ?

Goal

- Automatically build an automaton equivalent to a Lustre program

How ?

- Idea: an (explicit) state ⇔ a valauation of the memory
- N.B. finite number of states ⇒ finite memory (e.g Boolean)

Example of `CptF`

- **`S1`** = initial state = "**`init`** true, all other undefined"
- simplifed code : **`cpt = 0`**
- integer memorization: still the same
- Boolean memorization: state transition

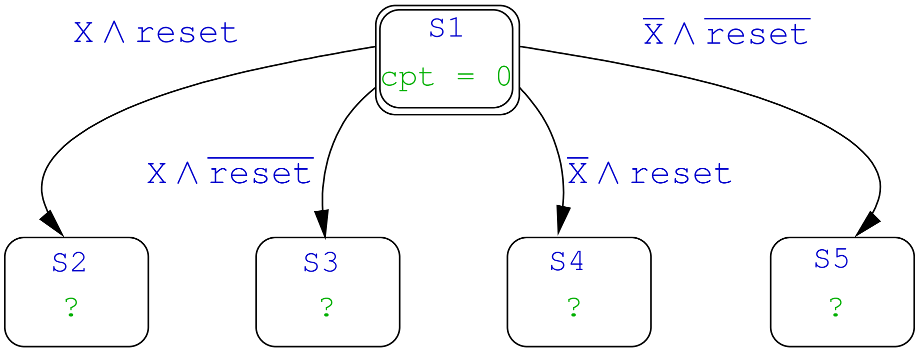
Transitions

- State **`S1`** (initial):

  `init = false; pX = X; preset = reset;`

Depending on the values of `X` and `reset`, 4 next states:

- $\texttt{X} \wedge \texttt{reset} \rightarrow \texttt{S2} \equiv \overline{\texttt{init}} \wedge \texttt{pX} \wedge \texttt{preset}$
- $\texttt{X} \wedge \overline{\texttt{reset}} \rightarrow \texttt{S3} \equiv \overline{\texttt{init}} \wedge \texttt{pX} \wedge \overline{\texttt{preset}}$
- $\overline{\texttt{X}} \wedge \texttt{reset} \rightarrow \texttt{S4} \equiv \overline{\texttt{init}} \wedge \overline{\texttt{pX}} \wedge \texttt{preset}$
- $\overline{\texttt{X}} \wedge \overline{\texttt{reset}} \rightarrow \texttt{S5} \equiv \overline{\texttt{init}} \wedge \overline{\texttt{pX}} \wedge \overline{\texttt{preset}}$



- Code of the other states:

↪ S2 → cpt = 0

↪ S3 → cpt = pcpt

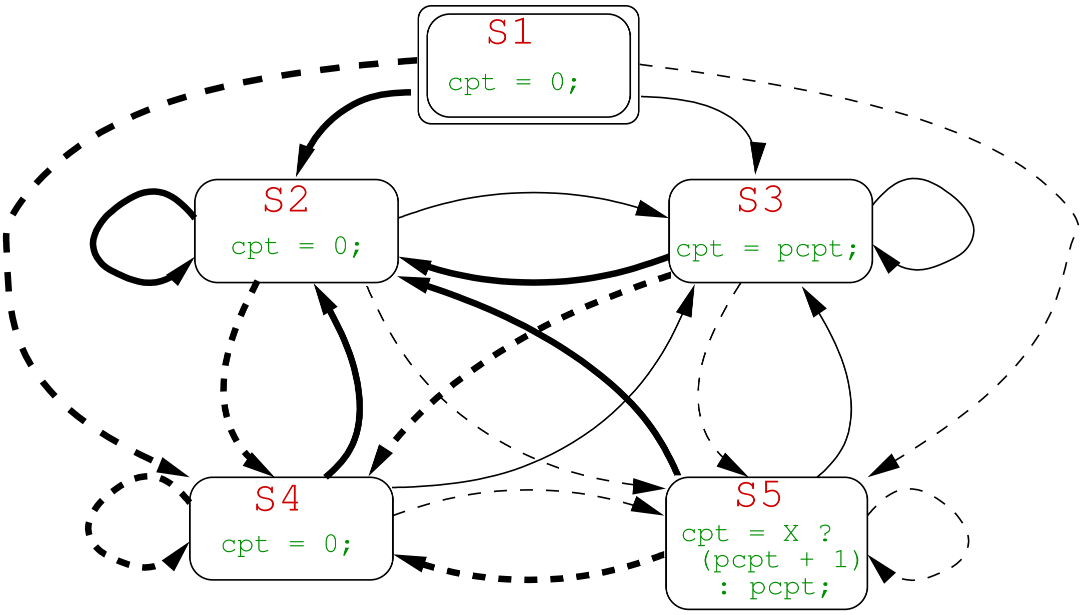
↪ S4 → cpt = 0

↪ S5 → F = X, cpt = X? (pcpt + 1) : pcpt

- Transitions of the other states:

↪ same than S1 (only depend on inputs)

Finally ...



⇒ problem: size!

Remarks on the size

- n memories $\Leftrightarrow$ (worst case) 2^n states, 2^{2n} transitions

  $\Rightarrow$ *Combinatorial explosion*

But not always:

- Unreachable states

  ↪ Example : `(pre X, pre(X or Y))` $\Rightarrow$ "only" 3 states

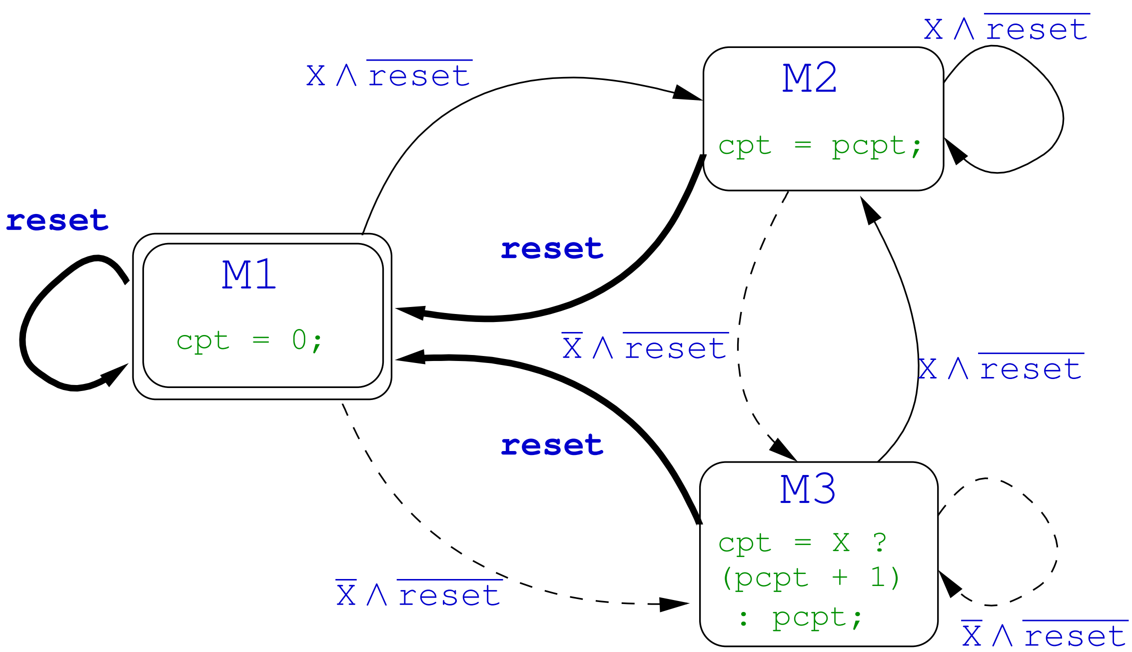
  ↪ Counter-example : `CPtF` !

- State equivalence

  ↪ Example `CPtF` : `S1`, `S2` et `S4` "*are doing the same thing*"

  $\Rightarrow$ *Importance of producing a minimal automaton*

Minimal automaton of `CptF`



Implementation en C

With a switch (for instance):

```
typedef enum {M1, M2, M3} TState;
TState state = M1;
void CptFiltre_step(){
   switch (state) {
      case M1:  cpt = 0; break;
      case M2:  cpt = pcpt; break;
      case M3:  cpt = X? (pcpt + 1):pcpt; break;
   }
   pcpt = cpt;
   if (reset) state = M1;
   else if (X) state = M2;
   else state = M3;
}
```


Simple loop or automaton ?

Automate

- Optimal in computation time
- Possible huge size

Simple loop

- Less slower
- Linear size

⇒ Only “reasonable” solution fram an industrial point of view

Automaton, what for?

- Not reasonable for code generation, but ...
- Precious for *reasoning* about programs, i.e. for validation.

Example/demo

The stopwatch

```
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
```

- expand, identify memory, sequentialize ...
- automaton ...