On Combining Synchronous and Functional Programming

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Overview

- The origins
- From Lustre to Lucid Synchrone
- Developing a Language
- Conclusion

The origins (sept. 94 – june 96)

(VERIMAG, Montbonnot & McGill University, Montreal)

The origins

What are the relationships between:

- Kahn Process Networks
- Synchronous Data-flow Programming (e.g., Lustre)
- (Lazy) Functional Programming (e.g., Haskell)
- Types and Clocks

What can we learn from the relationships between synchronous and functional programming?

The first intuitions

In 1993 (I was still doing my PhD thesis in "Bat 8" at Rocquencourt...) Paul noticed the relationships between functional programming and synchronous programming in two papers:

- **Lucid Synchrone** [Caspi, OPOPAC 93],
- **Towards Recursive Block Diagrams** [Caspi, RTP 94]

He made the following observations:

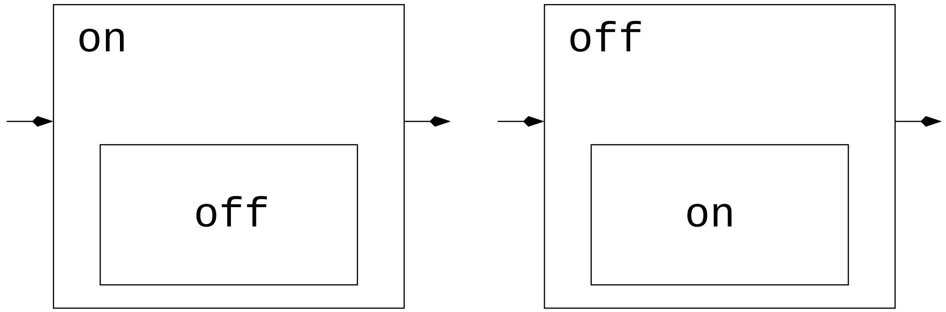
- Synchronous dataflow can be simulated in a functional lazy language in a few lines (LazyML at that time).
- We can program in the semantics.
- We can benefit from all the features of the host language: type inference, modularity, higher-order, recursion.
- with the idea that extending Lustre with functional features was both natural and fruitful

Lustre and Lazy streams

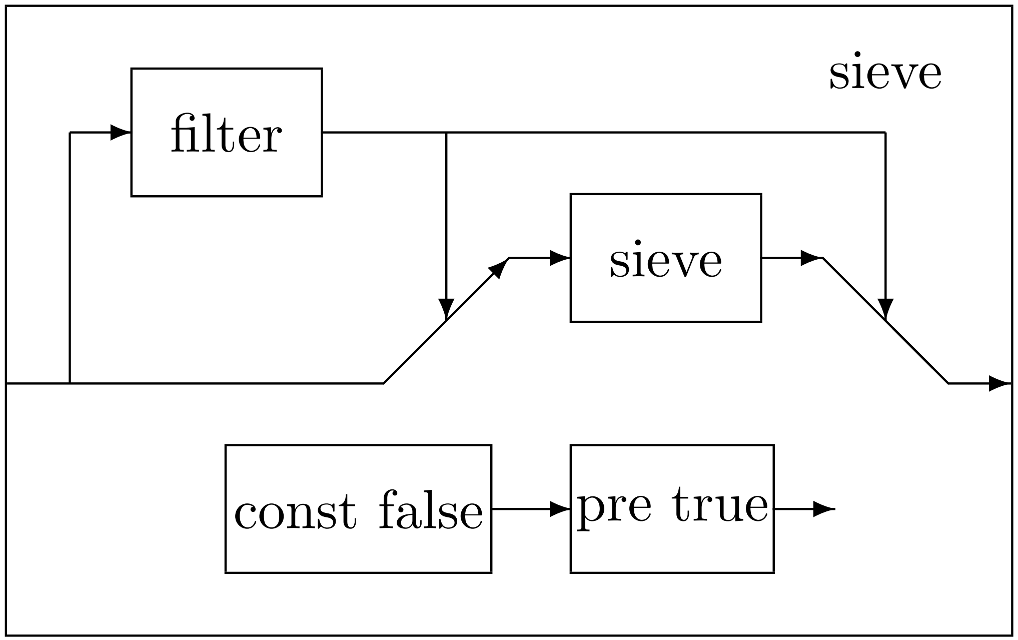
```
module Streams where

-- lifting constants
constant x = x : (constant x)

-- pointwise application
extend (f:fs) (x:xs) = (f x):(extend fs xs)

-- delays
(x:xs) `fby` y = x:y
pre x y = x : y

-- sampling
(x : xs) `when` (True : cs)  = (x : (xs `when` cs))
(x : xs) `when` (False : cs) = xs `when` cs

merge (True : c)  (x : xs) y  = x : (merge c xs y)
merge (False : c) x (y : ys)  = y : (merge c x ys)
```

Recursive Block Diagrams

- Dynamic reconfiguration (i.e., imperative constructs of Esterel) can be encoded as classical tail-recursive functions



- More general (dynamic) networks can be considered such as the Eratosthene sieve, etc.



Extending Synchronous Data-flow

- Synchronous data-flow are some class of static bounded memory data-flow networks.
- They are not recursively defined and obey some "synchronous" constraints (*clock calculus*).
- Those networks enjoy efficient compilation techniques.

Synchrony can be related to Wadler's listlessness and deforestation techniques ([Wadler, LFP 84, TCS 90])

- Listlessness is a compilation techniques which eliminates intermediate data-structures from stream programs, e.g., `hd (x : y) = x`
- avoid the need of a lazy evaluation mechanism

Can we extend the class of static synchronous data-flow to higher-order and dynamical networks?

Synchrony and Listlessness evaluation

But deforestation techniques failed to deforest (i.e., diverge) on simple programs such as `current v (x ‘when‘ c) c` which are trivially accepted in Lustre.

```
(xo : x) ‘when‘ (True : c) = xo : (x ‘when‘ c)
(xo : x) ‘when‘ (False : c) = x ‘when‘ c
```

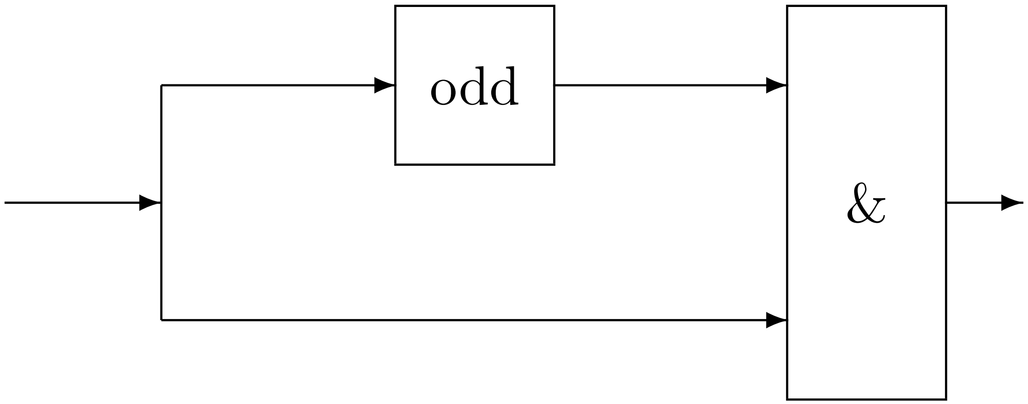
```
curr v (x0 : x) (True : c) = x0 : (current xo x c)
current v x (False : c) = v : (current v x c)
```

In **Lustre** syntax: `(current (x when c))`

In **SCADE**: `condact(c; v; id)` (where `id x = x`)

Existing deforestation techniques at that time (e.g., “A Short Cut to Deforestation” [FPCA 93]) failed to deforest many useful synchronous programs

Clock Constraints and Synchrony



The computation of $(x_n \,\&\, x_{2n})_{n \in \mathbb{N}}$ is not real-time

```
let odd x = x when half
let non_synchronous x =  x & (odd  x)
                             ^^^^^^^^^

This expression has clock 'a on half, but is used with clock 'a.
```

Execution with unbounded FIFOs!!!

- Deforestation techniques diverge on those programs
- We should statically reject those programs
- This is the purpose of the *clock calculus* in synchronous data-flow languages

Synchronous Kahn Networks [ISLIP'95, ICFP'96]

Provide an extension of synchronous data-flow by:

- defining a functional kernel with abstraction, application and recursion whose first order restriction is Lustre,
- define a synchronous operational semantics for it, generalizing existing ones;
- define a clock calculus for this language and express it as a type-system, which, in turn, allows us to generalize it to functional features

Property: well clocked program can be executed synchronously

From Lustre to Lucid Synchrone

(McGill University, Université Paris 6)

A Co-iterative Characterization of Synchronous Stream Functions [CMCS 98]

These first works with Paul showed that it was possible to implement an extension of Lustre and it was of course called Lucid Synchrone

- a small functional kernel (higher-order and recursion)
- a dependent type clock calculus
- causality check was trivial (graph based)
- a partial compilation method: this was the hard part (we failed to make it modular)

We started working on the problem in june 96 (after ICFP), from the work of Jacob & Rutten (pre-version of "A tutorial on (co)algebras and (co)induction", EATCS Bulletin 97

- found a modular compilation technique for the extended kernel
- explain the classical compilation of SCADE in a few lines
- the method is time resistant: it is still in use in the current compiler

Functional Programming and Reactive Systems

At about the same period, several projects identified the interest of functional (data-flow) programming to model reactive systems.

- Mary Sheeran noticed in 84 the interest of functional programming for describing synchronous circuits in μFP [LFP 84]
- Various embedding of Hardware Description Languages in Haskell: Lava [Sheeran & all, ICFP 98], Hawk [Launchbury & all, ICFP 99], etc.
- Functional Reactive Programming [Hudak, Petterson, ICFP 99]
- Fran (Functional Reactive Animation) [Elliot & Hudak, ICFP 97]
- Now Multi-stage programming techniques [Taha PhD. 99, etc.], Arrows (Hughes [SCP 00], Paterson [ICFP 01]), ReFlect (Intel) [ICFP 05], etc.

Functional Reactive Programming (FRP, FRAN)

- more simulation-oriented (at the begining, at least); embedding of discrete and continuous signals, etc.
- accept too many programs: synchronous and asynchronous
- no *guaranty* at compile time
- memory leaks, unbounded recursion, etc.
- no compilation (or simply macro-expansion)
- Haskell run-time (but a macro-expansion to C is feasible)
- the type system of Haskell is not sufficient

Synchronous Circuits (e.g., Lava, Wired, Hydra, ReFlect, Hawk)

- very elegant and very well adapted to the design of synchronous circuits
- "two stage" approach: the execution of the program produces a net-list
- length-preserving functions mainly (circuits with a base clock)
- the type system of Haskell is not sufficient
- no static analysis (e.g., causality analysis) nor modular compilation

Developing a language (sept. 96 –)

(LIP6, Univ. Paris 6 & LRI, Univ. Paris-Sud 11)

Lucid Synchrone

How to extend Lustre in a conservative way (without breaking it)?

Build a “laboratory” language

- study (implement) extensions of Lustre
- experiment things, manage all the compilation chain and write programs!
- Version 1 (1995), Version 2 (2001), V3 (2006)

Follow a few principles:

- types everywhere
- clock based approach: everything should be explained in term of a basic clocked model with Kahn semantics
- modularity everywhere (type analysis, separate compilation)

Some developments I

Typing:

- Automatic type inference with polymorphism; various versions ([Emsoft 04])

Clock calculus: Clocks play a central role both on the semantics side and the implementation side.

- same philosophy as Lustre (differs from the one of Signal)
- clocks as types (provides both polymorphism and inference) making them more usable
- defined as a dependent type system [ICFP 96]
- start of the collaboration with Jean-Louis Colaço (Esterel-Technologies) on the design of a prototype compiler for SCADE ($\sim$ 2000)
- the prototype ReLuC compiler uses the first-order version of this calculus
- programming constructs (e.g., `merge`)
- then a simpler calculus reminiscent to Milner-type system [Emsoft 03]

Some developments II

Type-based program analysis:

- initialization analysis (with JL. Colaço, [STTT 04]
- both implemented in Lucid Synchrone and ReLuC
- causality analysis as a type-system (with Pascal Cuoq, [ESOP 01])

Mixing imperative constructs and data-flow:

- PhD. thesis of G. Hamon [PPDP 00, SLAP 04]
- work with Colaço & Pagano (ET) on the design of the mix of automata and data-flow systems
- semantics and compilation [Emsoft 05, 06]
- both implemented in ReLuC and Lucid Synchrone

Recently, we came back to the origins (N-Synchronous Kahn Networks [POPL'06]) to relax the semantics to allows non strictly synchronous systems for the implementation of video systems (project with Philips semiconductor, now NXP)

Laboratory language?

Many of these ideas, originally introduced by Paul, are now integrated in two industrial tools of the field.

- the ReLuC compiler of SCADE is based (and improves) techniques introduced in Lucid Synchrone
- same philosophy: types everywhere, modularity, etc.
- program constructs (e.g., `merge`), control-structures
- static analysis (initialization)
- design/semantics of ReLuC (next SCADE)

Athys (Dassault-Systèmes) is developing a programming environment into the Catia suite for PLC:

- progressively switching from an Esterel-like variant to a functional data-flow one
- ML-like module system and types, higher-order, link with simulation tools

Conclusion

- The direction was clearly drawn from the very beginning and only a few things really changed.
- Reformulating synchronous data-flow in the functional setting was very fruitful and many extensions came naturally.
- The language exists and contains most of the features we were looking at at the very beginning.
- The goal to make it a laboratory language succeed.
- Paul had a strong influence in it (simplicity of constructions, orthogonality of concept, unified semantics).

What's next?

Certified compilation

Implement a verified compiler for a Lustre-like language with the help of the proof assistant Coq

- Combine **certified compilation** and **translation validation**
- Kahn semantics (in Coq), preliminary compiler [APGES'07]

General-purpose Concurrent Programming

How to introduce synchronous principles into a general-purpose language?

- **ReactiveML = Ocaml + synchronous composition** (Mandel)
- (Surprisingly) useful, even for the design of embedded systems: routing protocol for ad-hoc or sensor networks, links with simulation tools (Maraninchi & Samper)

Video Intensive Computation

- Kahn Process networks widely used (in part. at NXP)
- links with traditional optimization/compilation techniques