Comparing functional Embedded Domain-Specific Languages for hardware description

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Section 1

Introduction

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Hardware design

Hardware design is *very complex* **and** *very expensive*:

- Mistakes discovered after sales are much more serious
  - No such thing as an "update" to a chip
- Thus the need for extensive simulation
  - Using specific and *expensive* systems
- The downfall of *Moore's Law* doesn't help either
  - More need for parallelism, fault-tolerance, etc.
  - Design *even more error-prone* and validation *even more* complex

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Hardware design

- The level of abstraction has been lifted already. . .
  - Verilog and VHDL in the 1980s
  - Popular, *de facto* industry standards
- *Functional* hardware design languages, also since the 1980s
  - Expressive type systems, equational reasoning, etc.
  - First, languages designed *from scratch*
  - Then, *embedded* in general-purpose functional languages
    - Prominently, in Haskell
    - Several of them available nowadays
    - Each with its own strengths and weaknesses

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Goals of this project

Compare exisiting functional Embedded Domain-Specific Languages (EDSLs) for hardware description.

- A representative sample of EDSLs
- Analyze a well-defined set of *criteria*
- Practical analysis, with a set of circuits as *case studies*

Detect possible improvements as future work

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Detect possible improvements as future work

Let's first review our object of study

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Domain-Specific Languages

A computer language (turing-complete or *not*) targeting a *specific application domain.*

Example DSLs:

- SQL (database queries)
- CSS (document formatting)
- MATLAB (Matrix programming)
- VHDL (Hardware description)

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Domain-Specific Languages

A computer language (turing-complete or *not*) targeting a *specific application domain.*
Example DSLs:

- SQL (database queries)
- CSS (document formatting)
- MATLAB (Matrix programming)
- VHDL (Hardware description)

A DSL can also be *embedded* in a general-purpose language.
Example EDSLs:

- Boost.Proto (C++ / parser combinators)
- Diagrams (Haskell / programmatic drawing)
- Parsec (Haskell / parser combinators)

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Example of an EDSL: Parsec

A simple parser for a "Game of Life"-like input format:

```
dead, alive :: Parser Bool
dead  = fmap (const False) (char '.')
alive = fmap (const True) (char '*')

line :: Parser [Bool]
line  = many1 (dead <|> alive)

board :: Parser [[Bool]]
board = line `endBy1` newline

parseBoardFromFile :: FilePath -> IO [[Bool]]
parseBoardFromFile filename = do
    result <- parseFromFile board filename
    return $ either (error . show) id result
```

- The shallow vs. deep-embedded divide
  - Parsec is *shallow*-embedded

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Hardware EDSLs

An EDSL used for hardware design-related tasks. Can encompass:

- Modeling / description
- Simulation (validation)
- Formal verification
- Synthesis to other (lower-level) languages

Example of a hardware EDSL (Lava):

```
halfAdder :: (Signal Bool, Signal Bool)
          -> (Signal Bool, Signal Bool)
halfAdder inputs = (xor2 inputs, and2 inputs)
```

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Section 2

Analyzed EDSLs

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Choice criteria

When choosing which EDSLs to study, our requirements were:

- Hosted on already-known languages
- Covered a wide range over the criteria we defined (variety)
- Originals instead of variants or improvements
- Relatively well-known, frequently cited

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Chosen EDSLs

The languages chosen, with the respective host language, were:

- Lava (Haskell - `chalmers-lava` variant)
- ForSyDe (Haskell)
- Coquet (Coq interactive theorem prover)

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Evaluation criteria

As *orthogonal* as possible:

- Simulation (validation)
- (Formal) verification
- Genericity (data, structure)
- Depth of embedding
- Tool integration
- Extensibility

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Section 3

Modeled Circuits

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Choice criteria

- Not too simple, not too complex
- Familiar to any hardware designer
    - No signal processing, etc.
- Well-defined, language-agnostic specification
    - Results to validate the models against

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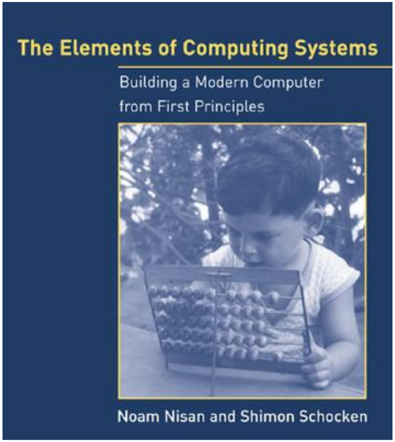
Chosen circuits

We cherry-picked circuits from the book "Elements of Computing Systems", as they satisfied all of our demands.



The Elements of Computing Systems

Building a Modern Computer from First Principles

Noam Nisan and Shimon Schocken

Figure: "Elements of Computing Systems" - Nisan, Schocken, available at `http://www.nand2tetris.org`.

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Chosen circuits

Circuit 1	A 2-input, 16-bit-wide, simple ALU
Circuit 2	A 64-word long, 16-bit wide memory bank
Circuit 3	An *extremely* reduced instruction set CPU, the *Hack* CPU.

Let's take a quick look at each of these circuit's specification. . .

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Circuit 1: ALU

Some of the circuit's key characteristics:

- 2 *operand inputs* and 1 *operand output*, each 16-bit wide
- 2 *output flags*
- Can execute 18 different *functions*, among which:
    - Addition, subtraction
    - Bitwise AND / OR
    - Constant outputs
    - Increment / decrement
    - Sign inversion

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Circuit 1: block diagram

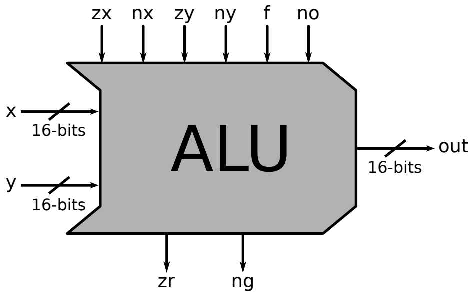

Figure: Input/Output ports of *circuit 1*, the ALU.

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Circuit 1: specification

The behaviour of the ALU is specified by the values of the *control bits* and *flags*:

zx and zy	*Zeroes* the “x” and “y” inputs, respectively
nx and ny	*bitwise negation* on the “x” and “y” inputs
f	Selects the function to be applied: “f” $= 1$ for addition, “f” $= 0$ for bitwise AND
no	*bitwise negation* on the output ALU output
zr and ng	The output *flag* “zr” $= 1$ *iff* the ALU output is zero. “ng” $= 1$ *iff* the output is negative.

Formal definition and test cases in the book.

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Circuit 2: RAM64

Some of the circuit's key characteristics:

- *Sequential* circuit, with clock input
- 64 memory words stored, each 16-bit wide
- Address port has width $\log_2 64 = 6$ bit

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Circuit 2: block diagram

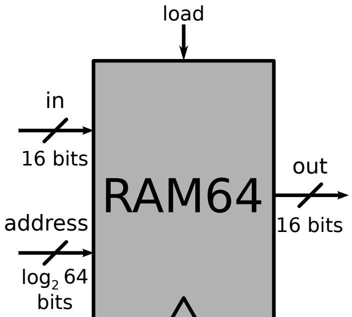

Figure: Input/Output ports of *circuit 2*, the RAM64 block.

Circuit 2: specification

- The output “out” holds the value at the memory line indicated by “`address`”.
- *Iff* “`load`” $= 1$, then the value at input “`in`” will be loaded into memory line “`address`”.
- The loaded value will be emitted on “out” at the *next* clock cycle.

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Circuit 3: Hack CPU

- A *very* reduced instruction set CPU
  - Only 2 instructions: “`C`” and “`A`”
- Follows the *Harvard architecture*
  - Separate *data* and *instruction* memory blocks
- Instructions are 16-bits wide
  - As well as the memory input and output
- Two *internal* registers: “`D`” and “`A`”

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Circuit 3: block diagram

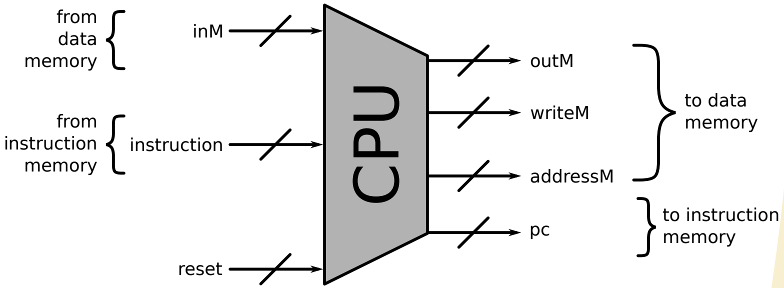

Figure: Input/Output ports of *circuit 3*, the *Hack* CPU.

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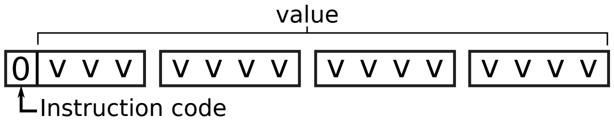
Circuit 3: specification

Circuit 3 runs “A” and “C” instructions, according to the *Hack assembly specification*.

- The “A” instruction: sets the “A” register.



- The value in “A” can be used:
  - As operand for a subsequent computation
  - As address for jumps

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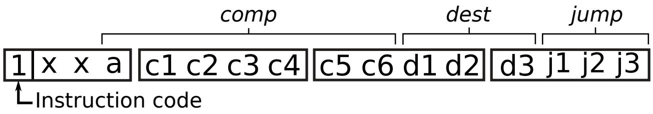
Circuit 3: specification

Circuit 3 runs “A” and “C” instructions, according to the *Hack assembly specification*.

- The “C” instruction: sets the “C” register, performs *computation* or jumps.



- Some peculiarities:
  - Bits “c1” to “c6” control the ALU
  - *conditional* or *unconditional* jumps
  - *destination* of the computation result: “A”, “D”, “M”

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Circuit 3: specification (parts)

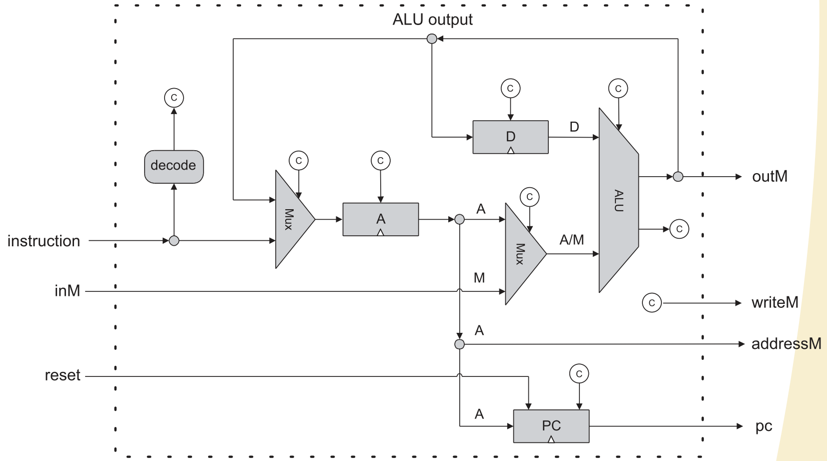

Figure: Parts used to build the *Hack* CPU, and their interconnection.

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Section 4

Analysis of the EDSLs

Lava

- Developed at Chalmers University of Technology, Sweden
  - Initially by Koen Claessen and Mary Sheeran
  - Later also Per Bjesse and David Sands
- Has several *dialects*
  - `chalmers-lava`, `xilinx-lava`, `kansas-lava`, etc.
  - We focus on the “canonical” `chalmers-lava`

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Lava's *key* characteristics

- Deep-embedded
- Observable sharing
  - "Type-safe pointer equality" to detect sharing and recursion
  - Advantages and disadvantages clearer with examples
- Capable of simulation, verification and synthesis
  - Generates *flat* VHDL
  - External tools for verification
- Very "functional" style of hardware description
  - Will become clearer with examples

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Lava: Adders

```
type SB = Signal Bool

halfAdder :: (SB, SB) -> (SB, SB)
halfAdder inputs = (xor2 inputs, and2 inputs)

fullAdder :: (SB, (SB, SB)) -> (SB, SB)
fullAdder (cin, (a, b)) = (s, cout)
    where
      (ab, c1) = halfAdder (a, b)
      (s, c2)  = halfAdder (ab, cin)
      cout     = or2 (c1, c2)

rippleCarryAdder :: [(SB, SB)] -> [SB]
rippleCarryAdder ab = s
    where (s, _) = row fullAdder (low, ab)
```

- Straightforward Haskell constructs
- “and2”, “xor2”, etc. are Lava’s *atomic* circuits

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Lava: Simulation and verification

- A taste of simulation in Lava:

```
type SB = Signal Bool
testHalfAdder :: [(SB, SB)]
testHalfAdder = map (simulate halfAdder) input
    where input = [ (low,low), (low,high)
                  , (high,low), (high,high)]
```

  - Cannot be easily automated: equality of `Signal` is non-trivial

- And verification...

```
prop_FullAdderCommutative :: (SB, (SB, SB)) -> SB
prop_FullAdderCommutative (c, (a, b)) =
    fullAdder (c, (a, b)) <==> fullAdder (c, (b, a))

-- satzoo prop_FullAdderCommutative
```

  - Advantage: Fully automated (external SAT solver)
  - Disadvantage: Only verifies instances of *specific size*

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Lava: ALU

```
type ALUControlBits = (SB, SB, SB, SB, SB, SB)

alu :: ([SB], [SB], ALUControlBits) -> ([SB], SB, SB)
alu (x, y, (zx, nx, zy, ny, f, no)) = (out’, zr, ng)
    where x’     = mux (zx, (x, replicate (length x) low))
          x’’    = mux (nx, (x’, map inv x’))
          y’     = mux (zy, (y, replicate (length x) low))
          y’’    = mux (ny, (y’, map inv y’))
          out    = let xy’’ = zip x’’ y’’
                   in mux (f, (andl xy’’, adder xy’’))
          out’   = mux (no, (out, map inv out))
          zr     = foldl (curry and2) low out’
          ng     = equalBool high (last out’)
          adder  = rippleCarryAdder
```

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Remarks

- Cannot introduce new, meaningful datatypes
  - Only `Signal Bool` is synthesizable
  - Or tuples/lists thereof
- Input/Output types have to be *uncurried*
- Weak type-safety over the inputs/outputs
  - Working with tuples is tiresome and has limitations
  - Lists don't enforce *size* constraints

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Lava: RAM64

```haskell
reg :: (SB, SB) -> SB
reg (input, load) = out
    where dff = mux (load, (out, input))
          out = delay low dff

regN :: Int -> ([SB], SB) -> [SB]
regN n (input, load) = map reg $ zip input (replicate n load)

ram64Rows :: Int -> ([SB], (SB,SB,SB,SB,SB,SB), SB) -> [SB]
ram64Rows n (input, addr, load) = mux64WordN n (addr, regs)
    where memLine sel = regN n (input, sel <&> load)
          regs        = map memLine (decode6To64 addr)
```

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Remarks

Positive:

- Uses host language for binding (`let`/`where`) and recursion
- Uses host language for structural combinators

Negative:

- Again, weak type-safety of lists
  - Extra `Int` parameter controls port *sizes*
  - But not *type-safe*
- *No modularity* in the generated VHDL code.

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Lava: *Hack* CPU (new parts)

```
programCounter :: Int -> (SB, SB, [SB]) -> [SB]
programCounter n (reset, set, input) = out where
    incr     = increment out
    out      = delay (replicate n low) increset
    incinput = mux (set, (incr, input))
    increset = mux (reset, (incinput, replicate n low))

type Dest     = (SB, SB, SB)
type JumpCond = (SB, SB, SB)
type CPUCtrl  = (SB, SB, Dest, JumpCond, ALUCtrl)

instructionDecoder :: HackInstruction -> CPUCtrl
instructionDecoder (i0,_,_,i3,i4,i5,i6,i7,i8,i9,...,i15)
    = (aFlag, cAM, cDest, cJump, cALU) where
    aFlag = i0
    cAM   = inv i3
    cDest = (i10, i11, i12)
    cJump = (i13, i14, i15)
    cALU  = (i4, i5, i6, i7, i8, i9)
```

Final remarks

Lava could benefit from:

- Fixed-length vectors
    - ForSyDe-style or with type-level naturals in recent GHC.
- Slicing operators over vectors
- *Synthesizable* user-defined datatypes
- Better way of providing observable sharing

ForSyDe

- Based on the “Formal System Design” approach
    - Royal Institute of Technology - KTH, Stockholm
- Available for Haskell and SystemC
- Has BOTH shallow and deep-embedded “versions”
    - Same library, subtle distinction
    - Will become clearer with examples
- *Template Haskell* to express circuits with Haskell syntax

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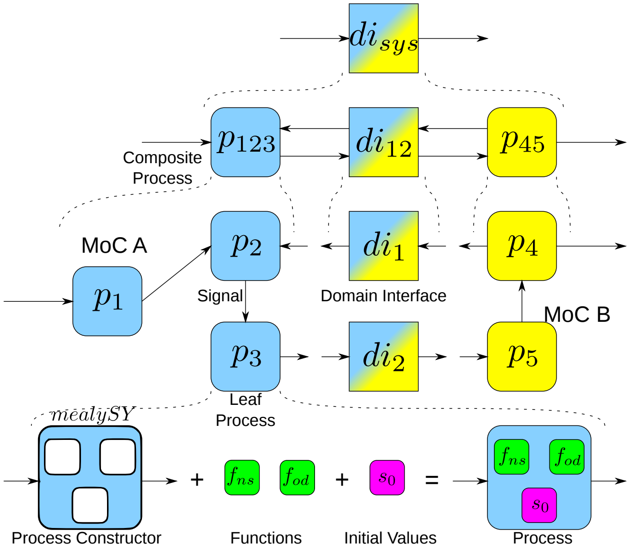
ForSyDe's key concepts

- Models of Computation (MoCs)
  - We focus on the *synchronous* MoC
- Processes
  - Basic unit of computation
  - A process belongs to a MoC
  - Built with a *process constructor*
- Signals
  - Connections among processes

ForSyDe's key concepts



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ForSyDe: ALU (non-synth)

```
type S = Signal
type Word = Int16

data ALUOp = ALUSum | ALUAnd
    deriving (Typeable, Data, Show)

$(deriveLift1 ''ALUOp)

type ALUCtrl = (Bit, Bit, Bit, Bit, ALUOp, Bit)
type ALUFlag = (Bit, Bit)

bo, bb :: Bit -> Bool
bo = bitToBool
bb = boolToBit
```

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ForSyDe: ALU (non-synth)

```
aluFunc :: ProcFunc (ALUCtrl -> Word -> Word -> (Word,ALUFlag))
aluFunc = $(newProcFun [d|
  aluFunc' (zx,nx,zy,ny,f,no) x y =
      ( out,  (bb (out == 0), bb (out < 0)) )
    where
      zf z w    = if bo z then 0 else w
      nf n w    = if bo n then complement w else w
      (xn, yn) = (nf nx $ zf zx $ x,  nf ny $ zf zy $ y)
      out       = nf no $ case f of
                     ALUSum -> xn + yn
                     ALUAnd -> xn .&. yn   |] )

aluProc :: S ALUCtrl -> S Word -> S Word -> S (Word,ALUFlag)
aluProc = zipWith3SY "aluProc" aluFunc
```

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ForSyDe: synthesis restrictions

Restrictions imposed on a model by ForSyDe so that it can be translated to VHDL:

- ProcFun-related:
  - Limited argument types (instances of `ProcType`)
  - `Int`, `Int8`, `...`, `Bool`, `Bit`
  - Enumerated types (deriving `Data` and `Lift`)
  - Tuples and `FSVec`'s
- VHDL engine-related:
  - No point-free notation
  - Single clause / no pattern matching
  - No `where` or `let` bindings

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ForSyDe: ALU (synthesizable)

```
zProc :: ProcId -> S Bit -> S Word -> S Word
zProc name = zipWithSY name $(newProcFun [d|
    f :: Bit -> Word -> Word
    f z w = if z == H then 0 else w |])

nProc :: ProcId -> S Bit -> S Word -> S Word
nProc name = zipWithSY name $(newProcFun [d|
    f :: Bit -> Word -> Word
    f n w = if n == H then negate w else w |])

compProc :: S Bit -> S Word -> S Word -> S Word
compProc = zipWith3SY "compProc" $(newProcFun [d|
    f :: Bit -> Word -> Word -> Word
    f o x y = if o == H then x + y else x .&. y |])

tzProc :: S Word -> S Bit ...
tnProc :: S Word -> S Bit ...
```

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ForSyDe: ALU (synthesizable)

```
type ALUCtrl = (Bit, Bit, Bit, Bit, Bit, Bit)
type ALUFlag = (Bit, Bit)

aluProc :: S ALUCtrl -> S Word -> S Word -> S (Word, ALUFlag)
aluProc c x y =
    zipSY "aluProc" out (zipSY "flagsProc"
                           (tzProc out) (tnProc out))
  where
    (zx,nx,zy,ny,f,no) = unzip6SY "ctrlProc" c
    out  = nProc "no" no comp
    comp = compProc f (nProc "nx" nx $ zProc "zx" zx $ x)
                      (nProc "ny" ny $ zProc "zy" zy $ y)
```

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ForSyDe: RAM64

```haskell
reg :: S Word -> S Bit -> S Word
reg input load = out where
    out = delaySY "delay" (0 :: WordType) dff
    dff = (instantiate "mux2" mux2SysDef) load out input

ram64 :: S Word -> S (FSVec D6 Bit) -> S Bit -> S Word
ram64 input addr load = mux' addr (zipxSY "zipRows" rs) where
  mux'      = instantiate "mux" mux64SysDef
  decoder'  = instantiate "decoder" decode6To64SysDef
  reg' l    = instantiate l regSysDef
  and' l    = instantiate l andSysDef
  r (s,l) = (reg' l) input ((and' (l ++ ":and")) load s)
  rs'     = unzipxSY "unzipAddr" $ decoder' addr
  rs      = V.map r $ V.zip rs' (V.map (\n -> "r" ++ show n)
                                  (V.unsafeVector d64 [0..63]))

ram64SysDef = newSysDef ram64 "ram64" ["i","a","l"] ["o"]
```

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Remarks

- Component *instantiation*
  - Introduces *hierarchy* in the design
  - Influences generated VHDL
- *Manual* name management
  - Error-prone
  - Every process must have a *unique* identifier
  - Already was a (lesser) issue with the muxes

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ForSyDe: *Hack* CPU (part)

```
type HackInstruction = FSVec D16 Bit
type Dest = (Bit, Bit, Bit)
type Jump = (Bit, Bit, Bit)

instructionDecoder :: S HackInstruction
                   -> S (Bit, Bit, Dest, Jump, ALUCtrl)
instructionDecoder = mapSY "mapSYdecoder" decoderFun where
  decoderFun = $(newProcFun [d|
    f :: HackInstruction -> (Bit, Bit, Dest, Jump, ALUCtrl)
    f i = ( i!d0
          , not (i!d3)
          , (i!d10, i!d11, i!d12)
          , (i!d13, i!d14, i!d15)
          , (i!d4,  i!d5,  i!d6, i!d7, i!d8, i!d9)
          ) |])
```

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Coquet

- Developed by Thomas Braibant (INRIA, France)
    - Seminal paper published in 2011
- Library embedded in the *Coq* proof assistant
    - Deep-embedded
    - Models the *architecture* of circuits
- Allows for *correctness proofs* of circuits
    - According to a given *specification*
    - Provides *tactics* to help with these proofs
    - More powerful, inductive proofs

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Coquet: The `Circuit` type

```
Context {tech : Techno}
Inductive Circuit : Type -> Type -> Type :=
| Atom : forall {n m : Type} {Hfn : Fin n} {Hfm : Fin m},
                techno n m -> Circuit n m

| Plug : forall {n m : Type} {Hfn : Fin n} {Hfm : Fin m}
               (f : m -> n), Circuit n m

| Ser  : forall {n m p : Type},
                Circuit n m -> Circuit m p -> Circuit n p

| Par  : forall {n m p q : Type},
                Circuit n p -> Circuit m q
                -> Circuit (n + m) (p + q)

| Loop : forall {n m p : Type},
                Circuit (n + p) (n + p) -> Circuit n m
```

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Features from the `Circuit` type

- Circuit *structure* as constructors of the datatype
  - *Explicit* loops (recursion) as constructor
- Parameterized by one type of *fundamental gate* (`Atom`)
  - For example, `NOR` or `NAND`
- Circuit I/O ports are defined by *finite* types
  - Instances of the “`Fin`” typeclass

Coquet: circuit example

```
Definition HADD a b s c: circuit ([:a]+[:b]) ([:s]+[:c]) :=
    Fork2 ([:a] + [:b])  |>  (XOR a b s  &  AND a b c).


Program Definition FADD a b cin sum cout :
    circuit ([:cin] + ([:a] + [:b])) ([:sum] + [:cout]) :=

   (ONE [: cin]  &  HADD a b "s" "co1")
|> Rewire (*  (a, (b,c)) => ((a,b), c)  *)
|> (HADD cin "s" sum "co2" & ONE [: "co1"])
|> Rewire (*  ((a,b), c) => (a, (b,c))  *)
|> (ONE [:sum]  &  OR "co2" "co1" cout).

Next Obligation. revert H; plug_def. Defined.
Next Obligation. plug_auto. Defined.
Next Obligation. revert H; plug_def. Defined.
Next Obligation. plug_auto.Defined.
```

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Features from the example

- Circuit I/O types (finite types)
  - Parameterized by strings: *tagged units*
  - Default “`Fin`” instances for sums, units
- Serial/Parallel composition
- *Associativity plugs* (reordering) automatically defined
  - With help of proof search

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Coquet: How to prove correctness

To understand Coquet proofs, we need 2 concepts:

- Meaning relation
    - Circuit $\rightarrow$ *Prop*
- Behavioural specification
    - What should a circuit *do* with its inputs

Let's take a look at the definition for each of these concepts. . .

Coquet: Meaning relation

```
Inductive Sem : forall {n} {m},
   C n m -> (n -> Data) -> (m -> Data) -> Prop :=

| KAtom: forall n m {Hfn: Fin n} {Hfm: Fin m}
          (t: techno n m) i o, spec t i o -> Sem (Atom t) i o

| KSer: forall n m p (x: C n m) (y: C m p) i mid o,
         Sem x i mid -> Sem y mid o -> Sem (Ser x y) i o

| KPar: forall n m p q (x: C n p) (y: C m q) i o,
            Sem x (select_left i) (select_left o)
         -> Sem y (select_right i) (select_right o)
         -> Sem (Par x y) i o

| KPlug: forall n m {Hfn: Fin n} {Hfm: Fin m} (f: m -> n) i,
          Sem (Plug f) i (Data.lift f i)

| KLoop: forall n m l (x: C (n + l) (m + l)) i o ret,
            Sem x (Data.app i ret) (Data.app o ret)
          -> Sem (Loop x) i o
```

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Coquet: Specification

```
Context {n m N M : Type}
        (Rn : Iso (n -> T) N) (Rm : Iso (m -> T) M).

Class Realise (c : Circuit n m) (R : N -> M -> Prop) :=
  realise: forall i o, Semantics c i o -> R (iso i) (iso o)

Class Implement (c : Circuit n m) (f : N -> M) :=
  implement: forall i o, Semantics c i o -> iso o = f (iso i)
```

The semantics of a circuit *entails* (implies):

- A *relation* between inputs and outputs
- The application of a *function* to the inputs
- Up to isomorphisms...

Now for a (small) example of correctness proof...

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Coquet: Correctness proofs

```
Instance HADD_Implement {a b s c} :
    Implement (HADD a b s c) _ _
    (fun (x : bool * bool) =>
        match x with (a,b) => (xorb a b, andb a b) end).
Proof.
    unfold HADD; intros ins outs H; tac.
Qed.
```

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Coquet: How to prove correctness

```
Ltac tac :=
    rinvert;                  (* destruct the circuit *)
    realise_all;              (* use the hint data-base *)
    unreify_all bool;         (* unreify *)
    destruct_all;             (* destruct the booleans *)
    intros_all;
    clear;
    boolean_eq.
```

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Section 5

Conclusions

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Results

Summary of our findings, by aspect:

- **Depth of embedding**
  - Lava: deep-embedded, recursion and sharing through host
  - ForSyDe: *both* shallow and deep-embedded signals
  - Coquet: the *deepest* of all, circuit *structure in the AST*
- **Simulation**
  - Lava: straightforward, but not easily *automated*
  - ForSyDe: easy in both embedding depths
  - Coquet: one of the *example* interpretations, not sequential
- **Verification**
  - Lava: *safety properties* through external SAT solver
  - ForSyDe: no capabilities of verification whatsoever
  - Coquet: Interactive theorem proving, verifies *families* of circuits.

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Results

Summary of our findings, by aspect:

- **Genericity**
  - Lava: *families* of circuits, with extra arguments
  - ForSyDe: weak genericity, monomorphic types in `ProcFun`'s
  - Coquet: similar approach to Lava
- **Tool integration**
  - Lava: *flat* VHDL code (`Signal Bool`) and CNF formulas
  - ForSyDe: *modular* VHDL code and GraphML files
  - Coquet: no circuit extraction whatsoever
- **Extensibility**
  - Lava: no *data* extensibility, high *structural* extensibility
  - ForSyDe: possible to use custom *enumerated* types
  - Coquet: flexible approach to data extensibility with meaning relation

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Future work

- Modelling larger circuits
- Investigate and try to apply recent GHC developments
  - Data and type families
  - Type-level natural literals and operations
  - Datatype promotion and kind polymorphism
- Hardware description in *dependently-typed* languages
  - Coq verifiable *synthesis* of circuits
  - Hardware EDSL in the Agda language

Thank you!

Questions?