Compilation of synchronous programs

General problem

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

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Whole implementation of a reactive program $P$

```plaintext
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 $P_{\text{step}}$ procedure)
- As far as possible, generate efficient code

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Modular compilation problem ______________________________

The "obvious" way of compiling

A Lustre node $\rightarrow$ a step procedure.

```plaintext
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
```

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Problem

What about feed-back loops?

\[ X = A \times (2 - A) \]

- 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
  \( \rightarrow \) Strictly compliant with the principle of substitution.
  \( \rightarrow \) Forbids modular compilation.
- Scade: feedback loops (without \texttt{pre}) are forbidden.
  \( \rightarrow \) Reject correct parallel programs.
  \( \rightarrow \) Allow modular compilation.
  \( \rightarrow \) Reasonable choice in a industrial framework.
- Compilation into ordered blocks aka Modular Static Scheduling
  \( \rightarrow \) Intermediate solution
  \( \rightarrow \) Split the step into a minimal set of (sequential) blocks,
  \( \rightarrow \) 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 ($R$).

```plaintext
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 \texttt{pre}'s and \texttt{->}'s with memory constructs,
- sequentialize according to data-dependencies (i.e. static scheduling).

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Identify the memory

- Introduce a explicit variable for each \texttt{pre}:
  \begin{verbatim}
  pcpt = pre cpt;
preset = pre reset;
pX = pre X;
  \end{verbatim}
- Introduce a special memory
  \begin{verbatim}
  init = true -> false;
  \end{verbatim}
  and replace each:
  \begin{verbatim}
  x -> y
  \end{verbatim}
  with
  \begin{verbatim}
  if init then x else y
  \end{verbatim}

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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 “as it”
  (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)

```c
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

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

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Compilation into automaton __________________________________________

Idea

The following reactive automaton:

![Automaton Diagram]

is exactly equivalent to a Lustre program:

```plaintext
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 valuation 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”

• simplified code : cpt = 0

• integer memorization: still the same

• Boolean memorization: state transition

Compilation into automaton

Transitions

• State S1 (initial):
  
  \[ \text{init} = \text{false}; \ \text{pX} = \text{X}; \ \text{preset} = \text{reset}; \]

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

  • \( X \land \text{reset} \rightarrow S2 \equiv \overline{\text{init}} \land \text{pX} \land \text{preset} \)

  • \( X \land \overline{\text{reset}} \rightarrow S3 \equiv \overline{\text{init}} \land \text{pX} \land \overline{\text{preset}} \)

  • \( \overline{X} \land \text{reset} \rightarrow S4 \equiv \overline{\text{init}} \land \overline{\text{pX}} \land \text{preset} \)

  • \( \overline{X} \land \overline{\text{reset}} \rightarrow S5 \equiv \overline{\text{init}} \land \overline{\text{pX}} \land \overline{\text{preset}} \)
• Code of the other states:
  \[ \begin{align*}
  & S2 \rightarrow \text{cpt} = 0 \\
  & S3 \rightarrow \text{cpt} = \text{pcpt} \\
  & S4 \rightarrow \text{cpt} = 0 \\
  & S5 \rightarrow F = X, \text{cpt} = X? (\text{pcpt} + 1) : \text{pcpt}
  \end{align*} \]

• Transitions of the other states:
  \[ \begin{align*}
  & \text{same than S1 (only depend on inputs)}
  \end{align*} \]

\[
\begin{align*}
\Rightarrow \text{problem: size!}
\end{align*}
\]
Remarks on the size

- $n$ memories $\iff$ (worst case) $2^n$ states, $2^{2n}$ transitions
  $\Rightarrow$ Combinatorial explosion

But not always:

- Unreachable states
  $\leftarrow$ Example: $(\text{pre } X, \text{pre}(X \text{ or } Y))$ $\Rightarrow$ “only” 3 states
  $\leftarrow$ Counter-example: CptF!

- State equivalence
  $\leftarrow$ Example CptF: $S_1, S_2$ et $S_4$ “are doing the same thing”
  $\Rightarrow$ Importance of producing a minimal automaton

Minimal automaton of CptF

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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 from an industrial point of view

Automaton, what for?

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

```plaintext
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 ...

Example/demo ___________________________________ 24/24