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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
 - Sometimes even *exhaustive* 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 existing 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*

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Goals of this project

Compare existing 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*

Let's first review out object of study

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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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Chosen EDSLs

The language we chose to evaluate, with the respective host language, were:

- ▶ Lava (Haskell - *chalmers-lava dialect*)
- ▶ ForSyDe (Haskell)
- ▶ Coquet (Coq interactive theorem prover)

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Evaluation criteria

- ▶ Simulation
- ▶ Verification
- ▶ Genericity
- ▶ Depth of embedding
- ▶ Tool integration
- ▶ Extensibility

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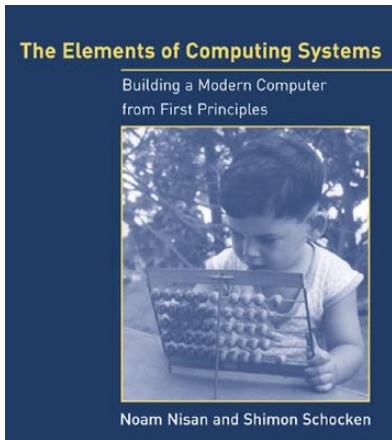
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Chosen circuits

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



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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 block

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: block diagram

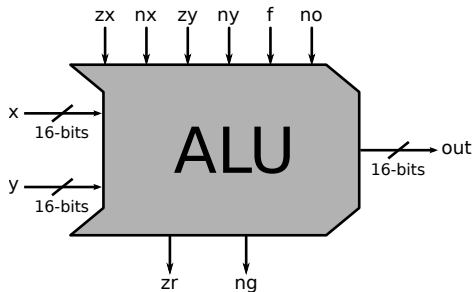


Figure: Input/Output ports of *circuit 1*, the ALU.

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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

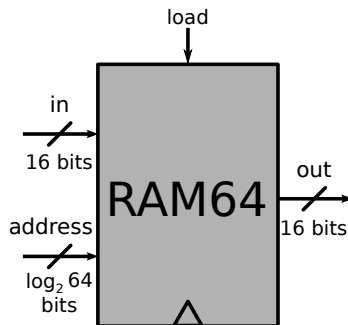


Figure: Input/Output ports of *circuit 2*, the RAM64 block.

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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: block diagram

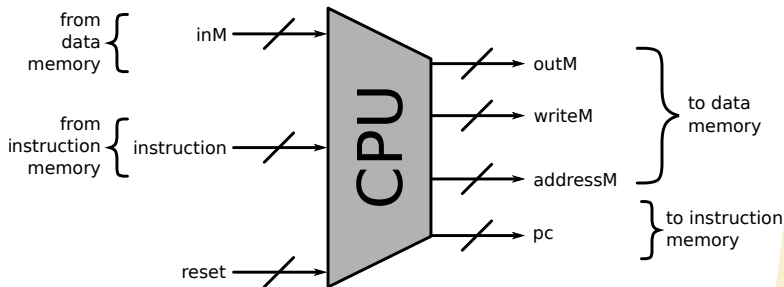


Figure: Input/Output ports of *circuit 3*, the *Hack CPU*.

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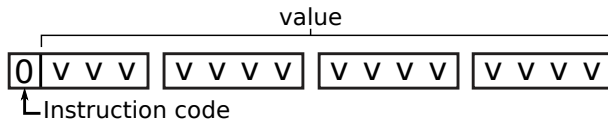


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Circuit 3: specification

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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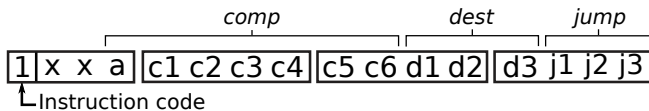


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Circuit 3: specification

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)

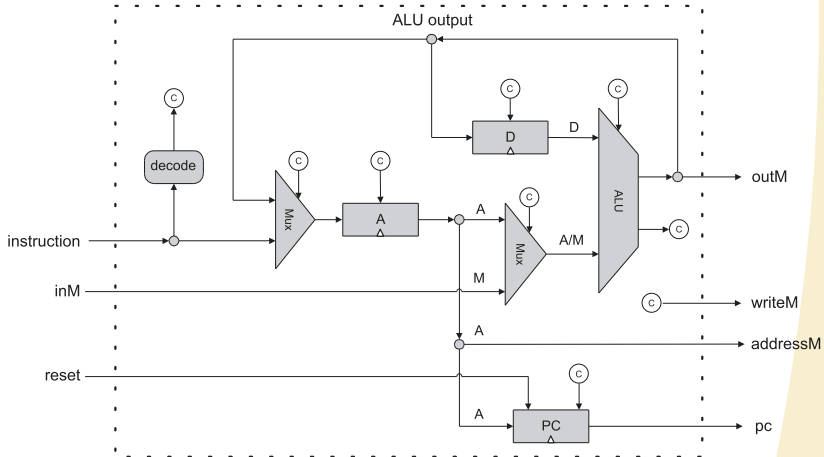


Figure: Parts used to build the *Hack* CPU, and their interconnection.

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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: 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: 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, (and1 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

```
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) -> [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
- ▶ *No modularity* in the generated VHDL code.

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Lava: *Hack* CPU (some 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)
```

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Remarks

Could benefit from:

- ▶ Fixed-length vectors
 - ForSyDe-style or with type-level naturals in recent GHC.
- ▶ Slicing operators over vectors
- ▶ *Synthesizable* user-defined datatypes

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- ▶ Based on the “Formal System Design” approach
 - Royal Institute of Technology - KTH, Sweden
- ▶ 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
 - A process belongs to a MoC
 - Built with a *process constructor*
- ▶ Signals
 - Connections among processes

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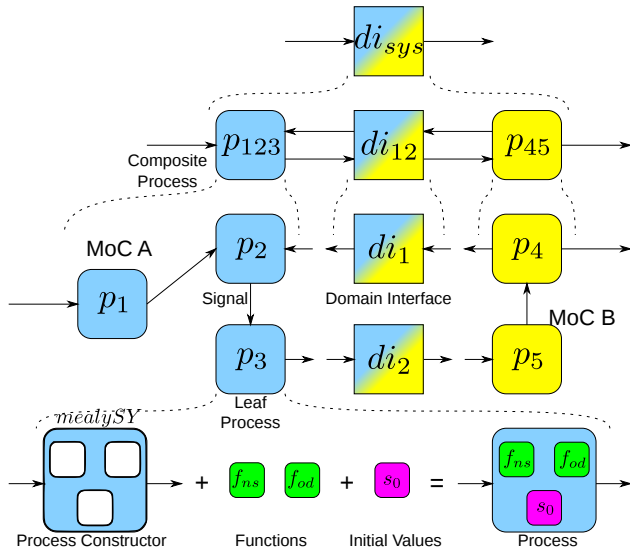
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ForSyDe's key concepts



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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: Muxes

```
mux2 :: S Bit -> S Word -> S Word -> S Word
mux2 = zipWith3SY "zipWith3SY" $(newProcFun [d|
  f s x y = if s == L then x else y |])
```

```
mux2SysDef :: SysDef (S Bit -> S Word -> S Word -> S Word)
mux2SysDef = newSysDef mux2 "mux2" ["s","i1","i2"] ["o"]
```

```
mux4 :: S (FSVec D2 Bit) -> S (FSVec D4 Word) -> S Word
mux4 ss is = (mux2' "m1") (sv ! d1) m00 m01 where
  mux2' l = instantiate l mux2SysDef
  sv      = unzipxSY "unzipSel" ss
  iv      = unzipxSY "unzipInp" is
  m00     = (mux2' "m00") (sv ! d0) (iv ! d0) (iv ! d1)
  m01     = (mux2' "m01") (sv ! d0) (iv ! d2) (iv ! d3)
```

```
mux4SysDef :: SysDef ( S (FSVec D2 Bit) -> S (FSVec D4 Word)
                      -> S Word)
mux4SysDef = newSysDef mux4 "mux4" ["s","is"] ["o"]
```

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Remarks

Positive:

- ▶ Generated VHDL is very *modular*
 - One VHDL *entity* per ForSyDe component
 - Good for tool integration

Negative:

- ▶ Interface “conflicts” caused by FSVec and process constructors
 - “zip-unzip” pattern

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ForSyDe: RAM64

```
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 (FVec 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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- ▶ 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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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: 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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Future work

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Thank you!

Questions?

