

# $\Pi$ -Ware: An Embedded Hardware Description Language using Dependent Types

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# What is $\Pi$ -Ware

“ *$\Pi$ -Ware* is a Domain-Specific Language (DSL) for hardware, embedded in the dependently-typed *Agda* programming language. It allows for the description, simulation, synthesis and verification of circuits, all in the same language.”

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# Hardware design is hard(er)

- ▶ Strict(er) correctness requirements
  - You can't simply *update* a full-custom chip after production
    - Intel FDIV
  - Expensive verification / validation (up to 50% of development costs)
- ▶ Low-level details (more) important
  - Layout / area
  - Power consumption / fault tolerance

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# Hardware design is growing

- ▶ Moore's law will still apply for some time
  - We can keep packing more transistors into same silicon area
- ▶ **But** optimizations in CPUs display diminishing returns
  - Thus, more algorithms *directly* in hardware

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# Hardware Description Languages

- ▶ All started in the 1980s
- ▶ *De facto* industry standards: VHDL and Verilog
- ▶ Were intended for *simulation*, not modelling or synthesis
  - *Unsynthesizable* constructs
  - Widely variable tool support

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# Functional Programming

- ▶ Easier to *reason* about program properties
- ▶ Inherently *parallel* and *stateless* semantics
  - In contrast to imperative programming

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# Functional Hardware Description

- ▶ A functional program describes a circuit
- ▶ Several *functional* Hardware Description Languages (HDLs) during the 1980s
  - For example,  $\mu$ FP [Sheeran, 1984]
- ▶ Later, *embedded* hardware DSLs
  - For example, Lava (Haskell) [Bjesse et al., 1998]

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# Embedded DSLs for Hardware

## ► Lava

- Simulation / Synthesis / Verification
- Limitations: almost untyped / no *size checks*

```
adder :: (Signal Bool, ([Signal Bool], [Signal Bool]))  
      -> ([Signal Bool], Signal Bool)
```

## ► Others:

- ForSyDe [Sander and Jantsch, 1999]
- Hawk [Launchbury et al., 1999], etc.

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# Dependently-Typed Programming

- ▶ Dependent type systems: systems in which types can *depend on values*
- ▶ It makes a big difference:
  - More expressivity
  - *Certified programming*
- ▶ DTP often touted as “sucessor” of functional programming
  - Very well-suited for DSLs [Oury and Swierstra, 2008]

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## Research Question / Methodology

► **Question:**

- What are the improvements that Dependently-Typed Programming (DTP) can bring to hardware design?
  - Compared to other functional hardware languages

► **Methodology:**

- Develop a hardware DSL, *embedded* in a dependently-typed language (Agda)
  - Called  **$\Pi$ -Ware**
  - Allowing simulation, synthesis and verification

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# Dependently-Typed Programming

- ▶ **Disclaimer:** Suspend disbelief in syntax
  - Examples are in *Agda*
  - Syntax similar to Haskell, details further ahead
- ▶ Types can depend on values
  - Example:  
`data Vec (a : Set) : ℕ → Set where...`
  - Compare with Haskell:  
`data List (a :: *) :: * where`
- ▶ Types of arguments can depend on *values of previous arguments*
  - Ensure a “safe” domain
  - `take : (m : ℕ) → Vec α (m + n) → Vec α m`

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# Dependently-Typed Programming

- ▶ Type checking requires *evaluation* of functions
  - We want `Vec Bool (2 + 2)` to unify with `Vec Bool 4`
- ▶ Consequence: all functions must be *total*
- ▶ Termination checker (heuristics)
  - Structurally-decreasing recursion
  - This passes the check:  

```
add : ℕ → ℕ → ℕ
add zero    y = y
add (suc x') y = suc (add x' y)
```
  - This does not:  

```
silly : ℕ → ℕ
silly zero    = zero
silly (suc n') = silly [ n' /2]
```

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# Dependently-Typed Programming

- ▶ Dependent pattern matching can *rule out* impossible cases
- ▶ Classic example: *safe head* function
$$\text{head} : \text{Vec } \alpha \ (\text{suc } n) \rightarrow \alpha$$
$$\text{head } (x :: xs) = x$$
  - The **only** constructor returning  $\text{Vec } \alpha \ (\text{suc } n)$  is  $\_\ :: \_\$

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# Dependent types as logic

- ▶ Programming language / Theorem prover
  - Types as propositions, terms as proofs [Wadler, 2014]

- ▶ Example:

- Given the relation:

```
data __≤__ : ℕ → ℕ → Set where
  z≤n : ∀ {n}                → zero ≤ n
  s≤s  : ∀ {m n} → m ≤ n → suc m ≤ suc n
```

- Proposition:

```
twoLEQFour : 2 ≤ 4
```

- Proof:

```
twoLEQFour = s≤s (s≤s z≤n)
s≤s (s≤s (z≤n : 0 ≤ 4)) : 1 ≤ 4 : 2 ≤ 4
```

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# Agda syntax for Haskell programmers

- ▶ Liberal identifier lexing (Unicode **everywhere**)
  - $a \equiv b + c$  is a valid identifier,  $a \equiv b + c$  an expression
  - Used a lot in Agda's standard library:  $\times$ ,  $\uplus$ ,  $\wedge$
  - And in  $\Pi$ -Ware:  $\mathbb{C}$ ,  $\llbracket c \rrbracket$ ,  $\Downarrow$ ,  $\Uparrow$
- ▶ *Mixfix* notation
  - $\_[_] := \_$  is the vector update function:  $v \ [ \# \ 3 \ ] := \text{true}$ .
  - $\_[_] := \_ \ v \ (\# \ 3) \ \text{true} \iff v \ [ \# \ 3 \ ] := \text{true}$
- ▶ Almost nothing built-in
  - $\_+_ \ : \mathbb{N} \rightarrow \mathbb{N} \rightarrow \mathbb{N}$  defined in `Data.Nat`
  - $\text{if\_then\_else\_} : \text{Bool} \rightarrow \alpha \rightarrow \alpha \rightarrow \alpha$  defined in `Data.Bool`

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# Agda syntax for Haskell programmers

- ▶ Implicit arguments

- Don't have to be passed if Agda can **guess** it
- Syntax:  $\varepsilon : \{ \alpha : \text{Set} \} \rightarrow \text{Vec } \alpha \text{ zero}$

► “For all” syntax:  $\forall n \iff (n : \_)$

- Where `_` means: guess this type (based on other args)
- Example:
  - $\forall n \rightarrow \text{zero} \leq n$
  - `data < : ℕ → ℕ → Set`

- ▶ It's common to combine both:

- $\forall \{ \alpha \ n \} \rightarrow \text{Vec } \alpha \ (\text{succ } n) \rightarrow \alpha \iff$   
 $\{ \alpha : \ \ \ \ \} \{ n : \ \ \ \ \} \rightarrow \text{Vec } \alpha \ n \rightarrow \alpha$

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# Low-level circuits

- Structural representation
- Untyped but *sized*

data  $\mathbb{C}' : \mathbb{N} \rightarrow \mathbb{N} \rightarrow \text{Set}$

data  $\mathbb{C}'$  where

Nil :  $\mathbb{C}' \text{ zero zero}$

Gate :  $(g\# : \text{Gates\#}) \rightarrow \mathbb{C}' (|\text{in}| g\#) (|\text{out}| g\#)$

Plug :  $\forall \{i\ o\} \rightarrow (f : \text{Fin } o \rightarrow \text{Fin } i) \rightarrow \mathbb{C}' i\ o$

DelayLoop :  $(c : \mathbb{C}' (i + l) (o + l)) \{\text{comb}'\ c\} \rightarrow \mathbb{C}' i\ o$

$\_ \gg' \_ : \mathbb{C}' i\ m \rightarrow \mathbb{C}' m\ o \rightarrow \mathbb{C}' i\ o$

$\_ |' \_ : \mathbb{C}' i_1\ o_1 \rightarrow \mathbb{C}' i_2\ o_2 \rightarrow \mathbb{C}' (i_1 + i_2) (o_1 + o_2)$

$\_ |+' \_ : \mathbb{C}' i_1\ o \rightarrow \mathbb{C}' i_2\ o \rightarrow \mathbb{C}' (\text{suc } (i_1 \sqcup i_2))\ o$

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# Atoms

- ▶ How to carry values of an Agda type in *one* wire
- ▶ Defined by the `Atomic` type class in `PiWare.Atom`

`record Atomic` : `Set1` `where`  
`field`

`Atom` : `Set`

`|Atom|−1` :  $\mathbb{N}$

`n→atom` : `Fin (suc |Atom|−1)`  $\rightarrow$  `Atom`

`atom→n` : `Atom`  $\rightarrow$  `Fin (suc |Atom|−1)`

`inv−left` :  $\forall i \rightarrow atom \rightarrow n (n \rightarrow atom i) \equiv i$

`inv−right` :  $\forall a \rightarrow n \rightarrow atom (atom \rightarrow n a) \equiv a$

`|Atom|` = `suc |Atom|−1`

`Atom#` = `Fin |Atom|`

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# Atomic instances

- ▶ Examples of types that can be **Atomic**
  - Bool, std\_logic, other multi-valued logics
  - Predefined in the library: **PiWare.Atom.Bool**
- ▶ First, define how many atoms we are interested in
  - Need at least 1 (later why)

$|B|-1 = 1$

$|B| = \text{suc } |B|-1$

- ▶ Friendlier names for the indices (elements of **Fin 2**)

pattern **False#** = Fz

pattern **True#** = Fs Fz

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# Atomic instance (Bool)

- Bijection between  $\{n \in \mathbb{N} \mid n < 2\}$  (Fin 2) and Bool

$$n \rightarrow B = \lambda \{ \text{False\#} \rightarrow \text{false}; \text{True\#} \rightarrow \text{true} \}$$
$$B \rightarrow n = \lambda \{ \text{false} \rightarrow \text{False\#}; \text{true} \rightarrow \text{True\#} \}$$

- Proof that  $n \rightarrow B$  and  $B \rightarrow n$  are inverses

$$\text{inv-left-B} = \lambda \{ \text{False\#} \rightarrow \text{refl}; \text{True\#} \rightarrow \text{refl}; \}$$
$$\text{inv-right-B} = \lambda \{ \text{false} \rightarrow \text{refl}; \text{true} \rightarrow \text{refl} \}$$

- With all pieces at hand, we construct the instance

$$\begin{aligned} \text{Atomic-B} = \text{record} \{ & \text{Atom} = B \\ & ; |\text{Atom}|-1 = |B|-1 \\ & ; n \rightarrow \text{atom} = n \rightarrow B \\ & ; \text{atom} \rightarrow n = B \rightarrow n \\ & ; \text{inv-left} = \text{inv-left-B} \\ & ; \text{inv-right} = \text{inv-right-B} \} \end{aligned}$$

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# Gates

- ▶ Circuits parameterized by collection of *fundamental gates*
- ▶ Examples:
  - {NOT, AND, OR} ([BoolTrio](#))
  - {NAND}
  - Arithmetic, Crypto, etc.
- ▶ The definition of what means to be such a collection is in [PiWare.Gates.Gates](#)

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# The Gates type class

$W : \mathbb{N} \rightarrow \text{Set}$

$W = \text{Vec Atom}$

record Gates : Set where

field

|Gates| :  $\mathbb{N}$

|in| |out| : Fin |Gates|  $\rightarrow \mathbb{N}$

spec :  $(g : \text{Fin } |Gates|)$   
 $\rightarrow (W (|in| \ g) \rightarrow W (|out| \ g))$

Gates# = Fin |Gates|

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# Gates instances

- ▶ Example: `PiWare.Gates.BoolTrio`
- ▶ First, how many gates are there in the library

`|BoolTrio| = 5`

- ▶ Then the friendlier names for the indices

```
pattern FalseConst# = Fz
pattern TrueConst#  = Fs Fz
pattern Not#         = Fs (Fs Fz)
pattern And#         = Fs (Fs (Fs Fz))
pattern Or#          = Fs (Fs (Fs (Fs Fz)))
```

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## Gates instance (BoolTrio)

- ▶ Defining the *interfaces* of the gates

```
[in] FalseConst# = 0
```

```
|in| TrueConst# = 0
```

```
|in| Not# = 1
```

$$|in|_{And\#} = 2$$

|in| Or# = 2

$$|out| = 1$$

- And the specification function for each gate

```
spec=false == [ false ]
```

```
spec-true      = [ true ]
```

$$\text{spec-not} \quad (x :: \varepsilon) \quad = \text{not } x$$

spec-and  $(x :: y :: \varepsilon) = [x \wedge y]$

spec-or       $(x :: y :: \varepsilon) = [x \vee y]$

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# Gates instance (BoolTrio)

- ▶ Mapping each gate index to its respective specification

specs-BoolTrio FalseConst# = spec-false

specs-BoolTrio TrueConst# = spec-true

specs-BoolTrio Not# = spec-not

specs-BoolTrio And# = spec-and

specs-BoolTrio Or# = spec-or

- ▶ With all pieces at hand, we construct the instance

BoolTrio : Gates

```
BoolTrio = record { |Gates| = |BoolTrio|  
                  ; |in|    = |in|  
                  ; |out|   = |out|  
                  ; spec    = specs-BoolTrio }
```

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# High-level circuits

- ▶ User is not supposed to describe circuits at low level ( $\mathbb{C}'$ )
- ▶ The high level circuit type ( $\mathbb{C}$ ) allows for *typed* circuit interfaces

- Input and output indices are Agda types

```
data  $\mathbb{C}$  ( $\alpha \beta : \text{Set}$ )  $\{i j : \mathbb{N}\} : \text{Set}$  where
  Mk $\mathbb{C}$  :  $\{ \{s\alpha : \Downarrow W \Uparrow \alpha \{i\}\} \} \{ \{s\beta : \Downarrow W \Uparrow \beta \{j\}\} \}$ 
         $\rightarrow \mathbb{C}' i j \rightarrow \mathbb{C} \alpha \beta \{i\} \{j\}$ 
```

- ▶ Mk $\mathbb{C}$  takes:

- Low level description ( $\mathbb{C}'$ )
- Information on how to *synthesize* elements of  $\alpha$  and  $\beta$ 
  - Passed as *instance arguments* (class constraints)

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# Synthesizable

- ▶  $\Downarrow W \Uparrow$  type class (pronounced Synthesizable)
  - Describes how to synthesize a given Agda type ( $\alpha$ )
  - Two fields: from element of  $\alpha$  to a *word* and back

```
record  $\Downarrow W \Uparrow$  ( $\alpha : \text{Set}$ )  $\{i : \mathbb{N}\} : \text{Set}$  where  
  constructor  $\Downarrow W \Uparrow[\_, \_]$   
  field
```

$$\Downarrow : \alpha \rightarrow W\ i$$

$$\Uparrow : W\ i \rightarrow \alpha$$

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## $\Downarrow W \Uparrow$ instances

- ▶ Any *finite* type can have such an instance
- ▶ Predefined in the library: `Bool`; `_×_`; `_⊔_`; `Vec`
- ▶ Example: instance for products (`_×_`)

$$\Downarrow W \Uparrow - \times : \{ \mid s\alpha : \Downarrow W \Uparrow \alpha \{i\} \} \{ \mid s\beta : \Downarrow W \Uparrow \beta \{j\} \} \\ \rightarrow \Downarrow W \Uparrow (\alpha \times \beta)$$

$$\Downarrow W \Uparrow - \times \{ \alpha \} \{ i \} \{ \beta \} \{ j \} \{ \mid s\alpha \} \{ \mid s\beta \} = \Downarrow W \Uparrow [ \text{down} , \text{up} ]$$

where  $\text{down} : (\alpha \times \beta) \rightarrow W (i + j)$   
 $\text{down} (a , b) = (\Downarrow a) ++ (\Downarrow b)$

$$\text{up} : W (i + j) \rightarrow (\alpha \times \beta)$$

$$\text{up } w \text{ with splitAt } i \text{ } w$$

$$\text{up } .(\Downarrow a ++ \Downarrow b) \mid \Downarrow a , \Downarrow b , \text{refl} = \Uparrow \Downarrow a , \Uparrow \Downarrow b$$

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# Synthesizable

- Both fields  $\downarrow$  and  $\uparrow$  should be inverses of each other

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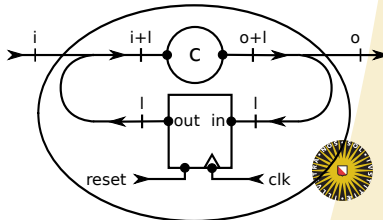
# Synthesis semantics

- ▶ Netlist: digraph with *gates* as nodes and *buses* as edges
- ▶ Synthesis semantics: given netlists of subcircuits, build combination

$\text{Nil} : \mathbb{C} \ 0 \ 0$

$$\frac{i \ o : \mathbb{N} \quad f : \text{Fin } o \rightarrow \text{Fin } i}{\text{Plug } f : \mathbb{C} \ i \ o}$$

$$\frac{g\# : \text{Gate}\#}{\text{Gate } g\# : \mathbb{C} \ (\text{ins } g\#) \ (\text{outs } g\#)}$$

$$\frac{c : \mathbb{C} \ (i+1) \ (o+1)}{\text{DelayLoop} : \mathbb{C} \ i \ o}$$


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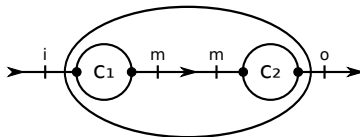
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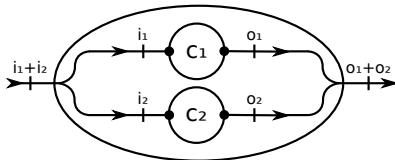


# Synthesis semantics

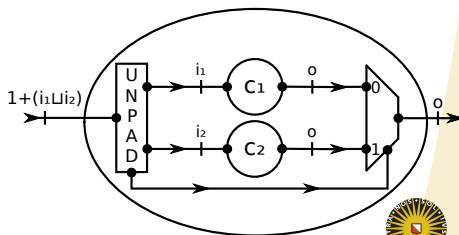
$$\frac{c_1 : \mathbb{C} \, i \, m \quad c_2 : \mathbb{C} \, m \, o}{c_1 \gg' c_2 : \mathbb{C} \, i \, o}$$



$$\frac{c_1 : \mathbb{C} \, i_1 \, o_1 \quad c_2 : \mathbb{C} \, i_2 \, o_2}{c_1 \mid' c_2 : \mathbb{C} \, (i_1 + i_2) \, (o_1 + o_2)}$$



$$\frac{c_1 : \mathbb{C} \, i_1 \, o \quad c_2 : \mathbb{C} \, i_2 \, o}{c_1 \mid + c_2 : \mathbb{C} \, (1 + (i_1 \sqcup i_2)) \, o}$$



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# Synthesis semantics

Missing “pieces”:

## ► Adapt **Atomic**

- New field: a **VHDLTypeDecl**
  - Such as: **type** ident **is** (elem1, elem2);
  - Enumerations, integers (ranges), records.
- New field: **atomVHDL** : **Atom#** → **VHDLExpr**

## ► Adapt **Gates**

- For each gate, a corresponding **VHDLEntity**
- **netlist** : (**g#** : **Gates#**) → **VHDLEntity** (**|in| g#**) (**|out| g#**)
  - The VHDL entity has the *interface* of corresponding gate

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## Combinational simulation (excerpt)

$$\llbracket \_ \rrbracket' : \forall \{i\ o\} \rightarrow (c : \mathbb{C}'\ i\ o) \{p : \text{comb}'\ c\} \rightarrow (\mathbb{W}\ i \rightarrow \mathbb{W}\ o)$$
$$[\text{Ni}]' = \text{const } \varepsilon$$
$$\llbracket \text{Gate } g^\# \rrbracket' = \text{spec } g^\#$$
$$[\![ \text{Plug } p \ ]\!] = \text{plugOutputs } p$$
$$\llbracket \text{DelayLoop } c \rrbracket' \{ () \} v$$
$$\llbracket c_1 \gg' c_2 \rrbracket' \{p_1, p_2\} = \llbracket c_2 \rrbracket' \{p_2\} \circ \llbracket c_1 \rrbracket' \{p_1\}$$
$$\llbracket \_+ \_ - \{i_1\} \ c_1 \ c_2 \rrbracket' \{p_1, p_2\} =$$

$$\llbracket \llbracket c_1 \rrbracket' \{p_1\}, \llbracket c_2 \rrbracket' \{p_2\} \rrbracket' \circ \text{untag} \{i_1\}$$

► Remarks:

- Proof requires  $c$  to be combinational
- **Gate** case uses specification function
- **DelayLoop** case can be *discharged*

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# Sequential simulation

- ▶ Inputs and outputs become **Streams**
  - $C' i o \implies \text{Stream } (W i) \rightarrow \text{Stream } (W o)$
  - **Stream**: infinite list
- ▶ We can't write a recursive evaluation function over **Streams**
  - *Sum* case  $(\_|+\_)$  needs  $(\text{Stream } (\alpha \uplus \beta) \rightarrow \text{Stream } \alpha \times \text{Stream } \beta)$ 
    - What if there are no *lefts* (or *rights*)?
- ▶ A stream function is not an accurate model for hardware
  - A function of type  $(\text{Stream } \alpha \rightarrow \text{Stream } \beta)$  can “look ahead”
  - For example,  $\text{tail } (x_0 :: x_1 :: x_2 :: xs) = x_1 :: x_2 :: xs$

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# Causal stream functions

Solution: sequential simulation based on a *causal* stream function

Some definitions:

- ▶ Causal context: past + present values

$$\Gamma c : (\alpha : \text{Set}) \rightarrow \text{Set}$$

$$\Gamma c \alpha = \alpha \times \text{List } \alpha$$

- ▶ Causal stream function: produces **one** (current) output

$$\_ \Rightarrow^c \_ : (\alpha \beta : \text{Set}) \rightarrow \text{Set}$$

$$\alpha \Rightarrow^c \beta = \Gamma c \alpha \rightarrow \beta$$

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# Causal sequential simulation

- Core sequential simulation function:

$$\begin{aligned} \llbracket \_ \rrbracket c &: \{i\ o : \mathbb{N}\} \rightarrow \mathbb{C}'\ i\ o \rightarrow (\mathbb{W}\ i \Rightarrow_c \mathbb{W}\ o) \\ \llbracket \text{Nil} \rrbracket c\ (w^0, \_) &= \llbracket \text{Nil} \rrbracket' w^0 \\ \llbracket \text{Gate } g\# \rrbracket c\ (w^0, \_) &= \llbracket \text{Gate } g\# \rrbracket' w^0 \\ \llbracket \text{Plug } p \rrbracket c\ (w^0, \_) &= \text{plugOutputs } p\ w^0 \\ \llbracket \text{DelayLoop } c\ \{p\} \rrbracket c &= \text{take}_v\ j \circ \text{delay } c\ \{p\} \end{aligned}$$

$$\llbracket c_1 \gg' c_2 \rrbracket c = \llbracket c_2 \rrbracket c \circ \text{map}^+ \llbracket c_1 \rrbracket c \circ \text{tails}^+$$

- Nil, Gate and Plug cases use combinational simulation
- DelayLoop calls a recursive helper (delay)
- Example structural case:  $\_ \gg' \_$  (sequence)
  - Context of  $\llbracket c_1 \rrbracket c$  is context of the whole compound
  - Context of  $\llbracket c_2 \rrbracket c$  is past and present *outputs* of  $c_1$

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# Sequential simulation

- We can then “run” the step-by-step function to produce a whole **Stream**

- Idea from “The Essence of Dataflow Programming” [Uustalu and Vene, 2005]

$\text{runc}' : (\alpha \Rightarrow_{\mathbf{c}} \beta) \rightarrow (\Gamma_{\mathbf{c}} \alpha \times \text{Stream } \alpha) \rightarrow \text{Stream } \beta$

$\text{runc}' f ((x^0, x^-), (x^1 :: x^+)) =$   
 $f (x^0, x^-) :: \# \text{runc}' f ((x^1, x^0 :: x^-), \mathbf{b} x^+)$

$\text{runc} : (\alpha \Rightarrow_{\mathbf{c}} \beta) \rightarrow (\text{Stream } \alpha \rightarrow \text{Stream } \beta)$

$\text{runc } f (x^0 :: x^+) = \text{runc}' f ((x^0, []), \mathbf{b} x^+)$

- Obtaining the stream-based simulation function:

$\llbracket \_ \rrbracket *' : \forall \{i \ o\} \rightarrow \mathbb{C}' \ i \ o \rightarrow (\text{Stream } (\mathbf{W} \ i) \rightarrow \text{Stream } (\mathbf{W} \ o))$

$\llbracket \_ \rrbracket *' = \text{runc} \circ \llbracket \_ \rrbracket_{\mathbf{c}}$

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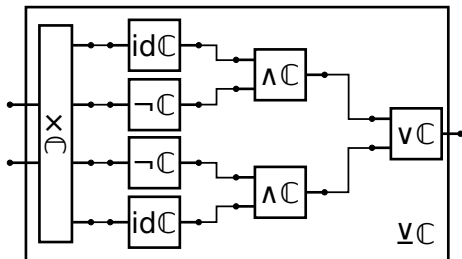


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# Sample circuit: XOR



$\underline{v}C : C (B \times B) B$

$\underline{v}C = \text{pFork}x$

$\gg (\neg C \parallel \text{id}C \gg \wedge C) \parallel (\text{id}C \parallel \neg C \gg \wedge C)$   
 $\gg vC$

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# Specification of XOR

- ▶ To define *correctness* we need a *specification function*
  - Listing all possibilities (truth table)
  - Based on pre-existing functions (standard library)
- ▶ Truth table

$\underline{\text{VC}}\text{-spec-table} : (B \times B) \rightarrow B$

$\underline{\text{VC}}\text{-spec-table} \text{ (false , false) } = \text{false}$

$\underline{\text{VC}}\text{-spec-table} \text{ (false , true) } = \text{true}$

$\underline{\text{VC}}\text{-spec-table} \text{ (true , false) } = \text{true}$

$\underline{\text{VC}}\text{-spec-table} \text{ (true , true) } = \text{false}$

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## Proof of XOR (truth table)

$$\text{vC-proof-table} : \llbracket \text{vC} \rrbracket (a, b) \equiv \text{vC-spec-table} (a, b)$$

```
VC-proof-table  false  false  = refl
```

```
VC-proof-table  false  true  = refl
```

```
VC-proof-table  true  false = refl
```

$$\text{vC-proof-table} \quad \text{true} \quad \text{true} \quad = \text{refl}$$

► Proof by *case analysis*

- Could be automated (reflection)

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# Specification of XOR

- ▶ Based (`_xor_`) from `Data.Bool`

`_xor_` :  $B \rightarrow B \rightarrow B$

`true xor b` = `not b`

`false xor b` = `b`

- ▶ Adapted interface to match exactly `⊔C`

`⊔C-spec-subfunc` :  $(B \times B) \rightarrow B$

`⊔C-spec-subfunc` = `uncurry' _xor_`

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# Proof of XOR (pre-existing)

- Proof based on `VC-spec-subfunc`

`VC-proof-subfunc` :  $\llbracket \text{VC} \rrbracket (a, b) \equiv \text{VC-spec-subfunc} (a, b)$   
`VC-proof-subfunc` = `VC-xor-equiv`

- Need a lemma to complete the proof
  - Circuit is defined using {NOT, AND, OR}
  - `_xor_` is defined directly by pattern matching

`VC-xor-equiv` :  $(\text{not } a \wedge b) \vee (a \wedge \text{not } b) \equiv (a \text{ xor } b)$

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# Circuit “families”

- ▶ We can also prove properties of circuit “families”
- ▶ Example: an AND gate definition with generic number of inputs

$\text{andN}' : \forall n \rightarrow \mathbb{C}' \ n \ 1$

$\text{andN}' \ \text{zero} = \text{TC}'$

$\text{andN}' \ (\text{suc } n) = \text{idC}' \mid' \text{andN}' \ n \ \gg' \wedge \mathbb{C}'$

- ▶ Example proof: when all inputs are **true**, output is **true**
  - For *any* number of inputs
  - Proof by induction on  $n$  (number of inputs)

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# Problems

- This proof is done at the *low level*

$$\begin{aligned}\text{proof-andN}' &: \forall n \rightarrow \llbracket \text{andN}' n \rrbracket' (\text{replicate true}) \equiv [\text{true}] \\ \text{proof-andN}' \text{ zero} &= \text{refl} \\ \text{proof-andN}' (\text{suc } n) &= \text{cong } (\text{spec-and} \circ (\_ :: \_ \text{ true})) \\ &\quad (\text{proof-andN}' n)\end{aligned}$$

- Still problems with inductive proofs in the high level
  - Guess: definition of  $\mathbb{C}$  and  $\llbracket \_ \rrbracket$  prevent goal reduction

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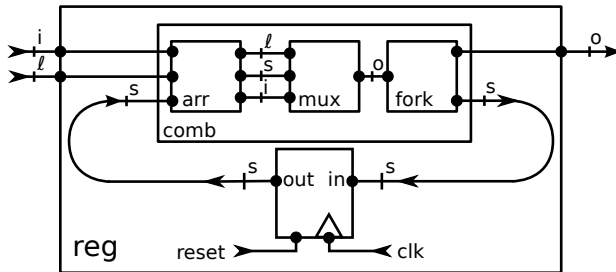


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## Sequential proofs

- ▶ Example of sequential circuit: a *register*



- Respective  $\Pi$ -Ware circuit description

$$\text{reg} : \mathbb{C} (B \times B) B$$

```
reg = delayC (arr >> mux2to1 >> xC)
```

where  $\text{arr} = (\uparrow\downarrow\mathbb{C} \parallel \text{id}\mathbb{C}) \gg \text{ALRC} \gg (\text{id}\mathbb{C} \parallel \uparrow\downarrow\mathbb{C})$

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# Register example

- ▶ Example (test case) of register behaviour

loads inputs : Stream Bool

loads = true :: # (true :: # (false :: # repeat false))

inputs = true :: # (false :: # (true :: # repeat false))

actual = take 42 ([ reg ] \* \$ zipWith \_,\_ inputs loads)

test-reg = actual  $\equiv$  true  $\triangleleft$  false  $\triangleleft$  replicate false

- ▶ Still problems with *infinite* expected vs. actual comparisons
  - Normal Agda equality ( $\_ \equiv \_$ ) does not work
  - Need to use *bisimilarity*

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# Current limitations / trade-offs

- ▶ Interface of generated netlists is always *flat*
  - One input, one output

```
entity fullAdd8 is
port (
  inputs   : in  std_logic_vector(16 downto 0);
  outputs  : out std_logic_vector(8  downto 0)
);
end fullAdd8;
```

- ▶ Due to the indices of  $\mathbb{C}'$  (naturals)
  - Can't distinguish  $\mathbb{C}'\ 17\ 9$  from  $\mathbb{C}'\ (1 + 8 + 8)\ (8 + 1)$

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# Current limitations / trade-offs

- ▶ Proofs on high-level families of circuits
  - Probably due to definitions of  $\mathbb{C}$  and  $\llbracket \_ \rrbracket$
- ▶ Proofs with infinite comparisons (sequential circuits)

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# Thank you!

## Questions?

Mede mogelijk gemaakt door:

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