University of Twente
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CλasH

From Haskell To Hardware

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What will we see?

- Small tour: what can we describe in CλasH
- Quick real demo

Virtuele demo

What is CλasH?

- CλasH: CAES Language for Hardware Descriptions
- Rapid prototyping language
- Subset of Haskell can be translated to Hardware (VHDL)
- Structural Description of a Mealy Machine

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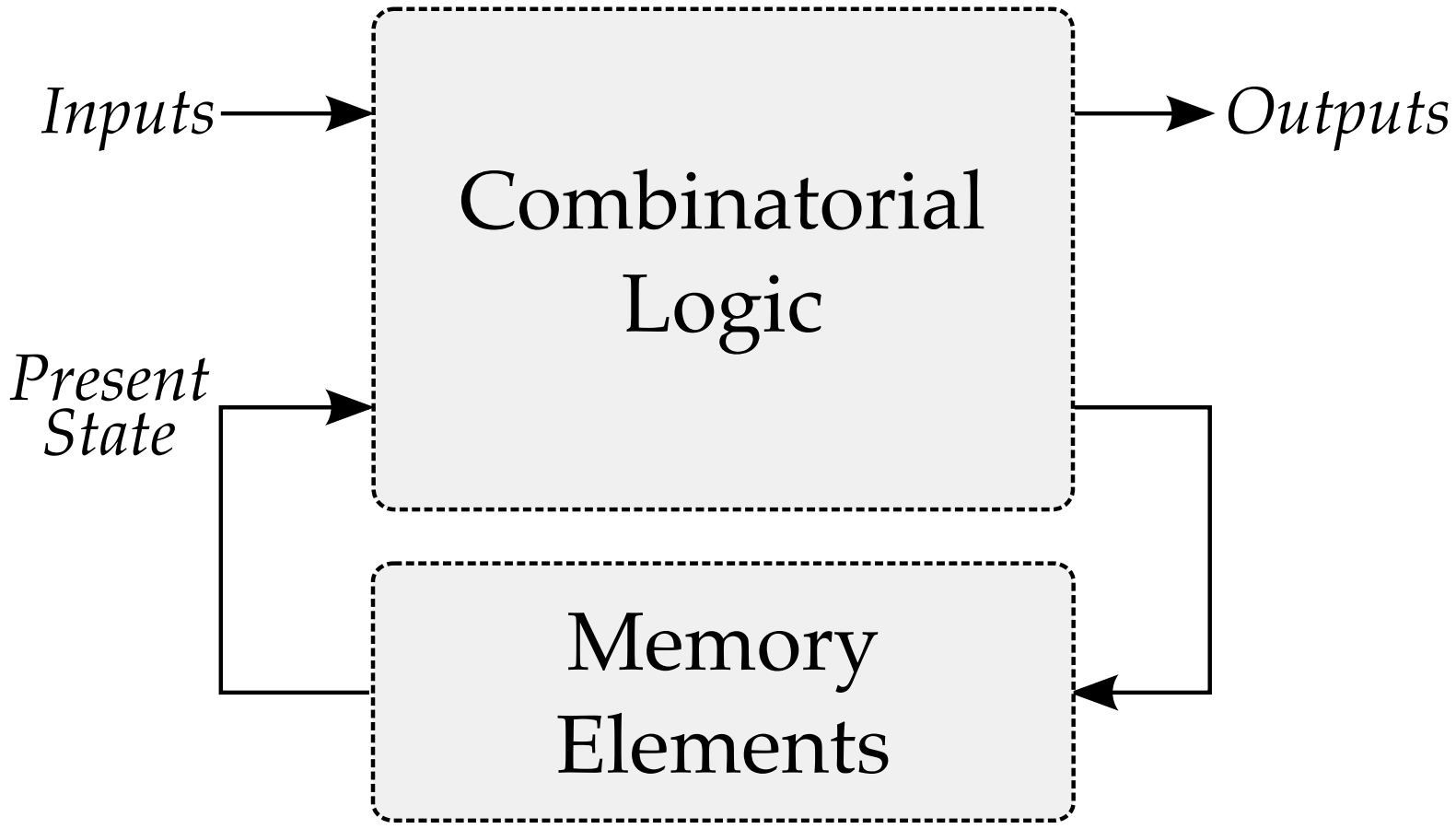
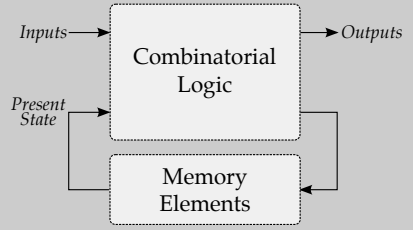
- Wij zijn wij
- CλasH voor rapid prototyping
- Subset haskell vertaalbaar
- Mealy machine beschrijving

Mealy Machine





Voor wie het niet meer weet, dit is een mealy machine

Haskell Description

```
mealyMachine ::
  InputSignals →
  State →
  (State, OutputSignals)
mealyMachine inputs state = (new_state, output)
  where
    new_state = logic state input
    outputs   = logic state input
```

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Simulating a Mealy Machine

$$
\begin{aligned}
&\mathit{run}\ \mathit{func}\ \mathit{state}\ [\,] = [\,] \\
&\mathit{run}\ \mathit{func}\ \mathit{state}\ (i : \mathit{input}) = o : \mathit{out} \\
&\quad \textbf{where} \\
&\qquad (\mathit{state}', o) = \mathit{func}\ i\ \mathit{state} \\
&\qquad \mathit{out} \qquad\quad = \mathit{run}\ \mathit{func}\ \mathit{state}'\ \mathit{input}
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```
run func state [] = []
run func state (i : input) = o : out
  where
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    out         = run func state' input
```

Small Use Case

- Small Polymorphic, Higher-Order CPU
- Each function is turned into a hardware component
- Use of state will be simple

Imports

Import all the built-in types, such as vectors and integers:

```
import CLasH.HardwareTypes
```

Import annotations, helps CλasH to find top-level component:

```
import CLasH.Translator.Annotations
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Type definitions

First we define some ALU types:

$$\textbf{type } Op\ s\ a\ = a \rightarrow Vector\ s\ a \rightarrow a$$
$$\textbf{type } Opcode = Bit$$

And some Register types:

$$\textbf{type } RegBank\ s\ a = Vector\ (s + D1)\ a$$
$$\textbf{type } RegState\ s\ a = State\ (RegBank\ s\ a)$$

And a simple Word type:

$$\textbf{type } Word = SizedInt\ D12$$

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Operations

We make a primitive operation:

$$primOp :: (a \rightarrow a \rightarrow a) \rightarrow Op\ s\ a$$
$$primOp\ f\ a\ b = a\ `f`\ a$$

We make a vector operation:

$$vectOp :: (a \rightarrow a \rightarrow a) \rightarrow Op\ s\ a$$
$$vectOp\ f\ a\ b = foldl\ f\ a\ b$$

- We support Higher-Order Functionality

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Simple ALU

We define a polymorphic ALU:

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alu ::
    Op s a →
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    Opcode → a → Vector s a → a
alu op1 op2 Low  a b = op1 a b
alu op1 op2 High a b = op2 a b
```

- We support Patter Matching

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Register Bank

Make a simple register bank:

```
registerBank ::
  (Some context...) ⇒ (RegState s a) → a → RangedWord s →
  RangedWord s → Bit → ((RegState s a), a)
registerBank (State mem) data_in rdaddr wraddr wrenable =
  ((State mem'), data_out)
  where
    data_out = mem ! rdaddr
    mem' | wrenable ≡ Low = mem
         | otherwise      = replace mem wraddr data_in
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Simple CPU

Combining ALU and register bank:

```
{-#ANN actual_cpu TopEntity#-}
actual_cpu ::
  (Opcode, Word, Vector D4 Word, RangedWord D9,
  RangedWord D9, Bit) → RegState D9 Word →
  (RegState D9 Word, Word)
actual_cpu (opc, a, b, rdaddr, wraddr, wren) ram = (ram', alu_out)
  where
    alu_out = alu (primOp (+)) (vectOp (+)) opc ram_out b
    (ram', ram_out) = registerBank ram a rdaddr wraddr wren
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- Annotation is used to indicate top-level component

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Is CλasH usable?

- It can be used for more than toy examples
- We designed a matrix reduction circuit
- We simulated it in Haskell
- Simulation results in VHDL match
- Synthesis completes without errors or warnings

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So how do you make Hardware from Haskell?

In three simple steps

- No Effort:
  GHC API Parses, Typechecks and Desugars Haskell
- Hard.. sort of:
  Transform resulting Core, GHC's Intermediate Language, to a normal form
- Easy:
  Translate Normalized Core to synthesizable VHDL

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How do we use CλasH?

As a library:

- Import the module: CLasH.Translator
- And call *makeVHDLAnnotations ghc_lib_dir [files_to_translate]*

Customized GHC:

- Call GHC with the –vhdl flag
- Use the :vhdl command in GHCi

Real Demo

- We will simulate the small CPU from earlier
- Translate the CPU code to VHDL
- Simulate the generated VHDL
- Synthesize the VHDL to get a hardware schematic

Some final words

- Still a lot to do: make a bigger subset of Haskell translatable
- Real world designs work
- We bring functional expressivity to hardware designs

Thank you for listening

Complete signature for registerBank

$$
\begin{aligned}
&\mathit{registerBank} :: \\
&\quad (\mathit{NaturalT}\ s \\
&\quad , \mathit{PositiveT}\ (s + D1) \\
&\quad , ((s + D1) > s) \sim \mathit{True})) \Rightarrow \\
&\quad (\mathit{RegState}\ s\ a) \rightarrow a \rightarrow \mathit{RangedWord}\ s \rightarrow \\
&\quad \mathit{RangedWord}\ s \rightarrow \mathit{Bit} \rightarrow ((\mathit{RegState}\ s\ a), a)
\end{aligned}
$$