ASSIGNMENT 1 — BASICS OF LANGUAGES

COMP 3010 — ORGANIZATION OF PROGRAMMING LANGUAGES

1. Compilers and Interpreters

Exercise 1 (Short Answer)**.** Explain the task of each of the following phases of a compiler:

(1) Lexical analyzer (*a.k.a.* lexer)
(2) Syntax analyzer (*a.k.a.* parser)
(3) Semantic analyzer
(4) Intermediate code generator
(5) Code optimizer
(6) Machine code generator

Exercise 2 (This or That)**.** Which of the following are advantages of compilers? Which are advantages of interpreters?

(1) Can pre-examine input program for semantic (*e.g.,* type) errors
(2) Have full knowledge of both program input and program implementation
(3) Can specialize parts of code to optimize for specific input data
(4) Can afford heavy weight optimizations over large sections of code
(5) Flexible, and can easily change program behavior dynamically at run-time
(6) Generated code can run many times

2. Computability

Exercise 3 (Short Answer)**.** (1) If Q is a program that solves the halting problem, what must $Q(P, x)$ do?
(2) What is the significance of the halting problem for computable functions?

Exercise 4 (Short Answer)**.** Suppose that the program Z is a *zero checker*. That is, Z takes two inputs, a string P representing a program and a number n, and checks whether or not running P with input n (written as $P(n)$) would output a 0:

$$Z(P, n) = \begin{cases} \texttt{true} & \text{if } P(n) \text{ returns } \texttt{0} \\ \texttt{false} & \text{otherwise} \end{cases}$$

Because of the *Full Employment Theorem for Compiler Writers*, we know that the *zero checker* is not a computable function. Show why the program Z cannot exist by explaining how it could be used to solve the halting problem.

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3. Induction

Exercise 5 (Multiple Choice)**.** Consider the total function

$$f(x) = 3x + 2$$

Which of the following inductive definitions are equivalent to the above f?

(a) $f(x + 1) = f(x) + 2$

(b) $f(x + 1) = f(x) + 3$

(c) $f(0) = 3 \qquad f(x + 1) = f(x) + 2$

(d) $f(0) = 2 \qquad f(x + 1) = f(x) + 3$

Exercise 6 (Multiple Choice)**.** Recall that a natural number x is *even* whenever it is double another natural number (that is to say, there is some other natural number n such that $x = 2n$). A natural number x is *odd* whenever it is one more than an even number (that is to say, there is a natural number n such that $x = 2n + 1$).

Consider the *partial* function

$$h(x) = \frac{x}{2} \qquad \text{if } x \text{ is even}$$

where $h(x)$ is undefined for odd numbers x.

Which of the following inductive definitions are equivalent to the above h?

(a) $h(x + 2) = h(x) + 1$

(b) $h(0) = 0 \qquad h(x + 2) = h(x) + 1$

(c) $h(1) = 1 \qquad h(x + 2) = h(x) + 1$

(d) $h(0) = 0 \qquad h(1) = 1 \qquad h(x + 2) = h(x) + 1$

Exercise 7. $\mathbb{N}$ stands for the set of all natural numbers, and $\mathbb{N}^*$ stands for the set of *all* finite lists of natural numbers of any length. For example, $\mathbb{N}^*$ contains each of the lists $[9, 9, 9]$, $[10, 9, 8, 7, \dots, 3, 2, 1]$ and $[5, 16, 8, 4, 2, 1]$. $\mathbb{N}^*$ is defined inductively as the smallest set such that:

- $\mathbb{N}^*$ contains the empty list $[]$, and
- given any natural number x_0 from $\mathbb{N}$ and any list $[x_1, \dots, x_n]$ already in $\mathbb{N}^*$, the set $\mathbb{N}^*$ also contains the list $[x_0, x_1, \dots, x_n]$.

Give an inductive definition for the function f, which takes a finite list of numbers xs and $f(xs)$ is double the sum of the list. Your definition of f should follow the inductive pattern

$$f([]) = \dots$$
$$f([x_0, x_1, \dots, x_n]) = \dots f([x_1, \dots, x_n]) \dots$$

so that it gives the same result as:

$$f([x_0, x_1, x_2, \dots, x_n]) = 2 \times (x_0 + x_1 + x_2 + \cdots + x_n)$$

on any argument. In the case of the empty list $[]$, the sum of $[]$ is 0.

Hint: you might find the fact that

$$2 \times (x_0 + x_1 + \cdots + x_n) = (2 \times x_0) + (2 \times x_1) + \cdots + (2 \times x_n)$$

is useful for writing your inductive definition of f.

Exercise 8 (Multiple Choice)**.** Let X be inductively defined as the smallest set of finite number lists (taken from $\mathbb{N}^*$) satisfying the following closure properties:

- Given any natural number n from $\mathbb{N}$, the set X contains the one-element list $[n]$.
- Given any list $[x_1, x_2, x_3, \ldots, x_n]$ already in X, the set X also contains the list $[x_1, x_2, x_3, \ldots, x_n, y]$ where the additional element y is the product $x_1 \times x_2 \times x_3 \times \cdots \times x_n$.

Which of the following lists is NOT in X?

(a) $[1, 1, 1, 1, 1]$
(b) $[2, 4, 16, 256]$
(c) $[3, 3, 9, 81]$
(d) $[4, 4, 16, 256]$

4. Syntax and Grammars

Exercise 9 (Multiple Choice)**.** Consider the grammar G (note that ϵ stands for the empty string):

$$S ::= \mathtt{a}S \mid T$$
$$T ::= \mathtt{b}T \mid U$$
$$U ::= \mathtt{c}U \mid \epsilon$$

(1) Which of the following strings is generated by the grammar G?
   (a) `aba`
   (b) `bab`
   (c) `ca`
   (d) `ccc`
(2) Which of the following is a derivation of `bbc` in the grammar G?
   (a) $S \to T \to U \to \mathtt{b}U \to \mathtt{bb}U \to \mathtt{bb}U \to \mathtt{bbc}$
   (b) $S \to \mathtt{b}T \to \mathtt{bb}T \to \mathtt{bb}U \to \mathtt{bbc}U \to \mathtt{bbc}$
   (c) $S \to T \to \mathtt{b}T \to \mathtt{bb}T \to \mathtt{bb}U \to \mathtt{bbc}U \to \mathtt{bbc}$
   (d) $S \to T \to \mathtt{b}T \to \mathtt{b}T\mathtt{b}T \to \mathtt{bb}T \to \mathtt{bb}U \to \mathtt{bbc}U \to \mathtt{bbc}$

Exercise 10 (Multiple Choice)**.** Which of the following grammars describes the same language as $\mathtt{0}^m\mathtt{1}^n$ where $m \leq n$?

(a) $S ::= \mathtt{0}S\mathtt{1} \mid \epsilon$
(b) $S ::= \mathtt{0}S\mathtt{1} \mid S\mathtt{1} \mid \epsilon$
(c) $S ::= \mathtt{0}S\mathtt{1} \mid \mathtt{0}S \mid \epsilon$
(d) $S ::= SS \mid \mathtt{0} \mid \mathtt{1} \mid \epsilon$

Exercise 11. Consider the following grammar for *abstract* syntax of arithmetic expressions:

$$E ::= E{+}E \mid E{-}E \mid E{\times}E \mid E/E \mid 1 \mid 2 \mid 3 \mid 4$$

with the usual associativity and precedence for the arithmetic operators (all operators are left-associative, $\times$ and $/$ have a higher precedence than $+$ and $-$).

(1) Draw an abstract syntax tree for each of the following strings:
   (a) $\mathtt{1} - \mathtt{2} + \mathtt{3}$
   (b) $\mathtt{1} \times \mathtt{2} + \mathtt{3}$
   (c) $\mathtt{1} \times \mathtt{2} - \mathtt{3/4}$

(2) (Multiple Choice & Short Answer) Which of the following pairs of strings with different parentheses represent the same abstract syntax tree according to the above precedence and associativity? Draw that abstract syntax tree.
   (a) $2 \times 4 - 3$ versus $2 \times (4 - 3)$
   (b) $1 + 2 + 3 + 4$ versus $1 + (2 + (3 + 4))$
   (c) $2 + 3 \times 4/2$ versus $2 + ((3 \times 4)/2)$