Programming Languages 3: Questions and Answers: April/May 2010
Duration: 90 minutes.
Rubric: Answer all four questions.

1. (*Functional programming*)

(a) Explain the principle of *primitive recursion* as applied to:

(i) non-negative integers;

(ii) lists.

[Notes]

(i) A function $f(n)$ is primitive-recursive if for $n = 0$ its result is determined directly, whilst for $n > 0$ its result is determined in terms of $f(n–1)$.

(ii) A function $f(l)$ is primitive-recursive if for l empty its result is determined directly, whilst for l non-empty its result is determined in terms of f(tail of l).

[2+2]

(b) In a fictional university, each student receives a *grade* (A, B, C, D, or F) for his/her work in each course. The student's *grade-point average* is the weighted average of the student's grades in all courses (where A counts as 4.0, B as 3.0, C as 2.0, D as 1.0, and F as 0.0).

Write a Haskell function, `gpa gs ws`, that yields the grade-point average of the grades in list `gs`, using the weights in `ws`. You may assume that `ws` has the same length as `gs`, and that the weights in `ws` add up to 1.0 exactly. For example:

```
gpa ['B','A','D'] [0.25,0.25,0.5]
```

should yield 2.25 (= 3.0×0.25 + 4.0×0.25 + 1.0×0.5).

Your answer must explicitly declare the type of the `gpa` function, and the types of any auxiliary functions.

[Unseen problem]

```
points :: Char -> Float
points 'A' = 4.0
points 'B' = 3.0
points 'C' = 2.0
points 'D' = 1.0
points 'F' = 0.0

gpa :: [Char] -> [Float] -> Float
gpa [] [] = 0.0
gpa (g:gs) (w:ws) =
    w * points g + gpa gs ws
```

Alternatively:

```
data Grade = F | D | C | B | A deriving Enum

points :: Grade -> Float
points g = fromInt (fromEnum g)

gpa :: [Grade] -> [Float] -> Float
gpa [] [] = 0.0
gpa (g:gs) (w:ws) =
     w * points g + gpa gs ws
```

[7]

(c) Consider a binary search tree (BST) whose nodes contain integers.

(i) Define a Haskell type suitable for such a BST.

(ii) Write a Haskell function, `search i t`, that yields true if and only if the BST `t` contains the integer `i`.

(iii) Write a Haskell function, `insert i t`, that yields the BST obtained by inserting a new node containing the integer `i` into the BST `t`.

Your answer must explicitly declare the type of each function.

[Unseen problem]

```
data Bst = NULL | NODE Int Bst Bst

search : Int -> Bst -> Bool
search i NULL =
     False
search i (NODE i' t1 t2) =
     if i == i'
     then True
     else if i < i'
     then search i t1
     else search i t2

insert :: Int -> Bst -> Bst
insert i NULL =
     NODE i NULL NULL
insert i (NODE i' t1 t2) =
     if i < i'
     then NODE i' (insert i t1) t2
     else NODE i' t1 (insert i t2)
```

[1+4+4]

[*total 20*]

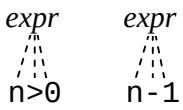
2. (*Syntax*)

Box 1 shows part of the EBNF grammar of the programming language Tiny, which featured in the course. It shows the syntax of commands. It does not show the syntax of expressions (not needed in this question).

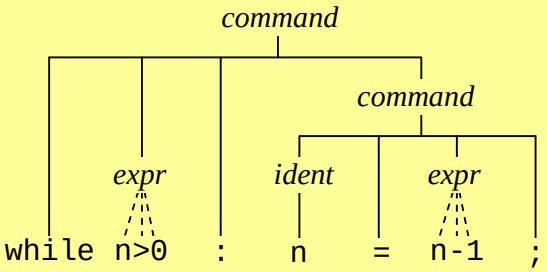
(a) Show the syntax tree of the following Tiny command:

```
while n>0: n = n-1;
```

You may assume that `n>0` and `n-1` are expressions. Your syntax tree should show these expressions in outline:



[Unseen problem]



[5]

(b) Suppose that Tiny is to be extended with a loop-command with multiple conditional exits. For example, the following loop-command contains two conditional exits:

```
loop {
     m = m+1;
     exit when m == n;
     f = f*m;
     exit when f > 1000;
}
```

In general, the loop-command may contain zero or more commands and conditional exits, in any order, all enclosed in a pair of curly brackets. Conditional exits are permitted immediately inside a loop-command, but nowhere else.

Modify the grammar to allow for loop-commands.

[Unseen problem]

command ::= …
| `loop {` *loop-body* `}`

loop-body ::= (*command* | `exit when` *expr* `;`)*

or:

loop-body ::=
| *command loop-body*
| `exit when` *expr* `;` *loop-body*

[5]
[*total 10*]

seq-command ::= *command*$^{+}$

command ::= *ident* `=` *expr* `;`
| `read` *ident* `;`
| `write` *expr* `;`
| `if` *expr* `:` *command* (`else` *command*)$^{?}$
| `while` *expr* `:` *command*
| `{` *seq-command* `}`

Box 1 Part of the grammar of Tiny (Question 2).
(Here *expr* is an expression, and *ident* is an identifier.)

3. (*Implementation*)

(a) Explain the difference between a *compiler* and *interpreter*.

[Notes]

A compiler translates high-level source code to low-level object code. It does not execute the code.

An interpreter executes source code directly, one instruction at a time. It does not translate the code.

[2]

(b) How does an interpreter work? What assumptions must be made about the interpreted language? What differences would you expect to see between an interpreter implemented in C and an interpreter implemented in Haskell?

[Notes]

An interpreter fetches, analyses, and executes source-code instructions, one at a time.

The source code must be flat, i.e., a sequence of simple instructions (which may include jumps).

An interpreter implemented in C models the state of the computation by a group of global variables. Interpreting a single instruction inspects and updates the state. The interpreter is structured as a loop that interprets one instruction at a time.

An interpreter implemented in Haskell models the state of the computation by a tuple. Interpreting a single instruction inspects the state and yields a modified state. The interpreter is structured as a recursive function that interprets one instruction at a time.

[8]

(c) Box 2 shows a description (in Haskell) of a simple stack machine, which is suitable for evaluating simple integer expressions. For example, the following integer expression:

$2\times(-(3+7))-4$

would be evaluated by executing the following list of stack-machine instructions:

```
[PUSH 2, PUSH 3, PUSH 7, ADD, NEG, MUL, PUSH 4, SUB]
```

Implement the function `execInstr`.

[Similar to seen problem]

```
execInstr (PUSH i) (RUNNING, pc, stack) =
     (RUNNING, pc+1, i:stack)
```

```
execInstr ADD (RUNNING, pc, i2:i1:stack) =
     (RUNNING, pc+1, (i1+i2):stack)

execInstr SUB (RUNNING, pc, i2:i1:stack) =
     (RUNNING, pc+1, (i1-i2):stack)

execInstr MUL (RUNNING, pc, i2:i1:stack) =
     (RUNNING, pc+1, (i1*i2):stack)

execInstr NEG (RUNNING, pc, i:stack) =
     (RUNNING, pc+1, (negate i):stack)

execInstr HALT (RUNNING, pc, stack) =
     (HALTED, pc, stack)
```

[10]
[*total 20*]

```
data Instruction =
          PUSH Int | ADD | SUB | MUL | NEG | HALT
-- This represents a single instruction. Its effect is:
--    PUSH i   push i on to the stack
--    ADD      pop i2; pop i1; push (i1+i2)
--    SUB      pop i2; pop i1; push (i1-i2)
--    MUL      pop i2; pop i1; push (i1*i2)
--    NEG      pop i; push (-i)
--    HALT     status <- HALTED

type Code = [Instruction]
-- This represents code by a list of instructions.

data Status = RUNNING | FAILED | HALTED

type Stack = [Int]
-- This represents a stack by a list of integers.
-- Elements may be added and removed only at the head
-- of the list (the stack top).

type State = (Status, Int, Stack)
-- This represents the state of the computation. A state
-- consists of a status, a program counter, and a stack.

state0 :: State
-- This is the initial state.
state0 = (RUNNING, 0, [])

execCode :: Code -> State -> State
-- execCode c s yields the state that results from
-- executing code c in state s.
…

execInstr :: Instruction -> State -> State
-- execInstr i s yields the state that results from
-- executing instruction i in state s.
…
```

Box 2 Description of a stack machine, expressed in Haskell (Question 3).

4. (*Concepts*)

(a) What is meant by the *lifetime* of a variable?

What is the lifetime of:

(i) a global variable?

(ii) a local variable?

(iii) a heap variable?

[Notes]

The lifetime of a variable is the time interval between its creation and its destruction.

(i) The lifetime of a global variable is the program's entire run-time.

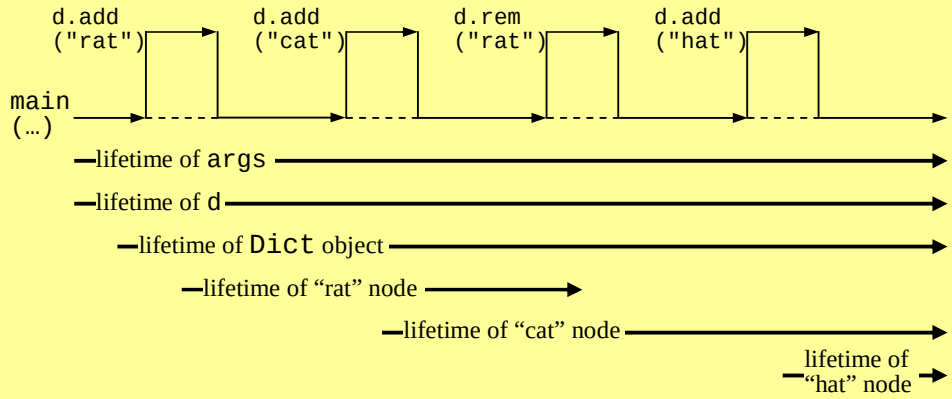
(ii) The lifetime of a local variable is an activation of the block in which it is declared.

(iii) The lifetime of a heap variable starts when it is created by an allocator; and finishes when it is destroyed by a deallocator, when it becomes unreachable, or when the program halts.

[5]

(b) Consider the Java program outlined in Box 3. Draw a diagram showing the lifetimes of all global and heap variables created by this program.

[Unseen problem]



[6]

(c) What is meant by the *scope* of a declaration?

Illustrate your answer by stating the scopes of the declarations of the variable `word`, the method `add()`, and the variable `d` in Box 3.

[Notes]

The scope of a declaration is the portion of the program text over which the declaration is visible.

The scope of the declaration of `word` is the `Dict` class declaration only.
The scope of the declaration of `add()` is the whole program.
The scope of the declaration of `d` is the body of `main()`.

[5]

(d) Briefly explain the general concept of *encapsulation* in programming languages. Why is this an important concept?

[Notes]

Encapsulation is the concept whereby some components of a program unit (such as a module, package, or class) are public whilst others are private. "Public" means visible to client code; "private" means visible only inside the program unit.

This is important because it narrows the program unit's interface, and frees the implementer of the program unit to add or remove private components at will, without invalidating client code.

[4]

(e) Encapsulation is supported in different ways by particular programming languages.

(i) How is encapsulation supported by Java? Illustrate your answer by referring to the Java code of Box 3.

(ii) How is encapsulation supported by Haskell? Illustrate your answer by outlining Haskell code to implement dictionaries as an abstract data type.

[Notes + seen problem]

(i) Java supports encapsulation by means of a class that specifies each of its components as either public or protected or private. In the class of Box 3, the components `word` and `rest` are specified as private, whilst `Dict()`, `add()`, `remove()`, and `main()` are specified as public.

(ii) Haskell supports encapsulation by means of a module whose heading lists which of its components are public. Outline of a dictionary module:

```
module Dictionaries (Dict, empty, add, remove)
where

data Dict = DICT [String]

empty :: Dict
empty = DICT []
```

```
add :: String -> Dict -> Dict
…

remove :: String -> Dict -> Dict
…
```

This module's components `Dict`, `empty`, `add`, `remove` are public, but `DICT` is private.

[4+6]
[*total 30*]

```
public class Dict {
     // A Dict object represents a dictionary by a sorted
     //linked list of words.

     private String word;
     private Dict rest;

     public Dict () { word = null; rest = null; }

     public void add (String w) {…}
     // Adds word w to this dictionary.

     public void rem (String x) {…}
     // Removes word x from this dictionary.

     public static void main (String[] args) {
          Dict d = new Dict();
          d.add("rat");
          d.add("cat");
          d.rem("rat");
          d.add("hat");
     }

}
```

Box 3 A Java class (Question 4).