High level architectural modelling for early estimation of power and performance

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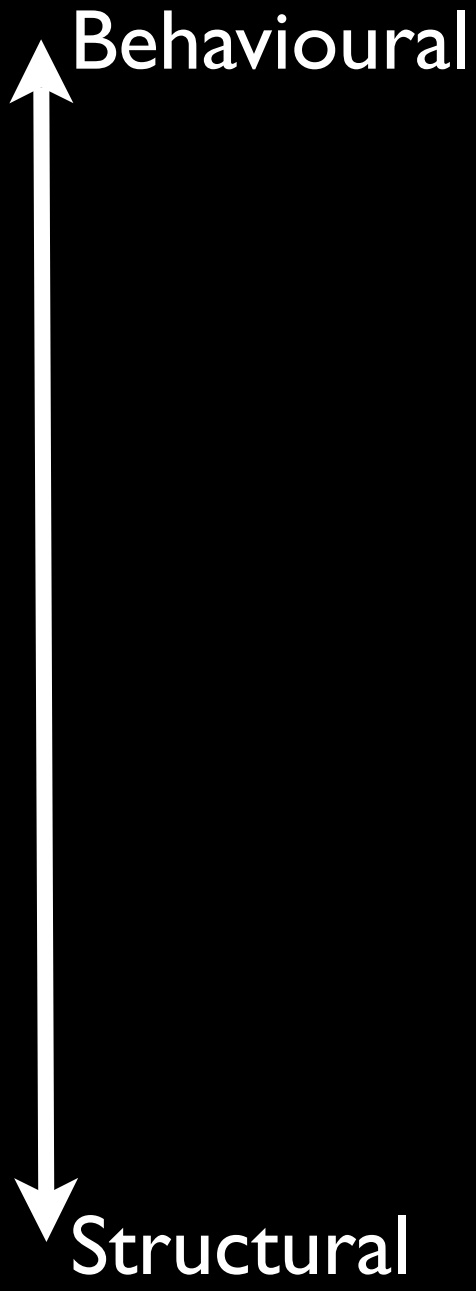
joint work with Koen Claessen, Carl Seger, Mary Sheeran, and Emily Shriver

Project stats

- Started February 2009.
- One year funding from Intel.
- Collaboration between:
  - Intel (Emily Shriver and Carl Seger);
  - Chalmers (Koen Claessen, Mary Sheeran, and myself).

Aim

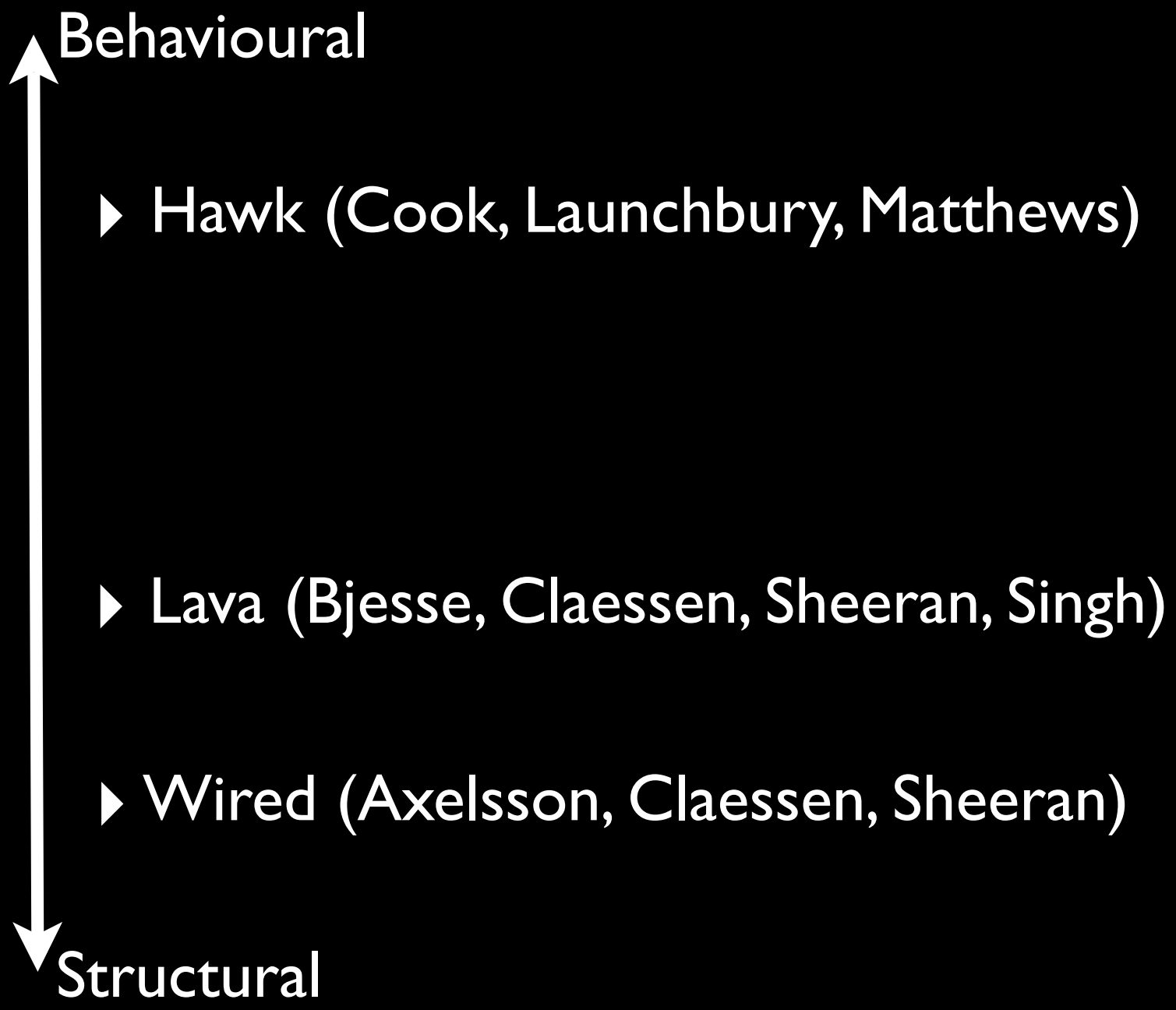
- Try to design a language that:
  - can work at different levels of abstraction;
  - is capable of early estimations of performance and power;
  - builds on our functional programming expertise.


Behavioural
Structural

Behavioural

- Hawk (Cook, Launchbury, Matthews)
- Lava (Bjesse, Claessen, Sheeran, Singh)

Structural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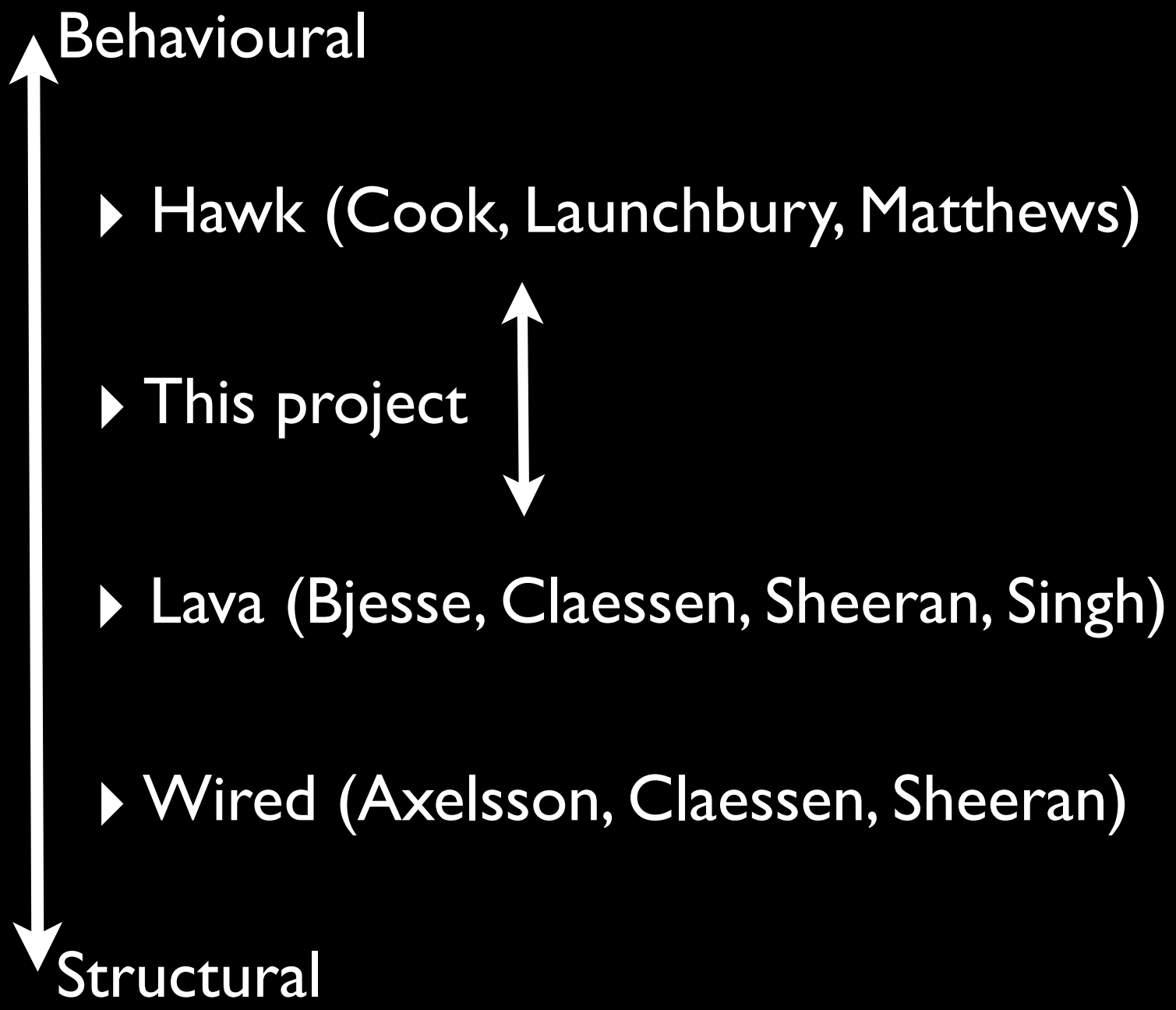

Behavioural
Hawk (Cook, Launchbury, Matthews)
This project
Lava (Bjesse, Claessen, Sheeran, Singh)
Wired (Axelsson, Claessen, Sheeran)
Structural

Lava

- A data type for primitive gates (and, not,...);
- Haskell combinators to assemble circuits (sequential composition, butterfly circuits, ...)
- VHDL generation for circuits;
- Simulation and testing using QuickCheck;
- Hooks into automatic theorem provers.

Hawk

- **Idea:** use Haskell as an executable hardware specification language.
- "Shallow embedding" – there is no separate data type to represent the AST.

Hawk - Signals

Signals assign values to every clock cycle:

```
type Signal a = Int -> a
```

Hawk combinators – I

Haskell functions to manipulate signals:

```
constant :: a -> Signal a
constant x = \c -> x

lift :: (a -> b) -> Signal a -> Signal b
lift f signal = \c -> f (signal c)
```

Hawk combinators – II

```
delay :: a -> Signal a -> Signal a
delay x s =
  \c -> if c == 0 then x else s (c-1)

select :: Signal Bool
  -> Signal a -> Signal a -> Signal a
select cs ts es =
  \c -> if cs c then ts c else es c
```

Counter example

- Using these combinators we can define a resettable counter:

```
counter :: Signal Bool -> Signal Int
counter resets = out
  where out = select reset (constant 0)
                   (delay 0 (lift incr out))
```

- (This definition relies on lazy evaluation.)

Non-trivial examples

- Hawk has been used to describe microprocessors
  - ALU and register files;
  - pipelining;
  - branch prediction;
  - ...

ALU

```
data Cmd = ADD | SUB | INCR

alu :: Signal Cmd -> Signal (Int,Int) ->
       Signal Int

alu = lift eval

  where eval ADD  (x,y) = x + y

        eval SUB  (x,y) = x - y

        eval INCR (x,_) = x + 1
```

Register file

```
data R = R0 | R1 | R2 | R3

type Regs = (Int,Int,Int,Int)

regFile :: Signal (Reg, Int) ->
  Signal Reg -> Signal Reg ->
  (Signal Int, Signal Int)
regFile = loop initRegs regStep
  where
  loop :: s -> (s -> (a,s)) -> Signal a
  regStep :: Regs -> ((Int,Int), Regs)
```

Simple Hawk Microprocessor

- We can assemble these pieces:

```
sham :: (Signal Cmd, Signal Reg,
         Signal Reg, Signal Reg)
        -> (Signal Reg, Signal Int)
sham (cmds, destReg, srcA, srcB) = ...
```

- ... by using our register file to lookup the state of the source registers;
- and passing this on to the alu.

Hawk review

- **Pro**: easy to write down executable specs;
- **Con**: you can't do anything with these specs besides execute them.
  - No generating VHDL;
  - No automatic theorem proving;
  - No power or performance analysis.

Goal

- Can we design a Hawkish specification language that
  - is capable of early power and performance estimates?
  - can be integrated with structural languages like Wired and Lava?

Problem

Suppose we want to write an interpreter for this language:

```
data Expr = Val Int
  | Add Expr Expr
  | Eq Expr Expr
  | If Expr Expr Expr
```

Evaluation

```
eval (Val i) = i

eval (Add l r) = eval l + eval r

eval (Eq x y) = eval x  == eval y

eval (If c t e) =

  if (eval c) then eval t else eval e
```

Evaluation

```
eval :: Expr -> ???
eval (Val i) = i
eval (Add l r) = eval l + eval r
eval (Eq x y) = eval x  == eval y
eval (If c t e) =
  if (eval c) then eval t else eval e
```

GADTs

```
data Expr a where
  Val :: Int -> Expr Int
  Add :: Expr Int -> Expr Int -> Expr Int
  Eq :: Expr Int -> Expr Int -> Expr Bool
  If :: Expr Bool ->
    Expr a -> Expr a -> Expr a
```

Evaluation revisited

```
eval :: Expr a -> a

eval (Val i) = i

eval (Add l r) = eval l + eval r

eval (Eq x y) = eval x  == eval y

eval (If c t e) =

  if (eval c) then eval t else eval e
```

Deeper embedding

```
data Hawk a where
 Pure :: a -> Hawk a
 App :: Hawk (b -> a) -> Hawk b -> Hawk a
 Delay :: a -> Hawk a -> Hawk a
```

Deeper embedding

```
data Hawk a where
 Pure :: a -> Hawk a
 App :: Hawk (b -> a) -> Hawk b -> Hawk a
 Delay :: a -> Hawk a -> Hawk a
```

I'll use an infix operator `<*>` instead of `App`

Example - mux

```
select :: Hawk Bool ->
  Hawk a -> Hawk a -> Hawk a
select cs ts es =
  pure (\c t e -> if c then t else e)
    <*> cs
    <*> ts
    <*> es
```

Example - recursion

- We can still use recursion:

```
iterate :: a -> Hawk (a -> a) -> Hawk a

iterate x h =

  delay x (h <*> iterate x h)
```

Counter example revisited

- We can still define the counter:

```
counter :: Signal Bool -> Signal Int
counter reset = iterate 0 c
  where c = select reset (pure (const 0))
                         (pure increment)
```

Execution

- It is easy to extract a pure Haskell function that executes “the first clock cycle”

```
exec :: Hawk a -> a
exec (Pure x) = x
exec (Delay x _) = x
exec (App f x) = (exec f) (exec x)
```

Simulation

- It is easy to extract original Hawk signal functions:

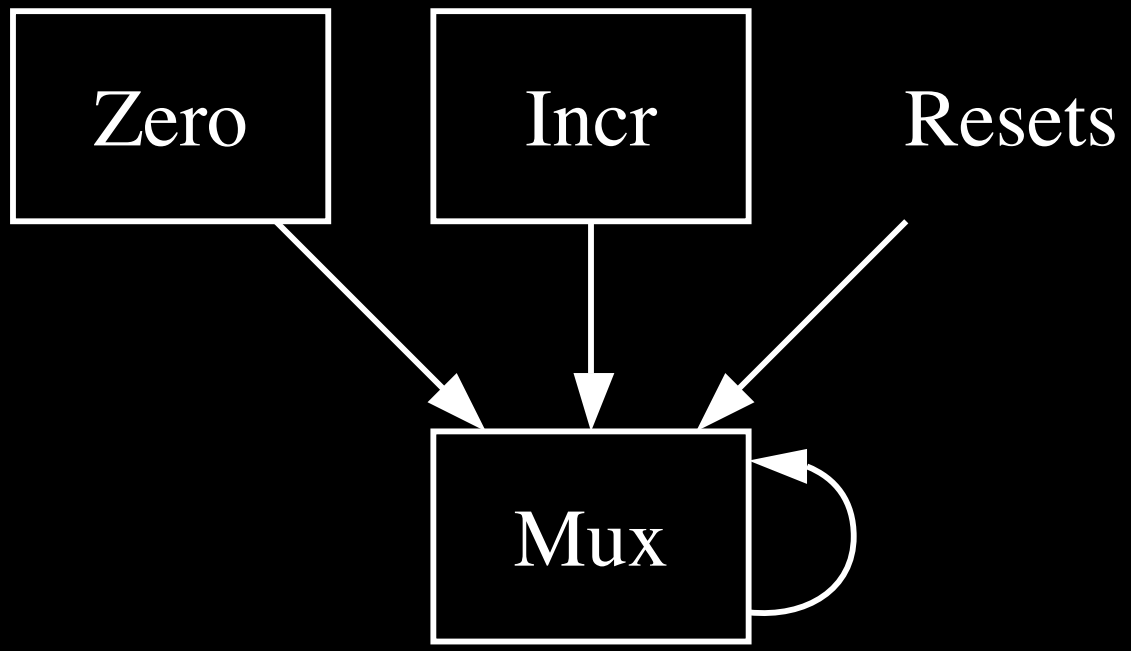
```
simulate :: Hawk a -> Signal a
simulate (Pure x) = \c -> x
simulate (Delay x h) =
  \c -> if c == 0 then x else h (c-1)
simulate (App f x) =
  \c -> (simulate f c) (simulate x c)
```

Recap

- Hypothesis: writing specs using these combinators is no harder than in Hawk;
- ...but we now have more structure at our disposal.
- We can use this info to do other analyses.

Example: circuit visualisation

- If we assign names to the pure components, we can traverse the circuit to extract the call graph...
- ...and visualise the circuit using Graphviz.



The counter graph

So what?

- We can (hopefully) use this structure to analyse processor specifications.
- For example, to estimate performance, pass a token through the flow network, assigning symbolic delay to each edge.
- *Processor Performance Modeling using Symbolic Simulation*; Omid Azizi, Jamison Collins, Dinesh Patil, Hong Wang and Mark Horowitz

Open questions

- How can we combine behavioural (Hawk) and structural (Lava, Wired) languages?
- How can we "plug" Lava circuits into a Hawk spec? Or show that a Lava circuit implements some `Pure` part of the spec?
- How can we change the level of abstraction? Or iteratively develop circuits? What is the right meta-abstraction?