High-level Synthesis from Functional Languages

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\((\lambda x.?) f = \text{FPGA}\)
Parallelism is the Big Question
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Massive On-Chip Parallelism is Inevitable

Intel’s 48-core “Single Chip Cloud Computer”
The Future is Wires and Memory
The Future is Already Here

Altera Stratix IV FPGA
The Memory Hierarchy is the Interesting Part
The Big Question

How Do Algorithms Manipulate Data?
My Hypothesis

How Do Algorithms Manipulate Data?

We will only be able to answer this in very disciplined languages.

E.g., pure functional languages with immutable data structures
Why Functional Specifications?

- Referential transparency/side-effect freedom make formal reasoning about programs vastly easier

- Inherently concurrent and race-free (Thank Church and Rosser). If you want races and deadlocks, you need to add constructs.

- Immutable data structures makes it vastly easier to reason about memory in the presence of concurrency
Multiprocessor Memory is a Headache

- Cache Coherency
- Write buffers
- Sequential Memory Consistency
- Memory barriers
- Data Races
- Atomic operations

Immutable data structures simplify these
I Don’t Think We Want Laziness

Laziness has certain semantic advantages, but the bookkeeping is probably not worth it
Approach

- We do not know the structure of future memory systems
  Homogeneous/Heterogeneous?
  Levels of Hierarchy?
  Communication Mechanisms?

- We do not know the architecture of future multi-cores
  Programmable in Assembly/C?
  Single- or multi-threaded?

Use FPGAs as a surrogate. Ultimately too flexible, but representative of the long-term solution.
The Big Question'

How do we synthesize hardware from pure functional languages for FPGAs?

Control and datapath are easy; the memory system is interesting.
To Implement Real Algorithms in Hardware, We Need

Structured, recursive data types

Recursion to handle recursive data types

Memories

Memory Hierarchy
Example: Huffman Decoder in Haskell

```haskell
data HTree = Branch HTree HTree |
          Leaf Char

decode :: HTree -> [Bool] -> [Char] -- Huffman tree & bitstream to symbols

decode table str = decoder table str
  where
    decoder (Leaf s) i = s : (decoder table i) -- Identified symbol; start again
    decoder _ [] = []
    decoder (Branch f _) (False:xs) = decoder f xs -- 0: follow left branch
    decoder (Branch _ t) (True:xs) = decoder t xs -- 1: follow right branch

Three data types: Input bitstream, output character stream, and Huffman tree
```
One Way to Encode the Types

Huffman tree nodes: (19 bits)

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8-bit character</td>
<td>(unused)</td>
<td>Leaf Char</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>9-bit tree ptr.</td>
<td>9-bit tree ptr.</td>
<td>Branch Tree Tree</td>
<td></td>
</tr>
</tbody>
</table>

Boolean input stream: (10 bits)

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(unused)</td>
<td>Nil</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>bit</td>
<td>8-bit tail pointer</td>
<td>Cons Bool List</td>
</tr>
</tbody>
</table>

Character output stream: (19 bits)

<p>| | | | |</p>
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<thead>
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<tr>
<td>1</td>
<td>8-bit character</td>
<td>10-bit tail pointer</td>
<td>Cons Char List</td>
</tr>
</tbody>
</table>
Intermediate Representation Desiderata

Mathematical formalism convenient for performing “parallelizing” transformations, a.k.a. parallel design patterns

- Pipeline
- Speculation
- Multiple workers
- Map-reduce
Intermediate Representation: Recursive “Islands”

\[
\begin{align*}
\text{program} & := \text{island}* \\
\text{island} & := \text{island} \text{ name arg}* = \text{expr state}^* \\
\text{state} & := \text{label arg}* = \text{expr} \\
\text{expr} & := \text{name var}^* \\
& \quad \mid \text{let } (\text{var} = \text{expr})^+ \text{ in } \text{expr} \\
& \quad \mid \text{case } \text{var} \text{ of } (\text{pattern} \rightarrow \text{expr})^+ \\
& \quad \mid \text{var} \\
& \quad \mid \text{literal} \\
& \quad \mid \text{recurse } \text{label var}^* (\text{var}^*) \\
& \quad \mid \text{return } \text{var} \\
& \quad \mid \text{goto } \text{label var}^* \\
\text{pattern} & := \text{name var}^* \mid \text{literal} \mid _
\end{align*}
\]

- Group of states w/ stack
- Arguments & expression
- Apply a function
- Parallel evaluation
- Multiway conditional
- Explicit continuation
- Branch to another state
- Constructor/literal/def.
Huffman as a Recursive Island

```
data HTree = Branch HTree HTree |
          Leaf Char

decode :: HTree -> [Bool] -> [Char]

decode table str = decoder table str
where
  decoder (Leaf s) i =
    s : (decoder table i)
  decoder _ [] = []
  decoder (Branch f _) (False:xs) =
    decoder f xs
  decoder (Branch _ t) (True:xs) =
    decoder t xs

island decoder treep ip =
  let r = dec treep treep ip in return r

island dec treep statep ip =
  let i = fetchi ip
      state = fetcht statep in
  case state of
    Leaf a -> recurse s1 a (treep treep ip)
    Branch f t ->
      case i of
        Nil -> let np = Nil in return np
        Cons x xsp ->
          case x of
            True -> goto dec treep t xsp
            False -> goto dec treep f xsp

s1 a rp = let rrp = Cons a rp
           in return rrp
```
Strobe-based interface: *go* indicates inputs are valid; *ready* pulses once when result is valid.
Translating Let and Case

Let makes new values available to an expression.

Case invokes one of its sub-expressions, then synchronizes.
Translating an Island

Each island consists of expressions for each state, its own stack, and a controller that manages the stack and invokes the states.
Constructors and Memory

A constructor is a function that stores data in memory.

\[
\text{constructor } \alpha :: \alpha \to \text{Ptr } \alpha
\]

Memory access functions turn pointers into data.

\[
\text{fetch } \alpha :: \text{Ptr } \alpha \to \alpha
\]

Memory stores return an address, not take one as an argument.

Constructor is responsible for memory management.

By default, each data type gets its own memory.
Duplication for Performance

\[
\begin{align*}
    fib \ 0 &= 0 \\
    fib \ 1 &= 1 \\
    fib \ n &= fib \ (n-1) + fib \ (n-2)
\end{align*}
\]
Duplication for Performance

\[
\begin{align*}
\text{fib} & \ 0 = 0 \\
\text{fib} & \ 1 = 1 \\
\text{fib} & \ n = \text{fib} \ ((n-1)) + \text{fib} \ (n-2) \\
\end{align*}
\]

After duplicating functions:

\[
\begin{align*}
\text{fib} & \ 0 = 0 \\
\text{fib} & \ 1 = 1 \\
\text{fib} & \ n = \text{fib}' \ (n-1) + \text{fib}'' \ (n-2) \\
\text{fib}' & \ 0 = 0 \\
\text{fib}' & \ 1 = 1 \\
\text{fib}' & \ n = \text{fib}' \ (n-1) + \text{fib}' \ (n-2) \\
\text{fib}'' & \ 0 = 0 \\
\text{fib}'' & \ 1 = 1 \\
\text{fib}'' & \ n = \text{fib}'' \ (n-1) + \text{fib}'' \ (n-2) \\
\end{align*}
\]

Here, \(\text{fib}'\) and \(\text{fib}''\) may run in parallel.
Unrolling Recursive Data Structures

Like a “blocking factor,” but more general. Idea is to create larger memory blocks that can be operated on in parallel.

Original Huffman tree type:

```
data Htree = Branch Htree HTree | Leaf Char
```

Unrolled Huffman tree type:

```
data Htree = Branch Htree’ HTree’ | Leaf Char
data Htree’ = Branch’ Htree” HTree” | Leaf Char
data Htree” = Branch” Htree HTree | Leaf” Char
```

Recursive instances must be pointers; others can be explicit.

Functions must be similarly modified to work with the new types.
Acknowledgements

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