

1 Calculator

We are beginning to dive into the realm of interpreting computer programs – that is, writing programs that understand other programs. In order to do so, we'll have to examine programming languages in-depth. The *Calculator* language, a subset of Scheme, was the first of these examples.

The Calculator language is a Scheme-syntax language that currently includes only the four basic arithmetic operations: $+$, $-$, $*$, and $/$. These operations can be nested and can take varying numbers of arguments. A few examples of calculator in action are given on the right. A Calculator expression is just like a Scheme list. To represent Scheme lists in Python, we use `Pair` objects.

For example, the list `(+ 1 2)` is represented as `Pair('+', Pair(1, Pair(2, nil)))`.

The `Pair` class is the same as the Scheme procedure `cons`, which would represent the same list as `(cons '+ (cons 1 (cons 2 nil)))`.

`Pair` is very similar to `Link`, the class we developed for representing linked lists, except that the second attribute doesn't have to be a linked list. In addition to `Pair` objects, we include a `nil` object to represent the empty list. `Pair` instances have methods:

1. `__len__`, which returns the length of the list.
2. `__getitem__`, which allows indexing into the pair.
3. `map`, which applies a function, `fn`, to all of the elements in the list.

`nil` has the methods `__len__`, `__getitem__`, and `map`.

Here's an implementation of what we described:

```
class nil:
    """Represents the special empty pair nil in Scheme."""
    def __repr__(self):
        return 'nil'
    def __len__(self):
        return 0
    def __getitem__(self, i):
        raise IndexError('Index out of range')
    def map(self, fn):
        return nil
```

```
nil = nil() # this hides the nil class *forever*
```

```
calc> (+ 2 2)
4
calc> (- 5)
-5
calc> (* (+ 1 2) (+ 2 3))
15
```

```

class Pair:
    """Represents the built-in pair data structure in Scheme."""
    def __init__(self, first, second):
        self.first = first
        self.second = second
    def __repr__(self):
        return 'Pair({}, {})'.format(self.first, self.second)
    def __len__(self):
        return 1 + len(self.second)
    def __getitem__(self, i):
        if i == 0:
            return self.first
        return self.second[i-1]
    def map(self, fn):
        return Pair(fn(self.first), self.second.map(fn))

```

Questions

- 1.1 Translate the following Calculator expressions into calls to the `Pair` constructor.

Hint: in the example from earlier, the list `(+ 1 2)` is represented as `Pair('+', Pair(1, Pair(2, nil)))`.

```
> (+ 1 2 (- 3 4))
```

```
> (+ 1 (* 2 3) 4)
```

- 1.2 Translate the following Python representations of Calculator expressions into the proper Scheme syntax:

```
>>> Pair('+', Pair(1, Pair(2, Pair(3, Pair(4, nil)))))
```

```
>>> Pair('+', Pair(1, Pair(Pair('*', Pair(2, Pair(3, nil))), nil)))
```

2 Evaluation

Evaluation discovers the form of an expression and executes a corresponding evaluation rule.

We'll go over two such expressions now:

1. **Primitive expressions** are evaluated directly. For example, the numbers 3.14 and 165 just evaluate to themselves, and the string “+” evaluates to the `calc_add` function.
2. **Call expressions** are evaluated in the same way you've been doing them all semester:
 - (1) **Evaluate** the operator.
 - (2) **Evaluate** the operands from left to right.
 - (3) **Apply** the operator to the operands.

Here's `calc_eval`:

```
def calc_eval(exp):
    """Evaluates a Calculator expression represented as a Pair."""
    if isinstance(exp, Pair):
        return calc_apply(calc_eval(exp.first),
                           list(exp.second.map(calc_eval)))
    elif exp in OPERATORS:
        return OPERATORS[exp]
    else: # Atomic expressions
        return exp
```

And here's `calc_apply`:

```
def calc_apply(op, args):
    """Applies an operator to a Pair of arguments."""
    return op(*args)
```

The `*args` syntax expands a list of arguments. For example:

```
>>> calc_apply(print, [1, 2, 3]) # Becomes print(1, 2, 3), not print([1, 2, 3])
1 2 3
```

Questions

- 2.1 Suppose we typed each of the following expressions into the Calculator interpreter. How many calls to `calc_eval` would they each generate? How many calls to `calc_apply`?

```
> (+ 2 4 6 8)
```

```
> (+ 2 (* 4 (- 6 8)))
```

- 2.2 Alyssa P. Hacker and Ben Bitdiddle are also tasked with implementing the `and` operator, as in `(and (= 1 2) (< 3 4))`. Ben says this is easy: they just have to follow the same process as in implementing `*` and `/`. Alyssa is not so sure. Who's right?
- 2.3 Now that you've had a chance to think about it, you decide to try implementing `and` yourself. You may assume the conditional operators (e.g. `<`, `>`, `=`, etc) have already been implemented for you.

```
def calc_eval(exp):
    if isinstance(exp, Pair):

        elif exp in OPERATORS:
            return OPERATORS[exp]
        else: # Atomic expression
            return exp

def eval_and(operands):
```

3 Tail-Call Optimization

Scheme implements tail-call optimization, which allows programmers to write recursive functions that use a constant amount of space. A **tail call** occurs when a function calls another function as its **last action of the current frame**. In this case, the frame is no longer needed, and we can remove it from memory. In other words, if this is the last thing you are going to do in a function call, we can reuse the current frame instead of making a new frame.

Consider this version of `factorial` that does **not** use tail calls:

```
(define (fact n)
  (if (= n 0)
      1
      (* n (fact (- n 1)))))
```

The recursive call occurs in the last line, but it is not the last expression evaluated. After calling `(fact (- n 1))`, the function still needs to multiply that result with `n`. The final expression that is evaluated is a call to the multiplication function, not `fact` itself. Therefore, the recursive call is **not** a tail call.

We can rewrite this function using a helper function that remembers the temporary product that we have calculated so far in each recursive step.

```
(define (fact n)
  (define (fact-tail n result)
    (if (= n 0)
        result
        (fact-tail (- n 1) (* n result))))
  (fact-tail n 1))
```

`fact-tail` makes a single recursive call to `fact-tail` that is the last expression to be evaluated, so it is a tail call. Therefore, `fact-tail` is a **tail recursive** process. Tail recursive processes can use a constant amount of memory because each recursive call frame does not need to be saved.

Our original implementation of `fact` required the program to keep each frame open because the last expression multiplies the recursive result with `n`. Therefore, at each frame, we need to remember the current value of `n`.

In contrast, the tail recursive `fact-tail` does not require the interpreter to remember the values for `n` or `result` in each frame. Instead, we can just *update* the value of `n` and `result` of the current frame! Therefore, we can keep reusing a single frame to complete this calculation.

3.1 Identifying tail calls

A function call is a tail call if it is in a **tail context**. However, it might not be a recursive tail call, as we saw earlier in `fact` which did multiplication instead. Tail context simply means the expression is the last to be evaluated in that form.

For example, we consider the following to be tail contexts:

- the last sub-expression in a lambda's body
- the second or third sub-expression in an `if` form
- any of the non-predicate sub-expressions in a `cond` form
- the last sub-expression in an `and` or an `or` form
- the last sub-expression in a `begin`'s body

These make sense intuitively; for `if`, consider that the last expression to be evaluated in an `if` form is not the condition, but rather either the second or third sub-expressions which are evaluated depending on if the condition is `True` or `False`. You should be able to provide a similar reasoning for the other tail contexts listed above.

Before we jump into questions, a quick tip for defining tail recursive functions is to use helper functions. A helper function should have all the arguments from the parent function, plus additional arguments like `total` or `counter` or `result`.

Questions

- 3.1 For each of the following functions, identify whether it contains a recursive call in a tail context. Also indicate if it uses a constant number of frames.

```
(define (question-a x)
  (if (= x 0)
      0
      (+ x (question-a (- x 1))))))
```

```
(define (question-b x y)
  (if (= x 0)
      y
      (question-b (- x 1) (+ y x))))
```

```
(define (question-c x y)
  (if (> x y)
      (question-c (- y 1) x)
      (question-c (+ x 10) y)))
```

```
(define (question-d n)
  (if (question-d n)
      (question-d (- n 1))
      (question-d (+ n 10))))
```

- 3.2 Write a tail recursive function that returns the n th fibonacci number. We define $\text{fib}(0) = 0$ and $\text{fib}(1) = 1$.

```
(define (fib n)
  (define (fib-sofar _____)

    (if _____

        _____

        (fib-sofar _____)

        (fib-sofar _____)))
```

- 3.3 Write a tail recursive function that takes in a Scheme list and returns the numerical sum of all values in the list. You can assume that the list is well-formed and contains only numbers (no nested lists).

```
(define (sum lst)
```

- 3.4 Write a tail recursive function that takes in a number and a sorted list. The function returns a sorted copy with the number inserted in the correct position.

- (a) Begin by writing a tail recursive function that reverses a list.

```
(define (reverse lst)
  (define (reverse-sofar lst lst-sofar)

    (if (null? lst) _____
        _____))
  _____)
```

- (b) Next, write a tail recursive function that concatenates two lists together. You may use `reverse`.

```
(define (append a b)
  (define (rev-append-tail a b)

    (if (null? a) _____
        _____))
  _____)
```

- (c) Finally, implement `insert`. You may use `reverse` and `append`.

```
(define (insert n lst)
  (define (rev-insert lst rev-lst)

    (cond ((null? lst) _____)
          ((> (car lst) n) _____)
          (else _____)))
  _____)
```