Dynamic Scheduling of Synchronous Programs in Lucid Synchrone

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What this is about

Alternative titles

- Modular code generation for Lustre / Lucy-n without static clock information
- Experiments with Latency-Insensitive Design in Lucid Synchrone
- One use of higher-order stream functions

Bottom line

A latency insensitive shallow embedding of Lustre/Lucy-n in Lucid Synchrone.

Introduction

Context

A latency-insensitive protocol

Prototype implementation in Lucid Synchrone

Conclusion

Original motivations

Lucy-n

A variant of Lustre with:

- ultimately periodic sampling/merging conditions;
- a buffer operator.

`lucync`

The compiler's role is to:

- infer clocks;
- compute buffer sizes;
- generate code.

Lustre 101

```
let node f c = o where
  rec o = merge c m 42
  and m = 0 fby (m + 1)
```

```
f(true fby false fby true fby true fby false fby true...)
```

time	t_0	t_1	t_2	t_3	t_4	t_5	...
c	*true*	*false*	*true*	*true*	*false*	*true*	
o	0	42	1	2	42	3	
m	0	.	1	2	.	3	

Clocks:

- `f :: 'a -> 'a`
- `m :: 'a on c`

In the generated code, state changes for `m` must occur exactly when `c` is true.

Lucy-n (101)

```
let node f x = o where
  rec o = buffer v1 + v2
  and v1 = x when (10)
  and v2 = x when (01)
```

time	t_0	t_1	t_2	t_3	t_4	t_5	...
(10)	1	0	1	0	1	0	
x	x_0	x_1	x_2	x_3	x_4	x_5	
v1	x_0		x_2		x_4		
v2		x_1		x_3		x_5	
buffer v1		x_0		x_2		x_4	
o		$x_0 + x_1$		$x_3 + x_2$		$x_5 + x_4$	

Clocks:

- `v1 :: 'a on (10)`
- `v2 :: 'a on (01)`
- `o :: 'a on (01)`

Traditional modular code generation for Lustre

```
let node f c = o where
  rec o = merge c m 42
  and m = 0 fby (m + 1)

m :: 'a on c
o :: 'a
```

```
class f:
  mem m = 0;
  method step(in c, out o):
    if (c):
      o := m;
      m := m + 1;
    else:
      o := 42;
```

- Compiling means translating equations with (implicit) activation rhythms to guarded affectations.
- Code generation translates clock types to conditional statements.

Modular code generation for Lucy-n

```
let node f (x, y) = x when (1001) + y when (0110)

val f :: forall 'a.
 'a on (011110) * 'a on (110011) ->  'a on (010010)
```

Clocking Lucy-n

- Clock types feature ultimately periodic binary words rather than names.
- Clocking a program amounts to solving some cyclic scheduling problem.
- Clocks are *schedules*, and thus `lucync` has to invent clocks that are not present in the source program.
- This may pose a practical problem for code generation with the previous method.

Circumventing the clock generation problem

```
let node g () = (o1, o2) where
  rec n = 0 fby (n + 1)
  and o1 = buffer (n when (00101)) + 1 when (10)
  and o2 = buffer (n when (01)) + 2 when (01)
```

$\texttt{n} :: \alpha \texttt{ on } (1101010011001100110011010100110011001100)$

Ideas

- Have the clocking pass generate simpler clocks;
- generate more efficient code for the given clocks:
  - try some compression methods on words;
  - decompose words into simpler ones thanks to algebraic properties;
- discard the static clock information and compute the activation rhythms on line (*"clocking" at run-time*).

Intuitions

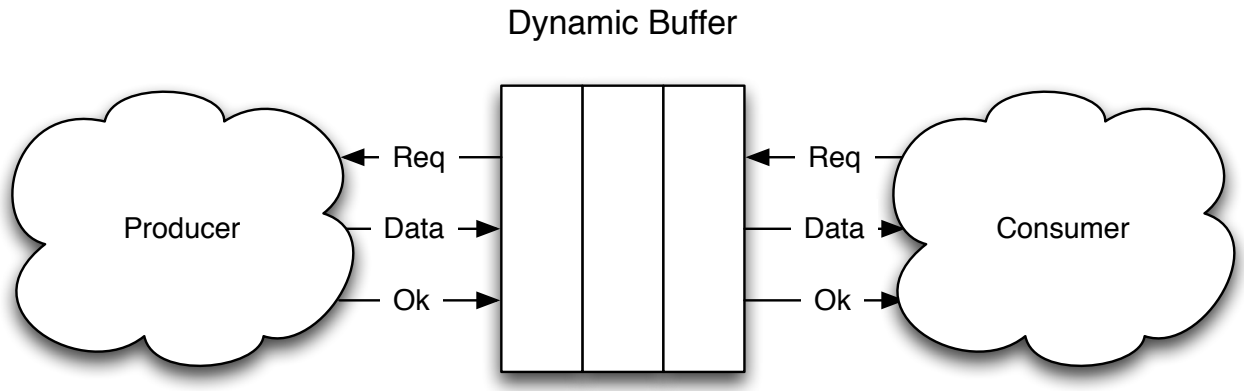
Where are clocks needed in Lucy-n?

- `fby`;
- node application;
- `buffer`.

Designing a protocol to compute clocks *on-line* means adding control signals and logic to the source program.

- Which control signals?
- What control logic?

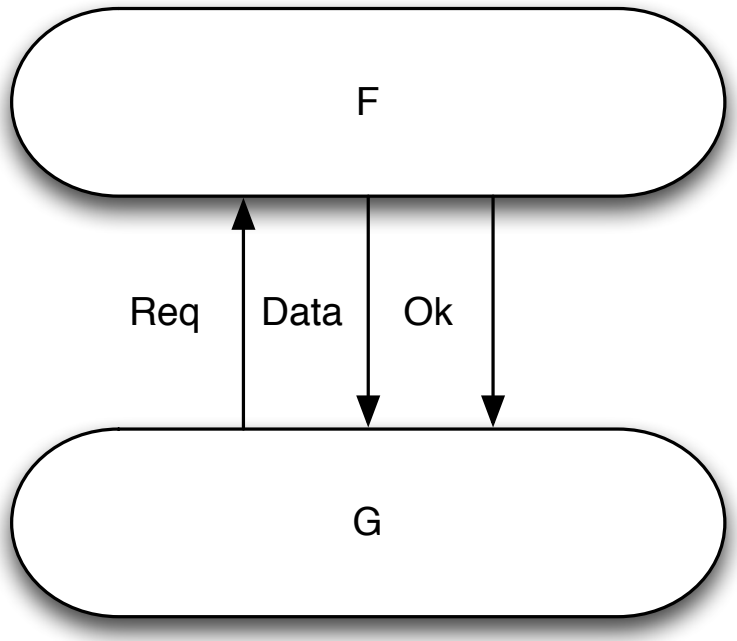
Understanding control signals through buffers



Which control signals for the buffer?

- *Req*: "I want to read in the buffer" bit.
- *Ok*: "I want to write in the buffer" bit.
- For modularity reasons, we add these signals everywhere.

The protocol



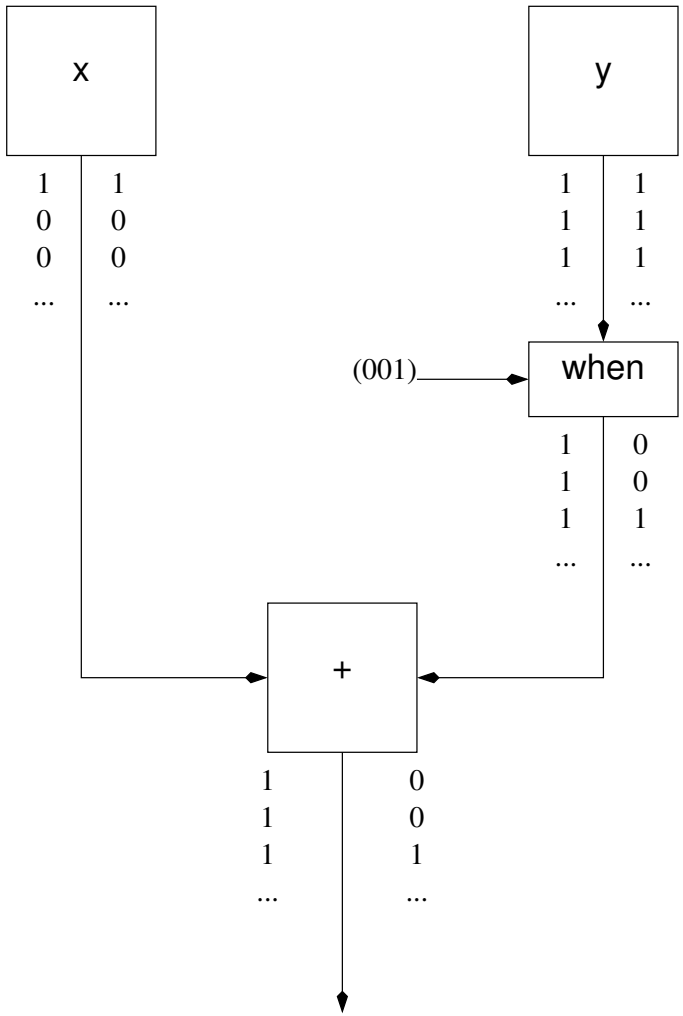
What's in an interface for source-level values of type α?

- *req*, boolean: G tells F "Give me data!";
- *data*, of type α: F sends G data of type α;
- *ok*, boolean: F tells G "I'm giving you valid data".

Behaviors for various constructs

- constants c:
  $ok = req, data = c$;
- synchronous operators (+, ...):
  force synchronization of operands;
- `merge` of e_1 and e_2:
  set either req_1 or req_2 according to condition;
- `when`:
  set ok according to the sampling condition;
- `buffer`:
  eager, always ask the producer for data when non-empty;
- `fby`:
  initialized buffer of size one.

Local synchronization




```
x + (y when (001))
```

Behaviors for various constructs

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  $ok = req, data = c$;
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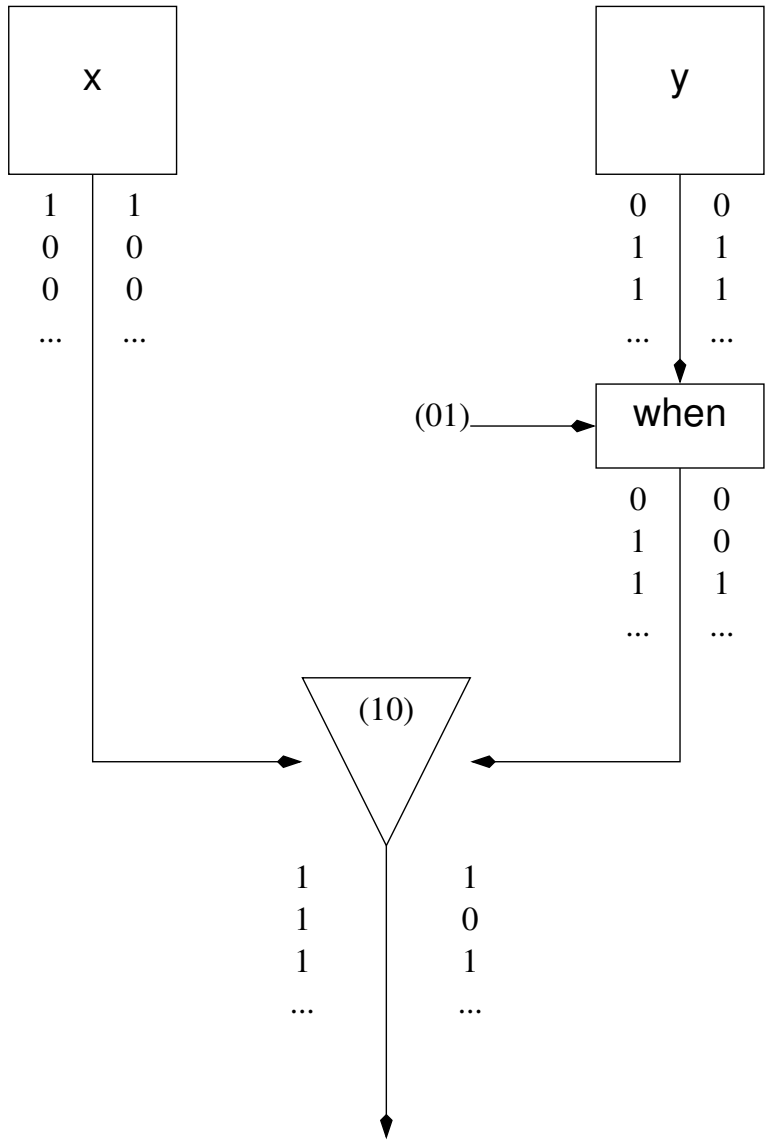
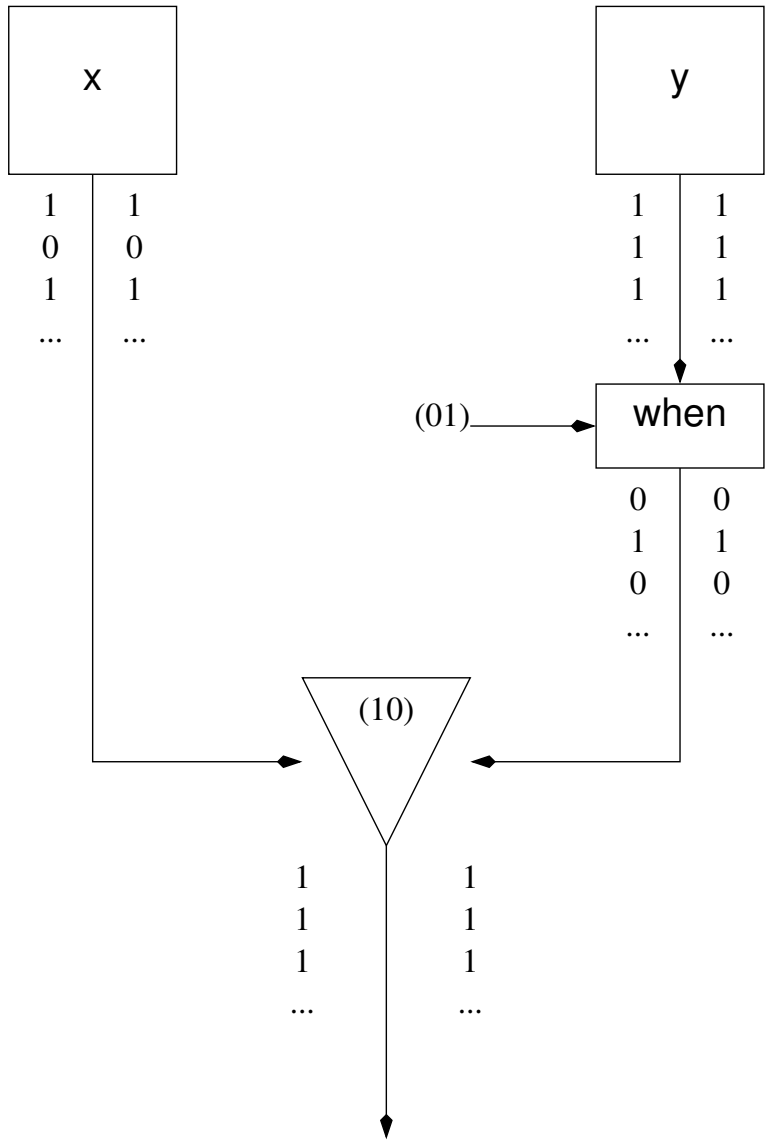
Lazy sampling




```
merge (10) x (y when (01))
```

Eager sampling




```
merge (10) x (y when (01))
```

Behaviors for various constructs

- constants c:
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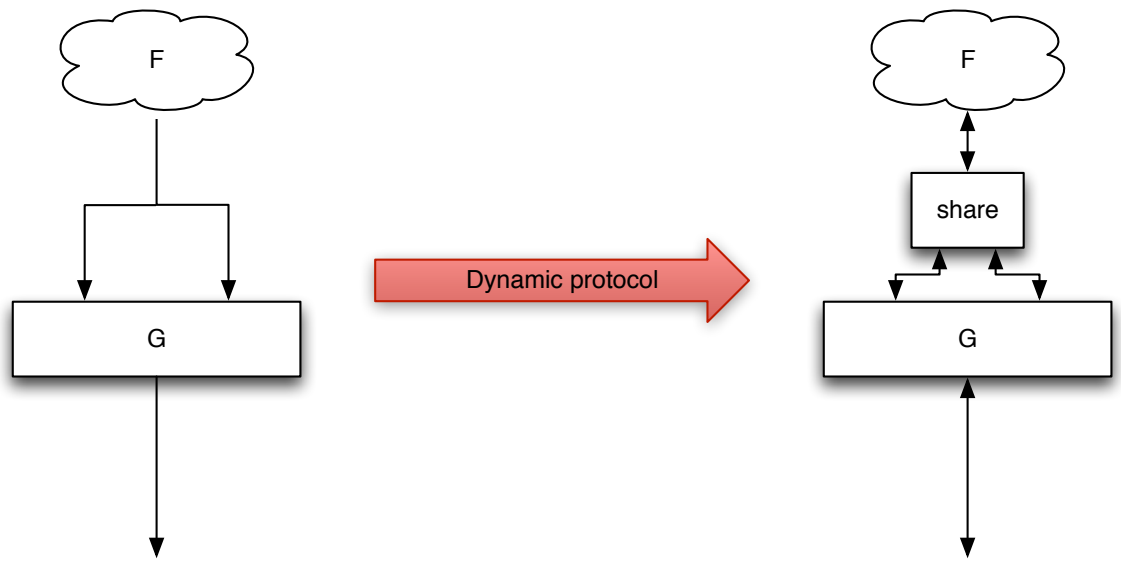
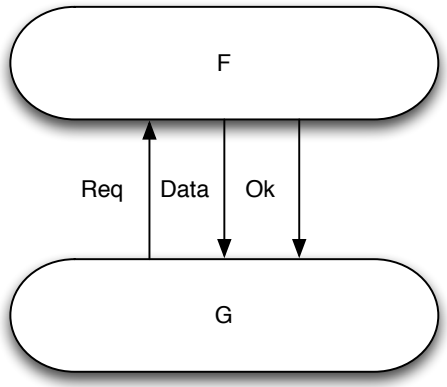
Some remarks

- Invariant: it is impossible to receive data that was not asked for: $\neg req \Rightarrow \neg ok$.
- Each construct is naturally delay insensitive, in the sense that the functional behavior of the program do not change if it receives spurious 0 on its control wires.
- Multiple reads are no longer free, since we have to somehow merge the two *req* wires!



Programming the protocol in Lucid Synchrone



Expressing the translation from the typing point of view?

$$[\![\alpha]\!] = \texttt{bool} \Rightarrow \alpha \times \texttt{bool}$$

In Lucid Synchrone, we can use higher-order stream functions:

```
my_plus : (bool => int * bool) * (bool => int * bool)
                                -> (bool => int * bool)
```

Some code

```
let node my_const c req = (c, req)

val my_const :: 'a -> (bool => 'a * bool)

let node my_when s e req = (o, ok) where
  rec req_in = req || not b
  and (o, ok) = run e req_in
  and ok = req && b && ok_in
  and b = bit_of s
  and w =
    s fby (if shift then shift_sampler s else s)

val my_when :
  sampler -> (bool => 'a * bool) -> (bool => 'a * bool)
```

Synchronization

```
let node my_synchro e1 e2 (clock req) = (o, ok) where
  rec req1 = req && empty1 and req2 = ...

  and (v1, ok1) = run e1 req1 and (v2, ok2) = ...

  and ok1' = ok1 || not empty1 and ok2' = ...
  and v1' = if empty1 then v1 else b1 and v2' = ...

  and ok = ok1' && ok2'
  and o = (v1', v2')

  and b1 = v1 fby v1' and b2 = ...

  and empty1 = true fby (ok || (not ok1 && empty1))
  and empty2 = ...
```

```
val my_synchro :
    (bool => 'a * bool) * (bool => 'b * bool)
-> (bool => ('a * 'b) * bool)
```

DEMO

Remarks and perspectives

Related work

- Latency-Insensitive Design (Carloni et al.), and in particular...
- **S**ynchronous **EL**astic **F**low (Kishinevsky et al.).

Remarks

- using statically scheduled code inside a dynamically scheduled context is easy;
- ignoring control-flow issues, a SELF-like protocol may be preferable.
- we do not target hardware implementation (combinatorial pathes everywhere!);
- we have experimented with a truly asynchronous implementation of the protocol in ERLANG.

Conclusion and future work

What we did present

A dynamic scheduling protocol for Lucy-n (or Lustre) akin to Latency-Insensitive Design.

TODO list

- Conjecture: well-clocked programs are live.
- Explore macro-expansion to imperative code or continuation-based functional code, and compare with the current static code generator.
- Does the Erlang experiment has anything to do with asynchronous circuits?