

# Advanced Programming Languages

## Homework Assignment 2F and 2C

EECS 590

**Logistics.** You must work alone. Your name and Michigan email address (and the bookkeeping problem) must appear on the first page of your PDF submission but *may not appear anywhere else*. This is to protect your identity during peer review. The first page of your submission is *not* shared during peer view but all subsequent pages are.

**Exercise 2F-1. Bookkeeping [2 points].** These answers should appear on the first page of your submission and are kept private.

1. Indicate in a sentence or two how much time you spent on this homework.
2. Indicate in a sentence or two how difficult you found it subjectively.

I've just sucked one year of your life away. I might one day go as high as five, but I really don't know what that would do to you. So, let's just start with what we have. What did this do to you? Tell me. And remember, this is for posterity, so be honest — how do you feel? — **Count Rugen, *The Princess Bride***

All subsequent answers should appear after the first page of your submission and may be shared publicly during peer review.

**Exercise 2F-2. Mathematical Induction [5 points].** Find the flaw in the following inductive proof that “All flowers smell the same”. Please indicate exactly which sentences are wrong in the proof via **highlighting** or underlining.

*Proof:* Let  $F$  be the set of all flowers and let  $\text{smells}(f)$  be the smell of the flower  $f \in F$ . (The range of  $\text{smells}$  is not so important, but we'll assume that it admits equality.) We'll also assume that  $F$  is countable. Let the property  $P(n)$  mean that all subsets of  $F$  of size at most  $n$  contain flowers that smell the same.

$$P(n) \stackrel{\text{def}}{=} \forall X \in \mathcal{P}(F). |X| \leq n \implies (\forall f, f' \in X. \text{smells}(f) = \text{smells}(f'))$$

(the notation  $|X|$  denotes the number of elements of  $X$ )

One way to formulate the statement to prove is  $\forall n \geq 1. P(n)$ . We'll prove this by induction on  $n$ , as follows:

*Base Case:*  $n = 1$ . Obviously all singleton sets of flowers contain flowers that smell the same (by the definition of  $P(n)$ ).

*Induction Step:* Let  $n$  be arbitrary and assume that all subsets of  $F$  of size at most  $n$  contain flowers that smell the same. We will prove that the same thing holds for all subsets of size at most  $n+1$ . Pick an arbitrary set  $X$  such that  $|X| = n+1$ . Pick two distinct flowers  $f, f' \in X$  and let's show that  $\text{smells}(f) = \text{smells}(f')$ . Let  $Y = X - \{f\}$  and  $Y' = X - \{f'\}$ . Obviously  $Y$  and  $Y'$  are sets of size at most  $n$  so the induction hypothesis holds for both of them. Pick any arbitrary  $x \in Y \cap Y'$ . Obviously,  $x \neq f$  and  $x \neq f'$ . We have that  $\text{smells}(f') = \text{smells}(x)$  (from the induction hypothesis on  $Y$ ) and  $\text{smells}(f) = \text{smells}(x)$  (from the induction hypothesis on  $Y'$ ). Hence  $\text{smells}(f) = \text{smells}(f')$ , which proves the inductive step, and the theorem.

(One indication that the proof might be wrong is the large number of occurrences of the word “obviously” :-))

**Exercise 2F-3. While Induction [10 points].** Prove by induction the following statement about the operational semantics:

For any BExp  $b$  and any initial state  $\sigma$  such that  $\sigma(x)$  is even, if

$$\langle \text{while } b \text{ do } x := x + 2, \sigma \rangle \Downarrow \sigma'$$

then  $\sigma'(x)$  is even. Make sure you state what you induct on, what the base case is and what the inductive cases are. Show representative cases among the latter. Do not do a proof by mathematical induction!

**Exercise 2F-4. Language Features, Large-Step [12 points].** We extend IMP with a notion of integer-valued *exceptions* (or *run-time errors*), as in Java, ML or C#. We introduce a new type  $T$  to represent command terminations, which can either be normal or exceptional (with an exception value  $n \in \mathbb{Z}$ ):

$$\begin{array}{ll} T ::= \sigma & \text{“normal termination”} \\ | \sigma \text{ exc } n & \text{“exceptional termination”} \end{array}$$

We use  $t$  to range over possible terminations  $T$ . We then redefine our operational semantics judgment:

$$\langle c, \sigma \rangle \Downarrow T$$

The interpretation of

$$\langle c, \sigma \rangle \Downarrow \sigma' \text{ exc } n$$

is that command  $c$  terminated abruptly by throwing an exception with value  $n \in \mathbb{Z}$  at a point in  $c$ 's execution when the state was  $\sigma'$ . We only model one type of exception, but every exception has an integer “argument”  $n$  (or “payload” or “value”) that is set when the exception is thrown and available when the exception is caught.

Note that our previous command rules must be updated to account for exceptions, as in:

$$\frac{\langle c_1, \sigma \rangle \Downarrow \sigma' \text{ exc } n}{\langle c_1; c_2, \sigma \rangle \Downarrow \sigma' \text{ exc } n} \text{seq1} \quad \frac{\langle c_1, \sigma \rangle \Downarrow \sigma' \quad \langle c_2, \sigma' \rangle \Downarrow t}{\langle c_1; c_2, \sigma \rangle \Downarrow t} \text{seq2}$$

We also introduce three additional commands:

```

throw e
try c1 catch x c2
after c1 finally c2

```

- The `throw e` command raises an exception with argument  $e$ .
- The `try` command executes  $c_1$ . If  $c_1$  terminates normally (i.e., without an uncaught exception), the `try` command also terminates normally. If  $c_1$  raises an exception with value  $e$ , the variable  $x \in L$  is assigned the value  $e$  and then  $c_2$  is executed.
- The `finally` command executes  $c_1$ . If  $c_1$  terminates normally, the `finally` command terminates by executing  $c_2$ . If instead  $c_1$  raises an exception with value  $e_1$ , then  $c_2$  is executed:
  - If  $c_2$  terminates normally, the `finally` command terminates by throwing an exception with value  $e_1$ . (That is, the original exception  $e_1$  is re-thrown at the end of the `finally` block, as in Java.)
  - If  $c_2$  throws an exception with value  $e_2$ , the `finally` command terminates by throwing an exception with value  $e_2$ . (That is, the new exception  $e_2$  overrides the original exception  $e_1$ , also as in Java.)

These constructs are intended to have the standard exception semantics from languages like Java, C# or OCaml — except that the `catch` block merely assigns to  $x$ , it does not bind it to a local scope. So unlike Java, our `catch` does not behave like a `let`. We thus expect:

```

x := 0 ;
{ try
  if x <= 5 then throw 33 else throw 55
  catch x
  print x } ;
while true do {
  x := x - 15 ;
  print x ;
  if x <= 0 then throw (x*2) else skip
}

```

to output “33 18 3 -12” and then terminate with an uncaught exception with value -24.

Give the large-step operational semantics inference rules (using our new judgment) for the three new commands presented here. You should present six (6) new rules total.

**Exercise 2F-5. Language Features, Analysis [6 points].** Argue for or against the claim that it would be more natural to describe “IMP with exceptions” using small-step contextual semantics. You may use “simpler” or “more elegant” instead of “more natural” if you prefer. Do not exceed two paragraphs (one should be sufficient). Both your ideas and also the clarity with which they are expressed (i.e., your English prose) matter.

**Exercise 2C. Language Features, Coding.** Download the Homework 2 code pack from the course web page. Modify `hw2.ml` so that it implements a complete interpreter for “IMP with exceptions (and `print`)”. You may build on your code from Homework 1 (although the `let` command is not part of this assignment). Using OCaml’s exception mechanism to implement IMP exceptions is actually slightly harder than doing it “naturally”, so I recommend that you just implement the operational semantics rules. The `Makefile` includes a “`make test`” target that you should use (at least) to test your work.

Hint: to check if a termination `term` is an exception, use syntax like

```
begin match term with
| Normal -> do_something
| Exceptional(n) -> do_something_else using n
end
```

Modify the file `example-imp-command` so that it contains a “tricky” terminating IMP command (presumably involving exceptions) that can be parsed by our IMP test harness (e.g., “`imp < example-imp-command`” should not yield a parse error).

**Submission.** Turn in the formal component of the assignment as a single PDF document via the `gradescope` website. Your name and Michigan email address must appear on the first page of your PDF submission but may not appear anywhere else. Turn in the coding component of the assignment via the `autograder.io` website.