CS252 – Midterm Exam Study Guide

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Lecture #01 – General Introduction

Reasons for Different Programming Languages	Programming Language Design Choices	Features of Good Programming Languages
1. **Different domains** (e.g. web, security, bioinformatics) 2. **Legacy code and libraries** 3. **Personal preference**	1. **Flexibility** 2. **Type safety** 3. **Performance** 4. **Build Time** 5. **Concurrency**	1. **Simplicity** 2. **Readability** 3. **Learnability** 4. **Safety** (e.g. security and can errors be caught at compile time) 5. **Machine independence** 6. **Efficiency** **Goals almost always conflict**

Conflict: Type Systems	Blub Paradox	Current Programming Language Issues	Advantages of Web and Scripting Languages
• **Advantage:** Prevents bad programs. • **Disadvantage:** Reduces programmer flexibility.	**Blub Paradox:** Why do I need advanced programming language techniques (e.g. monads, closures, type inference, etc.)? My language does not have it, and it works just fine.	• **Multi-code "explosion"** • **Big Data** • **Mobile Devices**	• **Examples:** Perl, Python, Ruby, PHP, JavaScript • **Highly flexible** • **Dynamic typing** • **Easy to get started** • **Minimal typing** (i.e. type systems)

Major Programming Language Research Contributions	Programs that Manipulate Other Programs	Formal Semantics	Types of Formal Semantics
• **Garbage collection** • ***Sound* type systems** • **Concurrency tools** • **Closures**	• **Compilers & interpreters** • **JavaScript rewriting** • **Instrumentation** • **Program Analyzers** • **IDEs**	• Used to **share information *unambiguously*** • **Can formally prove a language supports a given property** • ***Crisply define how a language works***	• **Operational** ○ Big Step "***natural***" ○ Small Step "***structural***" • **Axiomatic** • **Denotational**

Haskell

	Duck Typing	
• **Purely functional** – Define "*what stuff is*" • **No side effects** • **Referential transparency** – **A function with the same input parameters will always have the same result.** ○ **An expression can be replaced with its value and nothing will change.** • **Supports type inference.**	**Duck Typing** – Suitability of an object for some function is determined not by its type but by presence of certain methods and properties. ○ **More flexible** but **less safe**. ○ **Supported by Haskell** ○ **Common in scripting languages** (e.g. Python, Ruby)	**Side Effects in Haskell** • Generally not supported. • **Example of Support Side Effects**: File IO • Functions that do have side effects must be separated from other functions. **Lazy Evaluation** • **Results are not calculated until they are needed** • **Allows for the representation of infinite data structures**

Lecture #02 – Introduction to Haskell

Key Traits of Haskell	ghci	Run Haskell from Command Line	Hello World in Haskell
1. **Purely functional** 2. **Lazy evaluation** 3. **Statically typed** 4. **Type Inference** 5. **Fully curried functions**	**ghci** – Interactive Haskell. **let** – Keyword required in ghci to set a variable value. **Example**: `> let f x = x + 1` `> f 3` `4`	Use `runhaskell` keyword. **Example**: `> runhaskell <FileName>.hs`	`main :: IO ()` `main = do` `  putStrLn "Hello World"`

Primitive Classes in Haskell	Lists		Ranges
1. `Int` – **Bounded** `Integers` 2. `Integer` – **Unbounded** 3. `Float` 4. `Double` 5. `Bool` 6. `Char`	• **Base 0** • Comma separated in square brackets • **Operators** ○ `:` Prepend ○ `++` Concatenate ○ `!!` Get element a specific index ○ `head` First element in list ○ `tail` All elements after head	○ `last` Last element in the list ○ `init` All elements in the list except the last one ○ `take n` Take first n elements from a list ○ `replicate l m` Create a list of length `l` containing only `m` ○ `repeat m` Create an infinite list containing only `m`	• Can be infinite or bounded • Use the "`..`" notation. **Examples**: `> [1..4]` `[1, 2, 3, 4]` `> [1,2..6]` `[1, 2, 3, 4, 5, 6]` `> [1,3..10]` `[1, 3, 5, 7, 9]` `> [5, 4..1]` `[5, 4, 3, 2, 1]`
Hello World in Haskell `main :: IO ()` `main = do` `  putStrLn "Hello World"`	**List Examples** `> putStrLn $ "Hello " ++ "World"` `"Hello World"` `> let s = bra in s !! 2 : s ++ 'c' : last s : 'd' : s` `"abracadabra"`		**Infinite List Example** `> let even = [2,4..]` `> take 5 even` `[2, 4, 6, 8, 10]`

List Comprehension

- Based off set notation.
- Supports filtering as shown in second example
- If multiple variables (e.g. a, b, c) are specified, iterates through them like nested for loops.
- Uses the pipe (|) operator. Examples:

```
> [ 2*x | x <- [1..5]]
[2, 4, 6, 8, 10]
```

```
> [(a, b, c) | a <- [1..10], b <-[1..10],
               c <- [1..10], a^2 + b ^2 == c^2]

 [(3, 4, 5), (4, 3, 5), (6, 8, 10), (8, 6, 10)]
```

A Simple Function

```
> let inc x = x + 1
> inc 3
4

> inc 4.5
5.5

> inc (-5) -- Negative
-4
```

Type Signature

- Uses symbols "::" and "->"
- Example:

```
inc :: Int -> Int
inc x = x + 1
```

Pattern Matching

- Used to handle different input data
- Guard uses the pipe (|) operator
- Example:

```
inc :: Int -> Int
inc x
  | x < 0 = error "invalid x"
inc x = x + 1
```

Recursion

- Base Case – Says when recursion should stop.
- Recursive Step – Calls the function with a *smaller version* of the problem

Example:

```
addNum :: [Int] -> Int
addNum [] = 0
addNum (x:xs) = x + addNum xs
```

Lab #01 – Max Number

```
> maxNum :: [Int] -> Int
> maxNum [] = error "Invalid Input"
> maxNum [x] = x
> maxNum (x:xs) = if x > maxXs then x else maxXs
>   where maxXs = maxNum xs
```

Reasons for a Large Number of Programming Languages

- Different domains
- Different design choices

Recursion

- `:t` or `:type` – Gets the type of a variable or function.

Example:

```
> :type 'A'
'A' :: Char
> :t "Hello"
"Hello" :: [Char]
```

Haskell's Base Typeclasses

- `Ord` – Can be ordered
- `Eq` – Can perform equality check
- `Show` – Can convert to String
- `Read` – Can convert from String
- `Enum` – Sequentially Ordered
- `Bounded` – Has upper and lower bound.

Lecture #03 – Operational Semantics

Formal Semantics

Crisply define how the language features work.

Abstract Syntax Tree

Tree representation of the abstract syntactic structure of a program's source code. Example is Bool* language below.

Bool * Language

`e ::= true | false | if e then e else e`	*Expressions:* constant true, constant false, conditional
`v ::= true | false`	*Values:* constant true, constant false

Formal Semantic Styles

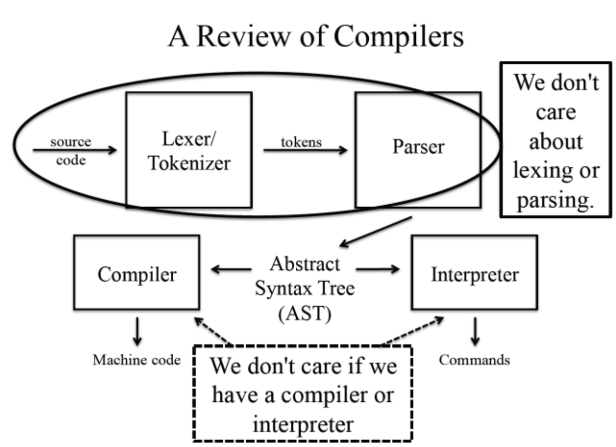
- Operational – Specify how expressions should be evaluated.
  - Big-Step ("Natural")
  - Small-Step ("structural")
- Axiomatic
- Denotational

Big Step Operational Semantics

- Evaluates every expression to a value
- $\Downarrow$: "*Evaluates to*" symbol in Big-Step operational semantics.
- Example Formatting:

$$e \Downarrow v$$

- Read as: "Expression e *evaluates* to the value v"



Small-Step Operational Semantics

- Evaluate an expression until it is in ***normal form***
- Normal Form – Any form that cannot be evaluated further.
- $\rightarrow$: "*Evaluates to*" symbol in small step operational semantics. Example:

$$e \rightarrow e' \rightarrow e'' \rightarrow v$$

- $\rightarrow^*$: Many evaluation steps required. Example:

$$e \rightarrow^* v$$

Bool* Small-Step Operational Semantics Rules

`E-IfTrue:`

$$\frac{}{\text{if true then } e_2 \text{ else } e_3 \rightarrow e_2}$$

`E-IfFalse:`

$$\frac{}{\text{if false then } e_2 \text{ else } e_3 \rightarrow e_3}$$

`E-If:`

$$\frac{e_1 \rightarrow e_1'}{\text{if } e_1 \text{ then } e_2 \text{ else } e_3 \rightarrow \text{if } e_1' \text{ then } e_2 \text{ else } e_3}$$

Example: Reduce the expression
if (**if** true **then** false **else** true) **then** true **else** false

Step #1: Use rule "`E-IfTrue`" with "`E-If`"

if false **then** true **else** false

Step #2: Use rule "`E-IfFalse`" (Now in normal form)

false

Bool* Extension: Numbers

- 0 : The Number "0"
- succ 0 : Represents "1"
- succ succ 0 : Represents "2"
- pred n : Gets the predecessor of "n"

Extended Bool * Language

```
e ::=
    true
  | false
  | if e then e else e
  | 0
  | succ e
  | pred e
v ::= true | false
    | IntV

IntV ::= 0 | succ IntV
```

Literate Haskell

- File Extension: ".lhs"
- Code lines begin with ">"
- All other lines are comments.
- "Essentially swaps code with comments."

Case Statement in Haskell

- Keywords: case, of, otherwise
- Operator: ->

Example:

```
case x of
    val1 -> "Value 1"
    val2 -> "Value 2"
    otherwise -> "Everything else."
```

Lab #02 Review

Bool Expression Type

```
> data BoolExp = BTrue
>       | BFalse
>       | Bif BoolExp BoolExp BoolExp
>       | B0
>       | Bsucc BoolExp
>       | Bpred BoolExp
>   deriving Show
```

BoolVal Type

```
> data BoolVal = BVTrue
>              | BVFalse
>              | BVNum BVInt
>   deriving Show

> data BVInt = BV0
>            | BVSucc BVInt
>   deriving Show
```

Type Constructors: BoolExp, BoolVal, BVInt

***Non-nullary* Value Constructors:** BIf, Bsucc, Bpred, BVSucc, BVNum

Note: Even constants like B0, BTrue, BFalse, BVTrue, and BVFalse are nullary value constructors (since they take no arguments)

Lecture #04 – Higher Order Functions

Lambda

- Analogous to anonymous classes in Java.
- Based off Lambda calculus
- Example:

```
> (\x -> x + 1) 1
2
>(\x y -> x + y) 2 3
5
```

Function Composition

- Uses the period (.)
- `f(g(x))` can be rewritten `(f . g) x`

Point-Free Style

- Pass function arguments no arguments. Example:

```
> let inc = (+1) – No args
> inc 3
4
```

Example: Lambda with Function Composition

```
> let f = (\x -> x – 5)
        . (\y -> y * 2)
> f 7
9

> let f = (\x y -> x – y)
        . (\z -> z * (-1))
> f 3 4
-7
```

Iterative vs. Recursive

- Iterative tends to be more efficient than recursive.
- Compiler can optimize tail recursive function.

Tail Recursive Function – The recursive call is the last step performed before returning a value.

Not Tail Recursive

```
public int factorial(int n) {
  if (n==1) return 1;
  else {
    return n * factorial(n-1);
  }
}
```

Last step is the multiplication so not tail recursive.

Tail Recursive Factorial

```
public int factorialAcc(int n, int acc)
{
  if (n==1) return acc;
  else {
    return factorialAcc(n-1, n*acc);
  }
}
```

Tail recursive code often uses the accumulator pattern like above.

Tail Recursion in Haskell

```
fact' :: Int -> Int -> Int
fact' 0 acc = acc
fact' n acc = fact' (n - 1) (n * acc)
```

Higher Order Functions

Functions in Functional Programming

- Functional languages treat programs as mathematical functions.
- **Mathematical Definition of a Function:** A function f is a rule that associates to each x from some set X of values a unique y from a set of Y values.

$$(x \in X \land y \in Y) \rightarrow y = f(x)$$

- f – Name of the function
- x – Independent variable
- y – Dependent variable
- X – Domain
- Y – Range

Qualities of Functional Programming

- Functions clearly distinguish:
  - Incoming values (parameters)
  - Outgoing Values (results)
- No (re)assignment
- No loops
- Return values depend only on input parameters
- ***Functions are first class values***; this means they can:
  - Passed as arguments to a function
  - Be returned from a function
  - Construct new functions dynamically

Higher Order Function

Any function that **takes a function as a parameter *or* returns a function as a result**.

Function Currying

Transform a function with multiple arguments into multiple functions that each take exactly one argument.

Named after Haskell Brooks Curry.

Currying Example

```
addNums :: Num a => a -> a -> a
```

addNums is a **function that takes in a number and returns a function that takes in another number**.

map

- Built in Haskell higher order function
- **Applies a function to all elements of a list.**

```
map :: (a -> b) -> [a] -> [b]

> map (+1) [1, 2, 3]
[2, 3, 4]
```

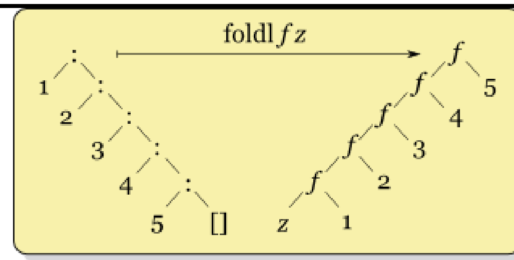
foldl

- Built in higher order function
- **Does not support infinite lists.**
- **Should only be used for special cases.**

```
foldl :: (b -> a -> b) -> b -> a -> b
```

Example:

```
> foldl (\x y -> x - y) 0 [1, 2, 3, 4]
-10 -- (((0-1) - 2) - 3) - 4
```



filter

- Built in Haskell higher order function
- **Removes all elements from a list that do not satisfy (i.e. make true) some predicate.**

```
filter :: (a -> Bool) -> [a] -> [a]

> filter (>2) [1, 2, 3, 4]
[3, 4]
```

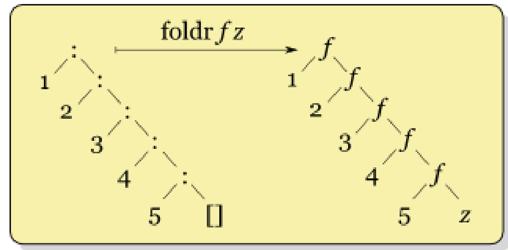
foldr

- Built in higher order function
- **Supports infinite lists.**
- "***Usually the right fold to use***"

```
foldr :: (b -> a -> a) -> a -> b -> a
```

Example:

```
> foldr (\x y -> x + y) 0 [1, 2, 3, 4]
-2 -- 1 – (2 – (3 – (4 – 0)))
```



Thunk – A delayed computation

Due to lazy evaluation, **foldl and foldr build thunks rather than calculate the results as they go.**

foldl'

- `Data.list.foldl'` evaluates its results eagerly (i.e. does not use **thunks**)
- **Good for large, but finite lists.**

Lecture #05 – Small-Step Operational Semantics

WHILE Language

- Unlike the Bool* language, **WHILE supports mutable references.**

`e ::= a`	Variable/addresses
`| v`	Values
`| a:=e`	Assignment
`| e;e`	Sequence
`| e op e`	Binary Operations
`| if e then e else e`	Conditional
`| while (e) e`	While Loops
`v ::= i`	Integers
`| b`	Boolean
`op ::= + | - | * | / | >= | > | <= | <`	

Small Step Semantics with State

- Since the WHILE language supports mutable references, the grammar must be updated to support it.

While Relation:

$$e, \sigma \rightarrow e', \sigma'$$

- σ – Store. **Maps *references* to values.**

Example Operations:

- $\sigma(a)$ – Retrieves the value at address "a"
- $\sigma[a := v]$ – Identical to the original store with the exception that it now stores the value v at address "a"

Evaluation Order Rules

- **Tend to be repetitive and clutter the semantics.**
- **Context based rules tend to represent the same information as evaluation order rules but more concisely.**

Reduction Rule

Rewrites the expression. Example:

E-IfFalse:

`if false then e2 else e3 → e3`

Context Rule

Specify the order for evaluating expressions. Example:

E-If:

$$\frac{e_1 \rightarrow e_1'}{\textbf{if } e_1 \textbf{ then } e_2 \textbf{ else } e_3 \rightarrow \textbf{if } e_1' \textbf{ then } e_2 \textbf{ else } e_3}$$

Reducible Expression (**Redex**) – Any expression that can be transformed (reduced) in one step.

Example: Redex

if true **then** (**if** true **then** false **else** false) else true

This reduces to "**if** true **then** false **else** false"

Example: Not a Redex

if (**if** true **then** false **else** false) **then** true else true

Not a redex as expression "**if** true **then** false **else** false" must be evaluated first.

Evaluation Contexts

- **Alternative to evaluation order rules.**
- **Marker** (●) / **hole** indicate the **next place for evaluation** (i.e. where we will do the work).

Example:

C[r]
= **if** (**if** true **then** false **else** false) **then** true else true

r = **if** true **then** false **else** false

C = **if** ● **then** true else true

C[r] is the original expression.

Rewriting Evaluation Order Rules

Context based rules only apply to reducible expressions (redexes). **Example:**

EC-IfFalse:

$C[\text{if false then } e_2 \text{ else } e_3] \rightarrow C[e_3]$

Context Syntax

```
C ::= ●
    | if C then e else e
    | C op e
    | v op C
    | ...
```

Data.Map

- **Library:** Data.Map
- **Immutable**
- **Example Methods:**
  - `Map.empty` – Creates and returns an empty map
  - `Map.insert k v m` – Inserts a value "`v`" at key "`k`" into map "`m`". **Returns a new, updated map.**
  - `Map.lookup k m` – Returns the value at key "`k`" in map "`m`". **Wrapped in a maybe.**

Precondition – Text above the line in a rule.

Context Rule for Binary Op: $\dfrac{v_3 = v_1 \text{ op } v_2}{C[v_1 \text{ op } v_2] \rightarrow C[v_3]}$

How to Read a Small Step Semantic Rule: "Given <*Precondition*>, then <*LeftSideArrow*> evaluates to <*RightSideArrow*>."

Lecture #06 – LaTeX

TeX
- Created by Donald Knuth
- **Domain specific language for typesetting documents.**
- Precisely controls the interface of content.
- Type of **Literate Programming** – **Logic is in natural language and code is interspersed.** "***Mark code instead of marking comments.***"

LaTeX
- Developed by Leslie Lamport. Derives from TeX.
- Type of **Domain Specific Language** (DSL) – A **computer language that is specialized for a particular application domain**.
- Enforces **separation of concerns** – Design principle for **separating a computer program into different sections, such that each section addresses a separate concern**.
  - **Example:** LaTeX separates formatting from content.
- **Literate Programming**

Specify Document Type
```
\documentclass{article}
```
Specify Title Block Content
```
\title{Hello World!}
```
Start Document
```
\begin{document}
```
Generate Title from Title Information
```
\title{Hello World!}
```
Close the Document
```
\end{document}
```

Cross-Reference
```
\ref{<referenceName>}
```
Reference a Bibliography Citation
```
\cite{<citationName>}
```
Create a Reference
```
\label{<referenceName>}
```
Create a Bibliography
```
\bibliography{<bibFileName>}
```
Create a List
```
\begin{itemize}
\item Text for #1
\item Text for #2
\end{itemize}
```

Create Section with Label
```
\section{Section #1}
\label{sec:one}
```
Create Subsection with Label
```
\subsection{<SubsectionName>}
\label{sec:<refName>}
```
Use of Tilde (~)

Creates an undividable space so the text `"Section~\ref{sec:one}"` will appear on one line

BibTeX
- **References are tedious to reformat and renumber.**
- Reference details shorted in a "***.bib**" file.

Create a Bibliography
```
\bibliography{biblio}
```
BibTeX filename for the example would be "**biblio.bib**"

Define Bibliography Style
```
\bibliographystyle{plainurl}
```

BibTeX Article Reference Example
```
@article{citationName,
   author = {Donald Knuth},
   title = {Literate Programming},
   journal = {},
   year = {1984},
   volume = {27},
   number = {2},
   pages = {97–111},
}
```

Lecture #07 – Types and Typeclasses

Maybe Type
- **Example of an algebraic data type**
- Enables behavior similar to **null** in Java
- Can be used to provide context.
- **Used when:**
  - **A function may not return a value**
  - **A caller may not pass an argument**
- **Definition:**

```
data Maybe a = Nothing
             | Just a
```

Maybe "Divide" Example
```
divide :: Int -> Int -> Maybe Int
divide _ 0 = Nothing
divide x y = Just $ x `div` y

> divide 5 2
2
> divide 4 0
Nothing
```
DO NOT FORGET THE `Just` IN CORRECT SOLUTION

Maybe Map Example
```
import Data.Map

m = Map.empty
m' = Map.insert "a" 42 m
case (Map.lookup "a") of
   Nothing -> error "Element not in map"
   Just x -> putStrLn $ show x
```
Since element may not be in the map, you need to use a maybe

Algebraic Data Type
- A **composite data type** (i.e. **a type made from other types**).
- **Created via the Keyword:** `data`
- **Examples:**
  - `Either`
  - `Maybe`
  - `Tree`

Example Algebraic Data Type
```
data Tree k = EmptyTree
            | Node (Tree k) (Tree k) val
            deriving (Show)
```
`k` – **Type parameter. Specifies a type not a value.**

`Node`: **Value Constructor that creates values of type "`Tree k`"**

- **`Tree` and `Tree Int` have no types since they themselves form a concrete type.**
- `Node` does have a type:

```
> :t Node
Node :: (Tree k) -> (Tree k) -> k -> (Tree k)
```
Explanation: To make a complete `Node` object, you pass it two objects of type "`Tree k`" and another object of type "`k`" and that returns a "`Tree k`" object.

Partially Applying a Value Constructor
- Value constructors can be partially applied similar to functions. **Example**:

```
> let leaf = Node EmptyTree EmptyTree

> Node (leaf 3) (leaf 7) 5
```
This creates a three node tree with value 5 at the root and values 3 and 7 at the leaves.

Type of the "+" Operator
```
> :t (+)
(+) :: (Num a) => a -> a -> a
```
Explanation: The plus sign takes two numbers of type "**a**" and returns an object of type "**a**".

Type of a Number
```
> :t 3
3 :: (Num a) => a
```
Explanation: Since "3" has no explicit type, it can for now be any type that satisfies the "Num" type class.

Kinds

- "*The type of types*".
- Concrete types have a kind of "*"
- Keyword `:k`, `:kind`
- Example:

```
> :k Tree
Tree :: * -> *
```

Explanation: A Tree requires one type parameter (e.g. `Int`) to be made a concrete type.

String Kind

```
> :kind String
String :: *
```

Map Kind

```
> :k Map
Map :: * -> * -> *
```

Maybe Kind

```
> :k Maybe
Map :: * -> *
```

Map String Kind

```
> :kind (Map String)
(Map String) :: * -> *
```

Explanation: Map String is has one of the two type parameters filled so it has one less asterisk.

Typeclasses

- Similar to interfaces in Java.
  - Like a contract.
  - Implementation details can be included in typeclass definition.
- No relation to classes in object-oriented programming.
  - Example: Do not have any data associated with them.
- Simplify polymorphism.

Example: `Eq` Typeclass

```
class Eq a where
    (==) :: a -> a -> Bool
    (/=) :: a -> a -> Bool
    x == y = not (x /= y)
    x /= y = not (x == y)
```

The last two lines in the type class definition allow the developer to program either (==) or (/=) but not necessarily both.

Example: Make `Maybe` an Instance of `Eq`

```
instance (Eq a) => Eq (Maybe a) of
      (==) Nothing Nothing    = true
      (==) (Just x) (Just y)  = x == y
      (==) _        _         = false
```

Need to ensure type "a" supports "Eq" so add that as a class constraint.

Class Constraint

- Operator: =>
- Ensures that a type parameter satisfies some typeclass requirement.

Kind of Typeclasses

```
> :k Eq
Eq :: * -> Constraint

> :k Num
Num :: * -> Constraint
```

Note: Typeclasses are a class constaint (not a type) so their kind is different.

Lecture #08 – Functors

Functor Type Class Definition

```
class Functor f where
  fmap :: (a -> b) -> f a -> f b
```

This is very similar to the definition of the higher order function "map"

```
map :: (a -> b) -> [a] -> [b]
```

Functor – Something that can be mapped over.

- Handles things "inside a box"

Example: List (`[]`) as an instance of `Functor`

```
instance Functor [] where
    fmap = map
```

Explanation: map is a specialized version of fmap for lists.

Examples: `map` and `fmap` on Lists

```
> map (+1) [1, 2, 3]
[2, 3, 4]

> fmap (+1) [1, 2, 3]
[2, 3, 4]

> fmap (+1) []
[]
```

Examples: `fmap` on Maybes

```
> fmap (+1) (Just 3)
Just 4

> fmap (+1) Nothing
Nothing
```

Example: `Maybe` as an Instance of `Functor`

```
instance Functor Maybe where
    fmap _ Nothing = Nothing
    fmap f (Just x) = Just (f x)
```

DO NOT FORGET THE `Just` IN VALID SOLUTION

Either Algebraic Data Type

```
data Either a b = Left a
                | Right b
         deriving (Eq,Ord,Read,Show)
```

- `Left` – Error type that is not mappable.
- `Right` – Expected type

Example: `Either` as an Instance of `Functor`

```
instance Functor (Either a) where
    fmap _ (Left x) = Left x
    fmap f (Right y) = Right (f y)

> fmap (+1) Leftt 20
20 -- No Change

> fmap (+1) Right 20
21 -- Changed
```

IO in Haskell

- Haskell avoids side effects but they are inevitable in real programs.
- Monads
  - Related to Functors
  - Compartmentalize side effects.
- ()
  - Unit type in Haskell

Type Signature of the `main` Function in Haskell

```
main :: IO ()
```

Hello World in Haskell

```
main = putStrLn "Hello World"
```

Type Signature of getLine

```
getLine :: IO String
```

- `do` – Allows for the chaining of multiple IO/Monad commands together. Syntactic sugar for bind ">>="
- `<-` Extracts data out of an IO/Monad "Box"
- `return` – Places data into an IO/Monad "Box"

do Example

```
main = do
    line <- getLine
    if null line -- Checks for empty str
       then return ()
       else putStrLn $ reverseWords line

reverseWords :: String -> String
reverseWords = unwords .
                 map reverse . words
```

return in Haskell

- Unrelated to "return" in other languages
- Better described as "wrap" or "box"

Summary:
`return` – Boxes an IO (since IO is a monad)

`<-` Unboxes an IO

Type of the Unit Type ()

- Base type

```
> :t ()
() :: ()
```

Type of return

```
> :t (return ())
(return ()) :: Monad m => m ()
```

`Monad` is a **typeclass**.

Using IO as a Functor

```
main = do
       line <- fmap (++"!!!") getLine
       putStrLn line
```

Explanation: This function takes a string input from standard in and appends "!!!" at which point it prints it to the console.

Definition of IO as a Functor

```
instance Functor IO where
  fmap f action = do
                 result <- action
                 return (f result)
```

Explanation: The action object is taken out of the IO box, the function "f" applied to it, and then returned to the IO box.

id Function

- Takes one input parameter and returns that input parameter unmodified. Examples:

```
> id 3
3

> id "Hello World"
"Hello World"
```

Functor Laws

Functor Law #1: If we map the id function over a Functor, the Functor that we get back should be the same as the original Functor.

Examples:

```
> fmap id (Just 3)
Just 3
> fmap id Nothing
Nothing
> fmap id [1, 2, 3]
[1, 2, 3]
```

Functor Law #2: Composing two functions and then mapping the resulting (composed) function over a Functor should be the same as first mapping one function over the Functor and then mapping the other one.

Law #2 Written Formally

```
fmap (f . g) = fmap f . fmap g
```

The Functor laws are NOT enforced. They are good practice that makes the code easier to reason about.

Lecture #09 – Applicative Functors

Functor – Something that can be mapped over. Allow you to map functions over different data types. Examples:

- Maybe
- Either
- IO
- Lists
- <*>

Functors return boxed up values.

Functor Example

```
> fmap (+1) [1, 2, 3]
[2, 3, 4]

> let x = fmap (+) [1, 2, 3]
```

Explanation: In this case **x** is:
`[(1+), (2+), (3+)]`

Applicative Functor

- Requires the importing of a special library as shown below:

```
import Control.Applicative
```

Functions in Applicative Typeclass:

- `pure` – Wraps/boxes a value
- `<*>` - Infix version of `fmap`. Is itself a Functor.

Example Uses of pure

```
> pure 7
7

> pure 7 :: Maybe Int
Just 7

> pure 7 :: [Int]
[7]
```

Type Class Definition of Applicative

```
class (Functor f) => Applicative f where
     pure :: a -> f a
     <*> :: f (a -> b) -> f a -> f b
```

Only difference between `<*>` and `fmap` is that the function in `<*>` is boxed while it is not in `fmap` (see the green `f`).

Make Maybe an Instance of Applicative

```
instance Applicative Maybe where
    pure = Just
    Nothing <*> _ = Nothing
    (Just f) <*> x = fmap f x
```

Explanation: `pure` simply wraps the value in `Just`. No need to explicitly check if "`x`" is maybe as `fmap` will do that for you.

Examples of Applicative Maybe

```
> Just (+3) <*> Just 4
Just 7
> pure (+3) <*> Just 4
Just 7
> pure (+) <*> Just 3 <*> Just 4
Just 7
> (+) <$> Just 3 <*> Just 4
Just 7
```

Explanation: `x <$>` is `fmap` as an infix operator. It is NOT necessarily the same as `pure x <*>`. **It should be based off Applicative Functor Law #1.**

Making [] an Instance of Applicative

```
instance Applicative [] where
   pure x = [x]
   fs <*> xs = [f x | f <- fs, x <- xs]
```

Explanation: The function is actually a list of functions so list comprehension is needed.

Example Use of Applicative on Lists

```
> (*) <$> [1, 2, 3] <*> [1,0,0,1]
[1,0,0,1,2,0,0,2,3,0,0,3]

> pure 7
7   -- No change
> pure 7 :: [Int]
[7]
```

Definition of IO as an Instance of Applicative

```
instance Applicative IO where
    pure = return
    a <*> b = do
              f <- a
              x <- b
              return (f x)
```

Example of `Applicative IO`

```haskell
import Control.Applicative

main = do
       a <- (++) <$> getLine <*> getLine
       putStrLn a
```

`liftA2`

A function that simplifies the application of a normal function to two Functors.

```haskell
liftA2 :: (Applicative f) => (a -> b -> c) -> f a -> f b -> fc
liftA2 f x y = f <$> a <*> b
```

Example of `liftA2`

```haskell
> (:) <$> Just 3 <*> Just [4]
Just [3, 4]
> liftA2 (:) (Just 3) (Just [4])
Just [3, 4]
```

Applicative Functor Definition

A functor you can apply to other Functors.

Applicative Functor Laws

Law 1: `pure f <*> x = fmap f x`	**Law 2:** `pure id <*> v = v`	**Law 3:** `pure (.) <*> u <*> v <*> w = u <*> (v <*> w)`
Law 4: `pure f <*> pure x = pure (f x)`	**Law 5:** `u <*> pure y = pure ($y) <*> u`	Similar to Functor Laws, these are not strictly enforced but are good practice to make it easier to reason about the code.

Monoids

Monoid: An **associative** binary function and a value that acts as an **identity** with respect to that function.

Examples

- x * 1 — Identity of Multiplication
- lst ++ [] — Identity of Concatenation
- x + 0 — Identity of Addition

Definition of Monoid Typeclass

```haskell
class Monoid m where
      mempty :: m
      mappend :: m -> m -> m
      mconcat :: [m] -> m
      mconcat = foldr mappend mempty
```

Monoid Rules

Rule #1: ``mempty `mappend` x = x``	**Rule #2:** ``x `mappend` mempty = x``	**Rule #3:** ``(x `mappend` y) `mappend` z = x `mappend` (y `mappend` z)``

Lecture #10 – Monads

Functor – Something that can be mapped over.
Definition:

```haskell
instance Functor f where
    fmap :: (a -> b) -> f a -> f b
```

Problem with Functors: Do not support chaining of multiple commands. **Example:**

```haskell
> fmap (+) (Just 3) (Just 4)
```

Returns an error since it cannot resolve `(Just 3+)` and `(Just 4)`

Applicative Functor: A Functor that can be applied to other Functors.

```haskell
class (Functor f) => Applicative f where
    (<*>) :: f (a -> b) -> f a -> f b
```

Requires library `Control.Applicative`

Even with Applicative Functors, it is not possible to chain together multiple commands. **Example:**

```haskell
> Just (+3) <*> Just (+4) <*> Just (+5)
```

Returns error

Monads: Can chain through a series of functions.

Key Operator: `>>=` (Bind)

Example #1: Using Just

```haskell
> (Just 3) >>= (\x -> Just (x + 4)) >>= (\y -> Just (y+5))
12
```

Example #2: Using `return`

```haskell
> (return 3) >>= (\x -> return (x + 4)) >>= (\y -> return (y+5))
12
```

Comparing `<*>` and `>>=`

Functor:

```haskell
(<*>) :: Applicative f => f (a -> b) -> f a -> f b
```

Monad:

```haskell
(>>=) :: Monad m => m a -> (a -> m b) -> m b
```

Differences:

1. Order of the arguments changed.
2. The function is boxed in Functor but not Monad
3. Monad function returns a boxed result.

Example of `<$>`, `<*>` and `>>=`

```haskell
> (\x -> x + 1) <$> Just 3
Just 4

> Just (\x -> x + 1) <*> Just(3)
Just 4

> (Just 3) >>= (\x -> Just(x+1))
Just 4
```

Example: Implement `applyMaybe` that applies a function to a `Maybe`

```haskell
applyMaybe :: Maybe a -> (a -> b) -
> (Maybe b)
applyMaybe Nothing _ = Nothing
applyMaybe (Just x) f = Just (f x)
```

Example: Implement `applyMaybe` that applies a function to a `Maybe`

```
applyMaybe :: Maybe a -> (a -> Maybe b)
             -> (Maybe b)

applyMaybe Nothing _ = Nothing
applyMaybe (Just x) f = Just (f x)
```

Chaining applyMaybe

```
> (Just 3) `applyMaybe` (\x -> Just (x*2))
           `applyMaybe` (\y -> Just (y-1))
Just 5

> (Just 3) `applyMaybe` (\_ -> Nothing)
           `applyMaybe` (\y -> Just (y-1))
Nothing
```

Additional Names for Monoids

- "Programmable Semicolons"
- "Applicative Functors you can chain."

Monad Typeclass Definition

```
class Monad m where
      return :: a -> m a
      (>>=) :: m a -> (a -> m b) -> m b

      (>>) :: m a -> m b -> m b
      x >> y = x >>= (\_ -> y) --Lamda

      fail :: String -> m a
      fail msg = error msg
```

Example a Robot Moving Towards a Goal (Not Failure)

```
--Location
type Robot = (Int, Int)

-- Functions
up (x,y) = (x, y+1)
down (x,y) = (x, y-1)
left (x,y) = (x-1, y)
right (x,y) = (x+1, y)
```

```
-- Define Operator and start location
x -: f = f x
start = (0, 0)

> start -: up -: right
(1, 1)

> start -: up -: left -: left -: right -: down
(-1, 0)
```

Maybe as an Instance of the Monad Typeclass

```
instance Monad Maybe where

    return = Just

    (>>=) Nothing  _ = Nothing
    (>>=) (Just x) f = Just (f x)

    fail _           = Nothing
```

Example a Robot Moving Towards a Goal (with Failure)

```
-- Once the goal is reached,
-- the robot stops
goal := Map.empty
        -: (Map.insert (0, 2) True)
        -: (Map.insert (-1, 3) True)
        -: (Map.insert (-3, -8) True)

moveTo :: Pos -> Maybe Pos
moveTo p = if Map.member p goal
                 then Nothing
                 else Just p

-- Since these are in bind, no need
-- to handle Nothing. Bind handles it.
up (x,y) = moveTo (x, y+1)
down (x,y) = moveTo (x, y-1)
left (x,y) = moveTo (x-1, y)
right (x,y) = moveTo (x+1, y)
```

```
start = (0, 0)

> return start >>= up >>= left >>= left
               >>= right >>= down
Just (-1, 0)

> return start >>= left  >>= left  >>= up
               >>= up    >>= right >>= up
               >>= right >>= right >>= down
Nothing
```

Explanation: Reached one of the goals (-1, 3) at the red `up`

Integer Division Using Monads

Integer Division with Bind and No "do"

```
mydiv :: Maybe Int -> Maybe Int -> Maybe Int
mydiv x y = x >>= (\numer ->
            y >>= (\denom  ->
            if denom > 0
                then Just (div numer denom)
                else fail "Div by zero"))
```

Integer Division with Bind with "do"

```
mydiv :: Maybe Int -> Maybe Int -> Maybe Int
mydiv x y = do
            numer <- x
            denom <- y
            if denom > 0
                then Just (div numer denom)
                else fail "Div by 0"
```

Integer Division with Bind with "do" and return

```
mydiv :: Maybe Int -> Maybe Int -> Maybe Int
mydiv x y = do
            numer <- x
            denom <- y
            if denom > 0
              then return $ div numer denom
              else fail "Div by 0"
```

List Monad

Making List an Instance of Monad

```
instance Monad [] where
        return x = [x]
        (>>=) xs f = concat(map f xs)
        fail _     = []
```

Explnation: `concat` is needed here as `f` returns elements already in a list. As such, `concat` merges the individual lists (from each call to `f`) into a single list.

Example Use of List as a Monad

```
listOfTuples :: [(Int, Char)]
listOfTuples = do
               n <- [1, 2]
               ch <- ['a', 'b']
               return (n, ch)
> listOfTuples
[(1,'a'), (1,'b'), (2,'a'), (2, 'b')]
```

Combining a Maybe and a List Monad

```
> Just [2,3] >>= (\x -> Just( fmap (+1) x))
[3, 4]
```

Lecture #11 – Parsing Combinators

Semantics: Enumerate **what a program means.** **Defined by the interpreter or compiler.**

Syntax: Enumerate **how a program Is structured.** **Defined by the lexer and parser.**

Compilation Flow

Step #1: Tokenizer/lexer generates a set of tokens.

Step #2: Parser turns the tokens into an abstract syntax tree.

Step #3: Compilers and interpreters convert the AST into machine code or commands respectively.

Lexer

Converts the characters of the program into words of the language.

Examples:
- Lex/Flex (C/C++)
- ANTLR & JavaCC (Java)
- Parsec (Haskell)

Categories of Tokens

- **Reserved Words/Keywords**.
  - Examples: while, if, then, else
- **Literals/Constants**.
  - Examples: 123, "Hello World!"
- **Special symbols**.
  - Examples: ";", "=>", "&&"
- **Identifiers**.
  - Examples: "balance", "myFunction"

Parsing

- **Parser converts tokens to abstract syntax trees.**
- **Defined by context free grammars** (CFG)
- **Types of Parsers:**
  - Bottom-up/Shift-Reduce Parsers
  - Top-down parsers

Context Free Grammars

- Grammars specify the language.
- Specified in Backus-Naur form format. Example:

```
Expr -> Number
      | Number + Expr
```

- **Terminal** – **Cannot be broken down** further.
- **Non-terminals** – **Can be broken down** further.

Example: "0", "1", "2", … , "9" are terminals but digit, number, and expression are not.

Example Grammar

```
expr -> expr + expr
      | expr – expr
      | ( expr )
      | number

number -> number digit
        | digit

digit -> 0 | 1 | 2 | … | 9
```

Bottom-Up / Shift-Reduce Parser

- Shift tokens onto a stack
- Reduce the stack to a non-terminal.
- LR – Left to right, Rightmost derivation
- LALR – Look-Ahead LR parsers are the most popular type of LR parsers.
  - Examples: YACC/Bison
- **Fading from popularity**

Top-Down Parser

- **Non-terminals are expanded to match tokens**.
- LL – Left to right, Leftmost derivation
- **LL(k) Parser** – Looks ahead up to *k* elements. Examples: Java CC, ANTLR
  - The higher the *k*, the more difficult language is to parse. ***k* can be arbitrary**.
  - ***LL(1)*** - Easy to parse using either LL or recursive descent parsers. **Many computer languages are designed to be LL(1)**.

Parser Combinator

Combine simpler parsers to make a more complex parser.

Example: Parsec

Useful Parsec Functions

- `many` – Parses **zero or more** occurrences of the given parser.
- `many1` – Parses **1 or more** occurrences of the given parser.
- `noneOf` – Anything but the specified value
- `spaces` – Whitespace characters
- `char` – The specific specified character
- `string` – The specific specified string.
- `sepBy` – Separate tokens by some token.

Example Parsec Code

```
import Text.ParserCombinators.Parsec

num :: GenParser st String
num = many1 digit

main = do
       print $ parse num "Hello" "42"
```

```
import Text.ParserCombinators.Parsec

num :: GenParser st Integer
num = do
      str <- many1 digit
      return $ read str

main = do
       print $ parse num "World" "42"
```

- `st` – "State." Always required for our purposes.
- `String`/`Integer` – Parser return type
- `many1` – Select one of more digits.
- `digit` – 0, 1, 2, 3, …, 9 (**terminal**)
- `num` – Parser entry function
- `"Hello"`/`"World"` – Debug string.
- `"42"` – String to parse.

Example with `try`, `<|>`, and `<?>`

```
eol =  try (string "\n")
   <|> string "\n\r"
   <?> "end of line"
```

- `try` – If an incomplete match is found, rewind.
- `<|>` – "Or" Operator for matching tokens.
- `<?>` – Otherwise with an accompanying error message.

Practice Midterm and Review Notes

Question #1	Question #2	Question #3	Question #4	Question #5
a. **True** b. **False** – Lazy evaluation c. **False** – Lazy evaluation d. **False** – Statically type e. **True**	a. **True** b. **False** – Applicative functor c. **True** d. **True** e. **True**	a. **False** – Big step b. **True** c. **False** – Use store d. **True** e. **False**	a. **False** – Imperative b. **True** c. **False** d. **True** e. **True**	a. **True** b. **False** – Typeclass c. **True** d. **False** e. **False** – Algebraic data type

Haskell	Purely Functional	Functional Languages	Operational Semantics
• **Purely Functional** • **Lazy evaluation** • **Fully Curried Language** • **Statically Typed** • **Type Inference** – Via context, Haskell can deduce the type.	• **Referential Transparency** – A **function call** can be replaced with its equivalent value without affecting the program • **No (re)assignment** • **No loop** • **No side effects**	• **Functions are first class objects** meaning they can be passed to a function, returned from it, or created on the fly. • **Higher order function support**	• **Small Step** – Structural Semantics • **Big Step** – Natural Semantics • "**Get stuck**" – When a function is encountered that does not have an associated rule.

CSV Parser Example

<table>
<tr><th>Verbose Approach</th><th>Concise Approach</th></tr>
<tr><td>

```
import Text.ParserCombinator.Parsec
import System.Environment

csvFile :: GenParser st [[String]]
csvFile = do
          arr <- many line
          char eof
          return arr

line :: GenParser st [String]
line = do
       result <- many1 cell
       char '\n'
       return result

cells :: GenParser st [String]
cells = do
        firstCell <- cellContents
        nextCells <- remainingCells
        return (firstCell:nextCells)

cellContent :: GenParser st String
cellContent = many $ noneOf ",\n" -- Two characters

remainingCells :: GenParser st [String]
remainingCells = do
                 (char "," >> cells)
                 <|> return []

main = do
       args <- getArgs
       p <- parseFromFile csvFile "example 1" (head args)
       case p of
           Left msg  -> error msg
           Right csv -> print csv
```

</td><td>

```
import Text.ParserCombinator.Parsec
import System.Environment

csvFile = lines `sepBy` eol

line = cells `sepBy` string ","

cells = many (noneOf "\n")

eol = try (string "\n")
   <|> string "\n\r"
   <?> "end of line"

main = do
       args <- getArgs
       p <- parseFromFile csvFile "example 1" (head args)
       case p of
           Left msg  -> error msg
           Right csv -> print csv
```

</td></tr>
</table>

Miscellaneous

Kind of Show and show

```
> :k Show
Show :: * -> Constraint
```

Type and Kind of show

```
> :k show
Error (A function not a type)
> :t show
show :: (Show a) => a -> String
```

Lambda and ADT Combined

```
> (\x -> Just (x+1)) 1
Just 2
```

Creating Type Alias

```
type String = [Char]
```

Allows for more readable code as developer can use a type name that makes more sense for a given application.

Example: `applyMaybe` that takes a `(Maybe a)` and applies to it a function that takes a normal `a` and returns a `(Maybe b)`

```
applyMaybe :: (Maybe a) -> (a -> Maybe b) -> (Maybe b)
applyMaybe Nothing _ = Nothing
applyMaybe (Just x) f = f x
```

Explanation: Since the function "`f`" already returns a Maybe, you do not need to re-box it. However, since it does not take a Maybe, you need to unbox the first input parameter.

Applying `return` to Items

```
> return 7
7
> return 7 :: Maybe Int
Just 7
> return 7 :: [Int]
[7] -- Need Int or get an error
```

Conclusion: **Behavior for return is the same as** `pure`. Both put the object in the **minimum default context that still yields that value**.

List comprehension is syntactic sugar for using lists as monads.

Monads and Lambda

When trying to chain multiple functions together in a Monad, remember the Monad must return a **boxed value**. Hence, **Lambda often work well as they simplifying boxing**.

Applicative Typeclass – Allows you to use normal functions on values that have a context (i.e. are inside a Functor).

Monad: Given a value of type, `a`, in a context, `m`, apply a function that takes a normal value of type `a` and returns a value in the context `m`.

```
(>>=) :: (Monad m) => m a -> (a -> m b) -> m b
```

Monads are just applicative functors that support bind (>>=).

Key Difference: **Applicative functors support normal functions that take and return unboxed values while Monads return boxed values**.

`return` – Monad equivalent of "pure" for Applicative Functors.

Cannot use `fmap` in the definition of a `Monad` since `fmap` returns a boxed value while the function of the `Monad` returns a boxed value. Hence, if you used `fmap` with a `Monad`, you would return a double boxed value.