You should review the questions from the sample midterm exams, the real midterm exams, and the homework, as well as these question.

1. Write a function \texttt{get\_primes: int \rightarrow int list} that returns the list of primes less than or equal to the input. You may use the built-in functions \(/\) and \(\mod\). You will probably want to write one or more auxiliary functions. Remember that 0 and 1 are not prime.

Solution:

```ocaml
let rec every p l = match l with [] -> true | x::xs -> p x && every p xs
let not_divides n q = (q = 0) || not(n mod q = 0)
let rec get_primes n = match n with 0 -> [] | 1 -> [] | _ -> let primes = get_primes (n-1) in if every (not_divides n) primes then n::primes else primes
```

2. Write a tail-recursive function \texttt{largest: int list \rightarrow int option} that returns \texttt{Some} of the largest element in a list if there is one, or else \texttt{None} if the list is empty.

Solution:

```ocaml
let rec largest_aux lgst list = match list with [] -> lgst | x :: xs -> match lgst with None -> largest_aux (Some x) xs | Some l -> largest_aux (if l > x then lgst else (Some x)) xs
let largest = largest_aux None

(* I would also accept *)
let largest list = List.fold_left (fun lgst x -> match lgst with None -> Some x | Some l -> if l > x then lgst else Some x) None list
```

3. Write a function \texttt{dividek: int \rightarrow int list \rightarrow (int \rightarrow 'a) \rightarrow 'a}, that is in full Continuation Passing Style (CPS), that divides \(n\) successively by every number in the list, starting from the last element in the list. If a zero is encountered in the list, the function should pass 0 to \(k\) immediately, without doing any divisions. You should use...
```ocaml
# let divk x y k = k(x/y);;
val divk : int -> int -> (int -> 'a) -> 'a = <fun>

for the divisions. An example use of dividek would be

# let report n = print_string "Result: "; print_int n; print_string \"\n\";;
val report : int -> unit = <fun>
# dividek 6 [1;3;2] report;;
Result: 1
- : unit = ()

Solution: let eqk a b k = k(a = b)
  let rec dividek n list k =
      match list
      with [] -> k n
        | 0::xs -> k 0
        | x::xs ->
          dividek n xs
          (fun r -> eqk r 0 (fun b -> if b then k 0 else divk r x k))

4. a. Give most general (polymorphic) types for following functions (you don’t have to derive them):

let first lst = match lst with
   | a:: aa -> a;;

let rest lst = match lst with
   | [] -> []
   | a:: aa -> aa;;

Solution: first : ∀ 'a. a' list → 'a
rest : ∀ 'a. a' list → 'a list

b. Use these types (i.e., start in an environment with these identifiers bound to these types) to give a
polymorphic type derivation for:

let rec foldright f lst z =
   if lst = [] then z
   else f (first lst) (foldright f (rest lst) z))

in foldright (+) [2;3;4] 0

You should use the following types: [] : ∀'a. 'a list, and (::) : ∀'a. 'a -> 'a list → 'a list. Assume that the Relation Rule is extended to allow equality at all types.
```
Solution: Let us use LR for the Let Rec rule, F for the Function rule, A for the Application rule, If for the If-then-else rule, C for the Constants rule, V for the variable rule, and R for the Relations rule. Let

\[ \Gamma = \{ \text{first} : \forall 'a. 'a \text{ list} \to 'a; \text{rest} : \forall 'a. 'a \text{ list} \to ('a \text{ list}) \} \]
\[ \Gamma_1 = \{ \text{foldright} : ('a \to 'b \to 'b) \to ('a \text{ list}) \to 'b \to 'b \} \cup \Gamma \]
\[ \Gamma_2 = \{ \text{foldright} : \forall 'a 'b. ('a \to 'b \to 'b) \to ('a \text{ list}) \to 'b \to 'b \} \cup \Gamma \]
\[ \Gamma_3 = \{ f : 'a \to 'b \to 'b \} \cup \Gamma_1 \]
\[ \Gamma_4 = \{ 1st : 'a \text{ list} \} \cup \Gamma_3 \]
\[ \Gamma_5 = \{ z : 'b \} \cup \Gamma_4 \]

Let Tree1 =

\[
\begin{align*}
\Gamma_5 \vdash & \text{first} : 'a \text{ list} \to 'a & \Gamma_5 \vdash & \text{lst} : 'a \text{ list} \\
\Gamma_5 \vdash & f : 'a \to 'b & \Gamma_5 \vdash & \text{lst} : 'a \text{ list} \\
\Gamma_5 \vdash & f (\text{first lst}) : 'b & \Gamma_5 \vdash & \text{rest lst} : 'a \text{ list} \\
\end{align*}
\]

Let Tree2 =

\[
\begin{align*}
\Gamma_5 \vdash & \text{foldright} : ('a \to 'b \to 'b) \to ('a \text{ list}) \to 'b \to 'b \\
\Gamma_5 \vdash & f : ('a \to 'b \to 'b) \\
\Gamma_5 \vdash & \text{foldright} f : ('a \text{ list}) \to 'b \to 'b \\
\Gamma_5 \vdash & \text{foldright} f (\text{rest lst}) : 'b \to 'b \\
\Gamma_5 \vdash & \text{foldright} f (\text{rest lst}) z : 'b
\end{align*}
\]

The type variable 'a in each instance of the Variable rule for first and rest, we specialize 'a to int.

Let Tree3 =

\[
\begin{align*}
(\cdot ::) : \text{int} & \to C \\
\text{int list} \to \text{int} & \to C \\
2 : \text{int} & \to A \\
(\cdot ::) : \text{int list} \to \text{int} & \to C \\
(\cdot ::) : \text{int list} \to \text{int} & \to C \\
(\cdot ::) : \text{int list} \to \text{int} & \to A \\
(\cdot ::) : \text{int list} \to \text{int} & \to A \\
(\cdot ::) : \text{int list} \to \text{int} & \to A \\
\Gamma_1 \vdash & [2;3;4] : \text{int list}
\end{align*}
\]

In each instance of the Constant Rule for (:) and [], we specialize 'a to int.
Let \( \text{Tree}4 = \)

\[
\text{foldright} : (\text{int} \to \text{int} \to \text{int}) \to (\text{int list} \to \text{int} \to \text{int}) \\
\text{foldright} (+) : \text{int list} \to \text{int} \to \text{int} \\
\text{foldright} (+) [2;3;4] : \text{int} \\
\text{foldright} (+) 0 : \text{int}
\]

In the Variable Rule we specialize both ‘a and ‘b to int.

Using these proofs we have:

\[
\text{foldright} (+) [2;3;4] 0 : \text{int}
\]

This time, the ‘a in the Constant Rule for [] is specialized to ‘a.

5. For each of the regular expressions below (over the alphabet \{a,b,c\}), give a right regular gramar that derives exactly the same set of strings as the set of strings generated by the given regular expression.

i) \(a^*v b^*\vee c^*

ii) \((aba\vee bab)c(aa\vee bb))^*

iii) \((a^*b^*)^*(c\vee e)(b^*a^*)^*

Solution: i) \(a^*v b^*\vee c^*\)
6. Consider the following ambiguous grammar (Capitals are nonterminals, lowercase are terminals):

\[
\begin{align*}
S &::= \varepsilon | aA | bB | cC \\
A &::= \varepsilon | aA \\
B &::= \varepsilon | bB \\
C &::= \varepsilon | cC
\end{align*}
\]

ii) \((aba\lor bab)(aa\lor bb))^* \quad \begin{align*}
S &::= \varepsilon | aA | bB \\
A &::= bC \\
B &::= aD \\
C &::= aE \\
D &::= bE \\
E &::= cF \\
F &::= aG | bH \\
G &::= aS \\
H &::= bS
\end{align*}

iii) \((a^*b^*)(c\lor\varepsilon)(b^*a^*))^* \quad \begin{align*}
S &::= \varepsilon | aS | bS | cA \\
A &::= \varepsilon | aA | bA
\end{align*}

6. Consider the following ambiguous grammar (Capitals are nonterminals, lowercase are terminals):

\[
\begin{align*}
S &::= A \ a \ B \ | \ B \ a \ A \\
A &::= b \ | \ c \\
B &::= a \ | \ b
\end{align*}
\]

a. Give an example of a string for which this grammar has two different parse trees, and give their parse trees.
   **Solution:** A string with two parses is “bab”, and its parse trees are:

   ![Parse Trees for “bab”]

b. Disambiguate this grammar.
   **Solution:** \[ S ::= b \ a \ a \ | \ b \ a \ b \ | \ c \ a \ a \ | \ c \ a \ b \ | \ a \ a \ b \ | \ a \ a \ c \ | \ b \ a \ c \]
7. Write an unambiguous grammar for regular expressions over the alphabet \{a, b\}. The Kleene star binds most tightly, followed by concatenation, and then choice. Here we will have concatenation and choice associate to the right. Write an Ocaml datatype corresponding to the tokens for parsing regular expressions, and one for capturing the abstract syntax trees corresponding to parses given by your grammar. Write a recursive descent parser for regular expressions, taking a list of tokens and producing an option (Some) of an abstract syntax tree if a parse for the whole list exists, or None otherwise.

Solution:

\[
\begin{align*}
\text{reg} &::= a \mid b \mid \varepsilon \mid (\text{reg}) \mid \text{reg} \lor \text{reg} \mid \text{reg} \cdot \text{reg} \\
\text{Atom} &::= a \mid b \mid \varepsilon \mid (\text{RegExp}) \\
\text{Star} &::= \text{Atom} \lor \text{Star} \\
\text{Concat} &::= \text{Star} \lor \text{Star} \lor \text{Concat} \lor \text{RegExp} \\
\text{RegExp} &::= \text{Concat} \lor \text{Concat} \lor \text{RegExp}
\end{align*}
\]

type tokens = A_tk | B_tk | Epsilon_tk | LParen | RParen | Star_tk | Or_tk

type atom = A | B | Epsilon | Paren of regexp

and star = Atom of atom | Star of star

and concat = StarAsConcat of star | Concat of (star * concat)

and regexp = ConcatAsRegExp of concat | Choice of (concat * regexp)

let rec mk_star (tree, tokens) =
match tokens with
Star_tk::more_toks -> mk_star (Star tree, more_toks)
| _ -> (tree, tokens)

let rec atom tokens =
match tokens with
(A_tk::rem_toks) -> (Some A,rem_toks)
| (B_tk::rem_toks) -> (Some B,rem_toks)
| (Epsilon_tk::rem_toks) -> (Some Epsilon,rem_toks)
| (LParen::more_toks) ->
(match regexp more_toks with
(Some tree, RParen::rem_toks) -> (Some(Paren tree),rem_toks)
| (_, rem_toks) -> (None, rem_toks))
| _ -> (None, tokens)

let rec mk_atom_tokens =
match atom tokens with
(Some tree, rem_toks) -> (Some A,rem_toks)
| (Some tree, rem_toks) -> (Some B,rem_toks)
| (Some Epsilon, rem_toks) -> (Some Epsilon, rem_toks)
| (Some Paren tree, rem_toks) -> (Some Paren tree, rem_toks)
| (_, rem_toks) -> (None, rem_toks)

and star_tokens =
match star_tokens with
(Some tree, rem_toks) -> (Some tree, rem_toks)
| (Some tree, rem_toks) with
(match mk_star (Atom tree, rem_toks) with
(stree, toks) -> (Some stree, toks))
| (None, rem_toks) -> (None, rem_toks)

and concat_tokens =
match concat_tokens with
(Some tree, rem_toks) -> (Some tree, rem_toks)
| (Some tree, rem_toks) with
A_tk::_ ->
(match concat rem_toks with (Some tree1, more_toks) ->
(Some(Concat(tree,tree1)), more_toks)
8. a. Write the transition semantics rules for if _ then _ else and repeat _ until _. (A repeat _ until _ executes the code in the body of the loop and then checks the condition, exiting if the condition is true.)

Solution: Let \( m \) represent the current state. If then else rules:

\[
\begin{align*}
\text{(if true then } C_1 \text{ else } C_2 \text{ fi ,} m) & \rightarrow (C_1, m) \\
\text{(if false then } C_1 \text{ else } C_2, m) \text{ fi } & \rightarrow (C_2, m) \\
(B, m) & \rightarrow (B', m) \\
\text{(if } B \text{ then } C_1 \text{ else } C \text{ fi ,} m) & \rightarrow \text{(if } B' \text{ then } C_1 \text{ else } C_1 \text{ fi ,} m) \\
\text{(repeat } C \text{ until } B, m) & \rightarrow (C; \text{if } B \text{ then skip else (repeat } C \text{ until } B) \text{ fi ,} m)
\end{align*}
\]

b. Assume we have an OCaml type \texttt{bexp} with constructors \texttt{True} and \texttt{False} corresponding to true and false, and other constructors representing the syntax trees of non-value boolean expressions. Further assume we have a type \texttt{mem} of memory associating variables (represented by strings) with
values, a type \texttt{exp} for integer expressions in our language, a type \texttt{comm} for language commands with constructors including \texttt{IfThenElse} of \texttt{bexp * comm * comm}, \texttt{RepeatUntil} of \texttt{comm * bexp}, and \texttt{Seq}: \texttt{comm * comm}, and type

\[
\text{type eval_comm_result}\ =\ \text{Mid}\ of\ (\text{comm} * \text{mem})\ |\ \text{Done}\ of\ \text{mem}
\]

Further suppose we have a function \texttt{eval_bexp} : \texttt{(bexp * mem) -> (bexp * mem)} that returns the result of one step of evaluation of an expression.

Write Ocaml clauses for a function \texttt{eval_comm} : \texttt{(comm*mem) -> eval_comm_result} for the case of \texttt{IfThenElse} and \texttt{RepeatUntil}. You may assume that all other needed clauses of \texttt{eval_comm} have been defined, as well as the function \texttt{eval_bexp} : \texttt{(bexp*mem) -> (bexp*mem)}.

Solution: let rec eval_comm (comm, mem) =

\[
\text{match comm with} \\
\text{let rec eval_comm (comm, mem) =} \\
\text{match comm with} \\
\text{| IfThenElse (True, thenclause, elseclause) -> Mid (thenclause, mem)} \\
\text{| IfThenElse (False, thenclause, elseclause) -> Mid (elseclause, mem)} \\
\text{| IfThenElse (b, thenclause, elseclause) ->} \\
\text{let rec eval_comm (comm, mem) =} \\
\text{| repeatuntil (c, b) ->} \\
\text{mid (seq (c, ifthenelse (b, skip, repeatuntil (c, b))), mem)}
\]

9. Assume you are given the OCaml types \texttt{exp}, \texttt{bool_exp} and \texttt{comm} with (partially given) type definitions:

\[
\text{type comm} = \ldots | \text{If of (bool_exp * comm * comm)} | \ldots \\
\text{type bool_exp} = \text{True_exp} | \text{False_exp} | \ldots
\]

where the constructor \texttt{If} is for the abstract syntax of an \texttt{if.then.else} construct. Also assume you have a type \texttt{mem} of memory associating values to identifiers, where values are just integers (\texttt{int}). Further assume you are given a function \texttt{eval_bool} : \texttt{(mem * bool_exp) -> bool} for evaluating boolean expressions.

Write the OCaml code for the clause of \texttt{eval_comm} : \texttt{(mem * comm) -> mem} that implements the following natural semantics rules for the evaluation of \texttt{if.then.else} commands:

\[
\frac{}{(m, b) \downarrow \text{true} \quad (m, C_1) \downarrow m'} \quad \frac{}{(m, b) \downarrow \text{false} \quad (m, C_2) \downarrow m''} \\
\frac{}{(m, \text{if } b \text{ then } C_1 \text{ else } C_2) \downarrow m'} \quad \frac{}{(m, \text{if } b \text{ then } C_1 \text{ else } C_2) \downarrow m''}
\]

Solution: let rec eval_comm (mem, comm) =

\[
\text{match comm with} \ldots \\
\text{| If (bexp, c_1, c_2) ->} \\
\text{match eval_bool (mem, bexp) with true -> eval_comm (mem, c_1)} \\
\text{| false -> eval_comm (mem, c_2)} \\
\text{. . .
\]
10. Using the natural semantics rules given in class, give a proof that, starting with a memory that maps
x to 5 and y to 3, if x = y then z := x else z := x + y evaluates to a memory where x maps to 5,
y maps to 3. and z maps to 8.

Solution: Let \( m = \{ x \mapsto 5; y \mapsto 3 \} \).

\[
\begin{array}{ccc}
\langle m, x \rangle \downarrow 5 & \langle m, y \rangle \downarrow 3 & (5 = 3) = \text{false} \\
\langle \{ x \mapsto 5; y \mapsto 3 \}, x = y \rangle \downarrow \text{false} & \langle \{ x \mapsto 5; y \mapsto 3 \}, z := x + y \rangle \downarrow \langle \{ x \mapsto 5; y \mapsto 3; z \mapsto 8 \} \rangle \\
\end{array}
\]

11. Prove that \( \lambda x.x(\lambda z.xzx) \) is \( \alpha \)-equivalent \( \lambda z.z(\lambda x.xzx) \). You should label every use of \( \alpha \)-conversion and
congruence.

Solution: By \( \alpha \)-conversion

\( \lambda x.x(\lambda z.xzx) \xrightarrow{\alpha} \lambda y.y(\lambda z.zyz) \).

Because \( \alpha \)-conversion implies \( \alpha \)-equivalence, we have

\( \lambda x.x(\lambda z.xzx) \xrightarrow{\alpha} \lambda y.y(\lambda z.zyz) \).

By \( \alpha \)-conversion

\( \lambda z.zyz \xrightarrow{\alpha} \lambda x.xyx \)

and thus

\( \lambda z.zyz \xrightarrow{\alpha} \lambda x.xyx \).

By congruence for application, we have

\( \beta(\lambda z.zyz) \xrightarrow{\alpha} \beta(\lambda x.xyx) \),

and by congruence for abstraction, we have

\( \lambda y.y(\lambda z.zyz) \xrightarrow{\alpha} \lambda y.y(\lambda x.xyx) \).

By transitivity, we then have

\( \lambda x.x(\lambda z.xzx) \xrightarrow{\alpha} \lambda y.y(\lambda x.xyx) \).

By \( \alpha \)-conversion,

\( \lambda y.y(\lambda x.xyx)z \xrightarrow{\alpha} \lambda z.z(\lambda x.xzx) \)

Again, because \( \alpha \)-conversion implies \( \alpha \)-equivalence, we have

\( \lambda y.y(\lambda x.xyx) \xrightarrow{\alpha} \lambda z.z(\lambda x.xzx) \)

and by transitivity, we have

\( \lambda x.x(\lambda z.xzx) \xrightarrow{\alpha} \lambda z.z(\lambda x.xzx) \)

as was to be shown.
12. Reduce the following expression: \((\lambda x.\lambda y. yz)((\lambda x.xxx)(\lambda x.xx))\)

a. Assuming Call by Name (Lazy Evaluation)

**Solution:** With Call by Name (Lazy Evaluation):
\[(\lambda x.\lambda y. yz)((\lambda x.xxx)(\lambda x.xx)) \rightarrow (\lambda y. yz)\]

b. Assuming Call by Value (Eager Evaluation)

**Solution:** With Call by Value (Eager Evaluation):
\[(\lambda x.\lambda y. yz)((\lambda x.xxx)(\lambda x.xx)) \rightarrow (\lambda x.\lambda y. yz)((\lambda x.xx)(\lambda x.xx)(\lambda x.xx)) \rightarrow (\lambda x.\lambda y. yz)((\lambda x.xx)(\lambda x.xx)(\lambda x.xx)) \rightarrow \ldots \text{(the expression doesn’t terminate)}\]

c. To full \(\alpha\beta\)-normal form.

**Solution:** Since lazy evaluation yielded an \(\alpha\beta\)-normal form. we may use its reduction: \((\lambda x.\lambda y. yz)((\lambda x.xxx)(\lambda x.xx))\) \(\rightarrow (\lambda y. yz)\)

13. Give a proof in Floyd-Hoare logic of the partial correctness assertion:

\[
\{\text{True}\} \ y := w; \text{if } x = y \text{ then } z := x \text{ else } z := y \{z = w\}
\]

**Solution:** Because this proof tree is rather wide, we shall break it up into pieces.

Let \(Tree1 =\)

\[
\begin{align*}
((y = w) \land (x = y)) & \Rightarrow (x = w) \quad \{x = w\} \quad \{z := x \land z = w\} \quad \text{A} \\
\end{align*}
\]

PS

\[
\begin{align*}
\{(y = w) \land (x = y)\} & \Rightarrow z := x \land \{z = w\} \quad \text{PS} \\
\end{align*}
\]

Let \(Tree2 =\)

\[
\begin{align*}
\{(y = w) \land (x \neq y)\} & \Rightarrow (y = w) \quad \{y = w\} \quad \{z := y \land z = w\} \quad \text{A} \\
\end{align*}
\]

PS

\[
\begin{align*}
\{(y = w) \land (x \neq y)\} & \Rightarrow z := y \land \{z = w\} \quad \text{PS} \\
\end{align*}
\]

Then the main proof tree is

\[
\begin{align*}
\text{True} & \Rightarrow (w = w) \quad \{w = w\} \quad \{y := w \land y = w\} \quad \text{A} \\
\end{align*}
\]

PS

\[
\begin{align*}
\{\text{True}\} \ y := w \ {\{y = w\}} \quad \text{PS} \quad \begin{align*}
Tree1 & \quad Tree2 \\
\{y = w\} & \text{if } x = y \text{ then } z := x \text{ else } z := y \land \{z = w\} \quad \text{ITE} \\
\end{align*}
\]

Seq

\[
\{\text{True}\} \ y := w; \text{if } x = y \text{ then } z := x \text{ else } z := y \land \{z = w\}
\]

14. What should the Floyd-Hoare logic rule for \texttt{repeat C until B} be? The code causes \(C\) to be executed, and then, if \(B\) is true it completes, and otherwise it does \texttt{repeat C} \texttt{until B} again.
Solution:

\[
(Q \lor (P \land \neg B)) \text{ } C \{P\}
\]

\[
\{Q\} \text{ repeat } C \text{ until } B \{P \land B\}
\]

But I would accept the weaker

\[
\{P\} \text{ } C \{P\}
\]

\[
\{P\} \text{ repeat } C \text{ until } B \{P \land B\}
\]