CSE114A, Fall 2023: Final Exam

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This exam has 13 questions and 139 total points.

Instructions

- Please write directly on the exam.
- For multiple choice questions, **fill in the letter completely**, e.g. from ⓐ to ●
- For short response questions, try to keep your answer within the outlined box.
- **You have 180 minutes to complete this exam.** You may leave when you are finished.
- This exam is **closed book**. You may use one double-sided page of notes, but no other materials.
- Avoid seeing anyone else's work or allowing yours to be seen.
- Please, no talking. No notes, books, laptops, phones, or other electronic devices. Do not communicate with anyone but an exam proctor.
- To ensure fairness (and the appearance thereof), **proctors will not answer questions about the content of the exam**. If you are unsure of how to interpret a problem description, state your interpretation clearly and concisely. *Reasonable interpretations* will be taken into account by graders.

Good luck!

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Part 1: Lambda calculus

Question 1 (*5 points*)

Consider the following lambda expression EXPR1

```
(\x -> (\f -> f y ) (\z -> p z))
```

1.1 (2 points) The free variables of expression EXPR1 are :

- ⓐ x and y
- ⓑ y and p
- ⓒ y and z
- ⓓ f and z
- ⓔ None of the above

1.2 (3 points) Choose the best answer for EXPR1:

- ⓐ EXPR1 is in normal form
- ⓑ After one β-reduction EXPR1 will be in normal form
- ⓒ After two β-reductions EXPR1 will be in normal form
- ⓓ After three β-reductions EXPR1 will be in normal form
- ⓔ EXPR1 does not have a normal form

Question 2 (*10 points*)

2.1 (5 points) What does the following lambda expression evaluate to ?

```
INC ((\x y z -> x (z y)) INC (PAIR ONE TWO) FST)
```

- ⓐ ONE
- ⓑ TWO
- ⓒ THREE
- ⓓ FOUR
- ⓔ FIVE

2.2 (5 points) What does the following lambda expression evaluate to ?

```
(\x y z -> ITE (FST (PAIR TRUE ONE)) (x z) (y z)) FST SND (PAIR ONE TWO)
```

- ⓐ ONE
- ⓑ TWO
- ⓒ THREE
- ⓓ FOUR
- ⓔ FIVE

Part 2: Haskell

Question 3 (*9 points*)

Evaluate Haskell expressions.

3.1 (3 points) Consider the following Haskell expression

```
let sqrFun x = (sqr x) * (sqr x) in
  sqrFun 2
  where
    sqr = \x -> x * x
```

What is the result of evaluating this expression?

ⓐ 4
ⓑ 8
ⓒ 16
ⓓ None of the above
ⓔ Syntax or type error
ⓕ Won't terminate

3.2 (3 points) Consider the following Haskell expression

```
let
  rev :: [Int] -> [Int]
  rev []     = []
  rev (x:xs) = (rev xs) : x
  in
    rev [1,2,3,4,5]
```

What is the result of evaluating this expression?

ⓐ [1,2,3,4,5]
ⓑ [5,4,3,2,1]
ⓒ [1,2,3,4,5,5,4,3,2,1]
ⓓ None of the above
ⓔ Syntax or type error
ⓕ Won't terminate

3.3 (3 points) Consider the following Haskell function:

```
buildList x =
  [ (i,j) | i <- [0..x],
            j <- [0..x]]
```

What does `buildList 2` evaluate to?

ⓐ [(0,0),(0,1),(0,2),(1,0),(1,1),(1,2),(2,0),(2,1),(2,2)]
ⓑ [(0,0),(0,2),(2,0),(2,2)]
ⓒ [(0,0),(1,1),(2,2)]
ⓓ None of the above
ⓔ Syntax or type error
ⓕ Won't terminate

Part 3: Recursive Data Types

Question 4 (*18 points*)

Consider the following ADT that is used to represent a List

```
data List = Nil | Cons Int List
```

4.1 (3 points) instantiate the following list given the above definition: [1, 4, 3, 2]

Solution:

```
list = Cons 1 (Cons 4 (Cons 3 (Cons 2 Nil)))
```

4.2 (5 points) implement a function listLength, which returns the length of a given list.

Solution:

```
listLength :: List -> Int
listLength Nil = 0
listLength (Cons x xs) = 1 + listLength xs
```

4.3 (5 points) Define a function sumList, which returns the sum of the elements in the list

Solution:

```
sumList :: List -> Int
sumList Nil = 0
sumList (Cons x xs) = x + sumList xs
```

4.4 (5 points) The function `isListIncreasing` below determines whether a list of integers are sorted in increasing order.

```
isListIncreasing :: List -> Bool
isListIncreasing Nil = True
isListIncreasing (Cons x xs) = helper x xs
where
  helper x Nil = True
  helper x (Cons y ys) = if x > y then False else helper y ys
```

What should be the type signature of the `helper` function?

ⓐ `helper :: [Int] -> Bool`

ⓑ `helper :: [List] -> Int -> Bool`

ⓒ `helper :: Int -> List -> Bool`

ⓓ `helper :: [List] -> [Int] -> Bool`

ⓔ None of the above

Part 4: Higher-order Functions

Question 5 (*16 points*)

Higher-order Functions.

5.1 (5 points) Consider the following Haskell expression:

```
foldr (-) 0 [1,2,3,4,5]
```

What is the result of evaluating this expression?

Hint: You may find the implementation of `foldr` in the cheat sheet; evaluate the expression by hand to find the answer.

- ⓐ -5
- ⓑ 3
- ⓒ -15
- ⓓ None of the above
- ⓔ Syntax or type error
- ⓕ Won't terminate

5.2 (5 points) Consider the following Haskell expression:

```
foldl (-) 0 [1,2,3,4,5]
```

What is the result of evaluating this expression?

Hint: You may find the implementation of `foldl` in the cheat sheet; evaluate the expression by hand to find the answer.

- ⓐ -5
- ⓑ 3
- ⓒ -15
- ⓓ None of the above
- ⓔ Syntax or type error
- ⓕ Won't terminate

5.3 (3 points) Consider the following Haskell expression:

```
map (\x -> (x: x * x)) [0,1,2,3,4,5]
```

What is the result of evaluating this expression?

- ⓐ {0:0,1:1,2:2,3:3,4:4,5:5}
- ⓑ {0:0,1:1,2:4,3:9,4:16,5:25}
- ⓒ [0,1,4,9,16,25]
- ⓓ None of the above
- ⓔ Syntax or type error
- ⓕ Won't terminate

5.4 (3 points) Consider the following Haskell function:

```
mapFilter ls = map (filter (\x -> (x `mod` 2) /= 0)) ls
```

What does `mapFilter [[1,2,3,4,5]]` evaluate to?

- ⓐ [1,3,5]
- ⓑ [[1,3,5]]
- ⓒ [[1],[3],[5]]
- ⓓ None of the above
- ⓔ Syntax or type error
- ⓕ Won't terminate

Part 5: Semantics, scope, environments

Question 6 (*6 points*)

Consider the following Nano program:

```
let a = 1 in
  let b = 2 in
    let f = \x y -> x + y + a + b + c in
      let a = 3 in
        let c = 4 in
          f a b
```

6.1 (3 points) Under **static scope**, what would the above program evaluate to?

ⓐ 10

ⓑ 12

ⓒ 14

ⓓ error: unbound variable

6.2 (3 points) Under **dynamic scope**, what would the above program evaluate to?

ⓐ 10

ⓑ 12

ⓒ 14

ⓓ error: unbound variable

Question 7 (*10 points*)

Consider the following Nano program:

```
let a = 1 in
  let b = 2 in
    let f1 = \x y -> x + y + a in
      let f2 = \x y -> x - y - b in
        let a = f1 a b in
          let b = f1 a b in
            f2 a b
```

7.1 (5 points) Under **static scope**, what would the above program evaluate to?

ⓐ -5

ⓑ -10

ⓒ -16

ⓓ error: unbound variable

7.2 (5 points) Under **dynamic scope**, what would the above program evaluate to?

ⓐ -5

ⓑ -10

ⓒ -16

ⓓ error: unbound variable

Question 8 (*10 points*)

Consider the following Nano language

```
e ::= x | v | e1 + e2 |
      let x = e1 in e2 |
      \x -> e | e1 e2
v ::= n | \x -> e
where n ∈ ℕ, x ∈ Var
```

and the following operational semantics for the Nano language

```
                 e1 => e1'
[Add-L] -----------------------------
             e1 + e2 => e1' + e2


                 e2 => e2'
[Add-R] -----------------------------
             n1 + e2 => n1 + e2'


[Add] n1 + n2 => n          where n == n1 + n2


                      e1 => e1'
[Let-Def] -----------------------------------------
            let x = e1 in e2 => let x = e1' in e2

[Let] let x = v in e2 => e2[x := v]

             e1 => e1'
[App-L] --------------------
          e1 e2 => e1' e2


             e => e'
[App-R] ------------------
            v e => v e'


[App] (\x -> e) v => e[x := v]
```

(the cases for value substitution are given in the appendices)

8.1 (5 points) Which of the following reductions are valid ?

ⓐ `let x=9+1 in x+1 => let x=10 in x+1`

ⓑ `let x=10 in x+9 => 10+9`

ⓒ `let x=9 in (let y=5+6 in x+y) => let x=9 in (let y=11 in x+y)`

ⓓ a and b

ⓔ All of the above

8.2 (5 points) Which of the following reductions are valid ?

ⓐ
```
(\x y -> let z=y+1 in x+z)(3+4)(5+6)
=> (\y -> let z=y+1 in 3+4+z)(5+6)
```
ⓑ
```
(\x y -> let z=y+1 in x+z)(3+4)(5+6)
=> (\x y -> let z=y+1 in x+z)(7)(5+6)
```
ⓒ
```
(\y -> let z=y+1 in 7+z) (5+6)
=> (let z=(5+6)+1 in 7+z)
```
ⓓ
```
(\y -> let z=y+1 in y+z)(5+6)
=> (\y -> let z=y+1 in y+z)(11)
```
ⓔ b and d

Question 9 (*10 points*)

Consider the following grammar for Nano1

Grammar

```
e ::= x | v
| e1 + e2
| let x = e1 in e2
v ::= n
where n ∈ ℕ, x ∈ Var
```

Let the sizes for the terms in our grammar be the:

Term Size

```
size n = 1
size x = 1
size (e1 + e2) = 1 + size e1 + size e2
size (let x = e1 in e2) = size e1 + size e2
```

9.1 (5 points) Consider the Lemma and its corresponding proof below

Lemma: For any e, size e > 0

Proof: By induction on the term e

- Base case 1: size n = 1 > 0
- Base case 2: size x = 1 > 0
- Inductive case 1: size (e1 + e2) = 1 + size e1 + size e2 > 0 because size e1 > 0 and size e2 > 0 by IH

■

What is the inductive hypothesis (IH)?

ⓐ `size e1 > 0 and size e2 > 0`

ⓑ `size e = 1`

ⓒ `size e1 + size e2 > 0`

ⓓ `size n = 1 and size x = 1`

ⓔ None of the above

9.2 (5 points) The above proof is missing the `let` case. In the space below, complete the proof using the same format as the other cases above.

Solution: Inductive case 2: size(let x = e1 in e2) = size e1 + size e2 $>$ 0 because size e1 $>$ 0 and size e2 $>$ 0 by IH

Part 6: Type, type-inference, type-classes

Question 10 (*15 points*)

General Unifiers

10.1 (5 points) What is a unifier for the following types?

`a -> b` and `c -> Int -> String`

ⓐ `[a / c, b / Int -> String]`
ⓑ `[a / c -> Int, b / String]`
ⓒ `[a / Bool, b / Int -> String, c / Bool]`
ⓓ `(a) and (b)`
ⓔ `(a) and (c)`
ⓕ `(b) and (c)`
ⓖ Cannot unify

10.2 (5 points) What is a unifier for the following types?

`a -> Int` and `b -> Int -> Int`

ⓐ `[a / Int, b / Int -> Int]`
ⓑ `[a / Int -> Int, b / Int]`
ⓒ `[a / Int, b / Int]`
ⓓ `[a / Int -> Int, b / Int -> Int]`
ⓔ Cannot unify

10.3 (5 points) Consider the following types: `a -> Int -> Int` and `b -> c`.

Is the following unifier a **most** general unifier? `[a / Int, b / Int, c / Int -> Int]`

ⓐ Yes
ⓑ No, a most general unifier is `[b / a, c / Int -> Int]`
ⓒ No, a most general unifier is `[a / Int, b / Int -> Int, c /Int]`
ⓓ Cannot unify
ⓔ None of the above

Question 11 (*6 points*)

Let us extend our grammar for Nano1 to be

Grammar

```
e ::= x | v
| e1 + e2
| e1 * e2
| let x = e1 in e2
v ::= n
where n ∈ ℕ, x ∈ Var
```

Types

Types are represented by the following grammar:

```
T := Int | T1 -> T2
```

Type system

Below is a partial type system for this language.

The above rules are missing a rule for typing multiply expressions. Fill in the missing parts of the `T-Mul` rule below.

```
[T-Num] --------------------        [T-Var] ---------------------------
            G |- n :: Int                                  G |- x :: T


            G |- e1 :: Int  G |- e2 :: Int
[T-Add] ------------------------------------
            G |- e1 + e2 :: Int


            G |- e1 :: T1 G,x:T1 |- e2 :: T2
[T-Let] ------------------------------------
            G |- let x = e1 in e2 :: T2



            G |- (a)        G |-  (b)
   [T-Mul] --------------------------
                       (c)
```

11.1 (2 points) (a)

Solution: `e1 ::  Int`

11.2 (2 points) (b)

Solution: `e2 ::  Int`

11.3 (2 points) (c)

Solution: `G |- e1 * e2 ::  Int`

Question 12 (*9 points*)

Below is a partial typing derivation that shows that a Nano1 expression `5 + (let x = 9 in x+1)` has type `Int`. For each blank, fill in a type, the name of a typing rule, or the whole typing judgement (premise) to complete the typing derivation.

```
                                                [T-Var]----------   [(d)]-----------
                                                  x:Int |- x::Int   x:Int |- 1:: Int
                              [T-Num]-----------  [T-Add]---------------------
                                 [] |- 9 :: Int                 (c)
  [T-Num]-----------------   [T-Let]---------------------------------------
        [] |-  5 :: Int               [] |- let x = 9 in x+1 :: (b)
[(a)]-------------------------------------------------------------------
                              [] |- 5 + (let x = 9 in x+1) :: Int
```

12.1 (2 points) (a)

Solution: `T-Add`

12.2 (2 points) (b)

Solution: `Int`

12.3 (3 points) (c)

Solution: `x:Int |- x+1 ::  Int`

12.4 (2 points) (d)

Solution: `T-Num`

Question 13 (*15 points*)

Consider the three data types as follows

```haskell
data Circle = Circle{r::Double}
data Rectangle = Rectangle{w::Double, l::Double}
data Triangle = Triangle{b::Double, h::Double}
```

and the following `ShapeArea` class

```haskell
class ShapeArea a where
    area :: a -> Double
```

13.1 (10 points) Create instances for the typeclass `ShapeArea` for each data type `Circle`, `Rectangle` and `Triangle`. The `area` function returns area of the given shape. The area of a circle is calculated as (3.14*`radius`*`radius`), the area of a rectangle is calculated as (`width * height`), and the area of a triangle is calculated as (`0.5 * base * height`).

Solution:

```
instance ShapeArea Circle where
    area (Circle r) = 3.14 * r *r

instance ShapeArea Rectangle where
    area (Rectangle w l) = w * l

instance ShapeArea Triangle where
    area (Triangle b h) = 0.5 * b * h
```

13.2 (5 points) Write a Haskell function named `sumArea` that takes a list of type `a`, where `a` is an instance of `ShapeArea`, and returns sum of the areas.
E.g. `sumArea [(Rectangle 2.0 3.0),(Rectangle 10.0 2.0)]` returns `26.0`,
`sumArea [(Triangle 2.0 3.0),(Triangle 10.0 2.0)]` returns `13.0`.

Solution:

```
sumArea :: ShapeArea a => [a] -> Double
sumArea xs = sum (map area xs)
```

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1 Lambda calculus cheat sheet

```
-- Booleans --------------------------------
let TRUE =\x y -> x
let FALSE = \x y -> y
let ITE = \b x y -> b x y
let NOT = \b x y -> b y x
let AND = \b1 b2 -> ITE b1 b2 FALSE
let OR = \b1 b2 -> ITE b1 TRUE b2

-- Numbers ---------------------------------
let ZERO = \f x-> x
let ONE = \f x -> f x
let TWO = \f x -> f (f x)
let THREE = \f x -> f (f (f x))
let FOUR = \f x -> f (f (f (f x)))
let FIVE = \f x -> f (f (f (f (f x))))

-- Pairs -----------------------------------
let PAIR = \x y b -> b x y
let FST = \p -> p TRUE
let SND = \p -> p FALSE

-- Arithmetic ------------------------------
let INC   = \n f x -> f (n f x)
let ADD   = \n m -> n INC m
let MUL   = \n m -> n (ADD m) ZERO
let ISZ   = \n -> n (\z -> FALSE) TRUE
let DECR  = \n ->   -- decrement n by one --
let EQL   = \a b -> -- return TRUE if a == b, otherwise FALSE --

-- Recursion -------------------------------
let FIX = \stp -> (\x -> stp (x x)) (\x -> stp (x x))
```

2 Haskell cheat sheet

```
data  Maybe a  =  Nothing | Just a

foldr :: (a -> b -> b) -> b -> [a] -> b
foldr f b []     = b
foldr f b (x:xs) = f x (foldr f b xs)

foldl :: (b -> a -> b) -> b -> [a] -> b
foldl f b xs          = helper b xs
  where
    helper acc []     = acc
    helper acc (x:xs) = helper (f acc x) xs

filter :: (a -> Bool) -> [a] -> [a]
filter p []    = []
filter p (x:xs)
  | p x          = x : filter p xs
  | otherwise      = filter p xs

map :: (a -> b) -> [a] -> [b]
map _ []     = []
map f (x:xs) = f x : map f xs

flip :: (a -> b -> c) -> b -> a -> c
flip f x y = f y x

(.) :: (b -> c) -> (a -> b) -> a -> c
(.) f g x = f (g x)

(++) :: [a] -> [a] -> [a]
(++) []     ys = ys
(++) (x:xs) ys = x : xs ++ ys

-- returns the elements of a list in reverse order.
reverse :: [a] -> [a]

-- Extract the first element of a list, which must be non-empty.
head :: [a] -> a

-- Extract the elements after the head of a list, which must be non-empty.
tail :: [a] -> [a]

-- Extract the first n elements of a list.
take :: Int -> [a] -> [a]
```

3 Value substitution cheat sheet

```
x[x := v] = v
y[x := v] = y -- assuming x /= y
n[x := v] = n
(e1 + e2)[x := v] = e1[x := v] + e2[x := v]
(let x = e1 in e2)[x := v] = let x = e1[x := v] in e2
(let y = e1 in e2)[x := v] = let y = e1[x := v] in e2[x := v]
```

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