Circular vs. Higher-Order Shortcut Fusion

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Classical Shortcut Fusion [Gill et al., FPCA'93]

Example: $upTo\ n = go\ 1$

$$\begin{aligned} &\textbf{where}\ go\ i = \textbf{if}\ i > n\ \textbf{then}\ [\,] \\ &\qquad\qquad\qquad\quad \textbf{else}\ \ i : go\ (i+1) \end{aligned}$$

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Solution:

1. Write *upTo* in terms of *build*.
2. Write *sum* in terms of *foldr*.
3. Use the following fusion rule:

$$foldr\ h_1\ h_2\ (build\ g) \rightsquigarrow g\ h_1\ h_2$$

Circular Shortcut Fusion [Fernandes et al., Haskell'07]

Producing intermediate results:

$$\mathit{buildp} :: (\forall a.\ (b \rightarrow a \rightarrow a) \rightarrow a \rightarrow c \rightarrow (a, z)) \rightarrow c \rightarrow ([b], z)$$
$$\mathit{buildp}\ g\ \ c = g\ \ (:)\ [\,]\ c$$

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$$\mathit{filterAndCount} :: (b \to \mathit{Bool}) \to [b] \to ([b], \mathit{Int})$$
$$\mathit{filterAndCount}\ f = \mathit{buildp}\ \cdots$$

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Consuming intermediate results:

$$\mathit{pfold} :: (b \to a \to z \to a) \to (z \to a) \to ([b], z) \to a$$
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$$normalise :: ([Int], Int) \to [Float]$$
$$normalise = pfold\ \ \cdots$$

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The fusion rule:

$$\mathit{pfold}\ \ h_1\ \ h_2\ (\mathit{buildp}\ g\ \ c)$$
$$\rightsquigarrow$$
$$\mathbf{let}\ (a, z) = g\ (\lambda b\ \ a \rightarrow h_1\ \ b\ \ a\ \ z)\ (h_2\ \ z)\ c\ \mathbf{in}\ a$$

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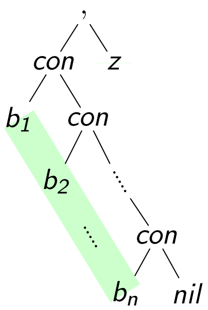
The type of g forces it to be essentially of the following form:

$\lambda con\ nil\ c \rightarrow$



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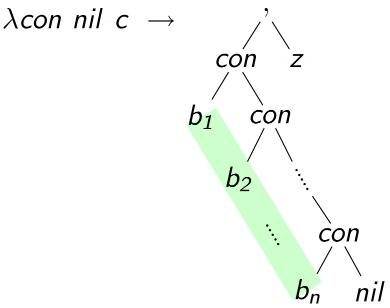

Formal justification: free theorems [Wadler, FPCA'89]

Circular Shortcut Fusion [Fernandes et al., Haskell'07]

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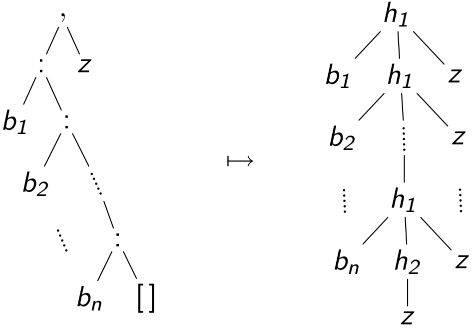
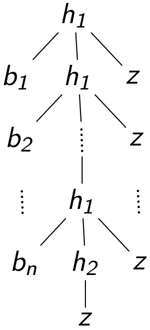
$$pfold\ h_1\ h_2\ (bs, z) = foldr\ (\lambda b\ a \to h_1\ b\ a\ z)\ (h_2\ z)\ bs$$

A concrete output (*buildp g c*) will be consumed as follows:



Circular Shortcut Fusion [Fernandes et al., Haskell'07]

$pfold\ h_1\ h_2\ (g\ (:)\ []\ c) \rightsquigarrow$



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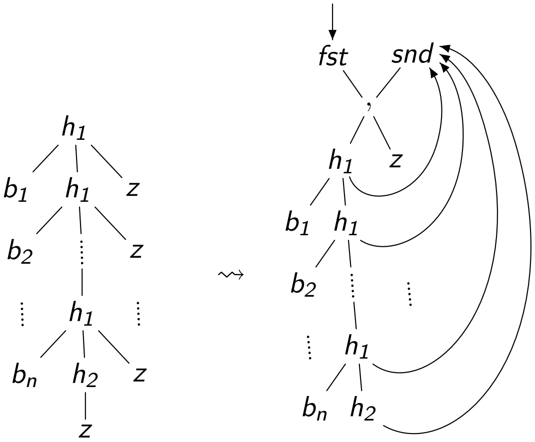

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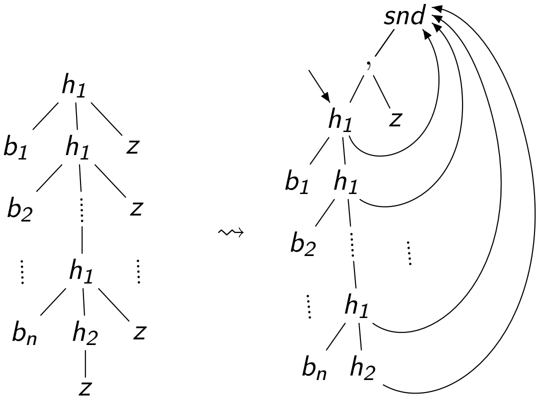

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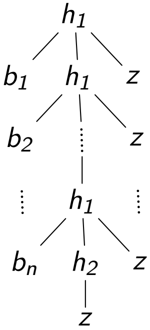

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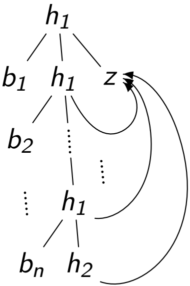

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- ...but been found to not be totally correct when considering certain language features [Johann and V., POPL'04].
- Circular shortcut fusion depends on evaluation order, which is precisely a "dangerous" corner for free theorems.
- So would it be possible to manufacture counterexamples?

A Problem with Selective Strictness

Producing intermediate results:

$$buildp :: (\forall a.\ (b \to a \to a) \to a \to c \to (a, z)) \to c \to ([b], z)$$
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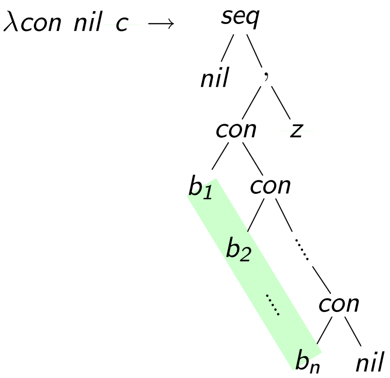
In Haskell, g could also be, for example, of the following form:



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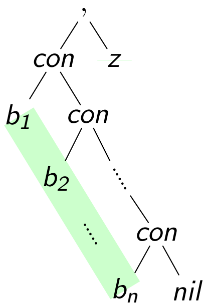

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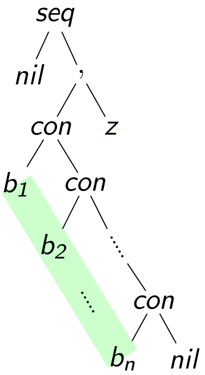

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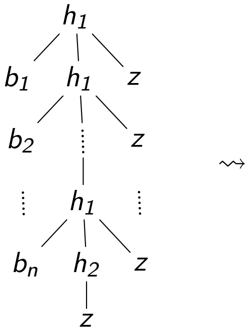

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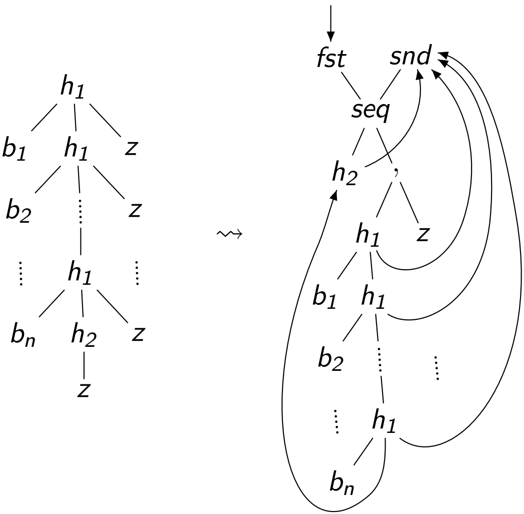

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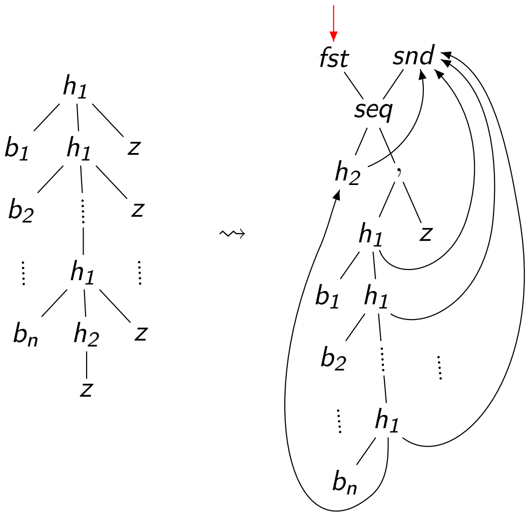

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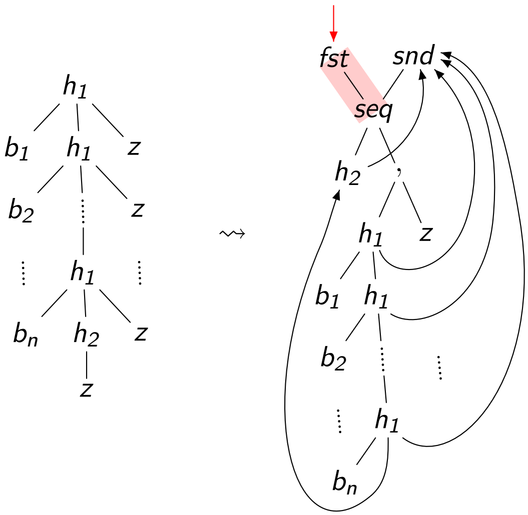

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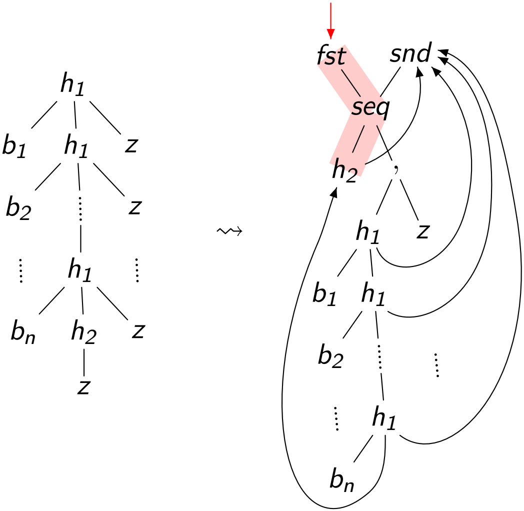

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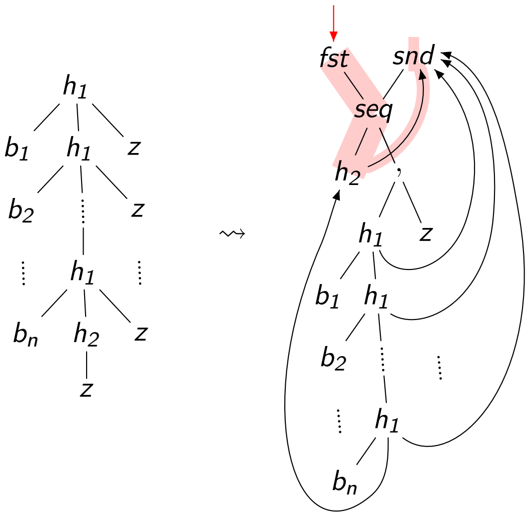

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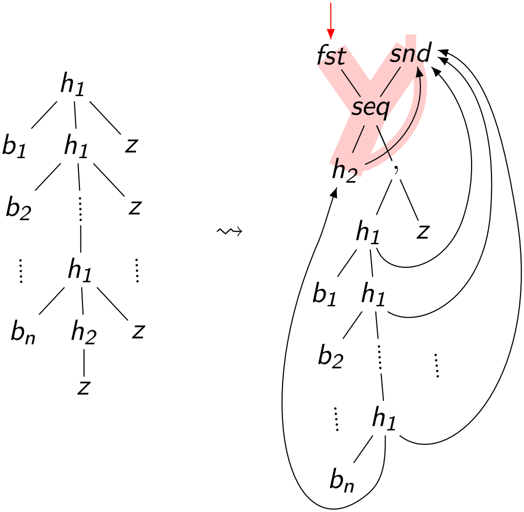

Total and Partial Correctness [V., FLOPS'08]

Theorem 1

If $h_2 \perp \neq \perp$ and $h_1 \perp \perp \perp \neq \perp$, then

$$pfold\ h_1\ h_2\ (buildp\ g\ c)$$
$$=$$
$$\mathbf{let}\ (a, z) = g\ (\lambda b\ a \rightarrow h_1\ b\ a\ z)\ (h_2\ z)\ c\ \mathbf{in}\ a$$

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Theorem 2

Without preconditions,

$$\begin{array}{c} \mathit{pfold}\ h_1\ h_2\ (\mathit{buildp}\ g\ c) \\ \sqsupseteq \\ \mathbf{let}\ (a, z) = g\ (\lambda b\ a \to h_1\ b\ a\ z)\ (h_2\ z)\ c\ \mathbf{in}\ a \end{array}$$

Replacing Circularity by Higher-Orderedness

$$\mathit{pfold}\ h_1\ h_2\ (g\ (:)\ [\,]\ c) \rightsquigarrow \textbf{let}\ (a, z) = g\ (\lambda b\ a \rightarrow h_1\ b\ a\ z)\ (h_2\ z)\ c\ \textbf{in}\ a$$

Replacing Circularity by Higher-Orderedness

$$
\begin{aligned}
pfold\ h_1\ h_2\ (g\ (:)\ [\,]\ c) \leadsto\ & \textbf{let}\ (a, z) = g\ (\lambda b\ a \rightarrow h_1\ b\ a\ z)\ (h_2\ z)\ c\ \textbf{in}\ a \\
& \textbf{case}\ g\ (\lambda b\ k\ z \rightarrow h_1\ b\ (k\ z)\ z)\ (\lambda z \rightarrow h_2\ z)\ c \\
& \textbf{of}\ (k, z) \rightarrow k\ z
\end{aligned}
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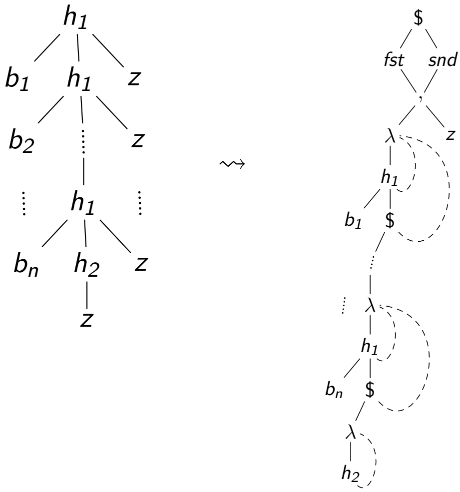

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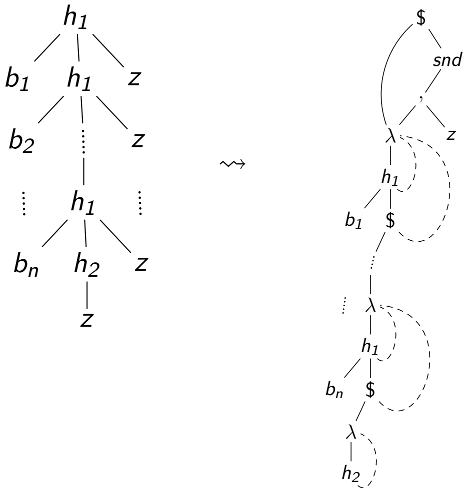

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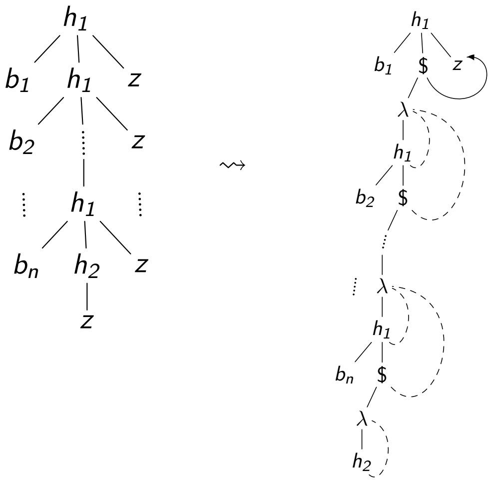

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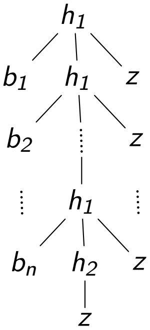
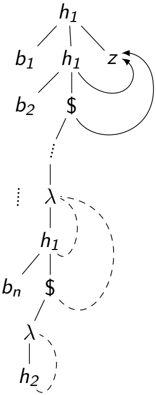


$\rightsquigarrow$



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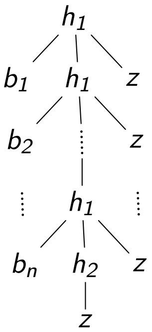

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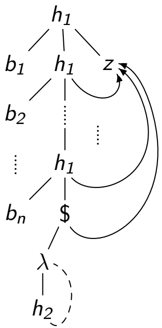

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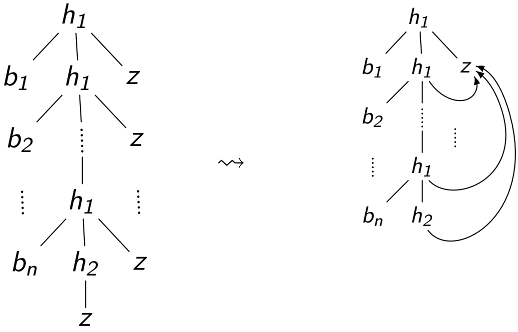
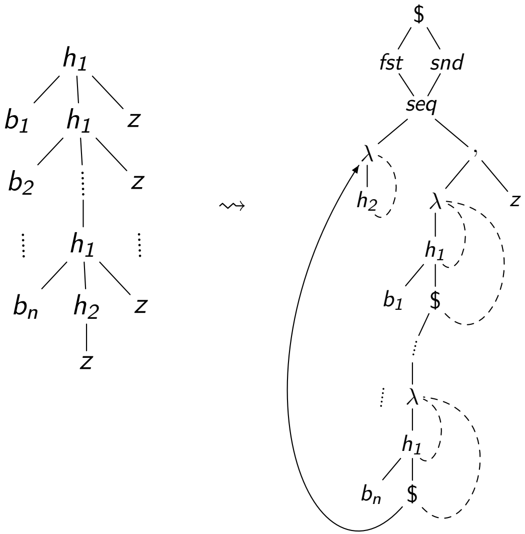


No Problem with Selective Strictness

For a g of the problematic form considered earlier:



Total Correctness [V., FLOPS'08]

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- But semantically, the high-order approach is more robust.
- Performance measurements do not give a very clear picture.
- There are interesting interactions with rather low-level details of the language implementation!

Tricky Sharing Issues — Circular Shortcut Fusion

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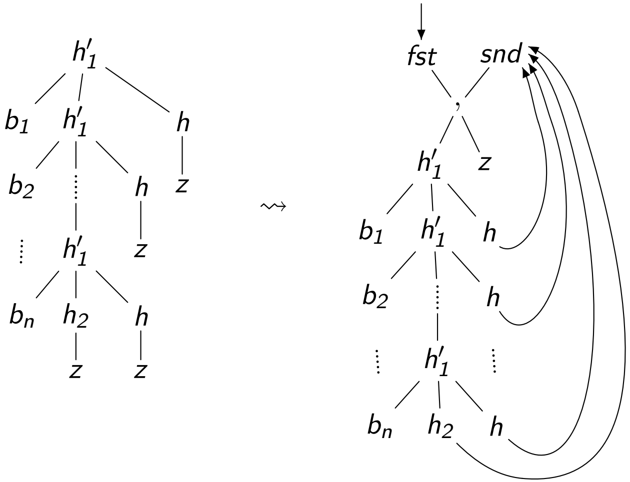

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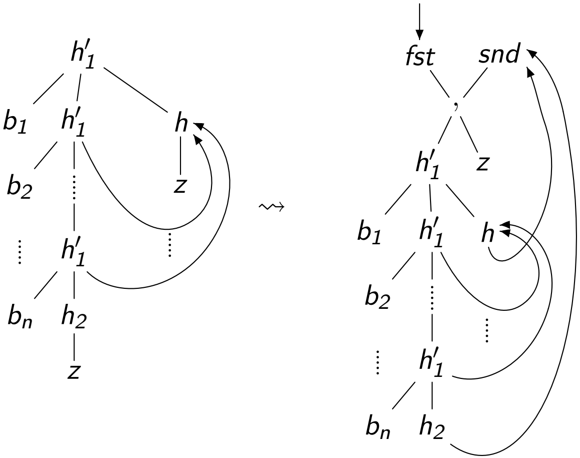
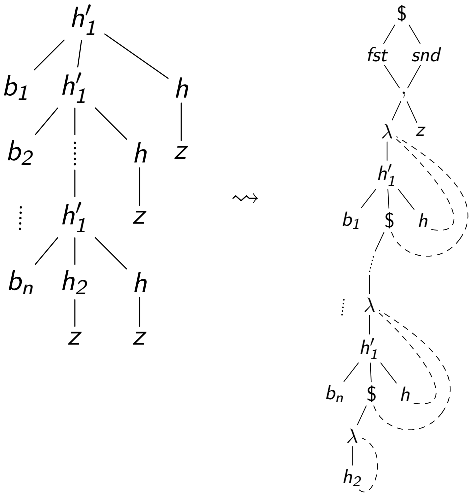


Tricky Sharing Issues — Higher-Order Shortcut Fusion

$$\begin{aligned} pfold\ h_1\ h_2\ (buildp\ g\ c) \rightsquigarrow\ & \textbf{case}\ g\ (\lambda b\ k\ z \to h_1\ b\ (k\ z)\ z)\ (\lambda z \to h_2\ z)\ c \\ & \textbf{of}\ (k, z) \to k\ z \end{aligned}$$

If $h_1 = \lambda b\ a\ z \to h_1'\ b\ a\ (h\ z)$, then:



Tricky Sharing Issues — Higher-Order Shortcut Fusion

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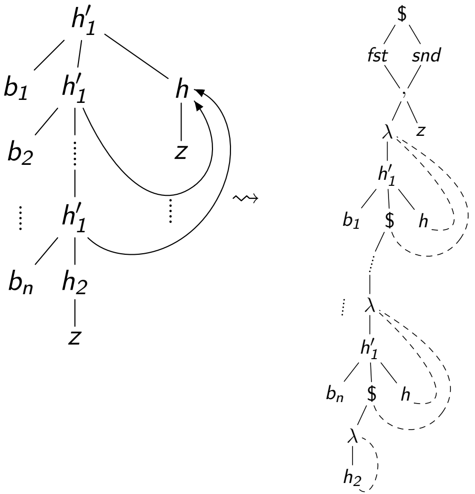

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- Both semantic and pragmatic considerations can motivate studying new rules as well as new combinators.
- These lessons also inform new developments for more classical shortcut fusion techniques.
- There is still an interesting design space to explore!

Recent (and Future?) Developments

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- From a semantics perspective, the circular flavour is again more intriguing.
- The higher-order flavour is (again) more generally applicable.
- It should be interesting to investigate the interplay with other fusion work involving monads [V., MPC'08].

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