CIS 1200 Final Exam May 9, 2023

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Name (printed): ________________________________

PennKey (penn login id): ________________________

I certify that I have complied with the University of Pennsylvania's Code of Academic Integrity in completing this examination.

Signature: ________________________________ Date: ______________________

- There are 120 total points. The exam period is 120 minutes long.
- There are 13 pages in the exam and an Appendix for your reference.
- Please begin by writing your PennKey (e.g., `stevez`) at the bottom of all the odd-numbered pages in the rest of the exam.
- Please skim the entire exam first—some of the questions will take significantly longer than others.
- Do not spend too much time on any one question. Be sure to recheck all of your answers.
- We will ignore anything you write on the Appendix.
- For coding problems: aim for accurate syntax, but we will not grade your code style for indentation, spacing, etc.
- If you need extra space for an answer, you may use the scratch page at the end of the exam; make sure to clearly indicate that you have done this in the normal answer space for the problem.
- Good luck!

OCaml Concepts (27 points total)

Appendix A contains the definitions of several OCaml types and functions that should be familiar from class: `'a tree`, `'a ref`, `transform`, and `fold`.

Binary Search Trees (8 points) For each tree below, check the box indicating whether it satisfies the *binary search tree* invariants. **NOTE:** If it does not, cross out and replace *one* node value such that the resulting **`int`** `tree` *does* satisfy the invariants (the result does not need to have the same nodes).

```
  3                7                4                6
   \              / \              / \              / \
    2            5   7            1   5            4   8
     \                           / \              / \   \
      4                         0   3            1   2   9
```

☐ is a BST ☐ is not BST	☐ is a BST ☐ is not BST	☐ is a BST ☐ is not BST	☐ is a BST ☐ is not BST

Higher-order Functions (8 points)

Consider the following four functions defined using `transform` or `fold`.

```
let hof1 = transform (fun x -> insert x 120)
let hof2 = fold (fun x acc -> insert acc x) Empty
let hof3 = fold (fun x acc -> (insert x 120) :: acc) []
let hof4 = fold (fun x acc -> insert x 120) Empty
```

Match each of the functions to one of the following English descriptions of its behavior. (choose one option for each function; a choice may be used by more than one function)

(A) Returns a list of trees obtained by adding the value `120` to every tree in a given list.

(B) Returns either `Empty` or the tree obtained by adding `120` to the first tree in a given list.

(C) Returns a (binary search) tree containing the elements of a provided list.

(D) Returns a list of trees obtained by adding the value `120` to `Empty` for every tree in a given list.

- `hof1` is described by: ☐ A ☐ B ☐ C ☐ D
- `hof2` is described by: ☐ A ☐ B ☐ C ☐ D
- `hof3` is described by: ☐ A ☐ B ☐ C ☐ D
- `hof4` is described by: ☐ A ☐ B ☐ C ☐ D

Aliasing and mutable state Recall that OCaml supports mutable state via type declarations such as for the `'a ref` type shown below (and in Appendix A). Consider the following well-typed program:

```
type 'a ref = { mutable contents : 'a }

let x = { contents = { contents = "1200" } }
let y = { contents = "PENN" }
;; x.contents <- y
let z = y
;; y.contents <- "RULES"
let w = y.contents

;; print_endline ("x.contents.contents = " ^ x.contents.contents)
;; print_endline ("y.contents = " ^ y.contents)
;; print_endline ("z.contents = " ^ z.contents)
;; print_endline ("w = " ^ w)
```

(a) (4 points) What is the type of each variable in the above code? (choose one each)

- `x :` ☐ `string` ☐ `string ref` ☐ `unit ref` ☐ `(string ref) ref`
- `y :` ☐ `string` ☐ `string ref` ☐ `unit ref` ☐ `(string ref) ref`
- `z :` ☐ `string` ☐ `string ref` ☐ `unit ref` ☐ `(string ref) ref`
- `w :` ☐ `string` ☐ `string ref` ☐ `unit ref` ☐ `(string ref) ref`

(b) (4 points) Fill in the blanks below to show what gets printed when this program is run. Fill each slot with one of the strings `1200`, `PENN`, or `RULES`

`x.contents.contents =` ____________________

`y.contents =` ____________________

`z.contents =` ____________________

`w =` ____________________

(c) (3 points) After running the program above, which values will *alias* `y`? (mark all that apply)

☐ `x` ☐ `z`
☐ `x.contents` ☐ `z.contents`
☐ `x.contents.contents` ☐ `w`

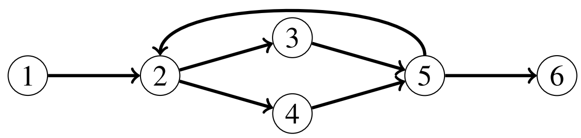
Java Programming

The next several questions refer to the Java code found in Appendix C. Some of the questions test your understanding of Java concepts; other questions will ask you to follow our design process to implement (parts of) a collection datatype for *graphs*. You may find the (excerpt of) the Java Documentation found in Appendix B to be useful.

Step 1: Understand the problem (4 points total)

Besides the *set* and *finite map* collections that we have studied in class, another frequently used collection type is the *graph*. A *graph* contains a set of *nodes* along with a collection of (directed) *edges*, each of which connects a *source* node to a *target* node. We consider graphs where there is at most one edge between any pair of nodes.

We draw nodes as labeled circles ⓝ and edges as arrows pointing from the source to the target ⓢ→ⓣ. For example, the diagram below depicts a graph whose nodes are the integers 1 through 6, and whose edges are indicated by the seven arrows.



As with other collections, there are many operations that we might want our graphs to support. In addition to methods to add nodes and edges to the graph, we focus on just two other operations. First, determining the *neighbors* of a node, which is just the set of nodes reachable via an edge. For instance, in the graph above, the neighbors of ② are ③ and ④, but node ⑥ has no neighbors. Second, we can determine whether there is a *path* from some node ⓢ to a node ⓣ that follows the edges in the graph. For instance, in the example graph above, there are paths ①→②→④→⑤ and ⑤→②→③ but there is no path from node ③ to node ①. Note that there is always a (trivial) path from any node to itself and that *a path might visit the same node multiple times*.

(a) (2 points) In the example graph above, which nodes are *neighbors* of node ⑤? (mark all that apply)

☐ ①   ☐ ②   ☐ ③   ☐ ④   ☐ ⑤   ☐ ⑥

(b) (2 points) How many paths are there from node ④ to node ③? (choose one)

☐ 0

☐ 1

☐ 2

☐ there are infinitely many paths due to the cycle in the graph

Step 2: Design the interface (14 points total)

Just as with Java's `Set<E>` and `Map<K,V>` interfaces, which are generic in the data they store, we will make the interface `Graph<Node>` polymorphic in the type `Node`. The `Graph<Node>` interface supports `add` and `contains` operations with the same specification of those methods in `Set`; it also supports three new graph-specific methods: `addEdge`, `neighbors`, and `hasPath`. Code defining the interface is shown in Appendix C.1.

Java concepts: (12 points) With respect to `Graph<Node>`, indicate whether the following statements are true or false; if false give a brief justification.

1. According to the method signature on line 25, `addEdge` might throw an `IOException`.

   ☐ True
   ☐ False because:____

2. According to the method signature on line 25, `addEdge` might throw a `NullPointerException`

   ☐ True
   ☐ False because:____

3. The following snippet of code will compile successfully (but may produce warnings):

   ```
   Graph<Integer> g = null;
   g.contains("CIS1200");
   ```

   ☐ True
   ☐ False because:____

4. The following snippet of code will compile successfully (but may produce warnings):

   ```
   Graph<Integer> g = new Graph<>();
   g.contains(3);
   ```

   ☐ True
   ☐ False because:____

Design question: (2 points) Suppose that, rather than `neighbors`, the `Graph<Node>` interface provides a method `boolean hasEdge(Node src, Node tgt)`, which returns **`true`** if there is an edge from `src` to `tgt` (and throws `NoSuchElementException` if `src` is not a node in the graph).

1. Consider implementing `hasEdge` using `neighbors`: (choose one)

   ☐ It is not possible to implement `hasEdge` using `neighbors`.

   ☐ `g.contains(src)&& g.neighbors(tgt)` implements `g.hasEdge(src,tgt)`

   ☐ `g.neighbors(src).contains(tgt)` implements `g.hasEdge(src,tgt)`

   ☐ `g.neighbors(tgt).contains(src)` implements `g.hasEdge(src,tgt)`

Step 3: Write test code for `Graph` (12 points total) Even before we have code that implements the `Graph<Node>` interface, we can write test cases that check our examples and properties. These test cases can use *subtype polymorphism* to implement tests that work for any implementation: we will assume that each such generic test is provided a instance of a graph object freshly created by **`new`**. For instance, in **Step 4** (later in the exam) you will work with `TreeGraph`. We will assume that a test for `TreeGraph` is called via `test(new TreeGraph())`.

(a) (4 points) Consider the following test case:

```
1   private void testNoSuchSource(Graph<Integer> g) {
2       assertFalse(g.contains(0));
3       assertThrows(NoSuchElementException.class, () -> g.neighbors(0));
4   }
```

Which of the following statements are true? (mark all that apply)

- ☐ This test case will succeed only if `g.contains(0)` returns **`false`**.
- ☐ The syntax `NoSuchElementException.class` (line 3) creates an instance of an *anonymous inner class*.
- ☐ The syntax `() -> g.neighbors(0)` (line 3) creates an instance of an *anonymous inner class*.
- ☐ The following test case is equivalent to the one above.

```
private void testNoSuchSourceAlternate(Graph<Integer> g) {
    assertFalse(g.contains(0));
    try {
        g.neighbors(0);
    } catch (NoSuchElementException e) { fail(); }
}
```

(b) (2 points) Complete the following test case so that all assertions succeed. It is based on the example graph pictured earlier:

```
private void testNeighbors(Graph<Integer> g) {
    g.addEdge(1,2);  g.addEdge(2,3);  g.addEdge(2,4);  g.addEdge(3,5);
    g.addEdge(4,5);  g.addEdge(5,6);  g.addEdge(5,2);

    TreeSet<Integer> expected1 = new TreeSet<>();

    expected1.add(_________);
    assertEquals(expected1, g.neighbors(1));

    TreeSet<Integer> expected2 = new TreeSet<>();
    expected2.add(3);
    expected2.add(____________);
    assertEquals(expected2, g.neighbors(___________));

    TreeSet<Integer> expected3 = new TreeSet<>();

    assertEquals(expected3, g.neighbors(___________));
}
```

(c) (6 points) Briefly explain (in English and/or pseudocode) how to write a test case that can fail if the `neighbors` method does not properly encapsulate some state associated with the graph implementation.

Step 4: Implement it As with the Java Collections library, we might have different implementations of the `Graph` interface that use different internal representations. We will follow the design there by using an **`abstract class`** to implement the `hasPath` algorithm once so that different representations of the graph abstract type can share that code.

Java concepts (16 points total) These questions are about the implementation of the `AbstractGraph` code in Appendix C.2. (Note: you should be able to answer these questions *without* understanding the details of the `hasPath` search algorithm; they are just about Java concepts.)

1. (4 points) Which of the following are *supertypes* of `AbstractGraph<Integer>`? (mark all that apply)

   - ☐ `AbstractGraph<Integer>`
   - ☐ `AbstractGraph<Object>`
   - ☐ `AbstractSet<Integer>`
   - ☐ `Set<Node>`
   - ☐ `AbstractGraph<Node>`
   - ☐ `Object`

2. (4 points) Suppose a well-typed program declares a variable `Graph<Integer> g = (* omitted *);`. Which of the following statements are true? (mark all that apply)

   - ☐ The *static type* of `g` is `Graph<Integer>`.
   - ☐ It is possible for the *dynamic class* associated with `g` to be `AbstractGraph<Integer>`
   - ☐ It is possible for the *dynamic class* associated with `g` to be a *subtype* of `AbstractGraph <Integer>`
   - ☐ In code after this declaration it is possible for the expression `g.equals(g)` to throw an exception.

3. (4 points) Note that there is a comment in the documentation for `AbstractGraph` indicating that the implementation assumes that `Node` implements the `Comparable<Node>` interface. Which of the following best explains why? (choose one)

   - ☐ The implementation of **`this`**`.contains`, as used on line 11, requires `compareTo` in its implementation.
   - ☐ The method `toSearch.removeFirst()`, as used on line 24, needs `compareTo` to find the smallest node to remove from the list.
   - ☐ The implementation of `hasPath` uses a `TreeSet<Node>` to store the `alreadyVisited` nodes, as seen on lines 16, 25, and 30, and `TreeSet` requires its elements to support `compareTo`.
   - ☐ The method `current.equals(tgt)`, as used on line 27, requires `compareTo` in its implementation.

4. (4 points) Which of the following best describes what would happen if we removed the use of **`this`** from the conditional guard on line 11, i.e., so it reads:

```
if (!contains(src)|| !contains(tgt)){
```

   (choose one)

   - ☐ The `hasPath` method would *always* throw a `NoSuchElementException`.
   - ☐ The `hasPath` method would *never* throw a `NoSuchElementException`.
   - ☐ The `hasPath` method would always go into an infinite loop.
   - ☐ The behavior of the `hasPath` method would be unaffected.

Design question Now we will implement *two* different instances of the `Graph<Integer>` interface. Both inherit from `AbstractGraph<Integer>` and provide the missing `Graph<Integer>` methods. (Note that, for these types, the nodes are specialized to be `Integer` objects.)

(no more questions on this page)

Implementation 1: `ArrayGraph` (14 points total) The first implementation represents the nodes and edges of the graph using arrays of **`boolean`**s (sometimes called the "adjacency matrix"). Appendix C.3 contains code for this class.

The following are the *representation invariants* embodied by this code.

INV1 `nodes[n] == true` if and only if `n` is a node in the graph

INV2 `edges[src][tgt] == true` if and only if `src` and `tgt` are nodes in the graph and there is an edge from `src` to `tgt`

(a) (2 points) Which of the following best explains why the constructor (line 10) *establishes* these invariants? (choose one)

- ☐ The graph starts out with `maxNodes` nodes, and the default initializer for **`boolean`** is **`true`**.
- ☐ The graph starts out with `maxNodes` nodes, and the default initializer for **`boolean`** is **`false`**.
- ☐ The graph starts out empty, and the default initializer for **`boolean`** is **`true`**.
- ☐ The graph starts out empty, and the default initializer for **`boolean`** is **`false`**.

(b) (4 points) The `add` method is supposed to add a new node to the graph.

- Which line of code *relies on* INV1? (choose one):

  ☐ line 22 ☐ line 23 ☐ line 24 ☐ line 25

- Which line of code *establishes* INV1? (choose one):

  ☐ line 22 ☐ line 23 ☐ line 24 ☐ line 25

(c) (2 points) Which invariant would break if we delete line 37 from `addEdge`? (choose one)

☐ INV1 breaks ☐ INV2 breaks ☐ neither breaks ☐ both break

(d) (6 points) Complete the implementation of `neighbors`. (The code is not very long.)

```
@Override
public Set<Integer> neighbors(Integer src) {
    if (!this.contains(src)) { throw new NoSuchElementException(); }

    Set<Integer> nbrs = new TreeSet<>();










    return nbrs;
}
```

Implementation 2: `TreeGraph` (17 points) The second implementation represents the nodes and edges of the graph using the Java `TreeMap` and/or `TreeSet` collection(s). From the options below, choose appropriate *representation type(s)* or mark "not needed" if you don't need that field. Then write down the invariant and complete the missing parts of the `TreeGraph` following that plan.

```
class TreeGraph extends AbstractGraph<Integer> {
    private ☐ Set<Integer>    ☐ Set<Set<Integer>>
            ☐ Set<Map<Integer,Integer>>             nodes; // or ☐ NOT NEEDED

    private ☐ Map<Integer,Integer>    ☐Map<Integer,Set<Integer>>
            ☐ Set<Map<Integer,Integer>              edges; // or ☐ NOT NEEDED
    /* INVARIANT: FILL IN BELOW
     * n is a node exactly when:
     *
     *
     * s -> t is an edge exactly when:
     *
     */
    public TreeGraph() { /* Initializes the field(s) using new TreeSet or new TreeMap */ }
    public boolean add(Integer node) {
        if (!this.contains(node)) { /* FILL IN HERE: */



            return true;
        }
        return false;
    }
    public boolean contains(Object o) { /* FILL IN HERE: */



    }
    public void addEdge(Integer src, Integer tgt) {
        this.add(src);
        this.add(tgt);  /* FILL IN HERE: */



    }
    public Set<Integer> neighbors(Integer src) {
        if (!this.contains(src)) { throw new NoSuchElementException(); }
        Set<Integer> nbrs = new TreeSet<>();  /* FILL IN HERE: */





        return nbrs;
    }
}
```

Using a `Graph` (16 points total) Appendix C.4 contains a program that reads the edges of a graph from a file `example.txt` and then prints out, for each node `src` in the graph, a list of nodes that can be reached via a path from `src`. The file format is simple: nodes are numbers and each line of the file is of the form `s -> t`, representing an edge from `s` to `t` in the graph. Below you can see the sample `example.txt` associated with the example graph, along with the output printed to the console:

example.txt:	console output:
1 -> 2	1 ==> 1 2 3 4 5 6
2 -> 3	2 ==> 2 3 4 5 6
2 -> 4	3 ==> 2 3 4 5 6
3 -> 5	4 ==> 2 3 4 5 6
4 -> 5	5 ==> 2 3 4 5 6
5 -> 6	6 ==> 6
5 -> 2	

Java Concepts (a) (2 points) Suppose that we change line 25 of `GraphApp` to instead use the **`this`** keyword:

```
Graph<Integer> g = this.readGraph(new FileReader(filename));
```

What would be the result? (choose one)

- ☐ The program would compile successfully and its behavior would be unchanged.
- ☐ The program would compile successfully but it would throw an exception when run.
- ☐ The program would not compile because `main` is declared as **`static`**.
- ☐ The program would not compile because `readGraph` is declared as **`static`**.

Java Concepts (b) (2 points) Recall that you used the `BufferedReader` as part of your `TwitterBot` homework. Which of the following are true properties of the `BufferedReader` class. (Note: we have intentionally *not* provided JavaDocs for `BufferedReader`.) (mark all that apply)

- ☐ `BufferedReader` is more efficient than just using `FileReader` to read individual characters from the input.
- ☐ The `BufferedReader` methods do not throw `IOException`s.
- ☐ The `BufferedReader` `readLine` method provides the ability to read a whole line of input at once as a `String`.
- ☐ A `BufferedReader` constructor can accept any `Reader` as an input.

Design Question (a) (5 points) This program works, but could be made both simpler and more general. Suggest a change you would make to the `Graph<Node>` interface and briefly describe (in English and/or pseudocode) how it would let your simplify the code on lines 26–36 of `GraphApp`. **Note:** Your change should be suitable for inclusion in a Java Collections library class, i.e., it should not simply contain the code of from `GraphApp` and it should not do I/O.

Modify the `Graph<Node>` interface to ____
and then:

Design Question (b) (3 points) As it is currently written, `readGraph` *declares* the `IOException` and `main` uses **`try/catch`** to handle it, which is a bit awkward. Which of the following changes would lead to a cleaner design with the same functionality? (choose one)

- ☐ Remove the **`try/catch`** code on lines 24/37–41 and add **`throws`** `IOException` on line 21.
- ☐ Move the **`try/catch`** code from lines 24/37–41 to surround lines 9-16, modify `readGraph` to take `String filename`, and call the `FileReader` constructor on line 9.
- ☐ Change `readGraph` to take a `BufferedReader b`, delete the **`throws`** `IOException` from line 7, delete line 9, and call the `BufferedReader` constructor on line 25.

Design question (c) (4 points) Our implementations of `Graph<Integer>` have not said anything about the `equals` method. Would *overriding* `equals` be justified in this case? Briefly explain why or why not.

Implementations of `Graph<Integer>` ☐ should / ☐ should not override `equals`, because:

Scratch Space

Use this page for work that you do not want us to grade. If you run out of space elsewhere in the exam and you ***do*** *want to put something here that we should grade, make sure to put a clear note in the normal answer space for the problem in question.*