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Adding testing to Ask-Elle: An Interactive Functional Programming Tutor

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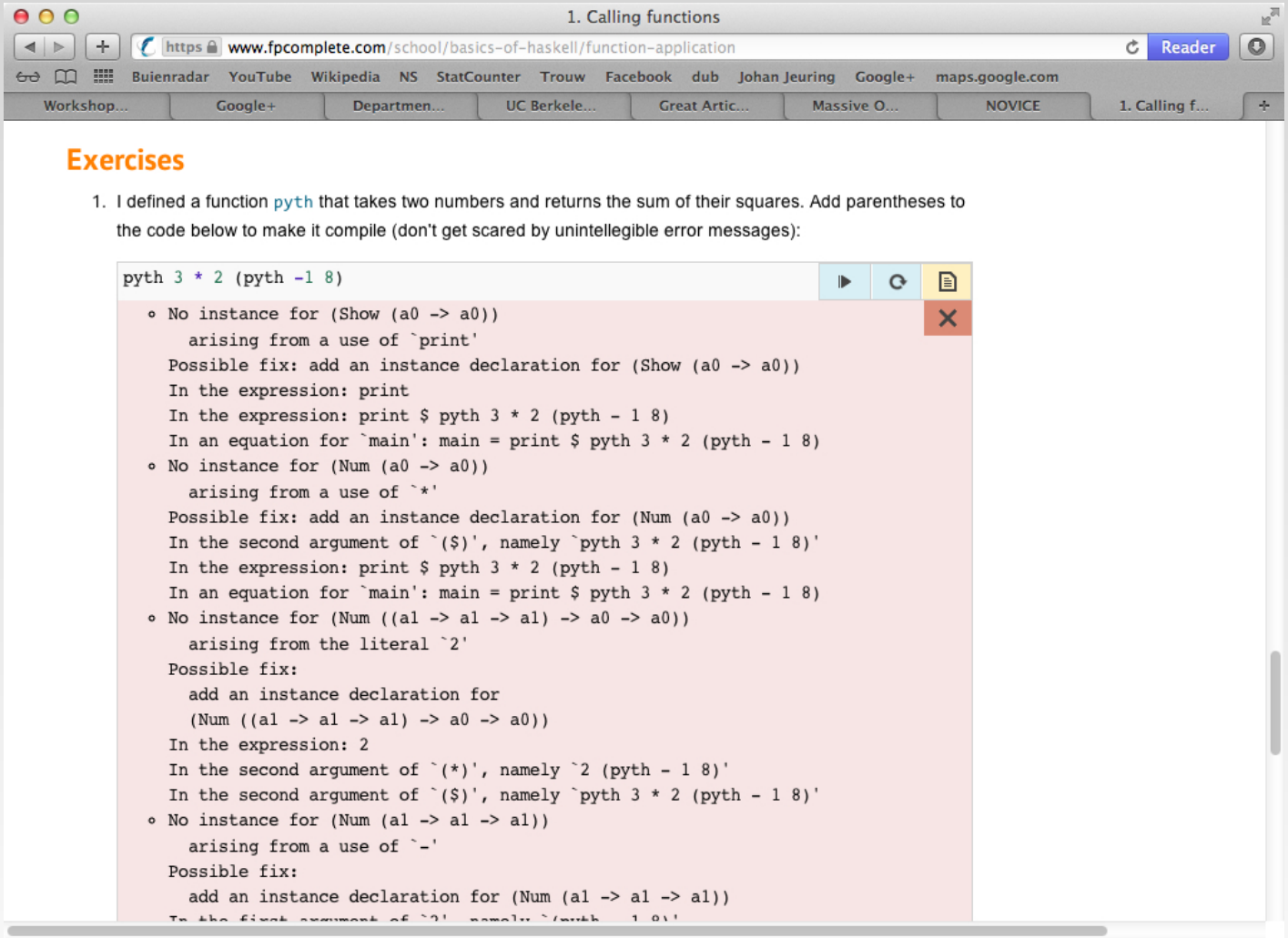
Learning to program

Learning to program is hard.

- Misconceptions about the syntax and semantics of a programming language
- Analysing and creating a model of the problem that can be implemented is difficult
- Decomposing a complex problem into smaller subproblems requires experience
- Most compilers give poor error messages



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Programming tutors

A programming tutor supports a student when learning how to program:

- giving hints (in varying level of detail)
- showing worked-out solutions
- reporting erroneous steps

Challenges for programming tutors

Programming tutors are not widely used.

- Building a tutor is a substantial amount of work
- Using a tutor in a course is hard for a teacher: adapting or extending a tutor is often very difficult or even impossible
- Having to specify feedback with each new exercise is often a lot of work

Preferably, a programming tutor:

- supports easy specification of exercises
- automatically derives feedback and hints

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This talk

Shows Ask-Elle, a programming tutor for Haskell, in action.

- Support developing beginners' Haskell programs
- Add programming exercises
- Adapt feedback
- Prove correctness
- Prove incorrectness

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Outline of presentation

Motivation

Ask-Elle: demo

Feedback

Future work and conclusions

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Ask-Elle: A programming tutor for Haskell

We are developing Ask-Elle: a programming tutor for Haskell. Using the tutor, a student can:

- develop her program incrementally
- receive feedback about whether or not she is on the right track
- can ask for a hint when she is stuck
- see how a complete program is stepwise constructed

A teacher specifies an exercise by means of model solutions.

The tutor targets first-year computer science students.

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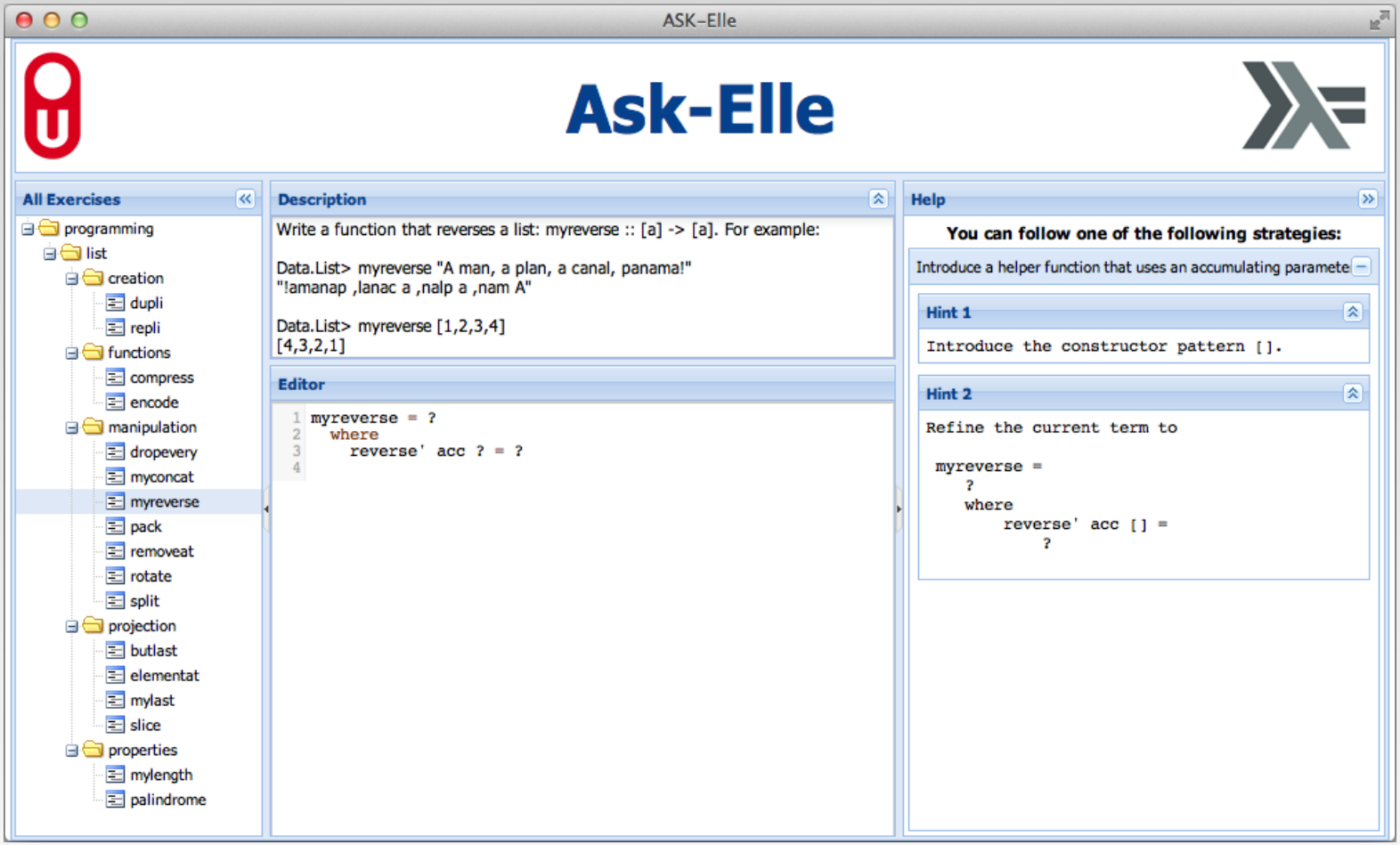
ASK-Elle
Ask-Elle
All Exercises
programming
list
creation
dupli
repli
functions
compress
encode
manipulation
dropevery
myconcat
myreverse
pack
removeat
rotate
split
projection
butlast
elementat
mylast
slice
properties
mylength
palindrome
Description
Write a function that reverses a list: myreverse :: [a] -> [a]. For example:
Data.List> myreverse "A man, a plan, a canal, panama!"
"!amanap ,lanac a ,nalp a ,nam A"
Data.List> myreverse [1,2,3,4]
[4,3,2,1]
Editor
1 myreverse = ?
2 where
3 reverse' acc ? = ?
4
Help
You can follow one of the following strategies:
Introduce a helper function that uses an accumulating paramete
Hint 1
Introduce the constructor pattern [].
Hint 2
Refine the current term to
myreverse =
?
where
reverse' acc [] =
?

An example interactive session

Programming task: write a program that reverses a list:

> ?

Tutor response on Hint:

There are several ways you can proceed:

- Introduce a helper function that uses an accumulating parameter.
- Use the *Prelude* function *foldl*.
- Use explicit recursion.

An example interactive session

Programming task: write a program that reverses a list:

$$
\begin{array}{l}
\mathit{reverse} = \mathit{reverse}'\ ? \\
\quad \textbf{where} \\
\quad\quad \mathit{reverse}'\ \mathit{acc}\ ?\ =\ ?
\end{array}
$$

Tutor response on Hint:

Apply $\mathit{reverse}'$ to $[\,]$, or use pattern matching for the second argument of $\mathit{reverse}'$, or refine the right-hand side of reverse'.

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An example interactive session

Programming task: write a program that reverses a list:

$$
\begin{array}{l}
reverse = reverse'\ [\,] \\
\quad \textbf{where} \\
\quad\quad reverse'\ acc\ [\,] = ?
\end{array}
$$

Tutor response on Hint:

Refine the right hand side of the empty list case.

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An example interactive session

Programming task: write a program that reverses a list:

$$
\begin{aligned}
&reverse = reverse'\ [\,] \\
&\quad \textbf{where} \\
&\qquad reverse'\ acc\ [\,] = [\,]
\end{aligned}
$$

Tutor response on Check:

Unexpected step, which may be incorrect.

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An example interactive session

Programming task: write a program that reverses a list:

$$
\begin{aligned}
&\mathit{reverse} = \mathit{reverse}'\ [\,] \\
&\quad \textbf{where} \\
&\qquad \mathit{reverse}'\ \mathit{acc}\ [\,] = \mathit{acc}
\end{aligned}
$$

Tutor response on Hint:

Define the non-empty list case of $\mathit{reverse}'$

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An example interactive session

Programming task: write a program that reverses a list:

$$
\begin{aligned}
&\mathit{reverse} = \mathit{reverse}'\ [\,] \\
&\quad \textbf{where} \\
&\qquad \mathit{reverse}'\ \mathit{acc}\ [\,] \quad\ = \mathit{acc} \\
&\qquad \mathit{reverse}'\ \mathit{acc}\ (x : \mathit{xs}) = ?
\end{aligned}
$$

Tutor response on Hint:

Define the recursive call of $\mathit{reverse}'$

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An example interactive session

Programming task: write a program that reverses a list:

$$
\begin{aligned}
&\mathit{reverse} = \mathit{reverse}'\ [\,] \\
&\quad \textbf{where} \\
&\qquad \mathit{reverse}'\ \mathit{acc}\ [\,] \qquad\quad = \mathit{acc} \\
&\qquad \mathit{reverse}'\ \mathit{acc}\ (x : \mathit{xs}) = \mathit{reverse}'\ (y : \mathit{acc})\ ?
\end{aligned}
$$

Tutor response on Check:

```
Error: Undefined variable y
```

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An example interactive session

Programming task: write a program that reverses a list:

$$
\begin{aligned}
&\mathit{reverse} = \mathit{reverse}'\ [\,] \\
&\quad \textbf{where} \\
&\qquad \mathit{reverse}'\ \mathit{acc}\ [\,] \qquad\quad = \mathit{acc} \\
&\qquad \mathit{reverse}'\ \mathit{acc}\ (x : \mathit{xs}) = \mathit{reverse}'\ (x : \mathit{acc})\ \mathit{xs}
\end{aligned}
$$

Tutor response on Check:

You have correctly solved the exercise.

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What kind of feedback?

- Syntax or type error
- Correct step
- Coming soon: violates the following property: ...
- Hint, in increasing detail
- Solved

Model solutions for *reverse*

The tutor derives feedback from model solutions.

$$
\begin{aligned}
&reverse_1\ [\,] &&= [\,] \\
&reverse_1\ (x : xs) &&= reverse_1\ xs +\!\!+ [x]
\end{aligned}
$$

$$
\begin{aligned}
&reverse_2 = reverse'_2\ [\,] \\
&\quad \textbf{where}\ reverse'_2\ acc\ [\,] &&= acc \\
&\qquad\qquad reverse'_2\ acc\ (x : xs) &&= reverse'_2\ (x : acc)\ xs
\end{aligned}
$$

$$
reverse_3 = foldl\ (flip\ (:))\ [\,]
$$

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Adapting feedback

A teacher fine-tunes feedback by annotating a model solution.

> *reverse* = *foldl* {-# FEEDBACK Note ... #-} (*flip* (:)) []

A teacher disallows or enforces a particular solution by:

> *reverse* = {-# MUSTUSE #-} *foldl* (*flip* (:)) []

Furthermore, we can add a property to a function, and use that to recognize student solutions:

> *reverse* =
> {-# ALT foldl op e == foldr (flip op) e . reverse #-}
> *foldl* (*flip* (:)) []

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Correctness

- Using annotated model solutions we can prove that a student solution is (partially) correct
- Compare (possibly partial) student solution with model solution after normalisations
- We can give hints, and show worked-out solutions
- We cannot say anything about incorrect or different solutions

Meta information for *reverse*

Besides model solutions, we store meta information about *reverse* in a configuration file:

$$
\begin{aligned}
&\mathit{function} = \mathit{reverse}\\
&\mathit{type} \quad\;\; = [a] \to [a]\\
&\mathit{groups} \quad = \mathit{programming}.\mathit{FP}\\
&\mathit{property} = (\lambda \mathit{xs} \to \mathit{whenFail}\\
&\qquad\qquad \texttt{"reverse does not reverse a list"}\\
&\qquad\qquad (\mathit{reverse}\ \mathit{xs} \equiv \mathit{reverse}_1\ \mathit{xs})\\
&\qquad\quad)
\end{aligned}
$$

property is the standard property:

$$\mathit{program}_{\mathit{student}} \equiv \mathit{program}_{\mathit{model}}$$

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Testing

- We use QuickCheck to test a property of a function.
- QuickCheck generates random values for which it tests the validity of a property.
- If QuickCheck finds a counterexample, it tries to shrink it to return a counterexample that is as small as possible.

Testing example

For the following erroneous student solution

$$
\begin{aligned}
&\mathit{reverse} \quad = \mathit{reverse}'\ [\,] \\
&\quad \textbf{where}\ \mathit{reverse}'\ \mathit{acc}\ [\,] \quad\quad = [\,] \\
&\qquad\qquad \mathit{reverse}'\ \mathit{acc}\ (x : \mathit{xs}) = \mathit{reverse}'\ (x : \mathit{acc})\ \mathit{xs}
\end{aligned}
$$

QuickCheck gives:

quickCheck property
Falsifiable, after 3 *tests* :
`"reverse does not reverse a list"`
`"counterexample: "` [1]

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More informative properties for testing

```
property = λx  →  prop_lengthatmost x
                  .&&. prop_lengthatleast x

prop_lengthatmost
    = λxs → whenFail
          "reverse duplicates list elements"
          (length (reverse xs) ⩽ length xs)

prop_lengthatleast
    = λxs → whenFail
          "reverse throws away list elements"
          (length (reverse xs) ⩾ length xs)
```

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Testing example revisited

For the following erroneous student solution

$$
\begin{aligned}
&\mathit{reverse} \quad = \mathit{reverse}'\ [\,] \\
&\quad \textbf{where}\ \mathit{reverse}'\ \mathit{acc}\ [\,] \quad\quad = [\,] \\
&\qquad\qquad \mathit{reverse}'\ \mathit{acc}\ (x : \mathit{xs}) = \mathit{reverse}'\ (x : \mathit{acc})\ \mathit{xs}
\end{aligned}
$$

QuickCheck gives:

quickCheck property
Falsifiable, after 3 *tests* :
`"reverse throws away list elements"`
`"counterexample: "` [1]

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Incorrectness

- Using testing we can prove that a student solution is incorrect
- We cannot say anything about correct solutions

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Why not only do testing?

fromBin converts a list of binary numbers to its decimal representation:

$$
\begin{aligned}
&\mathit{fromBin}\ [1,0,1,0,1,0] \\
&\quad \Rightarrow 42
\end{aligned}
$$

A solution:

$$
\begin{aligned}
&\mathit{fromBin} :: [\mathit{Int}] \rightarrow \mathit{Int} \\
&\mathit{fromBin} = \mathit{fromBin}'\ 2 \\
&\\
&\mathit{fromBin}'\ n\ [\,] \qquad\quad = 0 \\
&\mathit{fromBin}'\ n\ (x : xs) = x * n \mathbin{\hat{}} (\mathit{length}\ (x : xs) - 1) \\
&\qquad\qquad\qquad\qquad + \mathit{fromBin}'\ n\ xs
\end{aligned}
$$

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Why not only do testing?

This solution satisfies the expected properties, but it contains a number of (serious) imperfections:

- The length calculation is inefficient
- It takes time quadratic in the size of the input list
- Argument n is constant and should be abstracted

These imperfections occur frequently in student solutions.

$$
\begin{aligned}
&fromBin :: [Int] \to Int \\
&fromBin = fromBin'\ 2 \\
\\
&fromBin'\ n\ [\,] &&= 0 \\
&fromBin'\ n\ (x : xs) &&= x * n \mathbin{\hat{}} (length\ (x : xs) - 1) \\
&&&\quad + fromBin'\ n\ xs
\end{aligned}
$$

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Where is the error?

- Using QuickCheck we can generate counterexamples for erroneous solutions
- But where is the error?
- Interpret a property as a contract
- Infer contracts for components
- Determine contract violations using the counterexample

Testing example revisited

reverse satisfies the contract:

$$\lambda xs \rightarrow length\ (reverse\ xs) \equiv length\ xs$$

For the erroneous solution

$$\begin{aligned} reverse &= reverse'\ [\,] \\ \textbf{where}\ reverse'\ acc\ [\,] &= [\,] \\ reverse'\ acc\ (x : xs) &= reverse'\ (x : acc)\ xs \end{aligned}$$

we might infer that $reverse'$ satisfies the contract

$$\lambda xs \rightarrow length\ (reverse'\ xs\ ys) \equiv length\ xs + length\ ys$$

Using the inferred contract, we can show that the first line of $reverse'$ violates the contract.

Normalisation

$$
\begin{aligned}
&range1\ x\ y = \textbf{if}\ x \equiv y\ \textbf{then}\ [x]\ \textbf{else}\ x : range1\ (x+1)\ y \\
&range_2\ x\ y = \textbf{if}\ y \equiv x\ \textbf{then}\ [x]\ \textbf{else}\ x : range_2\ (x+1)\ y \\
&range_3\ x\ y = \textbf{if}\ x \not\equiv y\ \textbf{then}\ x : range_3\ (x+1)\ y\ \textbf{else}\ [x] \\
&range_4\ x\ y = \textbf{if}\ y \not\equiv x\ \textbf{then}\ x : range_4\ (x+1)\ y\ \textbf{else}\ [x] \\
&range_5\ x\ y = \textbf{if}\ x \not\equiv y\ \textbf{then}\ x : range_5\ (1+x)\ y\ \textbf{else}\ [x] \\
&\qquad \text{-- and the 3 variants} \\
&range_6\ x \quad = \lambda y \rightarrow \textbf{if}\ x \equiv y\ \textbf{then}\ [x]\ \textbf{else}\ x : range_6\ (x+1)\ y \\
&\qquad \text{-- and the 7 variants} \\
&range_7 \qquad = \lambda x \rightarrow \lambda y \rightarrow \textbf{if}\ x \equiv y \\
&\qquad\qquad\qquad\qquad\qquad\quad \textbf{then}\ [x] \\
&\qquad\qquad\qquad\qquad\qquad\quad \textbf{else}\ x : range_7\ (x+1)\ y \\
&\qquad \text{-- and the 7 variants}
\end{aligned}
$$

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Conclusions

- Ask-Elle is a programming tutor for Haskell with advanced feedback functionality: both for correctness and incorrectness
- Easy to add and adapt programming exercises

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- General information:
  `http://ideas.cs.uu.nl/`
- Experiment on-line:
  `http://ideas.cs.uu.nl/ProgTutor/`
- Sources:
  `http://ideas.cs.uu.nl/trac/wiki/Download`