CS252 – Midterm Exam Study Guide

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Lecture #01 – General Introduction

Reasons for Different Programming Languages
1. Different domains (e.g. web, security, bioinformatics)
2. Legacy code and libraries
3. Personal preference

Programming Language Design Choices
1. Flexibility
2. Type safety
3. Performance
4. Build Time
5. Concurrency

Features of Good Programming Languages
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
- 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.

Current Programming Language Issues
- Multi-code "explosion"
- Big Data
- Mobile Devices

Advantages of Web and Scripting Languages
- 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
- Garbage collection
- *Sound* type systems
- Concurrency tools
- Closures

Programs that Manipulate Other Programs
- Compilers & interpreters
- JavaScript rewriting
- Instrumentation
- Program Analyzers
- IDEs

Formal Semantics
- Used to share information *unambiguously*
- Can formally prove a language supports a given property
- ***Crisply define*** *how a language works*

Types of Formal Semantics
- Operational
  - Big Step "*natural*"
  - Small Step "*structural*"
- Axiomatic
- Denotational

Haskell

- 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
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
```

Run Haskell from Command Line

Use runhaskell keyword. Example:

```
> runhaskell <FileName>.hs
```

Hello World in Haskell

```
main :: IO ()
main = do
  putStrLn "Hello World"
```

Primitive Classes in Haskell
1. `Int` – Bounded `Integers`
2. `Integer` – Unbounded
3. `Float`
4. `Double`
5. `Bool`
6. `Char`

Lists
- 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 except the last
  - `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 in`

Ranges
- 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]
```

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
```

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

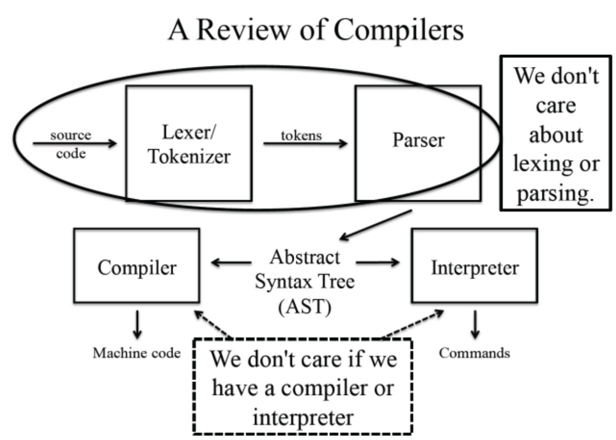
- Operational
  - Big-Step (“Natural”)
  - Small-Step (“structural”)
- Axiomatic
- Denotational

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
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.

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

- 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]
```

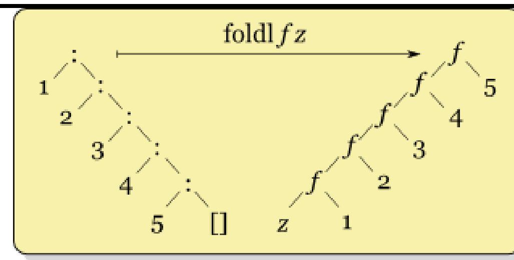
foldl

- 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]
```

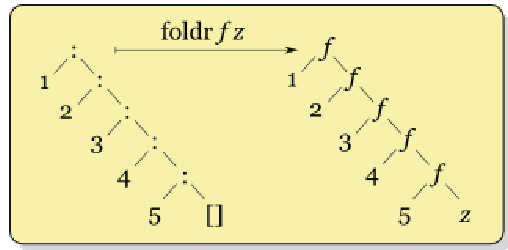
foldr

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

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

Example:

```
> foldl (\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"
- $\sigma[a \coloneqq v]$ – 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** indicates the **next place for evaluation**. Example:

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[if false then e_2 else e_3] → 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.**

Lecture #06 – LaTeX

TeX

- Created by Donald Knuth
- Precisely controls the interface of content.
- Type of **Literate Programming** – **Logic is in natural language and code is interspersed**.

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
- **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**).
- **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 to be made a concrete type.

String Kind

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

Map Kind

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

Maybe Kind

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

Map String Kind

```
> :k (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 type class requirement.

Typeclass Kinds

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

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

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