

Π -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, μ 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 **Π -Ware**
 - allowing simulation, synthesis and verification

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Dependently-Typed Programming

► Types can depend on values

- Example: `data Vec (α : 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 α ($m + n$) \rightarrow 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 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

$$\begin{aligned} \text{head} &: \text{Vec } \alpha \ (\text{succ } n) \rightarrow \alpha \\ \text{head } (x :: xs) &= x \end{aligned}$$

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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 Π -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:

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

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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 : ℕ

n→atom : Fin (suc |Atom|−1) → Atom

atom→n : Atom → 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

|B| - 1 = 1

|B| = 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 : 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
 - 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 α and β
 - Passed as *instance arguments*

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Synthesizable

- ▶ $\Downarrow W \Uparrow$ type class (pronounced Synthesizable)
 - Describes how to *synthesize* a given Agda type (α)
 - Two fields: from element of α 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 $\text{down} : (\alpha \times \beta) \rightarrow W (i + j)$
 $\text{down} (a , b) = (\Downarrow a) ++ (\Downarrow b)$

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

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

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

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Synthesizable

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

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Circuit semantics

- ▶ *Synthesis* semantics: produce a *netlist*
 - Tool integration / implement in FPGA or ASIC.
- ▶ *Simulation* semantics: *execute* a circuit
 - Given circuit model and inputs, calculate outputs
- ▶ Other semantics possible:
 - Timing analysis, power estimation, etc.
 - This possibility guided Π -Ware's development

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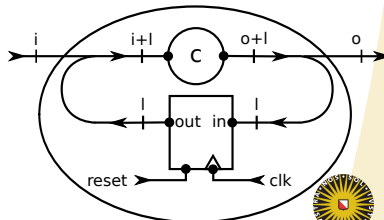
Synthesis semantics

- 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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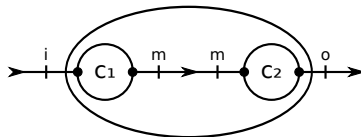
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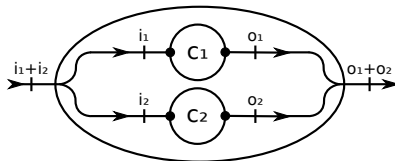
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Synthesis semantics

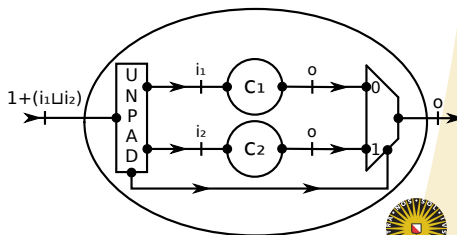
$$\frac{c_1 : \mathbb{C} \ i \ m \quad c_2 : \mathbb{C} \ m \ o}{c_1 \gg' c_2 : \mathbb{C} \ i \ o}$$



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



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



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

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Combinational simulation (excerpt)

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

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

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

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

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

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

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

► 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

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

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

- ▶ 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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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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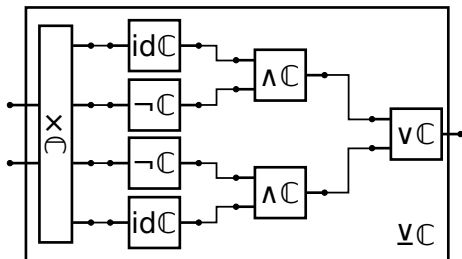
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Sample circuit: XOR



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

$\underline{v}C = \text{pForkX}$

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

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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

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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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- ▶ Proof by reflection for finite cases

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Thank you!

Questions?

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