CS252 – Final 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-core "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.
  - A function call 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 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`

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]

> [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

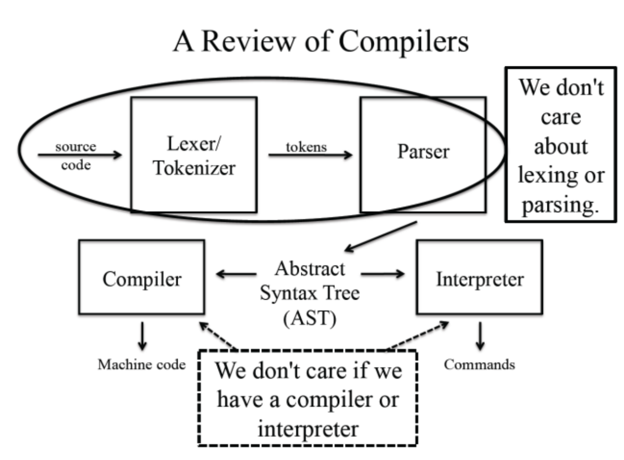
`e ::= true | false | if e then e else e`	*Expressions*: constant true, constant false, conditional
`v ::= true | false`	*Values*: constant true, constant false

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 no arguments to a function
- 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]
```

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]
```

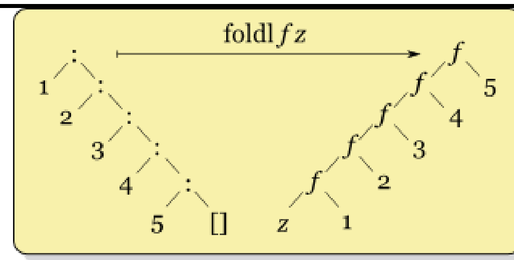
foldl

- 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
```



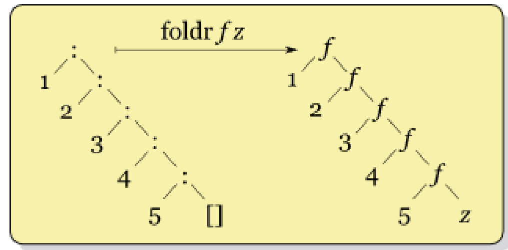
foldr

- 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.

`foldl` in terms of `foldr`

```
myFoldl' f acc x = foldr (flip f) acc (reverse x)
```

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 (redexs). 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:** import Data.Map as `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`.
  - `Map.member k m` – Returns true if k is in map "m" and false otherwise.

Precondition – Text above the line in a rule.

Context Rule for Binary Op:

$$\frac{v_3 = v_1 \text{ op } v_2}{C[v_1 \text{ op } v_2] \rightarrow C[v_3]}$$

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`

```
import Control.Applicative

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

`liftA2`

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

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

Example of `liftA2`

```
> (:) <$> 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

```
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:

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

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

```
> 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.

```
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:**

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

Returns error

Monads: Can chain through a series of functions.

Key Operator:
`>>=` (**Bind**)

Example #1: Using Just

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

Example #2: Using `return`

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

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

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

Monad:
```
(>>=) :: 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 `>>=`

```
> (\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`

```
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 = 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** – *L*eft to right, *R*ightmost derivation
- **LALR** – *L*ook-*A*head *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** – *L*eft to right, *L*eftmost 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

```haskell
import Text.ParserCombinators.Parsec

num :: GenParser st String
num = many1 digit

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

```haskell
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 `<?>`

```haskell
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**	a. **True**	a. **False** – Big step	a. **False** – Imperative	a. **True**
b. **False** – Lazy evaluation	b. **False** – Applicative functor	b. **True**	b. **True**	b. **False** – Typeclass
c. **False** – Lazy evaluation	c. **True**	c. **False** – Use store	c. **False**	c. **True**
d. **False** – Statically type	d. **True**	d. **True**	d. **True**	d. **False**
e. **True**	e. **True**	e. **False**	e. **True**	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

Verbose Approach	Concise Approach

Verbose Approach

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

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

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

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

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

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

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

Concise Approach

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

csvFile = line `sepBy` eol

line = cell `sepBy` string ","

cell = many (noneOf "\n")

eol = try (string "\n\r") -- Try more complex case first
   <|> string "\n"
   <?> "end of line"

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

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.**

Functor Definitions

Lists

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

Maybe

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

IO

```
instance Functor IO where
  fmap f a = do
             x <- a
             return (f x)
```

Applicative Functor Definitions

Lists

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

Maybe

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

IO

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

Monad Definitions

Lists

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

Maybe

```
instance Monad Maybe where
  return x  = Just x
  (>>=) Nothing  _ = Nothing
  (>>=) (Just x) f = f x
  fail  _    = Nothing
```

IO

```
instance Monad IO where
    (>>=) a f = do
                x <- a
                f x
   fail s = ioerror (userError s)
```

Lecture #12 – Introduction to JavaScript

JavaScript
- Developed at Netscape by Brendan Eichs in 10 days
- Originally named "Mocha"
- Syntax similar to Java

Multi-paradigm JavaScript
Supported programming paradigms:
- Imperative
- Functional
- Object-Oriented (through prototypes)

Where JavaScript is Run
- Client Side Versions
  - Runs on user machine
- Server-side Versions
  - JVM: Rhino & Nashorn
  - Node.js

Example: Imperative JavaScript
```
function addList(list){
  var = i, sum = 0;
  for( i = 0; i < list.length ; i++){
    sum += list[i];
  }
  return sum;
}
```

Example: Functional JavaScript
```
function addList(list){
  if(list.length == 0){
    return 0;
  }

  return list[0]
         + addList(list.slice(1));
}
```
`slice(begin[, end])` – Takes a subset of an array from the "`begin`" index to the "`end`" (exclusive). If no "`end`" is specified, it takes all elements to the end of the list.

Example: Object-Oriented JavaScript
```
function Adder(amount){
  this.amount = amount;
}
Adder.prototype.add = function(x){
                return this.amount + x;
            }
var myAdder = new Adder(1)
var y = myAdder.add(7)
```
`Adder` – Name of a new constructor. Convention is to start constructors with a capital letter.

`this` – Not optional in JavaScript.

Example: Quirks of JavaScript
```
var x = 42; // Create with var
y = 7; // No error without var
function add(a, b){
  return a + b;
}
function noReturnAdd(a, b){
  a + b;
}

// c is "undefined" since no return
var c = noReturnAdd(x, y)

//Lambda Function
var myLambda = function(x){return x * x;}
```

Printing to the Console in JavaScript
- **Standard Approach:**

  `console.log("…")`

  - Not supported by all implementations.
- JVM-based JavaScript Approach:
  `print`
- Solution to Support a Single Interface:
  `var print = console.log`

Closures
- Functions whose inner variables refer to independent (free) variables.

Example: Closure in JavaScript
```
var getNextInt = function (){
  var nextInt = 0;
  return function(){
         return nextInt++;
      }
}(); // Double paren to run the func
console.log(getNextInt()); // print "0"
console.log(getNextInt()); // print "1"
console.log(getNextInt()); // print "2"
```

Node.js
- JavaScript runtime environment and library designed to run outside the browser.
- Based off Google's V8 engine.
- `npm` – Package manager to get new packages.

Callback Function
- Functions in JavaScript are first class objects of type "Object".
- Not executed immediately.

JavaScript supports both "`null`" and "`undefined`"

Reading from a File with Callbacks in Node.js
```
var fs = require('fs')
fs.readFile('myFile.txt',
    function(err, data){
      if(err)
        throw err;
      else
        console.log("" + data);
    }
}
console.log("All done")
```
"`All done`" prints before the file contents due to callbacks.
`require` – Includes the JavaScript package "`fs`"

Synchronous File IO in Node
```
var fs = require('fs')
var data =
fs.readFileSync('myFile.txt');
console.log("All done")
```
To eliminate callbacks, most function names can be appended with "`Sync`"

Undeclared Object Fields
Any undeclared object fields or uninstantiated variables are undefined.
```
var y; // Uninstantiated

// Both print 'undefined'
console.log(y)
console.log(myDog.name)
```

Creating a JavaScript Object
```
var myDog = {age : 3,
            weight: 100}
```
Every object is a map.

Adding a Field to a JavaScript Object
```
myDog['height'] = 45 // Add a new height field
                     // Note the single quotes
```

Adding a Function to a JavaScript Object's Prototype
```
myDog.speak = function(){ console.log("Grr"); }
```

Delete a Function from a JavaScript Object's Prototype
```
delete myDog.speak
```

Prototypes

Object Prototypes
JavaScript prototypes are just like any other object.
```
var dogPrototype = {
    speak: function(){
      console.log("bark!");
    }
}
```

Defining an Object's Prototype
```
var rex = { name: "Rex",
            __proto__ : dogPrototype}
```

Prototypical Inheritance: If an object does not have a method of field, JavaScript looks to the object's `__proto__` object.

Add a Special "speak" Method to Rex

```
rex.speak = function(){
         console.log("Grr");
      };
rex.speak(); // Prints "Grr"

delete rex.speak;
// Prints "Bark!" from __proto__
rex.speak();

delete rex.speak; // Does nothing
rex.speak(); // Prints "Bark!"
```

Unspecified Function Arguments: In JavaScript, any unspecified function argument **defaults to "undefined"**.

Effect of the "new" Keyword

```
function Cat(name, breed){
  var this = {}; // Add when new is used
  this.prototype = Cat.prototype; // Also comes from new
  this.name = name;
  this.breed = breed;
  this.speak = function(){console.log("meow");};
  return this; // Also comes from new
}
```

No "return" in a Function

```
function noReturnAdd(x, y){
  x + y; // without "return"
}

// c is "undefined" since no return
var c = noReturnAdd(x, y)
console.log(c); // Prints "undefined"
```

Top Prototypes

`Object.prototype` – Top of all object prototypes

`Function.prototype` – Top of all function prototypes.

Iterating Using "forEach"

```
var arr = [1, 2, 3];
// Print each element in array
arr.forEach(function(val){
                 console.log(val);
              });
```

Note: This uses parentheses not curly brackets.

require

- Used to **import an external module** in **Node.js**
- Can be stored in a variable. **Example**:

```
var net = require('net');
```

Running from the Command Line

- Use the keyword "**node**" for Node.js. **Example**:

```
$ node my_program.js
```

Example: Create an Object with a Factory Method

```
var Droid = {
  speak: function() {
         console.log("I am "
                     + this.name);
       },
  create: function(name) {
            var clone = Object.create(this);
            clone.name = name;
            return clone;
         }
};
```

Example: Currying in JavaScript

```
Function.prototype.curry = function(){
  // Take slice from the Array class' prototype
  var slice = Array.prototype.slice;
  // Convert arguments to an array
  var args = slice.apply(arguments);
  var that = this;
  return function(){
    return that.apply(null,
                      args.concat(slice.apply(arguments));
  };
};
function add(x, y){
  return x + y;
}
var addOne = add.curry(1);
console.log(addOne(3)); // Prints "4"
```

Lecture #13 – Lambda Calculus

Expressions	Function Application		
`e ::= x` (Variables, immutable) `	λ x.e` (Lambda abstraction) `	e e` (Function application)  **Note:** Lambda (λ) is simply a function.  `v ::= (λ x.e)` (Lambda abstraction)	Given a function where **E** is a **complex expression**: $\lambda(x.E)v$ Then: $\lambda(x.E)v \rightarrow E[x \mapsto v]$ Hence, "v" replaces "x" in "E".	**Lambda Calculus is a simple, Turing complete language**. Hence it is equal in power to a Turing Machine. Lambda calculus stops evaluating when the result is in **normal form**.	

Small-Step Evaluation Order Rules for Lambda Calculus

Rule: SS-E1	Rule: SS-E2	Rule: SS-Lambda Context	Optional Rule: Lazy SS-Lambda Context
$\dfrac{e_1 \rightarrow e_1'}{e_1\, e_2 \rightarrow e_1'\, e_2}$	$\dfrac{e_2 \rightarrow e_2'}{(\lambda x.e)\, e_2 \rightarrow (\lambda x.e)\, e_2{}'}$	$(\lambda x.e)\, v \rightarrow e[x \mapsto v]$	$(\lambda x.e)\, e_2 \rightarrow e[x \mapsto e_2]$

Evaluation Strategies

Strict Evaluation Strategies		Lazy Evaluation Strategies	
Call by Value: Pass a **copy** of a parameter	**Call by Reference: Implicit reference** (e.g., pointer) to the parameter is passed.	**Call By Name: Re-evaluate the argument each time** it is used.	**Call by Need: Memoizes parameter value** after first use.

Language Equivalents of $(\lambda x.e)$		True and False in Lambda Calculus	
JavaScript: `function(x){return e;}`	**Haskell:** `(\x -> e)`	**True in Lambda Calculus:** $getFirstParam = tru = (\lambda x.\lambda y.x)$ **Note:** This returns the ***first*** parameter in the pair of values.	**True in Lambda Calculus:** $getSecondParam = fls = (\lambda x.\lambda y.y)$ **Note:** This returns the ***second*** parameter in the pair of values.

Conditional in Lambda Calculus

$$test = \lambda cond\,.\ \lambda then\,.\ \lambda els.(cond\ then\ els)$$

Example #1:	Example #2:
$test(tru\ tru\ fls)$	$test(fls\ tru\ fls)$
$\lambda cond\,.\ \lambda then\,.\ \lambda els.(cond\ then\ els)(tru\ tru\ fls)$	$\lambda cond\,.\ \lambda then\,.\ \lambda els.(cond\ then\ els)(fls\ tru\ fls)$
$\lambda then\,.\ \lambda els.(tru\ then\ els)(tru\ fls)$	$\lambda then\,.\ \lambda els.(fls\ then\ els)(tru\ fls)$
$\lambda els.(tru\ tru\ els)(fls)$	$\lambda els.(fls\ tru\ els)(fls)$
$(tru\ tru\ fls)$	$(fls\ tru\ fls)$
$(\lambda x.\lambda y.x)(tru\ fls)$	$\lambda x.\lambda y.y\ (tru\ fls)$
$(\lambda y.tru)(fls)$	$\lambda y.y\ (fls)$
tru	fls

Boolean And	Pair
$andd = \lambda b.\lambda c.(b\ c\ fls)$	$pair = \lambda f.\lambda s.\lambda b.(b\ f\ s)$ **Pair** – A tuple-like data structure in Lambda Calculus.

Working with a Pair in Lambda Calculus

First Element in a Pair	Second Element in a Pair
$first = \lambda p.(p\ tru)$	$second = \lambda p.(p\ fls)$

Note #1: In the case of both $first$ and $second$, the term p must be a pair.

Note #2: Both of these rely on the tru or fls being substituted for the "b" in the $pair$ data structure in term selecting either the first or second element.

Church Encoding Numerals	Successor Function	Plus in Lambda Calculus
$zero = \lambda s. \lambda z. z$ $one = \lambda s. \lambda z. s\ z$ $two = \lambda s. \lambda z. s\ s\ z$ $three = \lambda s. \lambda z. s\ s\ s\ z$	$scc = \lambda n. \lambda s. \lambda z. s(n\ z)$ Example: $one' = scc\ zero$ $two' = scc\ one' = scc(scc\ zero)$	$plus = \lambda m.\ \lambda n\ (\lambda s.\ \lambda z\ .\ m\ s\ (n\ s\ z))$ Example: Use church encoding numerals $plus\ three\ two \rightarrow^{*} \lambda s.\ \lambda z\ .(three\ s\ (two\ s\ z))$

Omega – Infinite Loop	Fix Combinator	
$Omega = (\lambda x\ .x\ x)\ (\lambda x\ .x\ x)$	$fix = \lambda f.(\lambda x. f(\lambda y. x\ x\ y))\ (\lambda x. f(\lambda y. x\ x\ y))$ Note: Can be used to do factorial operations. Usage: $fix(g\ x) = g((fix\ g)x)$	

Lecture #14 – JavaScript Scoping

Example: First Class Function

```
function makeAdder(x){
  return function(y){
          return x + y;
        };
}
var addOne = makeAdder(1);
// Prints "11"
console.log(addOne(10));
```

Example: Function Application

```
function makeAdderList(arr){
  var i;
  var output = [];
  for(i  = 0; i < output.length; i++){
    // Need to create a new scope
    function(){
      // Can add to arr without append
      output[i] = function(y){
                    return arr[i] + y;
                  };
    }
  }
}
```

JavaScript lacks block scope for the closure to be right, must create the function inside another function.

Block Scope – The scope (i.e. visibility) of a variable is limited to a specific block (e.g., `for` loop, `if` statement, etc.).

- Unlike most languages, JavaScript does not have block scope.
- To create a new scope, use an anonymous function.

Variable Hoisting – All variable declarations (i.e., use of "`var`") are treated as if they are at the beginning of the function.

"`this`" in JavaScript

`this` – Refers to the scope where the function is called.

- In Normal Function Calls – `this` refers to the global "`this`"
- Object Methods – The object itself.
- Constructor (using "`new`") – The newly created object.
- Exceptions: `apply`, `call`, and `bind`. Inline event handles on DOM elements

Any time a new function is created, the other "this" is no longer in scope

Execution Context

Consists of three part:

- A Variable Object – Container for variables and functions.
- Scope Chain – Variable object plus parent scopes
- Context Object – `this`

Global Context

- Top Level Context
- Variable object is known as the "global object"
- `this` – Refers to the global object.

Any variable declared without `var` is added to the global context.

Function Contexts

- Activation or Variable Objects which include:
    - Arguments passed to the function
    - A special arguments object
    - Local variables

`apply`, `bind`, `call` Example

```
x = 3;
function foo(y) {
   console.log(this.x + y);
}
foo(100); // Prints "103"

// Array passed for args
foo.apply(null, [100]);
// Update the context
foo.apply({x:4}, [100]);

// No array needed
foo.call({x:4}, 100);

// Create a new function
var bf = foo.bind({x:5});
bf(100);
```

- `apply` – Calls a function with the arguments passed as an array.
- `call` – Calls a function with the arguments passed in comma separated.
- `bind` – Used to create a new function with a custom context.

Lecture #14.5 – JSLint and TypeScript

Issues in JavaScript

- No block scope
- Forgetting `var` can lead to unexpected behavior since variables become global.
- Operator "==" is not transitive.
- Switch/case statements require "`break`"

JavaScript Automatically Inserts Semicolons

```
function makeObject() {
  return // Semicolon inserted here
  {
    madeBy: 'Austin Tech. Sys.'
  }
}
var o = makeObject();
console.log(o.madeBy); // error
```

Function "`parseInt`" can Yield Unexpected Results

```
// Drops the " tons"
console.log("what do you get? "
            + parseInt("16 tons"));

// Prints just "1" due to the "Oh"
parseInt("1O1");
```

Behavior of "`typeOf`"

`typeOf` – Returns a string. May yield unexpected results.

```
typeOf 5 // "number"
typeOf "hi" // "string"

typeOf NaN // "number"

typeOf null // "object"
```

Behavior of "`typeOfChar`"

`typeChar` – Returns a string. Classifies letters as "digits".

```
typeOfChar "5" // "digit"

typeOfChar "q" // "digit"

// "Other character"
typeOfChar " "
```

JSLint

- A tool to write cleaner and safer JavaScript.
- Requires that `"use strict";` (with quotes and followed by semicolon) be added at the beginning of all functions.
- Performs static code analysis.
- Helps catch common programming errors by requiring:
  - Variables declared before they are used.
  - Semicolons are always used.
  - Double equals never used.
- Inspired by the "lint" tool from C

Benefits of Type Systems

- Tips for compilers
- Hints for IDEs
- Enforced documentation
- Prevent code with errors from running.

TypeScript

- Developed by Microsoft
- Static type checker for JavaScript.
- A new "superset" language of JavaScript with:
  - Type annotations
  - Classes
- Compiles to JavaScript

Function Type Annotations in TypeScript

```
function greet(person: string){
  console.log("Hello "
              + person);
}
var user : string = "Vlad";

// Prints "Hello Vlad"
greet(user);
```

Types in TypeScript

- `number` (`var pi : number = 3.14`)
- `boolean` (`var b : boolean = true`)
- `string` (`var greet : string = "hi"`)
- `array` (`var lst : number[] = [1, 2]`)
- `enum`
- `any` (`var a : any = 3; var b : any = "hi"`)
- `void`

TypeScript Class

```
class Employee{
  name : string;
  salary : number;

  constructor(name : string, salary : number){
    this.name = name;
    this.salary = salary;
  }
  display(){ console.log(this.name); }
}

var emp = new Employee('Jon', 50000);
emp.display();
```

TypeScript Function Example

```
function swap(arr : number[], i : number,
              j : number) {
  var tmp : number;
  tmp = arr[i]; arr[i] = arr[j]; arr[j] = tmp;
}
function sortAndGetLargest (arr : number[]) {
  var tmp : number;
  var i : number;
  var j : number;
  tmp = arr[0]; // largest elem
  for (i=0; i<arr.length; i++) {
    if (arr[i] > tmp) tmp = arr[i];
    for (j=i+1; j<arr.length; j++)
    if (arr[i] < arr[j]) swap(arr,i,j);
  }
  return tmp;
}
var largest = sortAndGetLargest([99,2,43,8,0,21]);
console.log(largest); // Prints 99
```

JSLint Requirements

- `++` - This should be replaced with "+= 1"
- `var` – Each var declaration should be on its own line and must be at the top of the function/file.
- Single line `if` and `for` statements still need curly brackets.

Lecture #15 – Event-Based Programming and Cryptocurrencies

JavaScript Embedded in HTML

Create a button on a website that prints "Hello" when clicked. **Inline event handlers are considered bad practice**.

```
<html>
  <input
    type='button'
    onclick='alert("Hello");'
    value='Say hi' />
</html>
```

Improved JavaScript in HTML

Give buttons an "id" and update its "onclick" method

```
<html>
  <input id='thebutton'
    type='button'
    value='Say hi' />

  <script type="text/javascript">
    var btn = document.
                 getElementById('thebutton');
    btn.onclick = function() {
                   alert('Groovy');
              };
  </script>
</html>
```

Adding an Event Listener

- If clicking a button should perform multiple functions, then an event listener should be used.

```
function sayGroovy(){
  console.log("Groovy");
}

// Add an "onclick" event listener
btn.addEventListener('click',
                     sayGroovy);

// Add another event listener
btn.addEventListener('click',
         function(){
            console.log("Bogus");
         });
```

Removing an Event Listener

- Event listeners can be **removed by function name**. **Example**:

```
btn.removeEventListener('click',
                        sayGroovy);
```

Events in JavaScript

- **JavaScript is single threaded**.

An event must run to completion before the next event handler can run.

Event Emitter

- Import the "events" module using the syntax

```
var ee =
  require('events').EventEmitter;
```

- Used to create event via the keyword "**on**". **Example**:

```
ee.on('die', function(){
           console.log("Died");
        });
```

- Invoking (emitting) an event using the keyword "emit" **Example**:

```
setTimeout( function(){
            ee.emit('die');
         }, 100); // in ms
```

Create a TCP Server in Node.js Using Event Listeners

```
var net = require('net');
var eol = require('os').EOL;
var srvr = net.createServer();

// Add an event listener
srvr.on('connection', function(client) {
  client.write('Hello there!' + eol);
  client.end();
});
srvr.listen(9000);
```

`telnet` – Used to connect to a TCP server on the command line.

`127.0.0.1` – IP address of localhost

Cryptocurrencies

Types of Keys

- **Private Key**: Known only by the *owner*
- **Public Key**: Known by everyone

Digital Signature

- **Non-Repudiation** – **Involves associating actions or changes to a unique individual.**
  - **Solution in Cryptocurrency:** Digital signature.
- **Procedure:**
  - **Step #1**: Owner encrypts the message with his private key
  - **Step #2**: Use the public key to decrypt the message.
- **Analogy:** Enclosed Bulletin Board

Private Key Encryption

Used to transmit sensitive data to a specific recipient.

- **Procedure**:
  - **Step #1**: A user encrypts his data using the recipient's public key.
  - **Step #2**: The intended recipient decrypts the data using his private key.
- **Analogy:** A public mailbox. Anyone can put letters in, but only the mailman has the key to open the box.

- `update` – Used to update the signature with the specified message contents. Each signature object can only be updated once.
- `hex` – Specifies that the output should be in hexadecimal format.
- `Sync` – Ensures that the file read is done immediately without relying on a callback.
- `SHA` – "Secure Hash Algorithm"
- `RSA` – Signature algorithm

Example: JavaScript Signer Example

```
var crypto = require('crypto');
var fs = require('fs');

// Constructor for a "Signer" object
function Signer(privKeyFile){
  this.privKey = fs.readFileSync(privKeyFile).toString('ascii');
}

// Add a "signMessage" function to the Signer prototype
Signer.prototype.signMessage = function(msgFileName){
    var msg = fs.readFileSync(msgFileName).toString('ascii');
    var sign = crypto.createSign('RSA-SHA256');

    return sign.update(msg).sign(this.privKey, 'hex');
}
```

Double Spending – **Spend the same funds in multiple places**.

Solutions to Prevent Double Spending:

- **Centralized Authority** – Disadvantages include that the central authority would charge a fee and not everyone trusts central authorities.
- **Decentralized Authority** – Broadcast transactions to everyone.

Ledger – Used to keep a **history of all transactions** and the funds held by all users.

Example: JavaScript Verifier Example	**Bitcoin Mining**
``var crypto = require('crypto');``` ```var fs = require('fs');``` ```// Constructor for a "Verifier" object``` ```function Verifier(publicKeyFile){``` ``` this.publicKey = fs.readFileSync(privKeyFile).toString('ascii');``` ```}``` ```// Add a "verifySignature" function to the Verifier prototype``` ```Verifier.prototype.verifySignature = function(msgFileName, signature){``` ``` var msg = fs.readFileSync(msgFileName).toString('ascii');``` ``` // Create a verifier``` ``` var ver = crypto.createVerifier('RSA-SHA256').update(msg);``` ``` // Verify signature matches the hash``` ``` var legit = ver.verify(this.publicKey, signature, 'hex');``` ``` return legit;``` ```}```	• **Block Chain** – Defines the transaction history. ○ **Used to prevent double spending.** • **Proof of Work** – Verification of the block chain. • Miners hash transaction details plus a "proof" (i.e. nonce) ○ **Reward**: New bitcoins are mined for the first to find a proof. • **Cost to *Derive* a Proof:** 2^N where N is the number of the initial bits that must be "0" for the proof to be valid. • **Cost to Verify a Proof:** A single hash • Bitcoin protocol is designed to make mining more profitable than cheating.

Attributes of a Good Hash Function

Role of a Hash Function: Compress arbitrary length inputs to small, fixed length outputs.	**One Way:** Given an output "y", it is infeasible to find an "x" such that: $h(x) = y$	**Collision Resistant**: It is infeasible to find any "x" and "y" such that: $h(x) == h(y)$	**Compression**	**Efficient**

Lecture #16 – Typed Arith

Benefits of Type Systems

- Tips for **compilers to make code more efficient**.
- Tips for **IDEs and other tools to make writing code easier**.
- **Enforced documentation**.
- **Prevent code with errors from running**.

Typing Rules

Format:

`e : T`

Meaning: Expression e falls into one of two categories:

1. **`e` evaluates to a value of type `T`**
2. **Goes into an infinite loop**.

The Typed Arith Language

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

v ::= true
    | false
    | nv
n ::= 0
    | succ nv

T ::= Bool
    | Int
```

Good and Bad Typing Systems

- **Good type systems** prevent "bad" programs from running.
- **Bad type systems** prevent valid programs from running.
- **Typchecking** – In an expression "typechecks", the expression is either:
  - A value
  - An evaluation rule reduces the expression to a different expression.

Type Safety = Progress + Preservation

Progress

A well typed expression does not "get stuck"

Formal Definition: Given that `e:T`, then either:

1. `e` is a value
2. There exists an `e'` such that `e -> e'`

Preservation

A well-type expression will not change its type during evaluation.

Formal Definition: Given that `e:T` and `e -> e'`, then:

`e':T`

Lecture #17 – Macros and Sweet.js

Macros

- Short for "*macroinstruction*"
- Rule specifies how an **input sequence maps** to a **replacement sequence**.

Macros in C

- Performed by a ***preprocessor***
- **Rely on text substitution.**
- Embedded languages like PHP, Ruby, etc. use a similar approach.

Example: C Preprocessor Example

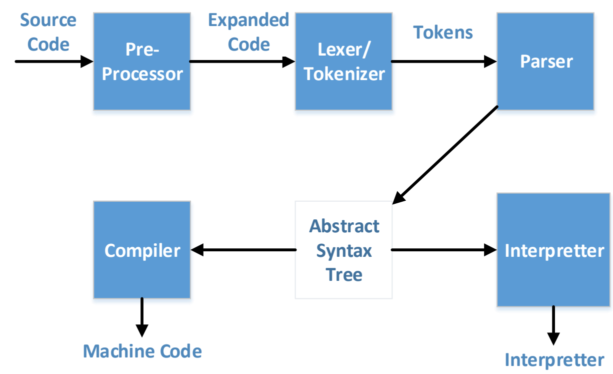
```
#define PI 3.14159
#define SWAP(a,b) {int tmp=a;a=b;b=tmp;}

int main(void){
  int x = 4, y=5, diam = 7;
  double circum = diam * PI;
  SWAP(x,y)
}
```

C Preprocessor Output

```
int main(void){
  int x = 4, y = 5, diam = 7;
  double circum = diam * 3.14159;
  {int tmp=x;x=y;y=tmp;}
}
```

Basic Compiler Structure with C-Style Macros



Problem with C Macros (Input)

```
// Macro should be on one line
#define SWAP(a,b) {int tmp=a;
                   a=b;
                   b=tmp;}

int main(void){
  int x = 4, tmp = 5;
  SWAP(x,tmp)
}
```

Problem with C Macros (Output)

```
int main(void){
  int x = 4, tmp = 5;
  { int tmp = x;
    a = tmp;
    tmp = tmp;
  }
}
```

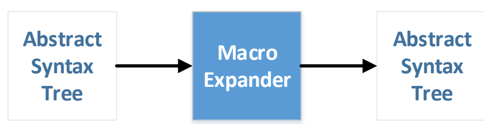
Hence, a **variable name collision** between the two variables named "tmp". This is known as "**inadvertent variable capture**"

Hygienic Macro – Any macro whose expansion is **guaranteed not to cause the accidental capture of identifiers**.

Syntactic Macros

- Derive from Lisp since Lisp programs are essentially one big AST.
- **Work at the level of abstract syntax trees.**
- Powerful by expensive.
- **Hygiene easier to address at the AST level.**
- Essentially a **source-to-source compiler**.

Basic Compiler Structure with Syntactic Macros



Macros in JavaScript

- **No standard macro system for JavaScript**
- Sweet.js has been gaining interest.
- Recently redesigned.

Sweet.js

- **Borrows concepts from Racket.**
- **Source-to-source compiler** (i.e., transpiler) for JavaScript.
- Examples of other JavaScript transpilers:
  - TypeScript
  - CoffeeScript
  - Dart (includes its own VM)
- Project backed by Mozilla

Invoking Sweet.js

- From command line:
  `$ sjs myfile.js -d out/`
- Compiled files run normally (as shown below for Node):
  `$ node out/myfile.js`

Writing a Swap Function in Sweet.js

```
syntax swap = function(ctx){
  let innerCtx = ctx.next().value.inner();
  let first = innerCtx.next().value;
  // Eat the comma
  innerCtx.next(); // No need for "value()"

  // Get the second parameter
  let second = innerCtx.next().value;
  return #`var tmp = ${first};
           ${first} = ${second};
           ${second} = tmp;`;
}
swap(a, b); // Invokes the macro
```

Note #1: The returned string is preceded by a pound (#) sign and is enclosed in backticks (`).

Note #2: Sweet.js variables are declared with "let".

Concatenating Multiple Result Strings

This function squares a set of input variables.

```
syntax square = function(){
  var innerCtx = ctx.next().value.inner();
  // Start with empty results
  result = #``;
  while(let stx of innerCtx){
    result =
      result.concat(#`${stx}=${stx}*${stx};`);
    // Eat comma
    // Ignored if no comma present
    innerCtx.next();
  }
}
square(a, b, c); // Invokes the macro
```

Note #1: Use ".concat" to concatenate multiple result strings.

Note #1: If a token is not present, ".next()" does not cause an error.

Keywords in Sweet.js

- `let` – Create a Sweet.js variable.
- `ctx.next().value` – Get the next value from the context.
- `` #`...` `` - Used to define a result string.
- `concat` – Used to combine two result strings.
- `let xxx of yyy` – Iterate over a list of tokens.
- `isIndentifier` – Used to check if a Sweet.js variable matches some string.

Input JavaScript class Code to be Parsed by Sweet.js

```
class Droid{
  constructor(name, color){
    this.name = name;
    this.color = color;
  }

  rollWithIt(it){
    console.log(this.name + " is rolling "
               + "with " + it);
  }
}
```

A class in Sweet.js

```
syntax class = function(ctx){
  let className = ctx.next().value;
  let bodyCtx = ctx.next().value.inner();

  // By default assume empty constructor
  let construct = #`function() { }`;
  let result = #``;

  while( let item of bodyCtx ){

    // Check if constructor
    if(item.isIndenifier('constructor')){
      // Get arguments then function code
      construct = #`function ${className}
                    ${bodyCtx.next().value}
                    ${bodyCtx.next().value}`;
    }
    else {
      // Add the function to the class prototype
      result = result.concat(
          #`${className}.prototype.${item} =
              function ${bodyCtx.next.value}
              ${bodyCtx.next.value}`);
    }
    // Return the constructor and methods
    return construct.concat(result);
```

Lecture #18 – Simply Typed Lambda Calculus

The Typed Arith Language (with Lamda Functions)

```
e ::= true
    | false
    | 0
    | succ e
    | pred e
    | iszero e
    | if e then e else e
    | λ x.e
    | e e
    | x

v ::= true
    | false
    | i
    | λ x.e

T ::= Bool
    | Int
    | T -> T
```

Options for Determining Function Type

1. Type Inference
2. Require explicit type annotations

Type Annotation

λ x:T.e

Note: **T** is the type of the argument "**x**"

Managing the Type of a Variable

- Use a **typing environment**.
  - **Maps variables to types**
  - Referred to using the Greek letter: **Γ** (gamma)
- **Typing rules must be defined in terms of the typing environment**.

Turnstile

- ⊢ - Used in revised typing relations to indicate that the typing rule is with respect to the specified typing environment (**Γ**)

Omega Combinator

Definition:

$\text{Omega} = (\lambda x.\, x\, x)(\lambda x.\, x\, x)$

Description: Results in an infinite loop since the combinator keeps returning itself. Omega **is a valid a valid program supported by untyped lambda calculus**.

Issue: If this expression is type checked, it enters an infinite type checking loop which causes it to fail

@ Symbol in Haskell

@ – Allows the programmer to represent an entire expression using a shortened notation.

Example:

```
e @ (ESucc e1)
```

Arith Typing Rules Using a Typing Environment (Γ)

[T–True] $\Gamma \vdash \text{true}: \text{Bool}$	**[T-If]** $\dfrac{\Gamma \vdash e_1: \text{Bool},\ \ \Gamma \vdash e_2: T,\ \ \Gamma \vdash e_3: T}{\Gamma \vdash \text{if}\ (e_1)\ \text{then}\ (e_2)\ \text{else}\ (e_3) : T}$
[T–False] $\Gamma \vdash \text{false}: \text{Bool}$	
[T–succ] $\dfrac{\Gamma \vdash e: \text{Int}}{\Gamma \vdash \text{succ}\ e: \text{Int}}$	**[T-FunctionApplication]** $\dfrac{\Gamma \vdash e_1: T_1 \rightarrow T_2,\ \ \Gamma \vdash e_2: T_1}{\Gamma \vdash e_1\ e_2 : T_2}$ Note: e_1 is a function while e_2 is a parameter.
[T–pred] $\dfrac{\Gamma \vdash e: \text{Int}}{\Gamma \vdash \text{pred}\ e: \text{Int}}$	**[T-LambdaVariable]** $\dfrac{x: T \in \Gamma}{\Gamma \vdash x : T}$
[T–iszero] $\dfrac{\Gamma \vdash e: \text{Int}}{\Gamma \vdash \text{iszero}\ e: \text{Bool}}$	**[T-LambdaContext]** $\dfrac{\Gamma \vdash x: T_1,\ \ \Gamma \vdash e: T_2}{\Gamma \vdash \lambda\, x.\ e : T_1 \rightarrow T_2}$

Lecture #19 – Metaprogramming and JS Proxies

Metaprogramming: Writing programs that manipulate other programs.
- Proposed in ECMAScript 6 for JavaScript.

Terminology in Reflection
- **Introspection:** Ability to examine (but not modify) the structure of a program.
- **Self-modification**: Ability to modify the structure of a program.

Introspection
Ability to **examine** (but not modify) **the structure of a program**.

JavaScript Examples

Property Lookup
```
"x" in o; //o is an object
```

Iterate Over All Properties of an Object
```
for( prop in o ){
  // Do something
  ...
}
```

Self-modification
Ability to **modify the structure of a program.**

JavaScript Examples
```
o["x"]; // Computed property
o.y = 42; // Add new property
delete o.y; // Delete property

// Reflected method call
o["m"].apply(null, [38]);
```

Proxies in JavaScript
- **Metacircular Interpretation** – The language is able to understand its own language.
- Until recently, JavaScript did not support intercession.
  - Javascript proxies are intended to fix that.
- **Node.js' implementation of proxies lags behind the standard.**
- **Proxies only exist for objects and functions.**
  - **Proxies do not exist for primitives.**

Proxies and Common Lisp
- Lisp was developed before object oriented languages were popular.
- Many libraries were created with non-standard OO systems.
- **Common Lisp Object System (CLOS)** – Standard object oriented system for Lisp.

Achieving Lisp Object Backwards Compatibility
Option #1: Rewrite all libraries using CLOS.
Disadvantages:
- Huge number of libraries.
- Not feasible to rewrite them all.

Option #2: Make a complex API.
Disadvantages:
- API difficult to understand.
- Systems had conflicting features.

Option #3: Keep API simple and modify object behavior to fit different systems.
- This approach relies on **metaobject protocols**.

Proxies and Handlers
- The behavior of a proxy is determined by **traps** specified in its **handler** (i.e., the **metaobject**).
- **Trap** – **Methods that intercept an operation.**
- **Handler** – The metaobject that **specifies the details of the trap**. The handler itself is **usually a normal object**.
- Using proxies in node requires a special flag: "`--harmony-proxies`". **Example:**

```
$ node --harmony-proxies prog.js
```

Kinds of JavaScript Proxies
- **Object Proxies** – Defined with:

```
Proxy.create(handler, proto)
```

- **Functions** (with extra traps) - Defined with:

```
Proxy.createFunction(handler,
                     callTrap,
                     constructTrap)
```

- **Proxies do not exist for primitives.**

A Simple Proxy
```
var MyHandler = {
  get:function(myProxy, name){
    console.log(name
          + " accessed");
    return 1;
  }
}

var p = Proxy.create(MyHandler);
// Prints "hello accessed."
var q = p.hello;

// Prints "1"
console.log(q);

// Error since no "set" handler
p.name = "Me";
```

Read Only Handler
- **Information Control** – Share a reference to an object, but do allow it to be modified.
  - **Example**: Reference to the DOM.

```
function ReadOnlyHandler(obj){
  delete : function(name){
    return obj[name];
  }
  // rcvr can be ignored
  set : function(rcvr, name, val){
    return true;
  }
}
```

A No-op Proxy – All Operations Passed through Unchanged
```
function handlerMaker(obj){
  // Delete a property from an object
  delete : function(name){ return obj[name]; },

  // Check if object has the specified property
  has function(name){ return name in obj;},

  // Check if object (not prototype chain) has property
  hasOwn : function(name){return Object.property
                                 .hasOwn(obj, name);},

  // Get a property value
  get : function(name){ return obj[name]; },

  // Set a property value
  set : function(rcvr, name, val){ obj[name] = val; },

  // Get all properties of an object
  enumerate : function(){
    var props = [];
    var prop;
    for(prop in obj){ props.push(prop); }
    return props;
  },

  // Get all of the keys of an object
  keys: function(){ return Object.keys(obj); }
}
```

Aspect Oriented Programming
- **Some code not well organized into objects**. Example:
  - **Cross-cutting concern** where code is spread throughout a program.
- **Canonical Example:** Logging Statements
  - **Littered throughout the code**
  - **Swapping out a logger requires massive code changes**.
- **Solution:** Use a proxy

Lecture #20 – Introduction to Ruby

Influences of Ruby

- SmallTalk
  - Everything is an object
  - Blocks
  - Metaprogramming
- Perl
  - Regular Expressions
  - Function names

Ruby on Rails

- "Killer" app for Ruby
  - Lightweight web framework
  - "Convention over configuration" – If use standard configuration, very little configuration required.
- Initial framework was PHP, but that was abandoned.

Basic Ruby Syntax

```
puts "Hello World"

a = [1, 2, 3]
m = { 'a' => "Apple",
      'b' => "Bear",
      'c' => "Cat" }

# Prints "1"
puts a[0]

# Prints "Apple"
puts m['a']
```

Keywords

@ - Represents an object property

Returning From a Function

- Every function in Ruby returns a value, even if return is not used.
- If no return is specified, a function returns the last used value.

Basic Ruby Class

```
class Person
  # Constructor
  def initialize name # Parameter
    # Attribute
    @name = name
  end
  # Getter
  def name
    return @name
  end
  # Setter
  def name = newName
    @name = name
  end
  # Method
  def say_hi
    puts "Hi my name is #{@name}"
  end
end
```

Using Metaprogramming for Getters and Setters

```
class Person
  # Replaces getters and setters
  # Uses metaprogramming
  attr_accessor :name
  # Constructor
  def initialize name
    # Attribute
    @name = name
  End

  # Method
  def say_hi
    puts "Hi my name is #{@name}"
  end
end
```

Using a Class in Ruby

```
p = Person.new "Joe"

puts "Name is #{p.name}"

p.say_hi
```

`#{...}` – Embeds a variable in a Ruby String

Getters and Setters the Ruby Way

Relies on metaprogramming

- `attr_reader` – Getter only
- `attr_writer`- Setter only
- `attr_accessor` – Getter and setter

Reopening a Class in Ruby

- Class definitions can be changed during runtime in Ruby.
- This is known as "reopening the class"

Inheritance in Ruby

Parent Class

```
class Dog
  # Parentheses optional
  def initialize(name)
    @name = name
  end
  def speak
    puts "#{@name} says bark"
  end
end
```

Child Class

```
class GuardDog < Dog
  attr_accessor :breed
  def initialize(name, breed)
    # Use parent constructor
    super(name)
    @breed = breed
  end
  def attack
    puts "Grrr"
  end
end
```

Note: Inheritance is doing using the less than (<) operator.

Mixin

- Add features to a class
- Similar to interfaces in Java with the exception that they can include functionality.
- `module` – Keyword to define a Mixin.
- `include` – Keyword to include a Mixin into a class.

Blocks in Ruby

- Superficially similar to blocks in other languages.
- Create custom control structures.
- Can be represented with curly brackets ({…}) or do/end.

File IO without Blocks

```
file = File.open('test.txt','r')
file.each_line do |line|
  puts line
end
file.close
```

Note #1: Contains "boilerplate" code of open and closing the file.

Note #2: It is possible one may forget to the close the file.

File IO with Blocks

```
File.open('test.txt','r') do |file|
  file.each_line { |line|
    puts line
  }
end
```

Note #1: Eliminates the "boilerplate" code.

Note #2: When using a block (both do/end, and curly brackets), surround the variable names in pipes (|).

Example: Mixin

```
# Define the mixin
module RevString
  def to_rev_s
    # Object is implicit
    to_s.reverse
  end
end

# Reopen the Person Class
class Person include RevSting
  def to_s
    # Returns the value
    @name
  end
end
```

Dynamic Code Evaluation (eval)

- Executes source code dynamically
  - Code passed as either a string (or a block of code)
- Popular feature in JavaScript
  - Early usage was to convert JSON strings to variables since not supported by JavaScript.
- Source of security concerns.

Additional Ruby eval Methods

- `instance_eval` – Evaluates code within an object's body.
  - Access the internals of an object.
- `class_eval` – Evaluates code within a class' body.
  - Modifies the class' definition.
- Takes either a string or block of code. Block of code is more secure.

Example: Use instance_eval to Change an Object's Value

```
# Create with the name Bob
bob = Person.new "Bob"

# Change his name
bob.instance_eval do
  @name = "Steve"
end

# Prints "Steve"
puts bob.name
```

Regular Expressions in Ruby

- `sub` – Replaces the first instance of a string match.
  - To perform the modification in place, must include an exclamation point (!) after sub.
- `gsub` – Replaces all instance of a string match.
  - To perform the modification in place, must include an exclamation point (!) after sub.

Example: class_eval in Ruby

```
# Applies to all classes
class Class
  # Simulate the "attr_accessor" function
  def my_attr_accessor(args)
    args.each do |prop|
      # Create getter
      self.class_eval("def #{prop};
                         return @#{prop};
                       end")
      # Create setter
      self.class_eval("def #{prop} = v;
                         @#{prop} = v;
                       end")

    end
  end
end
# Use the new attribute
class Musician
  my_attr_accessor :name, :genre
end

m = Musician.new
m.name = "Bob Marley"
puts m.name # Prints "Bob Marley"
```

Example: Using Regular Expressions in Ruby

```
s = "Hi, I'm Larry; this is my" +
    " brother Darryl, and this" +
    " is my other brother Darryl."
s.sub(/Larry/,'Laurent')

# Prints s unchanged
puts s

# Changes first "Larry" to "Laurent"
s.sub!(/Larry/,'Laurent')
puts s

# Prints first "brother" replaced with
# "frere". s is unchanged, bt it did
# return the modified string.
puts s.sub(/brother/, 'frère')

# Same as previous except all where
# changed when printing.
puts s.gsub(/brother/, 'frère')
```

Regular Expression Symbols in Ruby

`/./` - Any character except a newline	`/\w/` – Any word character: `[a-zA-Z0-9_]`	`/\d/` – Any digit character: `[0-9]`	`/\w/` – Any whitespace character: `[ \t\r\n\f]`
	`/\W/` – Any non-word character: `[^a-zA-Z0-9_]`	`/\D/` – Any non-digit character: `[^0-9]`	`/\W/`– Any non-whitespace character: `[^ \t\r\n\f]`
`*` – Zero or more times	`+` – One or more times	`?` – Zero or one time (optional)	

Important Syntax in Ruby

For Each Loop

```
object.each do |val|
  ...
end
```

Create a Mixin

```
module Name
  ...
end
```

Return from a Block

```
def block_name
  ...
  yield x
  ...
end
```

Single Line If Statement

```
x = 5
# Does nothing
x = 3 if (x > 10)
puts x # Prints "5"
```

Ranges

```
# Create list from 1 to 5
x = (1..5)
```

Note: Uses parentheses.

Run Ruby on Command Line

`irb` – Command line for Ruby similar to GHCi.

Use a Mixin in a Class

```
class MyClass
  include MixinName
  ...
end
```

Reference a Variable in a String

```
age = 30
x = "My age is #{age}"
```

Note: Surround variable name is #{…}

Access Command Line Arguments

```
ARGV[0]  #First argument
ARGV[1]  #Second argument
```

For Loop

```
for i in (0..5)
  puts i
end
```

Note: This loop runs 6 times since the range is inclusive.

Select Case

```
case x
  when y
    ...
  when z
    ...
  else
    ...
end
```

Lecture #21 – Blocks and Messages

Influence of Smalltalk on Ruby

- Everything is an object
- Blocks
- Message passing

Benefits of Blocks in Ruby

- Create custom control structures
- Eliminate boilerplate code.
- Ruby blocks are closures, but they are different than JavaScript blocks.

Example: `do_noisy` Block

```
def do_noisy
  puts "About to call block"
  yield # Calls block code
  puts "Just called block
end
```

Note: Called with a `do`/`end` or with curly brackets.

Example: Extend Array Class to Return Lowercase Version of Every Element

```
# Reopen the Array class
class Array
  def each_downcase
    self.each do |val|
      yield val.downcase
    end
  end
end
```

Example: Using the `each_downcase` Block

```
arr = ["Alpha","Beta",
       "So On"]
arr.each_downcase do |val|
  puts val
end
```

Example: Probabilistic Run Block

```
# Probabilistic Run Block
def with_prob(prob)
  yield if (Random.rand < prob)
end

with_prob 0.42 do
  puts "Prints 42% of time."
end
```

Example: Passing Code to a Block

```
def with_prob2(prob, &blk)
  blk.call if (Random.rand < prob)
end
```

`blk` – Block of code passed to the function.

Note #1: Argument name has an ampersand (&) before it.

Note #2: No ampersand is used when calling the block.

Example: Sharing Code Between Blocks

```
def half_the_time(prob, &blk)
  with_prob2(0.5, &blk)
end
```

Note: Need to pass argument to the function with the ampersand (&).

Example: `with_prob` in JavaScript

```
function with_prob(prob, f){
  if(Math.random() < prob){
    return f();
  }
}
```

Note: The JavaScript implementation relies on callbacks.

Example: Difference Between Ruby and JavaScript Blocks

Ruby

```
def coin_flip
  with_prob 0.5 do
    return "Heads"
  end
  return "Tails"
end
```

Note: This returns "Heads" half the time and "Tails" half the time.

- This is because a return in a Ruby block returns for the entire function.

JavaScript

```
function coin_flip(){
  with_prob(0.5, function(){
                   return "Heads";}
  return "Tails";
}
```

Note: This always returns "Tails"

- This is because even if "with_prob" runs, the return only occurs within the anonymous function.

Singleton Classes

- In Ruby, every object has its own singleton class.
- This class holds methods and fields unique to that object.
- This is different from Singleton Objects in design patterns.

Example: Adding a Property to a *Variable* in *JavaScript*

```
function Employee(name, salary){
  this.name = name;
  this.salary = salary;
}
var a = new Employee("Alice", 500);
var b = new Employee("Bob", 1000);

// Add a signing bonus to "Alice"
a.signingBonus = 2000;
```

Accessing Singleton Classes in Ruby

- To open an object's singleton class, use double less than symbols ("<<").
- Code only added to the specific object being reference.

Example: Adding a Property to an *Object* in *Ruby*

```
class Employee
  attr_accessor :name,:salary
  def initialize(name, salary)
    @name = name
    @salary = salary
  end
  def to_s
    @name # No return required
  end
end

# Create the Objects
a = Employee.new("Alice", 500)
b = Employee.new("Bob", 1000)

# Access the singleton class of "a"
class << a
  def signing_bonus
    2000
  end
end
```

Example: **Using a Singleton Class to Create Static Methods**

```
# Add Static Methods to Employee Class
class Employee
  class << self
    def get_employee_by_name(name)
      @employee[name] # No return needed
    end
    # Called in constructor
    def add(emp)
      puts "Adding #{emp}"
      # Create map if not exist
      @employee = Hash.new unless @employee
      @employee[emp.name] = emp
    end
  end
end
```

Message Passing

- Represents **inter-object interaction**.
- **Sender Sends**:
  - **Method name**
  - Data: **Method parameters** (if any)
- **Receiver**:
  - **Processes the message**
  - (***Optionally***) **returns data**
- **Receiver may not understand the message**.

`method_missing`

- Method that is part of every class. Can by overridden.
  - **Smalltalk Name:** `doesNotUnderstand`
  - **Ruby Name:** `method_missing`
- Invoked whenever an unknown method is called.

Example: **`missing_method`** **in Ruby**

```
class Person
  attr_accessor :name
  def initialize(name)
    @name = name
  End
  # Called when method unknown
  def method_missing(m)
    puts "Didn't understand #{m}"
  end
end
```

Active Record and Message Passing

- Relational database tool in Ruby.
- Specify fields in the database to be extracted based off method names. **Example:**

```
Person.find_by_first_name "John"
```

Lecture #22 – Virtual Machines and Just-In Time Compilation

Virtual Machine Overview • Code is compiled to bytecode ○ **Byte code is low level** ○ **Platform independent** • The VM interprets the bytecode **Scheme** • Similar to an AST. Uses parentheses. • Relies on a stack.	**Supported VM Operations** • **PUSH** – Adds an argument to the stack • **PRINT** – Pops an argument off the stack and prints it. • **ADD** – Pops two elements off the stack, adds them, and places result on the stack. • **SUB** – Similar to add but for subtraction. If "A" is on the top of the stack and "B" is below it, the result is B – A • **MUL** – Similar to add but with multiplication.	**Compilers vs. Interpreters vs. JIT** • **Compiler** ○ **Efficient execution** • **Interpreter** ○ **Runtime flexibility** • **JIT** ○ **Efficient execution with runtime flexibility.**	**Just-In-Time Compliers** • Interpret code • "**Hot**" (i.e., heavily-used) **sections** are **compiled at runtime**. • **Advantages** ○ **Speed of compiled code** ○ **Flexibility of interpreter** • **Disadvantages** ○ **Overhead of compiler and interpreter** ○ **Complex implementation**

Dynamic Recompilation • JIT pursues aggressive optimizations ○ **Makes assumptions about the code** ○ **Guard conditions verify assumptions** • **Unexpected cases are interpreted** (i.e., not compiled) • **Can in some corner cases outperform static compilation**.	**Types of JITs** • **Method Based** – Compile Methods • **Trace Based** – Compile loops	**How to Support JITs for a Language** • **Option #1:** Build your own JIT. ○ Study the latest techniques ○ Build large code bases to test. ○ Profile the code execution • **Option #2:** Use someone else's Just-In-Time VM.	

Final Exam Review Notes

Parsec
- Parser combinator in Haskell.
- Example Question: Write a grammar at the same level of complexity as the CSV parser.

JavaScript
- Prototype based language.
  - Inherit from an object not from a class.
  - Add properties and methods on the fly.
- Closure – By wrapping an inner function with an outer function, the inner function can encapsulate variables.
  - Have a scope chain.

Example: Write a Function that Toggles a Variable Each Time the Function is Called

Example #1: Use a Global

```
var b = true;
function flip(){
  if(b) b = false;
  else  b = true;
  return b;
}
```

Example #2: Use a Closure

```
var flip = function(){
  var b = true;
  return function(){
    if(b)  b = false;
    else   b = true;
    return b;
  };
}(); // Needed to call out function
```

JavaScript – Multiparadigm Language
- Imperative
- Object Oriented
- Functional
  - Supports higher order functions but not purely functional since not immutable.

JavaScript Scoping
- No block scope
- Variable declaration hoisting to the top of the function.

`this` in JavaScript
- In a method, this refers to the associated object.
- In a non-method, this refers to the global scope.
- Constructor (with new) – Refers to the object being created.
- DOM for Event Listeners – Refers to the DOM element.
- `apply`, `call`, `bind` – User can define what "`this`" refers to.

Scope Precedence in JavaScript

From highest to lowest precedence

1. Variable object
   a. Arguments pass to the function
   b. Special `arguments` object
   c. Local variables
2. Scope Chain
3. Global object (i.e., `this`)

Example: Scope Chain

```
function my_hello(){
  var x = 5;
  // Scope Chain
  function print_hello(){
    console.log("Hello " + x);
  }
  print_hello();
}

my_hello();
```

Quirks of JavaScript
- Semicolon insertion
- `typeOf`
  - `typeOf NaN` – Number
  - `typeOf null` – Object
- == Not Transitive
  - If `a == b` and `b == c`, it is not guaranteed that `a == c`

JSLint
- Designed to catch common JavaScript errors.
- Based off lint for the C language.
- Performs static code analysis

TypeScript
- Developed by Microsoft
- Source-to-source compiler (i.e., transpiler)
- Compiles to JavaScript
- Provides type annotation and classes.

Event Based Programming
- Relies on listeners
- Events are placed into an event queue.
- No concurrency.
- `emit` – Invokes an event
- `on` – Registers a listener
- Client-Based Programming – Often used in GUIs.

Metaprogramming
- Reflection – Two primary categories. Both occur at runtime.
  - Introspection – Examine program's execution at runtime.
  - Self-modification – Modify a program execution at runtime.
- Intercession – Trigger or control interaction at runtime.
- Reflection is more common, but intercession is more powerful.

Aspect-Oriented Programming

Designed to address cross-cutting code (i.e., code that is interspersed everywhere in a program.

Metaobject Protocols
- Metaobject – Any object that can reason about the behavior of other objects.
  - Example: Proxies
- Handler
  - Type of Meta Object.
  - Defines traps.
- Trap – Methods that intercept an operation.

Macros Sweet.js
- Source-to-source compiler (transpiler)
- Hygiene – No inadvertent variable capture.
- Text Substitution Macro – Works at the lexeme or text level.
- Syntactic Macro – Works at the Abstract Syntax Tree (AST) level.

Lambda Calculus
- Simple, Touring complete language.
- Based off anonymous functions (lambda)
- Expressions:
  $x \mid \lambda x\,.\,e \mid e\ e$
- Values:
  $\lambda x\,.\,e$

Evaluation Strategies
- Strict Evaluation Strategies
  - Call by Value – Pass a copy of the parameter.
  - Call by Reference – Implicit reference (e.g., a pointer to the parameter is passed.
- Lazy Evaluation Strategies
  - Call by Name – Re-evaluate the expression each time it is needed.
  - Call by Need – Evaluate when needed and memo-ize the result.

Advantages and Disadvantages of Type Systems

Benefits:
- Enforced documentation
- Tips for IDEs and Developers
- Prevent code with errors from running.

Disadvantage:
- May prevent valid code from running.

Simply-Type Lambda Calculus
- Relies on a typing environment (Γ)
- **Not Turing complete.**

Type Safety – Two Components
- Progress – Valid input continues to evaluation or reaches a value.
- Preservation – Evaluation does not change the type of an object.

Influences of Ruby
- SmallTalk
  - Everything is an object
  - Blocks
  - Metaprogramming – `method_missing` and message passing.
- Perl
  - Regular expressions
  - Names of functions.

Goals of Ruby
- Object oriented scripting language.
- Dynamically typed
- Interpreted.

Ruby Features
- `eval` – Execute a string as code.
- Singleton Classes
  - No relation to singleton objects
  - Class for a single object.
  - Can be used to create static methods in a class.

Virtual Machine	Interpreters vs. Compilers	Just-In-Time Compiler
• Source compiled to **byte code**. • **Byte code executed by an interpreter**.	• **Interpreter** – Runtime flexibility • **Compiler** – Efficient code • **JIT** – **Benefits *and* overhead** of both an interpreter and compiler.	• Identify "**hot**" (i.e. frequently run) code. • **Optimize for most common cases and skip corner cases**. ○ Guards protect for corner cases which are interpreted. • **May outperform statically compiled code**.

```
var b = true;
function flip(){
  if(b) b = false;
  else  b= true;
  return b;
}

var flip = function(){
  var b = true;
  return function(){
    if(b)  b = false;
    else   b = true;
    return b;
  };
};
```