
Functional Programming
Introduction To Cool

Cunning Plan

- ML Functional Programming
  - Fold
  - Sorting
- Cool Overview
  - Syntax
  - Objects
  - Methods
  - Types

One-Slide Summary

- In **functional programming**, functions are first-class citizens that operate on, and produce, immutable data.
- Functions and type inference are **polymorphic** and operate on more than one type (e.g., List.length works on int lists and string lists).
- Ocaml and Haskell (and Cool) support **pattern matching** over user-defined data types.
- **fold** is a powerful and general higher-order function. It can simulate many others.
- **Cool** is an object-oriented language with enough features to be indicative of modern practice.

Pattern Matching (Error?)

- Simplifies Code (eliminates ifs, accessors)

```
type btree =   (* binary tree of strings *)
  | Node of btree * string * btree
  | Leaf of string
let rec height tree = match tree with
  | Leaf _ -> 1
  | Node(x,_,y) -> 1 + max (height x) (height y)
let rec mem tree elt = match tree with
  | Leaf str | Node(_,str,_) -> str = elt
  | Node(x,_,y) -> mem x elt || mem y elt
```

Pattern Matching (Error?)

- Simplifies Code (eliminates ifs, accessors)

```
type btree =   (* binary tree of strings *)
  | Node of btree * string * btree
  | Leaf of string
let rec height tree = match tree with
  | Leaf _ -> 1
  | Node(x,_,y) -> 1 + max (height x) (height y)
let rec mem tree elt = match tree with
  | Leaf str | Node(_,str,_) -> str = elt
  | Node(x,_,y) -> mem x elt || mem y elt
```

bug?

Pattern Matching (Error!)

- Simplifies Code (eliminates ifs, accessors)

```
type btree =   (* binary tree of strings *)
  | Node of btree * string * btree
  | Leaf of string
let rec bad tree elt = match tree with
  | Leaf str | Node(_,str,_) -> str = elt
  | Node(x,_,y) -> bad x elt || bad y elt
let rec mem tree elt = match tree with
 | Leaf str | Node(_,str,_) when str = elt -> true
 | Node(x,_,y) -> mem x elt || mem y elt
```

Recall: Polymorphism

- Functions and type inference are <u>polymorphic</u>
  - Operate on more than one type
  - let rec length x = match x with
  - | [] -> 0
  - | hd :: tl -> 1 + length tl
  - val length : α list -> int
  - length [1;2;3] = 3
  - length [“algol”; ”smalltalk”; ”ml”] = 3
  - length [1 ; “algol”] = type error!

α means “any one type”

Recall: Higher-Order Functions

- Function are first-class values
  - Can be used whenever a value is expected
  - Notably, can be passed around
  - Closure captures the environment
  - let rec map f lst = match lst with
  - | [] -> []
  - | hd :: tl -> f hd :: map f tl
  - val map : (α -> β) -> α list -> β list
  - let offset = 10 in
  - let myfun x = x + offset in
  - val myfun : int -> int
  - map myfun [1;8;22] = [11;18;32]
- Extremely powerful programming technique
  - General iterators
  - Implement abstraction

f is itself a function!

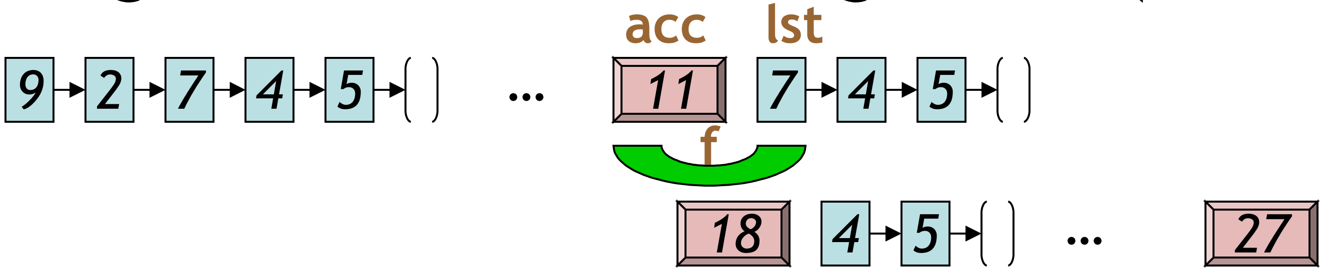
Fold

- The **fold** operator comes from Recursion Theory (Kleene, 1952)

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

  – **val fold : (α -> β -> α) -> α -> β list -> α**

- Imagine we're summing a list (f = addition):



It's Lego Time

- Let's build things out of Fold!
  - **length** lst = <u>fold</u> (fun acc elt -> acc + 1) 0 lst
  - **sum** lst = <u>fold</u> (fun acc elt -> acc + elt) 0 lst
  - **product** lst=<u>fold</u> (fun acc elt -> acc * elt) 1 lst
  - **and** lst = <u>fold</u> (fun acc elt -> acc & elt) true lst
- How would we do **or**?
- How would we do **reverse**?

Referential Transparency

- To find the meaning of a functional program we replace each reference to a variable with its definition.
  - This is called **referential transparency**.
- Example:

```
let y = 55
let f x = x + y
f 3
        --> means -->   3 + y
                              --> means -->  3 + 55
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
 | [] -> acc
 | hd :: tl -> fold f (f acc hd) tl
```

fold (*) 1 [8;6;7]

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

fold (*) 1 [8;6;7]

```
match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

fold (*) 1 [8;6;7]

with f=*, acc=1, and lst=[8;6;7]

```
match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
fold (*) 1 [8;6;7]
```

```
match [8;6;7] with
| [] -> 1
| hd :: tl -> fold (*) (* 1 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
match [8;6;7] with
| [] -> 1
| hd :: tl -> fold (*) (* 1 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
let hd :: tl = [8;6;7] in
fold (*) (* 1 hd) tl
```

```
match [8;6;7] with
| [] -> 1
| hd :: tl -> fold (*) (* 1 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
let hd :: tl = [8;6;7] in
fold (*) (* 1 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
 | [] -> acc
 | hd :: tl -> fold f (f acc hd) tl
```

```
let hd :: tl = [8;6;7] in
fold (*) (* 1 hd) tl
```

```
fold (*) (* 1 8) [6;7]
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
 | [] -> acc
 | hd :: tl -> fold f (f acc hd) tl
```

```
fold (*) 8 [6;7]
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

fold (*) 8 [6;7]

with f=*, acc=8, and lst=[6;7]

```
match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
fold (*) 8 [6;7]
```

↓

```
match [6;7] with
| [] -> 8
| hd :: tl -> fold (*) (* 8 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
match [6;7] with
| [] -> 8
| hd :: tl -> fold (*) (* 8 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
let hd :: tl = [6;7] in
fold (*) (* 8 hd) tl
```

```
match [6;7] with
| [] -> 8
| hd :: tl -> fold (*) (* 8 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
 | [] -> acc
 | hd :: tl -> fold f (f acc hd) tl
```

```
let hd :: tl = [6;7] in
fold (*) (* 8 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
 | [] -> acc
 | hd :: tl -> fold f (f acc hd) tl
```

```
let hd :: tl = [6;7] in
fold (*) (* 8 hd) tl
```

```
fold (*) (* 8 6) [7]
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

fold (*) 48 [7]

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
fold (*) 48 [7]
```

with f=*, acc=48, and lst=[7]

```
match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
fold (*) 48 [7]
```

```
match [7] with
| [] -> 48
| hd :: tl -> fold (*) (* 48 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
match [7] with
| [] -> 48
| hd :: tl -> fold (*) (* 48 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
let hd :: tl = [7] in
fold (*) (* 48 hd) tl
```

```
match [7] with
| [] -> 48
| hd :: tl -> fold (*) (* 48 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
let hd :: tl = [7] in
fold (*) (* 48 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

fold (*) (* 48 7) []

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

fold (*) 336 []

with f=*, acc=336, and lst=[]

```
match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

```
match [] with
| [] -> 336
| hd :: tl -> fold (*) (* 336 hd) tl
```

Worked Example: Product

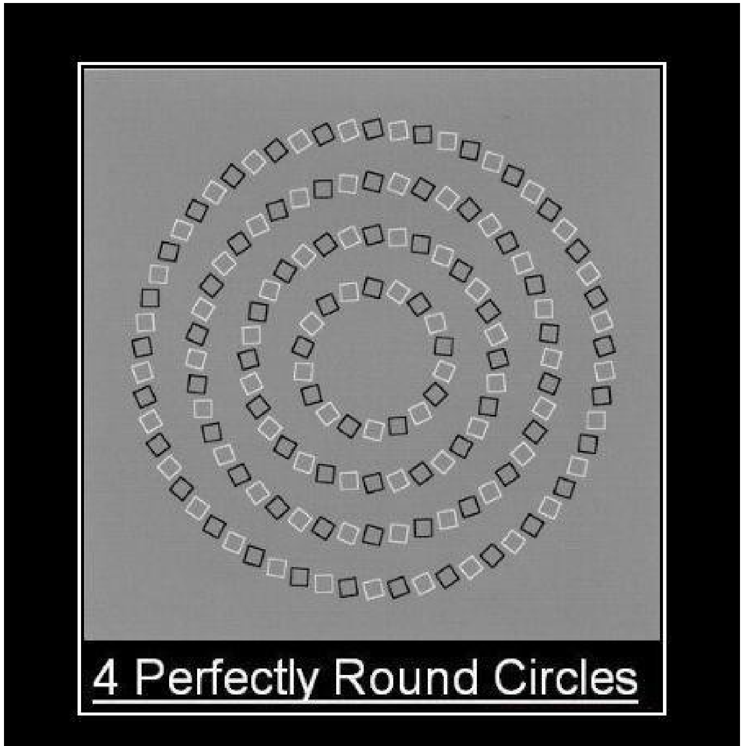
```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```

336

```
match [] with
| [] -> 336
| hd :: tl -> fold (*) (* 336 hd) tl
```

Worked Example: Product

```
let rec fold f acc lst = match lst with
| [] -> acc
| hd :: tl -> fold f (f acc hd) tl
```



336

Insertion Sort in OCaml

```
let rec insert_sort cmp lst =
  match lst with
  | [] -> []
  | hd :: tl -> insert cmp hd (insert_sort cmp tl)
and insert cmp elt lst =
  match lst with
  | [] -> [elt]
  | hd :: tl when cmp hd elt ->
          hd :: (insert cmp elt tl)
  | _ -> elt :: lst
```

What's the worst case running time?

Sorting Examples

- langs = [“fortran”; “algol”; “c”]
- courses = [216; 333; 415]
- sort (fun a b -> a < b) langs
  - [“algol”; “c”; “fortran”]
- sort (fun a b -> a > b) langs
  - [“fortran”; “c”; “algol”]
- sort (fun a b -> strlen a < strlen b) langs
  - [“c”; “algol”; “fortran”]
- sort (fun a b -> match is_odd a, is_odd b with
  | true, false -> true (* odd numbers first *)
  | false, true -> false (* even numbers last *)
  | _, _ -> a < b (* otherwise ascending *)) courses
  - [333 ; 415 ; 216]

Java uses Inner Classes for this.

Broadly Available

- ML, Python and Ruby all support functional programming
  - closures, anonymous functions, etc.
- ML has strong static typing and type inference (as in this lecture)
- Ruby and Python have "strong" dynamic typing (or duck typing)
- All three combine OO and Functional
  - … although it is rare to use both.

Modern Languages

- This is the most widely-spoken first language in the European Union. It is the third-most taught foreign language in the English-speaking world, after French and Spanish. Its word order is a bit more relaxed than English (since nouns are inflected to indicate their cases, as in Latin) – infamously, verbs often appear at the very end of a subordinate clause. The language's famous “Storm and Stress” movement produced classics such as *Faust*.

Natural Languages

- This linguist and cognitive scientist is famous for, among other things, the sentence **“Colorless green ideas sleep furiously”**. Introduced in his 1957 work *Syntactic Structures*, the sentence is correct but has not understandable meaning, thus demonstrating the distinction between syntax and semantics. Compare **“Time flies like an arrow; fruit flies like a banana.”** which illustrates garden path syntactic ambiguity.

Cool Overview

- Classroom Object-Oriented Language
- Designed to
  - Be implementable in one semester
  - Give a taste of implementing modern features
    - Abstraction
    - Static Typing
    - Inheritance
    - Dynamic Dispatch
    - And more ...
  - But many “grungy” things are left out

A Simple Example

```
class Point {
    x : Int <- 0;
    y : Int <- 0;
};
```

- Cool programs are sets of class definitions
  - A special **Main** class with a special method **main**
  - Classes are like those in Java or Python or C++
- **class** = a collection of fields and methods
- Instances of a class are **objects**

Cool Objects

```
class Point {
    x : Int <- 0;
    y : Int; (* use default value *)
};
```

- The expression "new Point" creates a new object of class Point
- An object can be thought of as a record with a slot for each attribute (= field)

x	y
0	0

Methods

```
class Point {
      x : Int <- 0;
      y : Int <- 0;
      movePoint(newx : Int, newy : Int) : Point {
            { x <- newx;
              y <- newy;
              self;
            } -- close block expression
      }; -- close method
}; -- close class
```

- A class can also define methods for manipulating its attributes
- Methods refer to the current object using **self**

Aside: Semicolons

```
class Point {
     x : Int <- 0;
     y : Int <- 0;
     movePoint(newx : Int, newy : Int) : Point {
          { x <- newx;
            y <- newy;
            self;
          } -- close block expression
     }; -- close method
}; -- close class
```

Yes, it's somewhat arbitrary. Still, don't get it wrong.

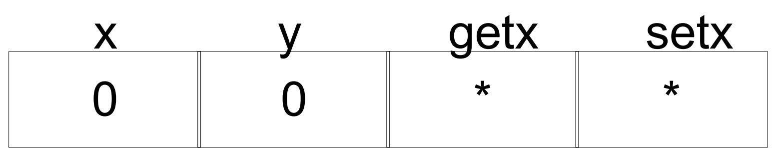
Information Hiding

- Methods are **global**
- Attributes are **local** to a class
  - They can *only* be accessed by *that class's methods*

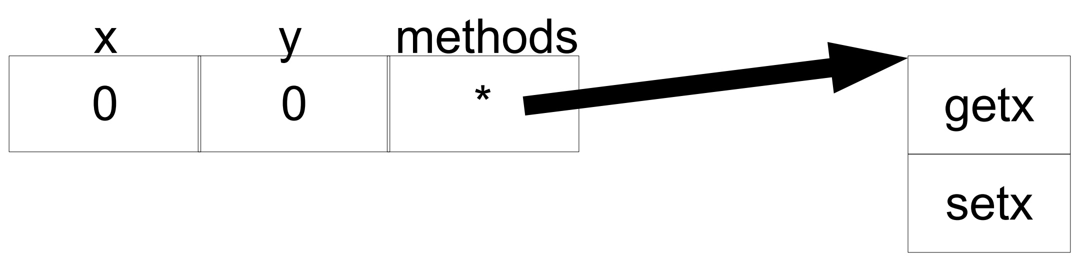
```
class Point {
      x : Int <- 0;
      y : Int <- 0;
      getx () : Int { x } ;
      setx (newx : Int) : Int { x <- newx };
};
```

Methods and Object Layout

- Each object knows how to access the code of its methods
- As if the object contains a slot pointing to the code



- In reality, implementations save space by sharing these pointers among instances of the same class



Inheritance

- We can extend points to color points using **subclassing** => **class hierarchy**

```
class ColorPoint extends Point {
      color : Int <- 0;
      movePoint(newx:Int, newy:Int) : Point {
            {   color <- 0;
                x <- newx; y <- newy;
                self;
            }
      };
};
```

Note references to fields x y –
They're defined in Point!

x	y	color	movePoint
0	0	0	*

Kool Types

- Every class is a **type**
- Base (built-in, predefined) classes:
  - **Int** for integers
  - **Bool** for booleans: true, false
  - **String** for strings
  - **Object** root of class hierarchy
- All variables must be declared
  - compiler infers types for expressions (like Java)

Cool Type Checking

- **x : Point;**
- **x <- new ColorPoint;**

- ... is well-typed if **Point** is an ancestor of **ColorPoint** in the class hierarchy
  - Anywhere a **Point** is expected, a **ColorPoint** can be used (Liskov, ...)
- Rephrase: ... is well-typed if **ColorPoint** is a **subtype** of **Point**
- **Type safety**: a well-typed program *cannot* result in run-time type errors

Method Invocation and Inheritance

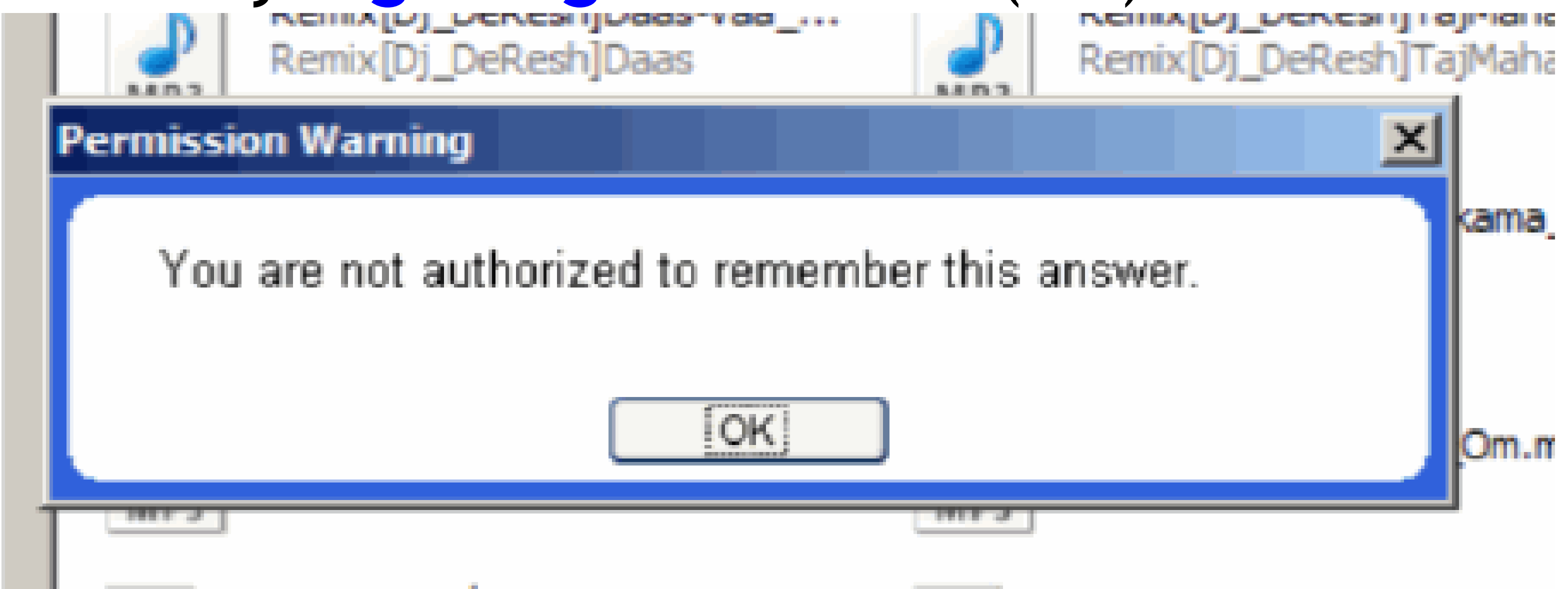
- Methods are invoked by (dynamic) **dispatch**
- Understanding dispatch in the presence of inheritance is a subtle aspect of OO
  - **p : Point;**
  - **p <- new ColorPoint;**
  - **p.movePoint(1,2);**
- p has static type Point
- p has dynamic type ColorPoint
- p.movePoint must invoke ColorPoint version

Other Expressions

- Cool is an expression language (like Ocaml)
  - Every expression has a type and a value
  - Conditionals   if E then E else E fi
  - Loops   while E loop E pool
  - Case/Switch   case E of x : Type => E ; ... esac
  - Assignment   x <- E
  - Primitive I/O   out_string(E), in_string(), ...
  - Arithmetic, Logic Operations, ...
- Missing: arrays, floats, interfaces, exceptions
  - Plus: you tell me!

Cool Memory Management

- Memory is allocated every time "**new E**" executes
- Memory is deallocated automatically when an object is not reachable anymore
  - Done by a **garbage collector** (GC)



Course Project

- A complete **interpreter**
  - Cool Source ==> Executed Program
  - No optimizations
  - Also no GC
- Split in 4 programming assignments (PAs)
- There is adequate time to complete assignments
  - But start early and follow directions
- PA2-5 ==> individual or teams (of max **2**)

Real-Time OCaml Demo

- I will code up these, with explanations, until time runs out.
  - Read in a list of integers and print the sum of all of the odd inputs.
  - Read in a list of integers and determine if any sublist of that input sums to zero.
  - Read in a directed graph and determine if node END is reachable from node START.
- You pick the order.
- Bonus: Asymptotic running times?

Homework

- PA1 Checkpoint
- Reading: Chapters 2.1 – 2.2, On-Line

- Bonus for getting this far: questions about **fold** are very popular on tests! If I say “write me a function that does foozle to a list”, you should be able to code it up with fold.