COMP 322: Parallel and Concurrent Programming

Lecture 3: Higher Order Functions

Zoran Budimlić and Mack Joyner
{zoran, mjoyner}@rice.edu

http://comp322.rice.edu

Since Java 8: Function interface

```
var oneplus = new Function<Integer, Integer>(){
  public Integer apply(Integer x){
    return x + 1;
  }
};

Function<Integer, Integer> oneplus2 = x -> x + 1;

System.out.println(oneplus.apply(5));
System.out.println(oneplus2.apply(7));
```

Operating on a list

Last lecture worksheet: functional, recursive

```
List<Integer> originalList = . . .
var resultList = evens(originalList);

static GList<Integer> evens(GList<Integer> input){
   if (input.isEmpty()) return input;
  return input.head() % 2 == 0
      ? evens(input.tail()).prepend(input.head())
      : evens(input.tail());
```

Operating on a list

Even better:

```
static GList<Integer> evens(GList<Integer> input) {
  return input.filter(i -> i % 2 == 0);
}
```

Operating on a list

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```
static GList<Integer> evens(GList<Integer> input) {
  return input.filter(i -> i % 2 == 0);
}
```

lambda expression

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static GList<Integer> evens(GList<Integer> input) {
  return input.filter(i -> i % 2 == 0);
}
```

lambda expression

another operation on GList (just like `prepend( )`)

Some FP terminology

First-class functions: functions can be treated as any other variable

- Assigned to any other variable
- Passed as an argument to a function
- Returned as a result from a function

First order functions: “normal” functions that do not take other functions as arguments or return a function as a result

Higher-order functions: functions that take other functions as arguments or return a function as a result

- Only possible if functions are first-class

repeatFunc

We'd like to "repeat" a function multiple times

```
Function<Integer,Integer> oneplus = x → x + 1;
assertEquals(2, oneplus.apply(1));

Function<Integer,Integer> fourplus = repeatFunc(oneplus, 4);
assertEquals(5, fourplus.apply(1));
```

repeatFunc needs to be a higher-order function: it takes a function as an argument, returns another function

Implementing *repeatFunc*

```
Function<Integer,Integer> oneplus = x -> x + 1;

static <T> Function<T,T> repeatFunc(Function<T,T> f, int n) {
  if(n == 0) {
    return x -> x;
  } else {
    return x -> f.apply(repeatFunc(f, n-1).apply(x));
  }
}

var fourplus = repeatFunc(oneplus, 4);


Function<String,String> doublestring = x -> x.concat(x);

var fourconcat = repeatFunc(doublestring, 4);
```

Functions are objects with methods

We can directly compose functions without lambda syntax

Methods defined on *java.util.function.Function* help make clean code.

```
static <T> Function<T,T> repeatFunc(Function<T,T> f, int n) {
  if (n == 0) {
    return Function.identity();
  } else {
    return f.compose(repeatFunc(f, n-1));
  }
}
```

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    return f.compose(repeatFunc(f, n-1));
  }
}
```

Java code now looks math-ish!

$$\text{identity}(x) = x$$

$$\text{repeat}(f, n) = \begin{cases} \text{identity}, & \text{if } n = 0 \\ f \circ \text{repeat}(f, n-1), & \text{otherwise} \end{cases}$$

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repeatFunc is a higher-order function

- "Higher order function": a function on functions!
  - This includes *Function.compose / andThen,* as well as our *repeatFunc*
  - `a.compose(b) ≡`
  - `b.andThen(a) ≡`
  - `x → a.apply(b.apply(x))`
- In Java, "everything is an object"
- Functions are just objects
  - with *apply* methods (the lambda body)
  - with composition methods
  - with cool lambda syntax to make them

Neat trick: Lexical scope

The lambda hangs onto *f* and *n*, after *repeatFunc* exits!

```
static <T> Function<T,T> repeatFunc(Function<T,T> f, int n) {
  if(n == 0) {
    return x -> x;
  } else {
    return x -> f.apply(repeatFunc(f, n-1).apply(x));
  }
}
```

Closure: a lambda expression that captures values from the outer lexical scope

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```
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  if(n == 0) {
    return x -> x;
  } else {
    return x -> f.apply(repeatFunc(f, n-1).apply(x));
  }
}
```

Closure: a lambda expression that captures values from the outer lexical scope

Java's lambda lexical scope rules

- A lambda can “capture” any primitive type (int, double, etc.) variables
  - Makes a copy, keeps it internally.
- A lambda can “capture” any *final* object-typed variables
  - Error if the variable might mutate (“effectively final” is required).
    - It really makes a copy of what the variable points to.
    - Would have been super-confusing if you could change the “outside” variable and the “inside” variable didn’t change.

Using lambdas: the GList filter function

```
public GList<T> filter(Predicate<T> predicate) {
  if (predicate.test(headVal)) {
    return tailVal.filter(predicate).prepend(headVal);
  } else {
    return tailVal.filter(predicate);
  }
}
```

Using lambdas: the GList filter function

```
public GList<T> filter(Predicate<T> predicate) {
  if (predicate.test(headVal)) {
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  } else {
    return tailVal.filter(predicate);
  }
}
```

An instance of the Predicate interface
(a *lambda* returning boolean)

Using lambdas: the GList filter function

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  if (predicate.test(headVal)) {
    return tailVal.filter(predicate).prepend(headVal);
  } else {
    return tailVal.filter(predicate);
  }
}
```

Applying the function

Functional programming vocabulary

- Predicate: a function that returns a boolean
- Operator: a function returning the same type
  - unary operator: one argument (e.g., trig functions)
  - binary operator: two arguments (e.g., addition, subtraction)
- Function: arguments and results can be different types
- Supplier: *produces* data (e.g., reading lines of text from a file), no input
- Consumer: eats data, has side effect (e.g., printing), returns nothing

Various forms of lambda syntax

These are all equivalent:

```
public class Foo {
  // "inline" lambdas
  Function<Integer,Integer> oneplus1 = x -> x + 1;
  Function<Integer,Integer> oneplus2 = (x) -> { return x + 1; };
  Function<Integer,Integer> oneplus3 = (Integer x) -> (x + 1);

  static int oneplusx(int x) {
    return x + 1;
  }

  // "method reference" lambda (works for static and instance methods)
  Function<Integer,Integer> oneplus4 = Foo::oneplusx;
}
```

Various forms of lambda syntax

These are all equivalent:

```
public class Foo {
  // "inline" lambdas
  Function<Integer,Integer> oneplus1 = x -> x + 1;
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  Function<Integer,Integer> oneplus3 = (Integer x) -> (x + 1);

  static int oneplusx(int x) {
    return x + 1;
  }

  // "method reference" lambda (works for static and instance methods)
  Function<Integer,Integer> oneplus4 = Foo::oneplusx;
}
```

Note: `Integer` (the "object type") rather than `int` (the "primitive type")

Common FP list operators

list.map(function) → *list*

Apply the function to every element of the list, return a new list

list.filter(predicate) → *list*

Compute a new list: every element where the predicate is true

list.fold(zero, function(accumulator, element)) → *value*

Apply the function to all elements, accumulating the value along the way

Also known as ***reduce***

list.sort(comparator) → *list*

Return a new list sorted by a function that says which is bigger

Mapping

Replace each element in a list with the function applied to it

```
GList<Integer> originals = ... ;
GList<Integer> squares = originals.map(i -> i * i);

GList<String> strings = ...;
GList<String> lowercases = strings.map(x -> x.toLowerCase());
GList<Integer> lengths = strings.map(String::length);
```

Function return type can be different (e.g., String::length)

Python's list comprehensions: equivalent to our *filter*, then *map*

Our approach is more general-purpose (e.g., mix-and-match operations)

map, implemented

```
class Cons<T> implements GList<T> {

  public <R> GList<R> map(Function<T, R> f) {
    return tailVal.map(f).prepend(f.apply(headVal));
  }
}

class Empty<T> implements GList<T> {

  public <R> GList<R> map(Function<T, R> f) {
    return empty();
  }
}
```

Filter

"Pick" which elements of the original list to keep

```
class Cons<T> implements GList<T> {
  public GList<T> filter(Predicate<T> predicate) {
    if (predicate.test(headVal)) {
        return tailVal.filter(predicate).prepend(headVal);
    } else {
        return tailVal.filter(predicate);
    }
  }
}

class Empty<T> implements GList<T> {
  public <R> GList<R> filter(Predicate<T> p) {
    return empty();
  }
}
```

Folding

Let's say we have a list of numbers to add: { 1, 2, 3, 4, 5, 6, 7, 8 }

What order should we add them?

Fold-left: (((((((1 + 2) + 3) + 4) + 5) + 6) + 7) + 8

Fold-right: 1 + (2 + (3 + (4 + (5 + (6 + (7 + 8))))))

For integer addition, we get the same answer, but not for others

```
GList<Integer> intList = ...
int sum = intList.foldRight(0, (x, y) → x + y);
```

zero / default value for empty list

Commutativity & associativity

Commutativity: $\forall_{a,b} : a + b = b + a$

Associativity: $\forall_{a,b,c} : a + (b + c) = (a + b) + c$

Integer math: associative and commutative

- FoldLeft and FoldRight will give you identical answers

String concatenation: associative, but not commutative

- FoldLeft and FoldRight *can* give you identical answers, if you're careful
- Otherwise, you'll end up reversing the order of the strings

Many uses for folding

List of strings

Join into one string, find longest string, find shortest string, etc.

List of integers

Minimum, maximum, average, sum, etc.

List of bitmap images

Overlay images, concatenate horizontally, etc.

Vocabulary note: "fold" and "reduce" are synonyms. If you've heard of "MapReduce", this is broadly how it works. (More in the coming lectures.)

foldRight, implemented

Fold-right: 1 + (2 + (3 + (4 + (5 + (6 + (7 + 8))))))

```
class Cons<T> implements GList<T> {
  public <U> U foldRight(U zero, BiFunction<T, U, U> operator) {
    return operator.apply(headVal, tailVal.foldRight(zero, operator));
  }
}

class Empty<T> implements GList<T> {
  public <U> U foldRight(U zero, BiFunction<T, U, U> operator) {
    return zero;
  }
}
```

Summary

- Functions are first-class objects in Java (since Java 8)
  - Enables functional programming paradigm in Java
  - Just Java interfaces and objects, with convenient lambda syntax
- Closures are lambdas that capture the values from the outer lexical scope
  - Only primitive variables or effectively final objects can be captured
- Higher-order functions take other functions as arguments and/or return functions as result
  - Very powerful concept, allows us to create generic functions that can perform all kinds of things
  - Higher-order functions Hall of Fame: ***map***, ***filter***, ***fold***