CS345H: Programming Languages

Lecture 19: Haskell

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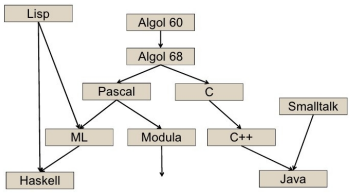
Overview

- Today: Look at the Haskell programming language
- Like LISP, Haskell is a functional language
- Unlike LISP, Haskell is statically typed and has an expressive type system
- Integrates many concepts we looked at: static typing, type inference, polymorphism, higher-order functions, ...
- At the cutting edge of PL research: designed by researchers, lots of new research done in the context of Haskell

Little Bit of History



- Haskell borrows ideas from both LISP and ML
- Like LISP and ML, functional language
- Like ML, has a strong, expressive static type system
- But also different from both in some ways: e.g., lazy functional language

History of Haskell

- Designed in the early 90's by a committee of researchers
- Goal was to unify research efforts in pure, lazy functional languages
- Feeling was that widespread use of lazy functional languages was being hampered by lack of standard language
- Goal of the committee was to design a lazy functional language that would become standard
- People who played key role in designing Haskell: Simon Peyton Jones (Microsoft Research), Philip Wadler (Edinburgh), Paul Hudak (Yale), John Hughes (Chalmers)

Why Called Haskell?

- The Haskell programming language is named after logician Haskell B. Curry
- Haskell curry well-known for Curry-Howard isopmorphism
- Curry-Howard isomorphism sheds light on relationship between constructive logic and functional programming languages
- Specifically, it says:
  1. Propositions are types
  2. Proofs are programs
  3. Proof checking is type checking

Overview of Haskell Features

- Lazy evaluation
- Expressive static type system
- Polymorphism and type classes
- Tagged unions, type constructors
- Pattern matching
- List comprehension

Lazy vs. Strict Programming Languages

- Haskell is different from many other functional languages in that it's lazy
- Lazy (or call-by-need, non-strict) languages delay evaluation of an expression until its value is actually required
- In contrast, eager (or strict, call-by-value) languages, an expression is evaluated as soon as it is bound to a variable, regardless of whether the variable is used or not
- The default behavior in many languages used today is eager evaluation: Java, C, C++, ML, Python, Lisp, Scheme ...

Example of Lazy vs. Eager

- Suppose you pass a divergent (i.e., non-terminating) expression as an argument to a function
- In an eager language, the program will definitely not terminate
- In a lazy language, the program will terminate if the value of that argument is not needed in the called function
- There are both advantages and disadvantages of lazy evaluation

Advantages and Disadvantages of Lazy Evaluation

Advantages of Lazy Evaluation:

- Unused arguments are not evaluated – can be a big win if evaluation of expression is expensive
- Can avoid divergent or buggy bahevior in some cases
- Can create infinite data structures

Disadvantages of Lazy Evaluation:

- Can be difficult to predict program behavior
- Doesn't work well in the presence of side effects
- Even in purely functional languages, things like IO become much more difficult

Expressive Static Type System

- Haskell is a statically typed language with a sound type system
- Does not allow ways to subvert the type system, such as casting
- Thus, if the Haskell compiler assigns type T to expression e, run-time value of e will be in the set of values defined by T
- Haskell performs type inference, so you don't have to explicitly annotate types of expressions
- Furthermore, Haskell has polymorphism: Types of variables can contain (universally-quantified) type variables

Example of Polymorphism in Haskell

- Consider the `id` function in Haskell: `let id x = x`
- This function has the inferred polymorphic type `a -> a`
- For any type `a`, if the value of the input is `a`, the output is also of type `a`
- The Haskell type `a -> a` is the same as $\forall\alpha.\alpha \rightarrow \alpha$

Another Example

- Let's look at a more interesting example:

```
map f [] = []
map f (x:xs) = f x :  map f xs
```

- Here, we define a higher-order `map` function which applies a function `f` to every element in the list
- This function definition illustrates pattern matching in Haskell: here, we pattern match on the second argument
- First line: if the input list is empty, then return the empty list
- Second line corresponds to case where list has at least one element

Example, cont.

```
map f [] = []
map f (x:xs) = f x :  map f xs
```

- By using the notation `(x:xs)`, we bind first element of input list to `x` and rest of the list to `xs`
- Second line: Applies function `f` to head `x` of the list
- Then, recursively invokes `map` with function `f` on the remainder `xs` of the list
- Finally, returns a list which is the concatanation of `f x` and result of recursive call

Example, cont.

```
map f [] = []
map f (x:xs) = f x :  map f xs
```

- Haskell compiler infers type of this function to be:

  `(a -> b) -> [a] -> [b]`
- Again, this is a polymorphic type
- Says: Given any function of type `a -> b` and a list of values of type `a`, return value is a list of values of type `b`
- Here, `a` and `b` are (implicitly) universally-quantified type variables

Type Classes

- Consider the Haskell function: `f x = x*2`
- What is the type of this function?
- We can't give it the polymorphic type `a -> a` because it only works on types for which multiplication is defined
- But assigning type `Integer -> Integer` also too restrictive because works for floats or other types for which `*` is defined
- Haskell solves this problem through type classes

Type Class Example

- The type of the function `f x = x*2` in Haskell is actually:

  `(Num a) => a -> a`
- Says: For any type `a` that belongs to type class `Num`, function `f` takes a value of type `a` and return a value of type `a`
- Since integers, floats etc. all belong to the `Num` type class, this type is very general!

Programming with Type Classes

- To use this feature of Haskell, first need to declare type classes
- A type class is simply a set of types that support a common set of operations
- To define the type class, declare the common operations and give type class a name
- Example:

```
class Num a where
(+) ::  a-> a -> a
(*) ::  a -> a -> a
...
```

- This declares a type class called `Num` that supports operations `+` and `*`

Programming with Type Classes, cont.

- Then, we declare instances of a type class
- Example:

```
instance Num Int where
a+b = intPlus a b
a*b = intTimes a b
...
```

- Instance declarations show how `Num` operations are implemented for a particular type
- Using type class and instance declarations, Haskell can infer general and useful types such as:

  `(Num a) => a -> a`

Algebraic Data Types

- Another useful feature of Haskell is algebraic data types, also called tagged unions or discriminated unions
- Suppose we want to have a type to represent students
- For undergraduates, we want to track their name and department
- For masters students, we want to track their name, department, and specialty
- In Haskell, you can have a data type to represent both undergraduate and masters students:

Tagged Union Example

```
data Student = BS (Name, Dept) | MS (Name, Dept, Area)
```

- Here, `BS` and `MS` are constructors
- The `BS` constructor must be applied to a pair consisting of a name and department
- The `MS` constructor must be applied to tuple consisting of name, department, and specialty
- Thus, `Student` is really a union of the two types `Name*Dept` and `Name*Dept*Area`
- Here, `A*B` is a product type which corresponds to type of tuple whose elements are of type `A` and `B`

Pattern Matching on Data Types

- Now, suppose we want to write a `name` function that gives the name of any student
- We can conveniently do this in Haskell through pattern-matching:

```
name (BS(n,d)) = n
name (MS(n,d, a)) = n
```

- Haskell compiler will infer type of `name` as `Student -> Name`
- This is another example of pattern matching in Haskell
- First line matches on students with type constructor `BS`
- Second line matches on students with type constructor `MS`

Recursive Data Types

- Data types in Haskell can also be recursive
- i.e., data type being declared can apprear as arguments of type constructors
- Example:

```
data Tree = Leaf Int | Node (Tree, Tree)
```

- Here is how you would write a function in Haskell that checks if a given integer is in the tree:

```
inTree x (Leaf y) = x==y
inTree x (Node(y,z)) = inTree x y || inTree x z
```


List Comprehension

- Haskell has another very convenient feature called list comprehension
- List comprehension allows conveniently building data structures from existing data structures
- List comprehension is similar to set-builder notation in math:

$$E = \{x | x \in A, x\%2 = 0\}$$

- This says set E contains all even numbers in set A, i.e., build new set from existing set
- List comprehension in Haskell has similar notation and is very convenient

List Comprehension Example

- Here is an example of list comprehension in Haskell:

```
myList = [1,2,3,4,5,6,7,8]
twiceMyList = [2*x | x<-myList]
```

- This code creates new list `twiceMyList` by going over every element in `myList` and multiplying it by two
- Just syntactic sugar, but very convenient
- Another example:

```
mysteryList = [ (x,y) | x<-list1, y<-list2]
```

- What does this code snippet do? takes cross product of two lists

Anonymous Functions in Haskell

- Just like L and Lisp, can write anonymous functions in Haskell, but slightly different syntax
- Here is an anonymous Haskell function that adds one to its argument: `\x -> x+1`
- Anonymous functions especially useful for simple functions passed as arguments to higher order functions
- Example: `map (\x -> x+1) myList`
- Here, argument to `map` is an anonymous function that adds one to its argument
- Result of this expression is a list where every element is one greater than corresponding element in `myList`

Revisiting Lazy Evaluation in Haskell

- Now that we are more familiar with Haskell syntax, let's revisit lazy evaluation is Haskell
- Consider the following function `magic`:

```
magic 0 _ = []
magic m n = m :(magic n (m+n))
```

- What is `magic 1 1`?
- The list of Fibonacci numbers: [1,1,2,3,5,8, . . .]
- Clearly, `magic 1 1` does not terminate since this list is infinite

Lazy Evaluation in Haskell Example

- Now, let's write a function to get n'th element from a list

```
get_nth [] _ = 0
get_nth (x:xs) 1 = x
get_nth (x:xs) n = get_nth xs (n-1)
```

- Will `get_nth (magic 1 1) 3` terminate?
- Yes – let's see why
- First, recall that since Haskell is lazy, `magic 1 1` will not be evaluated until it is needed in `get_nth`
- In `get_nth`, we need to figure out which pattern is matched
- This forces one step in the evaluation of `magic 1 1`

Example, cont.

```
magic 0 _ = []
magic m n = m :(magic n (m+n))
get_nth [] _ = 0
get_nth (x:xs) 1 = x
get_nth (x:xs) n = get_nth xs (n-1)
```

- After one step in evaluation of `magic 1 1`, we get: `1:(magic 1 (1+1))`
- Now, in `get_nth`, we match on the third case (since second argument is 3)
- Thus, we now evaluate `get_nth (magic 1 (1+1)) (3-1)`
- Now, again, we need to figure out which pattern matches; this forces one more evaluation step

Example, cont.

```
magic 0 _ = []
magic m n = m :(magic n (m+n))
get_nth [] _ = 0
get_nth (x:xs) 1 = x
get_nth (x:xs) n = get_nth xs (n-1)
```

- Thus, after one step in evaluation of `(magic 1 (1+1))`, we get: `1:(magic (1+1) (1+(1+1)))`
- Thus, our expression is now: `get_nth (1:(magic (1+1) (1+(1+1)))) (3-1)`
- Now, to figure out if we match second or third case, we evaluate 3−1: `get_nth (1:(magic (1+1) (1+(1+1)))) (2)`

Example, cont.

```
magic 0 _ = []
magic m n = m :(magic n (m+n))
get_nth [] _ = 0
get_nth (x:xs) 1 = x
get_nth (x:xs) n = get_nth xs (n-1)
```

```
get_nth (1:(magic (1+1) (1+(1+1)))) (2)
```

- Clearly, we are in the third case; thus, we evaluate: `get_nth ((magic (1+1) (1+(1+1)))) (2-1)`
- Continuing, we again need to know which pattern matches; hence forces one more step in evaluation of `magic`

Example, cont.

```
magic 0 _ = []
magic m n = m :(magic n (m+n))
get_nth [] _ = 0
get_nth (x:xs) 1 = x
get_nth (x:xs) n = get_nth xs (n-1)
```

```
get_nth ((magic (1+1) (1+(1+1)))) (2-1)
```

- Now, to figure out which pattern matches in `magic`, we need to evaluate first argument; this yields: `magic 2 (1+(1+1))`
- Now, second case matches, thus we have:
  `2:(magic 1+(1+1) (2+(1+(1+1))))`
- Now, we continue evaluating:
  `get_nth (2:(magic 1+(1+1) (2+(1+(1+1))))) (2-1)`
- This forces evaluation of 2−1

Example, cont.

```
magic 0 _ = []
magic m n = m :(magic n (m+n))
get_nth [] _ = 0
get_nth (x:xs) 1 = x
get_nth (x:xs) n = get_nth xs (n-1)
```

```
get_nth (2:(magic 1+(1+1) (2+(1+(1+1))))) 1
```

- This means we match on second case!
- Thus, the whole expression evaluates to 2!
- Although we wrote a function to generate infinite list, expression to extract element from this infinite list terminates!
- This is one of the nice aspects of lazy evaluation

Haskell Summary

- Haskell is a lazy, pure-functional language
- Intgerates a lot of research from PL community: polymorphism, type classes, type inference, . . .
- Statically typed, no escape hatches (e.g., casts) from type system
- Considered by many to be a very elegant language