

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

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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 Domain-Specific Languages (DSLs)
  - For example, Lava (Haskell) [Bjesse et al., 1998]

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# Embedded DSLs for Hardware

- ▶ Lava
- ▶ Limitations
  - Low level types
  - Not guaranteeing size match

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# Dependently-Typed Programming

Dependently-Typed Programming (DTP) är en  
programmationstechnik...

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# Research Question

“What are the improvements that DTP can bring to hardware design?”

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# 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

## ► Types can depend on values

- Example: `data Vec ( $\alpha$  : Set) :  $\mathbb{N} \rightarrow$  Set where...`
- Compare with Haskell (GADT style):  
`data List :: * -> * where...`

## ► Types of arguments can depend on *values of previous arguments*

- Ensure a “safe” domain
- `take : ( $m$  :  $\mathbb{N}$ )  $\rightarrow$  Vec  $\alpha$  ( $m + n$ )  $\rightarrow$  Vec  $\alpha$   $m$`

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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 ensures (heuristics)
  - Structurally-decreasing recursion
    - This passes the check:  
`add :  $\mathbb{N} \rightarrow \mathbb{N} \rightarrow \mathbb{N}$`   
`add zero y = y`  
`add (suc x') y = suc (add x' y)`
    - This does not:  
`silly :  $\mathbb{N} \rightarrow \mathbb{N}$`   
`silly zero = zero`  
`silly (suc n') = silly [ n' /2 ]`

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# Dependently-Typed Programming

- ▶ Dependent pattern matching can *rule out* impossible cases

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# Dependently-Typed Programming

## ► Dependent pattern matching can *rule out* impossible cases

- Classic example: *safe head* function

$\text{head} : \text{Vec } \alpha \ (\text{suc } n) \rightarrow \alpha$

$\text{head } (x :: xs) = x$

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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 (drawn triangle):

```
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
  - Actually used in Agda's standard library
  - 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 : Set<sub>1</sub> **where**

**field**

Atom : Set

|Atom|−1 : ℕ

n→atom : Fin (suc |Atom|−1) → Atom

atom→n : Atom → Fin (suc |Atom|−1)

inv-left :  $\forall i \rightarrow \text{atom} \rightarrow n \ (n \rightarrow \text{atom} \ i) \equiv i$

inv-right :  $\forall a \rightarrow n \rightarrow \text{atom} \ (\text{atom} \rightarrow n \ a) \equiv a$

|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

$|B|-1 = 1$

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

- ▶ 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 : 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)

- 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
  - The input and output indices are Agda types

```
data C (α β : Set) {i j : ℕ} : Set where
  MkC : { [ sα : ↓W↑ α {i} ] [ sβ : ↓W↑ β {j} ] }
        → C' i j → C α β {i} {j}
```

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

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

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

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

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

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# Synthesizable

- ▶ Both fields  $\Downarrow$  and  $\Uparrow$  should be inverses of each other

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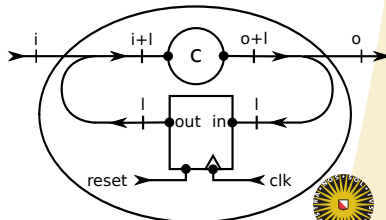
# Synthesis semantics

- Netlist: digraph with *gates* as nodes and *buses* as edges

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

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

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

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


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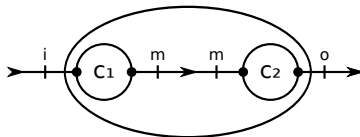
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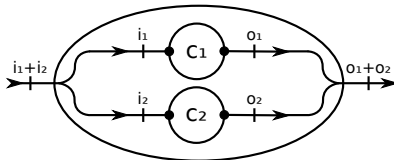
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# Synthesis semantics

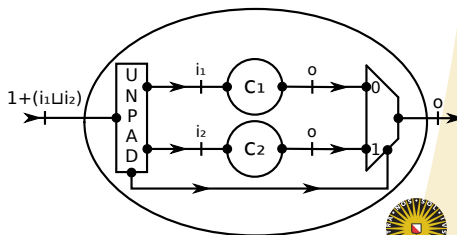
$$\frac{c_1 : \mathbb{C} \ i \ m \quad c_2 : \mathbb{C} \ m \ o}{c_1 \gg' c_2 : \mathbb{C} \ i \ o}$$



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



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



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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** :  $(g\# : \text{Gates\#}) \rightarrow \text{VHDLEntity}(|\text{in}| g\#)(|\text{out}| g\#)$ 
  - The VHDL entity has the *interface* of corresponding gate

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# Simulation semantics

## ► Two levels of abstraction

- High-level simulation ( $\llbracket \_ \rrbracket$ ) for high-level circuits ( $\mathbb{C}$ )
- Low-level simulation ( $\llbracket \_ \rrbracket'$ ) for low-level circuits ( $\mathbb{C}'$ )

## ► Two kinds of simulation

- Combinational simulation ( $\llbracket \_ \rrbracket$ ) for stateless circuits
- Sequential simulation ( $\llbracket \_ \rrbracket^*$ ) for stateful circuits

## ► High level defined in terms of low level

$$\llbracket \_ \rrbracket : \forall \{ \alpha \ i \ \beta \ j \} \rightarrow (c : \mathbb{C} \ \alpha \ \beta \ \{ i \} \ \{ j \}) \rightarrow (\alpha \rightarrow \beta)$$
$$\llbracket \text{MkC} \ \{ \ s \alpha \} \ \{ \ s \beta \} \ c' \ \rrbracket = \uparrow \circ \llbracket c' \rrbracket' \circ \downarrow$$

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# Combinational simulation (excerpt)

$$\llbracket \_ \rrbracket' : \forall \{i\ o\} \rightarrow (c : \mathbb{C}'\ i\ o) \{p : \text{comb}'\ c\} \rightarrow (W\ i \rightarrow W\ o)$$

$$\llbracket \text{Nil} \rrbracket' = \text{const } \varepsilon$$

$$\llbracket \text{Gate } g\# \rrbracket' = \text{spec } g\#$$

$$\llbracket \text{Plug } p \rrbracket' = \text{plugOutputs } p$$

$$\llbracket \text{DelayLoop } c \rrbracket' \{()\} v$$

$$\llbracket c_1 \gg' c_2 \rrbracket' \{p_1, p_2\} = \llbracket c_2 \rrbracket' \{p_2\} \circ \llbracket c_1 \rrbracket' \{p_1\}$$

$$\begin{aligned} \llbracket \_ | + ' \_ \{i_1\} c_1 c_2 \rrbracket' \{p_1, p_2\} = \\ \llbracket \llbracket c_1 \rrbracket' \{p_1\}, \llbracket c_2 \rrbracket' \{p_2\} \rrbracket' \circ \text{untag } \{i_1\} \end{aligned}$$

## ► Remarks:

- Proof required that  $c$  is combinational
- **Gate** case uses specification function
- **DelayLoop** case can be *discharged*

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# Sequential simulation

- ▶ Inputs and outputs become **Streams**
  - $\mathbb{C}' \ i \ o \implies \text{Stream} (\mathbb{W} \ i) \rightarrow \text{Stream} (\mathbb{W} \ o)$
  - **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, **tail**  $(x_0 :: x_1 :: x_2 :: xs) = x_1 :: x_2 :: xs$

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# Causal stream functions

Solution: sequential simulation using *causal* stream function

Some definitions:

- ▶ Causal context: past + present values

$$\Gamma_{\mathbf{c}} : (\alpha : \mathbf{Set}) \rightarrow \mathbf{Set}$$

$$\Gamma_{\mathbf{c}} \alpha = \alpha \times \mathbf{List} \alpha$$

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

$$\_ \Rightarrow_{\mathbf{c}} \_ : (\alpha \beta : \mathbf{Set}) \rightarrow \mathbf{Set}$$

$$\alpha \Rightarrow_{\mathbf{c}} \beta = \Gamma_{\mathbf{c}} \alpha \rightarrow \beta$$

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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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# Properties of circuits

- ▶ Tests and proofs about circuits depend on the *semantics*
  - We focused on the functional simulation semantics
  - Other possibilities (gate count, critical path, etc.)
- ▶ Very simple sample circuit to illustrate: XOR

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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

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## Proof of XOR (truth table)

- ▶ Proof by *case analysis*
  - Could be automated (reflection)

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# Specification of XOR

- Based (`_xor_`) from `Data.Bool`

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# Proof of XOR (pre-existing)

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

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# Problems

- Definition of  $\llbracket \_ \rrbracket$  blocks reduction

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# Current limitations

- ▶ Problem with proofs (definition of  $\llbracket\_ \rrbracket$ )
- ▶ Proofs on (infinite) **Streams**
- ▶ Bla

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# Future work

- ▶ Proof by reflection for finite cases

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# Thank you!

## Questions?

Mede mogelijk gemaakt door:

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