

```

1  (*
2                                     CS51 Lab 3
3                                     Polymorphism and record types
4  *)
5
6  (*
7                                     SOLUTION
8  *)
9
10 (*=====
11 Readings:
12
13     This lab builds on material from Chapters 7.4 and 9-9.5 of the
14     textbook <http://book.cs51.io>, which should be read before the lab
15     session.
16
17 Objective:
18
19     In this lab, you'll exercise your understanding of polymorphism and
20     record types. Some of the problems extend those from Lab 2, but we'll
21     provide the necessary background code from that lab.
22     =====*)
23
24 (*=====
25 Part 1: Records and tuples
26
27 Records and tuples provide two different ways to package together
28 data. They differ in whether their components are selected by *name*
29 or by *position*, respectively.
30
31 Consider a point in Cartesian (x-y) coordinates. A point is specified
32 by its x and y values, which we'll take to be ints. We can package
33 these together as a pair (a 2-tuple), as in the following data type
34 definition: *)
35
36 type point_pair = int * int ;;
37
38 (* Then, we can add two points (summing their x and y coordinates
39 separately) with the following function:
40
41     let add_point_pair (p1 : point_pair) (p2 : point_pair) : point_pair =
42         let x1, y1 = p1 in
43         let x2, y2 = p2 in
44         (x1 + x2, y1 + y2) ;;

```

```

45
46 .....
47 Exercise 1:
48
49 It might be nicer to deconstruct the points in a single match, rather
50 than the two separate matches in the two `let` expressions. Reimplement
51 `add_point_pair` to use a single pattern match in a single `let`
52 expression.
53 .....*)
54
55 let add_point_pair (p1 : point_pair) (p2 : point_pair) : point_pair =
56   let (x1, y1), (x2, y2) = p1, p2 in
57     x1 + x2, y1 + y2 ;;
58
59 (* Analogously, we can define a point by using a record to package up
60 the x and y coordinates. *)
61
62 type point_recd = {x : int; y : int} ;;
63
64 let example_point_recd = {x = 1; y = 3} ;;
65
66 (*.....
67 Exercise 2A:
68
69 Replace the two lines below with a single top-level `let` expression
70 that extracts the x and y coordinate values from `example_point_recd`
71 above into global variables `x1` and `y1`, respectively.
72 .....*)
73
74 let {x = x1; y = y1} = example_point_recd ;;
75
76 (*.....
77 Exercise 2B:
78
79 Implement a function `add_point_recd` to add two points of type
80 `point_recd` and returning a `point_recd` as well.
81 .....*)
82
83 (* A direct reimplementaion of `add_point_pair` would be: *)
84
85 let add_point_recd (p1 : point_recd) (p2 : point_recd) : point_recd =
86   let {x = x1; y = y1}, {x = x2; y = y2} = p1, p2 in
87     {x = x1 + x2; y = y1 + y2} ;;
88
89 (* By making use of dot notation for selecting record elements, this
90 version may be a bit cleaner

```

```

91
92     let add_point_recd (p1 : point_recd) (p2 : point_recd) : point_recd =
93         {x = p1.x + p2.x; y = p1.y + p2.y} ;;
94     *)
95
96     (* Recall the dot product from Lab 2. The dot product of two points
97     'x1, y1' and 'x2, y2' is the sum of the products of their x and y
98     coordinates.
99
100     .....
101     Exercise 3: Write a function 'dot_product_pair' to compute the dot
102     product for points encoded as the 'point_pair' type.
103     .....*)
104
105     let dot_product_pair (x1, y1 : point_pair) (x2, y2 : point_pair) : int =
106         x1 * x2 + y1 * y2 ;;
107
108     (* In this example, we've gone even further, performing the match
109     directly in the 'let' definition of the function itself. This is
110     actually the stylistically preferred way of implementing this in
111     OCaml, as discussed in the Style Guide. Can you adjust the solution
112     to Exercises 1 and 2B to use this syntactic sugar? *)
113
114     (*.....
115     Exercise 4: Write a function 'dot_product_recd' to compute the dot
116     product for points encoded as the 'point_recd' type.
117     .....*)
118
119     let dot_product_recd (p1 : point_recd) (p2 : point_recd) : int =
120         p1.x * p2.x + p1.y * p2.y ;;
121
122     (* Converting between the pair and record representations of points
123
124     You might imagine that the two representations have
125     different advantages, such that two libraries, say, might use
126     differing types for points. In that case, we may want to have
127     functions to convert between the two representations.
128
129     .....
130     Exercise 5: Write a function 'point_pair_to_recd' that converts a
131     'point_pair' to a 'point_recd'.
132     .....*)
133
134     let point_pair_to_recd (x, y : point_pair) : point_recd =
135         {x; y} ;;
136

```

```

137 (* Note the use of pattern-matching for deconstruction directly in the
138    argument and of "field punning". Without those techniques, we'd
139    have the more cumbersome:
140
141    let point_pair_to_recd (p : point_pair) : point_recd =
142      let x, y = p in
143      {x = x; y = y} ;;
144      *)
145
146 (*.....
147 Exercise 6: Write a function `point_recd_to_pair` that converts a
148 `point_recd` to a `point_pair`.
149 .....*)
150
151 let point_recd_to_pair ({x; y} : point_recd) : point_pair =
152   x, y ;;
153
154 (*=====
155 Part 2: A simple database of records
156
157 A college wants to store student records in a simple database,
158 implemented as a list of individual course enrollments. The enrollments
159 themselves are implemented as a record type, called `enrollment`, with
160 `string` fields labeled `name` and `course` and an integer student ID
161 number labeled `id`. The appropriate type definition is: *)
162
163 type enrollment = { name : string;
164                    id : int;
165                    course : string } ;;
166
167 (* Here's an example of a list of enrollments. *)
168
169 let college =
170   [ { name = "Pat";    id = 603858772; course = "cs51" };
171     { name = "Pat";    id = 603858772; course = "expos20" };
172     { name = "Kim";    id = 482958285; course = "expos20" };
173     { name = "Kim";    id = 482958285; course = "cs20" };
174     { name = "Sandy";  id = 993855891; course = "ls1b" };
175     { name = "Pat";    id = 603858772; course = "ec10b" };
176     { name = "Sandy";  id = 993855891; course = "cs51" };
177     { name = "Sandy";  id = 482958285; course = "ec10b" }
178   ] ;;
179
180 (* In the following exercises, you'll want to avail yourself of the
181 `List` module functions, writing the requested functions in
182 higher-order style rather than handling the recursion yourself.

```

```

183
184 .....
185 Exercise 7: Define a function called `transcript` that takes an
186 `enrollment list` and returns a list of all the enrollments for a given
187 student as specified by the student's ID.
188
189 For example:
190
191     # transcript college 993855891 ;;
192     - : enrollment list =
193       [{name = "Sandy"; id = 993855891; course = "ls1b"};
194        {name = "Sandy"; id = 993855891; course = "cs51"}]
195     .....*)
196
197 let transcript (enrollments : enrollment list)
198   (student : int)
199   : enrollment list =
200   List.filter (fun { id; _ } -> id = student) enrollments ;;
201   (*      ^^--- field punning!
202
203 Note the use of field punning, using the `id` variable to refer to
204 the value of the `id` field.
205
206 An alternative approach is to use the dot notation to pick out the
207 record field.
208
209     let transcript (enrollments : enrollment list)
210       (student : int)
211       : enrollment list =
212       List.filter (fun studentrec -> studentrec.id = student)
213         enrollments ;;
214     *)
215
216   (*.....
217 Exercise 8: Define a function called `ids` that takes an `enrollment
218 list` and returns a list of all the ID numbers in that list,
219 eliminating any duplicates. Hint: The `map` and `sort_uniq` functions
220 from the `List` module and the `compare` function from the `Stdlib`
221 module may be useful here.
222
223 For example:
224
225     # ids college ;;
226     - : int list = [482958285; 603858772; 993855891]
227     .....*)
228

```

```

229 (* Making good use of the recommended library functions, we have the
230    following succinct implementation: *)
231
232 let ids (enrollments: enrollment list) : int list =
233     List.sort_uniq (compare)
234         (List.map (fun student -> student.id) enrollments) ;;
235
236 (* This time we used the alternative strategy of picking out the 'id'
237    using dot notation.
238
239    By the way, the aggregation to eliminate duplicates can also be
240    done using a fold. We leave that strategy as an additional
241    exercise. *)
242
243 (* There's a big problem with this database design: nothing guarantees
244    that a given student ID is associated with a single name. The right
245    thing to do is to use a different database design where this kind of
246    thing can't happen; that would be an application of the *edict of
247    prevention*. But for the purpose of this lab, you'll just write a
248    function to verify that this problem doesn't occur.
249
250    .....
251    Exercise 9: Define a function 'verify' that determines whether all the
252    entries in an enrollment list for each of the ids appearing in the
253    list have the same name associated. Hint: You may want to use
254    functions from the 'List' module such as 'map', 'for_all',
255    'sort_uniq'.
256
257    For example:
258
259        # verify college ;;
260        - : bool = false
261
262    (Do you see why it's false?)
263    .....*)
264
265 (* We start with a function to extract all the names from the database. *)
266 let names (enrollments : enrollment list) : string list =
267     List.sort_uniq (compare)
268         (List.map (fun { name; _ } -> name) enrollments) ;;
269
270 (* Then we verify that for each id, the list of names associated with
271    the courses in that id's transcript has length 1. *)
272 let verify (enrollments : enrollment list) : bool =
273     List.for_all (fun l -> List.length l = 1)
274         (List.map

```

```

275         (fun student -> names (transcript enrollments student))
276         (ids enrollments)) ;;
277
278 (* By the way, the computed value in the example is false because
279    Sandy appears with Kim's ID number in one of the entries. *)
280
281 (*=====
282 Part 3: Polymorphism
283
284 .....
285 Exercise 10: In Lab 2, you implemented a function `zip` that takes two
286 lists and "zips" them together into a list of pairs. Here's a possible
287 implementation of `zip`:
288
289     let rec zip (x : int list) (y : int list) : (int * int) list =
290         match x, y with
291         | [], [] -> []
292         | xhd :: xtl, yhd :: ytl -> (xhd, yhd) :: (zip xtl ytl) ;;
293
294 As implemented, this function works only on integer lists. Revise your
295 solution to operate polymorphically on lists of any type. What is the
296 type of the result? Did you provide full typing information in the
297 first line of the definition? (As usual, for the time being, don't
298 worry about explicitly handling the anomalous case when the two lists
299 are of different lengths.)
300 .....*)
301
302 [@@@warning "-8"]
303 let rec zip (x : 'a list) (y : 'b list) : ('a * 'b) list =
304     match x, y with
305     | [], [] -> []
306     | xhd :: xtl, yhd :: ytl -> (xhd, yhd) :: (zip xtl ytl) ;;
307
308 (* Notice how a polymorphic typing was provided in the first line, to
309    capture the intention of the polymorphic function.
310
311    You can ignore the non-exhaustive match warning, which occurs
312    because we have no match cases for when only one of the two
313    argument lists is empty. We'll have better tools to address that
314    issue later. *)
315
316 (*.....
317 Exercise 11: Partitioning a list -- Given a function returning a
318 boolean, for instance
319
320     fun x -> x mod 3 = 0

```

```

321
322 and a list of elements, for instance
323
324     [3; 4; 5; 10; 11; 12; 1]
325
326 we can partition the list into two lists, the list of elements
327 satisfying the boolean function ([3; 12]) and the list of elements
328 that don't ([4; 5; 10; 11; 1]).
329
330 The library function List.partition partitions its list argument in
331 just this way, returning a pair of lists. Here's an example:
332
333     # List.partition (fun x -> x mod 3 = 0) [3; 4; 5; 10; 11; 12; 1] ;;
334     - : int list * int list = ([3; 12], [4; 5; 10; 11; 1])
335
336 What is the type of the partition function, keeping in mind that it
337 should be as polymorphic as possible?
338
339 Now implement the function yourself (without using List.partition of
340 course, though other List module functions may be useful).
341 .....*)
342
343 (* Let's start by working out the type. The partition function takes
344    two arguments, a boolean condition and a list of elements. The
345    boolean condition might apply to elements of any type, so it should
346    be a function of type 'a -> bool'. The list must contain elements
347    appropriate to apply the condition to, that is, elements of type
348    'a', so the list itself is of type 'a list'. The result is a pair
349    of lists, each of which contains elements of type 'a', that is,
350    'a list * 'a list'. The type of partition itself is then
351
352     ('a -> bool) -> 'a list -> 'a list * 'a list
353
354    The implementation is really straightforward if we just reuse the
355    filtering functionality of the List.filter function. *)
356
357 let partition (condition : 'a -> bool) (lst : 'a list)
358     : 'a list * 'a list =
359     let open List in
360     filter condition lst, filter (fun x -> not (condition x)) lst ;;
361
362 (* If, instead, we want to perform the walking of the list directly,
363    we might have
364
365     let rec partition (condition : 'a -> bool) (lst : 'a list)
366         : 'a list * 'a list =

```



```

367     match lst with
368     | [] -> [], []
369     | hd :: tl ->
370         let yeses, noes = partition condition tl in
371         if condition hd then (hd :: yeses), noes
372         else yeses, (hd :: noes) ;;
373
374     An implementation with a single fold is also possible.
375
376     let partition (condition : 'a -> bool) (lst : 'a list)
377         : 'a list * 'a list =
378         List.fold_right (fun elt (yeses, noes) ->
379             if condition elt then (elt :: yeses), noes
380             else yeses, (elt :: noes))
381             lst
382             ([], []) ;;
383
384     To think about: Which of these do you like best? What are the
385     advantages and disadvantages of each?
386 *)
387
388 (*=====
389 Part 4: Implementing polymorphic application, currying, and uncurrying
390
391 .....
392 Exercise 12: We can think of function application itself as a
393 polymorphic higher-order function (:exploding_head:). It takes two
394 arguments -- a function and its argument -- and returns the value
395 obtained by applying the function to its argument. In this exercise,
396 you'll write this function, called 'apply'. You might use it as in the
397 following examples:
398
399     # apply pred 42 ;;
400     - : int = 41
401     # apply (fun x -> x ** 2.) 3.14159 ;;
402     - : float = 9.86958772809999907
403     # apply int_of_float 3.14159 ;;
404     - : int = 3
405
406     An aside: You may think such a function isn't useful, since we
407     already have an even more elegant notation for function
408     application, as in
409
410     # pred 42 ;;
411     - : int = 41
412     # (fun x -> x ** 2.) 3.14159 ;;

```

```

413         - : float = 9.869587728099999907
414         # int_of_float 3.14159 ;;
415         - : int = 3
416
417         But we'll see a quite useful operator that works similarly --
418         the backwards application operator -- in Chapter 11 of the
419         textbook.
420
421     Start by thinking about the type of the function. We'll assume it
422     takes its two arguments curried, that is, one at a time.
423
424     1. What is the most general (polymorphic) type for its first argument
425         (the function to be applied)?
426
427     2. What is the most general type for its second argument (the argument
428         to apply it to)?
429
430     3. What is the type of its result?
431
432     4. Given the above, what should the type of the function `apply` be?
433
434     Now write the function.
435
436     Can you think of a reason that the `apply` function might in fact be
437     useful?
438     .....*)
439
440     (* Thinking through the types of the `apply` function:
441
442     1. Its first argument, the function to be applied, itself takes an
443         argument of some generic type, call it `arg`. (We're not
444         restricted to type variables like `a`, `b`, `c`. We might as
445         well use a good mnemonic type variable name like `arg`.) The
446         result type for the function to be applied we'll call
447         `result`. So the type of the first argument is `arg ->
448         result`.
449
450     2. Its second argument is the argument to apply that function to,
451         and must thus be of type `arg`.
452
453     3. The type of the result of the application is, of course,
454         `result`.
455
456     4. So the type for apply is given by the typing:
457
458         apply : (arg -> result) -> arg -> result

```

```

459
460     Types in hand, the apply function itself is truly trivial to
461     implement: *)
462
463 let apply (func : 'arg -> 'result) (arg : 'arg) : 'result =
464     func arg ;;
465
466 (* Something to think about: One reason the `apply` function might be
467    useful is that it might be handy as *an argument to another
468    higher-order function*. *)
469
470 (*.....
471 Exercise 13: In the next two exercises, you'll define polymorphic
472 higher-order functions `curry` and `uncurry` for currying and uncurrying
473 binary functions (functions of two arguments). The functions are named
474 after mathematician Haskell Curry '1920. (By way of reminder, a
475 curried function takes its arguments one at a time. An uncurried
476 function takes them all at once in a tuple.)
477
478 We start with the polymorphic higher-order function `curry`, which
479 takes as its argument an uncurried binary function and returns the
480 curried version of its argument function.
481
482 Before starting to code, pull out a sheet of paper and a pencil and
483 work out with your partner the answers to the following seven
484 questions.
485
486     *****
487     Do not skip this pencil and paper work.
488     *****
489
490 1. What is the type of the argument to the function `curry`? Write down
491    a type expression for the argument type.
492
493 2. What is an example of a function that `curry` could apply to?
494
495 3. What is the type of the result of the function `curry`? Write down a
496    type expression for the result type.
497
498 4. What should the result of applying the function `curry` to the
499    function from (2) be?
500
501 5. Given (1) and (2), write down a type expression for the type of the
502    `curry` function itself.
503
504 6. What would a good variable name for the argument to `curry` be?

```

505  
506 7. Write down the header line for the definition of the `'curry'` function.  
507  
508 Call over a staff member to go over your answers to these  
509 questions. Once you fully understand all this, its time to implement  
510 the function `'curry'`.  
511 .....\*)  
512  
513 (\* In order to think through this problem, it helps to start with the  
514 types of the functions. The `'curry'` function is a `*function*`; it has  
515 a function type, of the form `_ -> _`. It is intended to take an  
516 uncurried binary function as its argument, and return the  
517 corresponding curried function. An uncurried binary function is a  
518 function that takes its two arguments both "at the same time", that  
519 is, as a pair. Generically, the type of such a function is thus  
520  
521 `'a * 'b -> 'c'` (that's the answer to question (1) above)  
522  
523 An example (2) would be the function that adds the elements of an  
524 `'int'` pair:  
525  
526 `'fun (x, y) -> x + y'`  
527  
528 A curried binary function takes its two arguments "one at a time".  
529 Its type is  
530  
531 `'a -> ('b -> 'c)'`  
532  
533 which is the appropriate result type for the curry function (3). For  
534 instance, the curried version of the integer addition function is  
535 just the `'(+)'` operator itself (4).  
536  
537 Putting these together, the type of curry should be (5)  
538  
539 `(('a * 'b) -> 'c) -> ('a -> ('b -> 'c))` .  
540  
541 Dropping extraneous parentheses since the `'->'` type operator is right  
542 associative (and of lower precedence than `'*'`, we can also write this  
543 as  
544  
545 `('a * 'b -> 'c) -> 'a -> 'b -> 'c` .  
546  
547 A good name for the argument of the curry function is `'uncurried'`  
548 (6), to emphasize that it is an uncurried function.  
549  
550 This type information already gives us a big hint as to how to

```

551 write the curry function. We start with the first line giving the
552 argument structure (7):
553
554     let curry (uncurried : 'a * 'b -> 'c) : 'a -> 'b -> 'c = ...
555
556 The return type is a function type, so we'll want to build a
557 function value to return. We use the `fun _ -> _` anonymous
558 function construction to do so, carefully labeling the type of the
559 function's argument as a reminder of what's going on:
560
561     let curry (uncurried : 'a * 'b -> 'c) : 'a -> 'b -> 'c =
562         fun (x : 'a) -> ...
563
564 The type of the argument of this anonymous function is ``a` because
565 its type as a whole -- the return type of `curry` itself -- is ``a
566 -> ('b -> 'c)`. This function should return a function of type ``b
567 -> 'c`. We'll construct that as an anonymous function as well:
568
569     let curry (uncurried : 'a * 'b -> 'c) : 'a -> 'b -> 'c =
570         fun (x : 'a) ->
571             fun (y : 'b) -> ...
572
573 Now, how should we construct the value (of type ``c`) that this
574 inner function should return? Remember that curry should return a
575 curried function whose value is the same as the uncurried function
576 would have delivered on arguments `x` and `y`. So we can simply
577 apply `uncurried` to `x` and `y` (in an uncurried fashion, of
578 course), to obtain the value of type ``c`:
579
580     let curry (uncurried : 'a * 'b -> 'c) : 'a -> 'b -> 'c =
581         fun (x : 'a) ->
582             fun (y : 'b) -> uncurried (x, y) ;;
583
584 You'll note that all of these anonymous functions are a bit
585 cumbersome, and we have a nicer notation for defining functions in
586 let expressions incorporating the arguments in the definition part
587 itself. We've already done so for the argument uncurried. Let's use
588 that notation for the `x` and `y` arguments as well.
589
590     let curry (uncurried : 'a * 'b -> 'c) (x : 'a) (y : 'b) : 'c =
591         uncurried (x, y) ;;
592
593 To make clearer what's going on, we can even drop the explicit
594 types to show the structure of the computation:
595
596     let curry uncurried x y = uncurried (x, y) ;;

```

```

597
598 Here, we see what's really going on: `curry uncurried` when applied
599 to `x` and `y` in curried fashion gives the same value that
600 `uncurried` gives when applied to `x` and `y` in uncurried fashion.
601
602 By a similar argument (which it might be useful to carry out
603 yourself), uncurry is implemented as
604
605     let uncurry curried (x, y) = curried x y ;;
606
607 Below, we use the version with explicit types, as we generally want
608 to do to make our typing intentions known to the
609 compiler/interpreter. *)
610
611 let curry (uncurried : 'a * 'b -> 'c) (x : 'a) (y : 'b) : 'c =
612     uncurried (x, y) ;;
613
614 (*.....
615 Exercise 14: Now implement the polymorphic higher-order function
616 `uncurry`, which takes as its argument a curried function and returns
617 the uncurried version of its argument function. You may want to go
618 through the same 7-step process to get started.
619 .....*)
620
621 let uncurry (curried : 'a -> 'b -> 'c) (x, y : 'a * 'b) : 'c =
622     curried x y ;;
623
624 (*.....
625 Exercise 15: OCaml's built in binary operators, like `+` and `*` are
626 curried. You can tell from their types:
627
628     # ( + ) ;;
629     - : int -> int -> int = <fun>
630     # ( * ) ;;
631     - : int -> int -> int = <fun>
632
633 Using your `uncurry` function, define uncurried versions of the `+` and
634 `*` functions. Call them `plus` and `times`.
635 .....*)
636
637 let plus = uncurry ( + ) ;;
638
639 let times = uncurry ( * ) ;;
640
641 (* Did you write something like this?
642

```

```

643     let plus x y =
644         ...more stuff here...
645
646     Remember, functions are first-class values in OCaml; they can be
647     returned by other functions. So you don't always need to give the
648     arguments explicitly in a function definition.  *)
649
650     (*.....*)
651     Exercise 16: Recall the `prods` function from Lab 1:
652
653     let rec prods (lst : (int * int) list) : int list =
654         match lst with
655         | [] -> []
656         | (x, y) :: tail -> (x * y) :: (prods tail) ;;
657
658     Now reimplement `prods` using `map` and your uncurried `times`
659     function. Why do you need the uncurried `times` function?
660     .....*)
661
662     let prods = List.map times ;;
663
664     (* Elegant, no? *)

```