1 Macros

So far, we’ve mostly explored similarities between the Python and Scheme languages. For example, the Scheme list data structure is a close analogue to the Python linked list. As another example, we saw how tail-call optimization allows us to write recursive Scheme functions that use a constant amount of space. This makes it feasible to translate iterative code from Python.

On the other hand, macros are a Scheme feature that don’t have an apparent Python equivalent. Like functions, macros are a useful tool for simplifying code via abstraction. But while functions typically operate on values like numbers and lists, macros have the option of transforming unevaluated code, leading to a whole new world of possibilities!

As a reminder, most Scheme functions do not have side effects. One exception to this is print. Just like in Python, print doesn’t return anything! With that in mind, let’s consider an example where we want to repeat a piece of code twice.

\[
\text{(print 'woof)}
\]

A first attempt at this might be:

\[
\text{sce> (define (twice f) (begin f f))}
\text{twice}
\text{sce> (twice (print 'woof))}
\text{woof}
\]

Remember that print doesn’t return anything! So we would only see the first call to print in this case. The problem here is clear: we need to prevent the expression we want to double from evaluating, and then somehow call it twice.

As an example of this, imagine if the problem were less constrained and we could surround our original expression in a define expression. In that case, we could use higher order functions to get what we want:

\[
\text{sce> (define (speak) (print 'woof))}
\text{speak}
\text{sce> (define (twice f) (begin (f) (f)))}
\text{twice}
\text{sce> (twice speak)}
\text{woof}
\text{woof}
\]

But if the expression is given to us directly, there’s no way to “undo” the execution and delay it for later!
2 Macros & Streams

```
scm> (define (twice result)
  (begin
    (define (f) result) % This won't work!
    (f)(f))
twice
scm> (twice (print 'woof))
woof
```

Clearly, we need a special form, since we cannot evaluate our operand immediately. This is where we apply the define-macro special form.

```
scm> (define-macro (twice f) (list 'begin f f))
twice
```

This looks a bit like a function definition. twice is the name of the macro, and everything that follows in the same list is a required parameter. When we evaluate the macro form, we won't evaluate any parameters immediately. Instead, the body of the macro describes the final expression we want to evaluate, with the unevaluated parameters put in place! Recall that we want a final expression that looks like:

```
(begin
  (print 'woof)
  (print 'woof))
```

Now, let f be the snippet of print code from earlier (not the result of evaluation, which is simply nothing) The expression:

```
(list 'begin f f)
```

Creates our desired expression, and then finally evaluates it. Note that if we used:

```
'(begin f f)
```

This wouldn't work, since f would stay as f and wouldn't be replaced with our print expression. However, this seems easier to do than calling list a bunch of times. Is there a way to get the best of both worlds?

### 1.1 Quasiquoting

Recall that the quote special form prevents the Scheme interpreter from executing a following expression. You may have used it in the past to create lists without needing to call functions such as cons and list. However, you cannot create any lists that depend on the results of function evaluation due to the fact that quoting will suppress all evaluation. This is not the case with quasiquoting.

At first glance, the quasiquote (which can be invoked with the backtick ` or the quasiquote special form) behaves exactly the same.

However, using quasiquotes gives you the ability to unquote (which can be invoked with the the comma , or the unquote special form). This removes an expression from the quoted context, evaluates it, and places it back in.
By combining quasiquotes and unquoting, we can often save ourselves a lot of trouble when building macro expressions.

As one last example, we can create a quasiquoted version of our macro from earlier:

```scheme
(define-macro (twice f)
  `(begin ,f ,f))
```

## Questions

1.1 Write a macro that takes an expression and a number \( n \) and repeats the expression \( n \) times. For example, `(repeat-n expr 2)` should behave the same as `(twice expr)`.

Complete the implementation below, making use of the `replicate` function.

```scheme
(define (replicate x n)
  (if (= n 0) nil
      (cons x (replicate x (- n 1)))))

(define-macro (repeat-n expr n)
  scm> (repeat-n (print 'resistance is futile) 4)
  (resistance is futile)
  (resistance is futile)
  (resistance is futile)
  (resistance is futile)
```

1.2 Write a macro that takes in two expressions and or’s them together (applying short-circuiting rules). However, do this without using the `or` special form. You may also assume the name \( v1 \) doesn’t appear anywhere outside of our macro. Fill in the implementation below.

```scheme
(define-macro (or-macro expr1 expr2)
  `(let ((v1 ________________________________))
     (if ________________________________
       ________________________________)))

scm> (or-macro (print 'bork) (/ 1 0))
bork
scm> (or-macro (= 1 0) (+ 1 2))
3
1.3 Write a macro that takes in a call expression and strips out every other argument. The first argument is kept, the second is removed, and so on. You may find it helpful to write a helper function.

\begin{verbatim}
(define-macro (prune-expr expr))
\end{verbatim}
2 Streams

In Python, we can use iterators to represent infinite sequences (for example, the generator for all natural numbers). However, Scheme does not support iterators. Let's see what happens when we try to use a Scheme list to represent an infinite sequence of natural numbers:

```scheme
(define (naturals n)
  (cons n (naturals (+ n 1))))
naturals
```

Because the second argument to `cons` is always evaluated, we cannot create an infinite sequence of integers using a Scheme list.

Instead, our Scheme interpreter supports streams, which are lazy Scheme lists. The first element is represented explicitly, but the rest of the stream's elements are computed only when needed. Computing a value only when it's needed is also known as lazy evaluation.

```scheme
(define (naturals n)
  (cons-stream n (naturals (+ n 1))))
naturals
```

We use the special form `cons-stream` to create a stream. Note that `cons-stream` is a special form, because the second operand `(naturals (+ n 1))` is not evaluated when `cons-stream` is called. It's only evaluated when `cdr-stream` is used to inspect the rest of the stream.

- `nil` is the empty stream
- `cons-stream` creates a non-empty stream from an initial element and an expression to compute the rest of the stream
- `car` returns the first element of the stream
- `cdr-stream` computes and returns the rest of stream

Streams are very similar to Scheme lists. The `cdr` of a Scheme list is either another Scheme list or `nil`; likewise, the `cdr-stream` of a stream is either a stream or `nil`. The difference is that the expression for the rest of the stream is computed the first time that `cdr-stream` is called, instead of when `cons-stream` is used. Subsequent calls to `cdr-stream` return this value without recomputing it. This allows us to
efficiently work with infinite streams like the naturals example above. We can see this in action by using a non-pure function to compute the rest of the stream:

```scheme
(scm> (define (compute-rest n)
    ...> (print 'evaluating!)
    ...> (cons-stream n nil))
compute-rest
(scm> (define s (cons-stream 0 (compute-rest 1)))
s
(scm> (car (cdr-stream s))
evaluating!
1
(scm> (car (cdr-stream s))
1

Note that the symbol evaluating! is only printed the first time cdr-stream is called.

Questions

2.1 What would Scheme display?

(scm> (define (has-even? s)
   (cond ((null? s) #f)
         ((even? (car s)) #t)
         (else (has-even? (cdr-stream s))))
has-even?
(scm> (define f x) (* 3 x))
f
(scm> (define nums (cons-stream 1 (cons-stream (f 3) (cons-stream (f 5) nil))))
ums
(scm> nums

(scm> (cdr nums)
(scm> (cdr-stream nums)

(scm> (define (f x) (* 2 x))
f
(scm> (cdr-stream nums)

(scm> (has-even? nums)
2.2 Write a function range-stream which takes a start and end, and returns a stream that represents the integers between start and end - 1 (inclusive).

\[(\text{define } (\text{range-stream } \text{start } \text{end})\]

\[(\text{if } \text{expression } \text{else})\]

\[\text{nil}\]

\[(\text{cons-stream } \text{expression } \text{expression})\]

\[\text{scm> } (\text{define } s (\text{range-stream } 1 5))\]

\[s\]

\[\text{scm> } (\text{car } (\text{cdr-stream } s))\]

\[2\]

2.3 Write a function slice which takes in a stream s, a start, and an end. It should return a Scheme list that contains the elements of s between index start and end, not including end. If the stream ends before end, you can return nil.

\[(\text{define } (\text{slice } s \text{ start } \text{end})\]

\[\text{scm> } (\text{slice } \text{nat } 4 12)\]

\[(4 5 6 7 8 9 10 11)\]

2.4 Since streams only evaluate the next element when they are needed, we can combine infinite streams together for interesting results! Use it to define a few of our favorite sequences. We've defined the function combine-with for you below, as well as an example of how to use it to define the stream of even numbers.

\[(\text{define } (\text{combine-with } f \text{ xs } \text{ys})\]

\[(\text{if } \text{expression } \text{else})\]

\[\text{nil}\]

\[\text{cons-stream}\]

\[(f \text{ car } \text{xs}) \text{ (car } \text{ys})\]

\[(\text{combine-with } f \text{ (cdr-stream } \text{xs}) \text{ (cdr-stream } \text{ys}))\]

\[\text{scm> } (\text{define } \text{evens } (\text{combine-with } + \text{ (naturals } 0) \text{ (naturals } 0))\]

\[\text{evens}\]

\[\text{scm> } (\text{slice } \text{evens } 0 10)\]

\[(0 2 4 6 8 10 12 14 16 18)\]

For these questions, you may use the naturals stream in addition to combine-with.

(Continued on the next page)
Macros & Streams

i. `(define factorials`

```scheme`
(scm> (slice factorials 0 10)
(1 1 2 6 24 120 720 5040 40320 362880))
```
i. `(define fibs`

```scheme`
(scm> (slice fibs 0 10)
(0 1 1 2 3 5 8 13 21 34))
```

iii. Write `exp`, which returns a stream where the nth term represents the degree-n polynomial expansion for e^x, which is \( \sum_{i=0}^{n} \frac{x^i}{i!} \).

You may use `factorials` in addition to `combine-with` and `naturals` in your solution.

`(define (exp x)`

```scheme`
(scm> (slice (exp 2) 0 5)
(1 3 5 6.333333333 7 7.266666667))
```