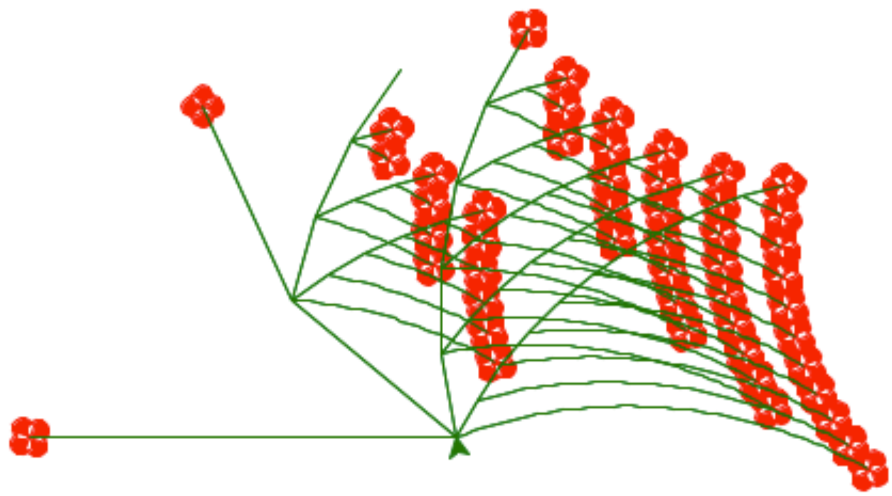
Project 4: A Scheme Interpreter



Eval calls apply,

which just calls eval again!

When does it all end?

Introduction

In this project, you will develop an interpreter for a subset of the Scheme language. As you proceed, think about the issues that arise in the design of a programming language; many quirks of languages are the byproduct of implementation decisions in interpreters and compilers.

You will also implement some small programs in Scheme. Scheme is a simple but powerful functional language. You should find that much of what you have learned about Python transfers cleanly to Scheme as well as to other programming languages. To learn more about Scheme, you can read the original Structure and Interpretation of Computer Programs online for free. Examples from chapters 1 and 2 are included as test cases for this project. Language features from Chapters 3, 4, and 5 are not part of this project, but of course you are welcome to extend your interpreter to implement more of the language. Since we only include a subset of the language, your interpreter will not match exactly the behavior of other interpreters such as STk.

The project concludes with an open-ended graphics contest that challenges you to produce recursive images in only a few lines of Scheme. As an example of what you might create, the picture above abstractly depicts all the ways of making change for $0.50 using U.S. currency. All flowers appear at the end of a branch with length 50. Small angles in a branch indicate an additional coin, while large angles indicate a new currency denomination. In the contest, you too will have the chance to unleash your inner recursive artist.

This project includes several files, but all of your changes will be made to the first four: `scheme.py`, `scheme_reader.py`, `questions.scm`, and `tests.scm`. You can download all of the project code as a zip archive.

`scheme.py`	The Scheme evaluator
`scheme_reader.py`	The Scheme syntactic analyzer
`questions.scm`	A collection of test cases written in Scheme
`tests.scm`	A collection of test cases written in Scheme
`scheme_tokens.py`	A tokenizer for scheme
`scheme_primitives.py`	Primitive Scheme procedures
`scheme_test.py`	A testing framework for Scheme
`scheme_grader.py`	A suite of tests for the project
`ucb.py`	Utility functions for 61A
`autograder.py`	Utility functions for grading

Logistics

This is a two-part, two-person project. All questions are labeled sequentially, but some are designated for certain people by a prefix of their letter (A or B). Both partners should understand the solutions to all questions.

In the first part, you will develop the interpreter in stages:

- Reading Scheme expressions
- Primitive procedure calls
- Symbol evaluation and definition
- Lambda expressions and procedure definition
- Calling user-defined procedures
- Evaluation of various special forms

In the second part, you will implement Scheme procedures that are similar to some exercises that you previously completed in Python.

There are 27 possible correctness points and 3 composition points. The composition score in this project will evaluate the clarity of your code *and* your ability to write tests that verify the behavior of your interpreter.

Submit the project using `submit proj4`. The only files you are required to submit are `scheme.py`, `scheme_reader.py`, `questions.scm`, and `tests.scm`.

The Scheme Language

Before you begin working on the project, review what you have learned in lecture about the Scheme language in Section 3.2 of Composing Programs.

Read-Eval-Print. The interpreter reads Scheme expressions, evaluates them, and prints the results.

```
scm> 2
2
scm> (((lambda (f) (lambda (x) (f f x)))
        (lambda (f k) (if (zero? k) 1 (* k (f f (- k 1)))))) 5)
120
```

The starter code for your Scheme interpreter in [scheme.py] can successfully evaluate the first expression above, since it consists of a single number. The second (a computation of 5 factorial) will not work just yet.

Load. Our `load` procedure differs from standard Scheme in that we use a symbol for the file name. For example, to load [tests.scm], evaluate the following call expression.

```
scm> (load 'tests)
```

Symbols. Unlike some implementations of Scheme, in this project numbers and boolean values cannot be used as symbols. Also, symbols are always lowercased.

```
scm> (define 2 3)
Traceback (most recent call last):
  0 (#define 2 3)
Error: bad argument to define
scm> 'Hello
hello
```

Turtle Graphics. In addition to standard Scheme procedures, we include procedure calls to the Python `turtle` package. You can read the turtle module documentation online.

Note: The `turtle` Python module may not be installed by default on your personal computer. However, the `turtle` module is installed on the instructional machines. So, if you wish to create turtle graphics for this project (i.e. for the contest), then you'll either need to setup `turtle` on your personal computer or use university computers.

Development

The `tests.scm` file contains a long list of example Scheme expressions and their expected values.

```
(+ 1 2)
; expect 3
(/ 1 0)
; expect Error
```

You can compare the output of your interpreter to the expected output by running `scheme_test.py`.

```
python3 scheme_test.py
```

For the example above, `scheme_test.py` will evaluate `(+ 1 2)` using your code in `scheme.py`, then output a test failure if `3` is not returned as the value. The second example tests for an error (but not the specific error message).

Only a small subset of tests are designated to run by default because `tests.scm` contains an `(exit)` call near the beginning, which halts testing. As you complete more of the project, you should move or remove this call. *Note that your interpreter doesn't know how to exit until Problems 3 and 4 are completed; all tests will run until then.*

Important: As you proceed in the project, add new tests to the top of `tests.scm` to verify the behavior of your implementation. Your composition score for this project will depend on whether or not you have tested your implementation in ways that are different from the autograder.

As always, you can run the doctests for the project.

```
python3 -m doctest scheme.py scheme_reader.py
```

You can also run the autograder tests.

```
python3 scheme_grader.py
```

```
python3 scheme_grader.py -q 1
```

Debugging. Try using the `trace` decorator from the `ucb` module to follow the path of execution in your interpreter.

Exceptions. As you develop your Scheme interpreter, you may find that Python raises various uncaught exceptions when evaluating Scheme expressions. As a result, your Scheme interpreter will halt. Some of these may be the results of bugs in your program, and some may be useful indications of errors in user programs. The former should be fixed (of course!) and the latter should be handled, usually by raising a `SchemeError`. All `SchemeError` exceptions are handled and printed as error messages by the `read_eval_print_loop` function in scheme.py. Ideally, there should never be unhandled Python exceptions for any input to your interpreter.

Running Your Scheme Interpreter

To run your Scheme interpreter in an interactive mode, type:

```
python3 scheme.py
```

You can use your Scheme interpreter to evaluate the expressions in an input file by passing the file name as a command-line argument to scheme.py:

```
python3 scheme.py tests.scm
```

Currently, your Scheme interpreter can handle a few simple expressions, such as:

```
scm> 1
1
scm> 42
42
scm> #t
```

```
True
```

To exit the Scheme interpreter, issue either `Ctrl-c` or `Ctrl-d` or evaluate the `exit` procedure:

```
scm> (exit)
```

The Reader

The function `scheme_read` in [scheme_reader.py] parses a `Buffer` ([buffer.py]) instance that returns valid Scheme tokens on invocations of `current` and `pop` methods. This function returns the next full Scheme expression in the `src` buffer, using this representation:

Scheme Data Type	Our Internal Representation
Numbers	Python's built-in `int` and `float` data types.
Symbols	Python's built-in `string` data type.
Booleans (`#t`, `#f`)	Python's built-in `True`, `False` values.
Pairs	The `Pair` class, defined in [scheme_reader.py].
nil	The `nil` object, defined in [scheme_reader.py].

Problem 1 (1 pt). Complete the `scheme_read` function in [scheme_reader.py] by adding support for quotation. This function dispatches on the type of the next token:

- If the next token in `src` is the string `"nil"`, return the `nil` object. (provided)
- If the next token is not a delimiter, then it is self-evaluating. Return it. (provided)
- If the current token is a single quote (such as the first character of `'bagel`), then return a quote special form (such as `(quote bagel)`).
- If the current token is a left parenthesis `"("`, return the result of `read_tail`. (provided)

Problem 2 (2 pt). Complete the `read_tail` function in [scheme_reader.py] by adding support for dotted lists. A dotted list in Scheme is not necessarily a well-formed list, but instead has an arbitrary `second` attribute that may be any Scheme value.

The `read_tail` function expects to read the rest of a list or dotted list, assuming the open parenthesis of that list has already been popped by `scheme_read`.

Consider the case of calling `scheme_read` on input "`(1 2 . 3)`". The `read_tail` function will be called on the suffix "`1 2 . 3)`", which is

- the pair consisting of the Scheme value `1` and the value of the tail "`2 . 3)`", which is
    - the pair consisting of the Scheme value `2` and the Scheme value `3`.

Thus, `read_tail` would return `Pair(1, Pair(2, 3))`.

Hint: In order to verify that only one element follows a dot, after encountering a `'.'`, read one additional expression and then check to see that a closing parenthesis follows.

To verify that your solutions to Problem 1 and 2 work correctly, run the doctests for [scheme_reader.py] and test your parser interactively by running,

```
# python3 scheme_reader.py
read> 42
42
read> '(1 2 3)
(quote (1 2 3))
read> nil
()
read> '()
(quote ())
read> (1 (2 3) (4 (5)))
(1 (2 3) (4 (5)))
read> (1 (9 8) . 7)
(1 (9 8) . 7)
read> (hi there . (cs . (student)))
(hi there cs student)
```

The Evaluator

All further changes to the interpreter will be made in scheme.py. For each question, add a few tests to the top of tests.scm to verify the behavior of

your implementation. In the implementation given to you, the `scheme_eval` function is complete, but few of the functions or methods it uses are implemented. In fact, the evaluator can only evaluate self-evaluating expressions: numbers, booleans, and `nil`.

Problem 3 (2 pt). Implement `apply_primitive`, which is called by `scheme_apply`. Primitive procedures are applied by calling a corresponding Python function that implements the procedure.

Scheme primitive procedures are represented as instances of the `PrimitiveProcedure` class, defined in [scheme_primitives.py](). A `PrimitiveProcedure` has two instance attributes:

- `fn` is the Python function that implements the primitive Scheme procedure.
- `use_env` is a boolean flag that indicates whether or not this primitive procedure will expect the current environment to be passed in as the last argument. The environment is required, for instance, to implement the primitive `eval` procedure.

To see a list of all Scheme primitive procedures used in the project, look in the [scheme_primitives.py]() file. Any function decorated with `@primitive` will be added to the globally-defined `_PRIMITIVES` list.

The `apply_primitive` function takes a `PrimitiveProcedure` instance, a Scheme list of argument values, and the current environment. Your implementation should:

- Convert the Scheme list to a Python list of arguments.
- If the `procedure.use_env` is `True`, then add the current environment `env` as the last argument.
- Call `procedure.fn` on those arguments (*hint*: use * notation).
- If calling the function results in a `TypeError` exception being thrown, then raise a `SchemeError` instead.

The doctest for `apply_primitive` should now pass. However, your Scheme interpreter will still not be able to apply primitive procedures, because your Scheme interpreter still doesn't know how to look up the values for the primitive procedure symbols (such as `+`, `*`, and `car`).

Problem 4 (2 pt) Implement the `lookup` method of the `Frame` class. It takes a symbol (Python string) and returns the value bound to that name in the first frame of the environment in which it is found. A `Frame` represents an environment via two instance attributes:

- `bindings` is a dictionary that maps Scheme symbol keys (represented as Python strings) to Scheme values.
- `parent` is the parent `Frame` instance. The parent of the Global Frame is `None`.

Your `lookup` implementation should,

- Return the value of a symbol in `self.bindings` if it exists.
- Otherwise, `lookup` that symbol in the parent if it exists.
- Otherwise, raise a `SchemeError`. (provided)

After you complete this problem, you should be able to evaluate primitive procedure calls, giving you the functionality of the Calculator language and more.

```
scm> +
#[primitive]
scm> (+ 1 2)
3
scm> (* 3 4 (- 5 2) 1)
36
scm> (odd? 31)
True
```

Problem A5 (1 pt). There are two missing parts in the `do_define_form` function, which handles the `(define ...)` special forms. Implement just the first part, which binds names to values but does not create new procedures. `do_define_form` should return the name after performing the binding.

```
scm> (define tau (* 2 3.1415926))
tau
```

You should now be able to give names to values and evaluate symbols to those values.

```
scm> (define x 15)
x
scm> (define y (* 2 x))
y
scm> y
30
scm> (+ y (* y 2) 1)
91
scm> (define x 20)
x
scm> x
20
```

Problem B6 (1 pt). Implement the `do_quote_form` function, which evaluates the `quote` special form. Once you have done so, you can evaluate quoted expressions.

```
scm> 'hello
hello
scm> '(1 . 2)
(1 . 2)
scm> '(1 (2 three . (4 . 5)))
(1 (2 three 4 . 5))
scm> (car '(a b))
a
scm> (eval (cons 'car '('(1 2))))
1
```

At this point in the project, your Scheme interpreter should be be able to support the following features:

- Evaluate atoms, which include numbers, booleans, nil, and symbols,
- Evaluate the `quote` special form,

- Evaluate lists,
- Define symbols, and
- Call primitive procedures, such as `(+ (- 4 2) 5)`

User-Defined Procedures

User-defined procedures are represented as instances of the `LambdaProcedure` class, defined in [scheme.py](). A `LambdaProcedure` instance has three instance attributes:

- `formals` is a Scheme list of the formal parameters (symbols) that name the arguments of the procedure.
- `body` is a single Scheme expression; the body of the procedure.
- `env` is the environment in which the procedure was defined.

Problem 7 (2 pt). First, implement the `begin` special form, which includes a list of one or more sub-expressions that are each evaluated in order. The value of the final sub-expression is the value of the `begin` expression.

```
scm> (begin (+ 2 3) (+ 5 6))
11
scm> (begin (display 3) (newline) (+ 2 3))
3
5
scm> (begin (print 3) '(+ 2 3))
3
(+ 2 3)
```

Hint: When `scheme_eval` evaluates one of the `LOGICAL_FORMS` in [scheme.py](), it calls `scheme_eval` on the **returned value**. Take care that your Scheme interpreter doesn't inadvertently call `scheme_eval` on the same value twice, or else you might have the following incorrect behavior:

```
scm> (begin 30 'hello)
Error: unknown identifier: hello
```

Problem 8 (2 pt). Implement the `do_lambda_form` method, which creates `LambdaProcedure` instances by evaluating `lambda` expressions. While you cannot call a user-defined procedure yet, you can verify that you have read the procedure correctly by evaluating a lambda expression.

```
scm> (lambda (x y) (+ x y))
(lambda (x y) (+ x y))
```

In Scheme, it is legal to have function bodies with more than one expression. In order to implement this feature, your `do_lambda_form` should detect when the body of a lambda expression contains multiple expressions. If so, then `do_lambda_form` should place those expressions inside of a `(begin ...)` form, and use that `begin` expression as the body:

```
scm> (lambda (y) (print y) (* y 2))
(lambda (y) (begin (print y) (* y 2)))
```

Problem A9 (1 pt). Currently, your Scheme interpreter is able to define user-defined procedures in the following manner:

```
scm> (define f (lambda (x) (* x 2)))
f
```

However, we'd like to be able to use the shorthand form of defining procedures:

```
scm> (define (f x) (* x 2))
f
```

Modify the `do_define_form` function so that it correctly handles the shorthand procedure definition form above. Make sure that it can handle multi-expression bodies. *Hint*: construct a `lambda` expression and evaluate it with `do_lambda_form`.

Once you have completed this problem, you should find that defined procedures evaluate to lambda procedures.

```
scm> (define (square x) (* x x))
square
scm> square
(lambda (x) (* x x))
```

Problem 10 (2 pt). Implement the `make_call_frame` method of the `Frame` class, which:

- Creates a new `Frame` instance, the parent of which is `self`. (provided)
- Binds formal parameters to their corresponding argument values.
- Raises a `SchemeError` if `make_call_frame` receives a different number of formal parameters and arguments.

Problem B11 (1 pt). Implement the `check_formals` function to raise an error whenever the Scheme list of formal parameters passed to it is invalid. Raise a `SchemeError` if the list of `formals` is not a well-formed list of symbols or if any symbol is repeated. (Hint: The `symbol?` procedure in [scheme_primitives.py]() returns whether a value is a Scheme symbol.)

Problem 12 (2 pt). Implement `scheme_apply` to correctly apply user-defined `LambdaProcedure` instances. (The case of `MuProcedures` is handled later in the project). It should:

- Create a new `Frame`, with all formal parameters bound to their argument values.
- Evaluate the body of `procedure` in the environment represented by this new frame.
- Return the value of calling `procedure`.

After you complete `scheme_apply`, user-defined functions (and lambda functions) should work in your Scheme interpreter. Now is an excellent time to revisit the tests in [tests.scm] and ensure that you pass the ones that involve definition (Sections 1.1.2 and 1.1.4). **You should also add additional tests of your own at the top of `tests.scm` to verify that your interpreter is behaving as you expect.**

Special Forms

Logical special forms include `if`, `and`, `or`, and `cond`. These expressions are special because not all of their sub-expressions may be evaluated.

In Scheme, only `#f` (also known as `false` or `False`) is a false value. All other values are true values. You can test whether a value is a true value or a false value using the provided Python functions `scheme_true` and `scheme_false`, defined in [scheme_primitives.py].

Problem A13 (1 pt). Implement `do_if_form` so that `if` expressions are evaluated correctly. This function should return either the second (consequent) or third (alternative) expression of the `if` expression, depending on the value of the first (predicate) expression.

```
scm> (if (= 4 2) true false)
False
scm> (if (= 4 4) (* 1 2) (+ 3 4))
2
```

It is legal to pass in just two expressions to the `if` special form. In this case, you should return the second expression if the first expression evaluates to a true value. Otherwise, return the special `okay` value, which represents an undefined value.

```
scm> (if (= 4 2) true)
okay
```

Problem B14 (2 pt). Implement `do_and_form` and `do_or_form` so that `and` and `or` expressions are evaluated correctly.

The logical forms `and` and `or` are *short-circuiting*. For `and`, your interpreter should evaluate each sub-expression from left to right, and if any of these evaluates to `False`, then `False` is returned. If all but the last sub-expressions evaluate to true values, return the last sub-expression from `do_and_form`.

For `or`, evaluate each sub-expression from left to right. If any evaluates to a true value, then `quote` that value and return it. These return values must be quoted because they are evaluated in `scheme_eval`. If all but the last sub-expression evaluate to false, return the last sub-expression from `do_or_form` without quoting it.

```
scm> (and)
True
scm> (or)
False
scm> (and 4 5 6)
6     ; all operands are true values
scm> (or 5 2 1)
5     ; 5 is a true value
scm> (and #t #f 42 (/ 1 0))
False     ; short-circuiting behavior of and
scm> (or 4 #t (/ 1 0))
4     ; short-circuiting behavior of or
```

Problem A15 (1 pt). Implement `do_cond_form` so that it returns the first result sub-expression corresponding to a true predicate (or else). Your implementation should match the following examples and the additional tests in tests.scm.

```
scm> (cond ((= 4 3) 'nope)
           ((= 4 4) 'hi)
           (else 'wait))
hi
scm> (cond ((= 4 3) 'wat)
```

```
            ((= 4 4))
            (else 'hm))
True
scm> (cond ((= 4 4) 'here 42)
            (else 'wat 0))
42
```

For the last example, where the body of a `cond` case has multiple expressions, you might find it helpful to replace `cond`-bodies with multiple expression bodies into a single `begin` expression, i.e., the following two expressions are equivalent.

```
(cond ((= 4 4) 'here 42))
(cond ((= 4 4) (begin 'here 42)))
```

If the body of a `cond` case is empty, then `do_cond_form` should quote the value of the predicate and return it, if the predicate evaluates to a true value.

```
scm> (cond (12))
12
scm> (cond ((= 4 3))
            ('hi))
hi
```

The value of a `cond` is undefined if there are no true predicates and no `else`. In such a case, `do_cond_form` should return `okay`.

Problem A16 (2 pt). The `let` special form introduces local variables, giving them their initial values. For example,

```
scm> (define x 'hi)
x
scm> (define y 'bye)
```

```
y
scm> (let ((x 42)
           (y (* 5 10)))
       (list x y))
(42 50)
scm> (list x y)
(hi bye)
```

Implement the `do_let_form` method to have this effect and test it, by adding test cases to the top of [`tests.scm`](tests.scm). Make sure your `let` correctly handles multi-expression bodies:

```
scm> (let ((x 42)) x 1 2)
2
```

The let special form is equivalent to creating and then calling a lambda procedure. That is, the following two expressions are equivalent:

```
(let ((x 42) (y 16)) (+ x y))
((lambda (x y) (+ x y)) 42 16)
```

Thus, a `let` form creates a new `Frame` (containing the `let` bindings) which extends the current environment and evaluates the body of the `let` with respect to this new `Frame`. In your project code, you don't have to actually create a `LambdaProcedure` and call it. Instead, you can create a new `Frame`, add the necessary bindings, and evaluate the expressions of the `let` body in this new environment.

Problem B17 (2 pt). Implement `do_mu_form` to evaluate the `mu` special form, a non-standard Scheme expression type. A `mu` expression is similar to a `lambda` expression, but evaluates to a `MuProcedure` instance that is dynamically scoped. The `MuProcedure` class has been provided for you.

Additionally, complete `scheme_apply` to call `MuProcedure` procedures using dynamic scoping. Calling a `LambdaProcedure` uses lexical scoping: the parent of the new call frame is the environment in which the procedure was defined. Calling a `MuProcedure` created by a `mu` expression uses dynamic scoping: the parent of the new call frame is the environment in which the call expression was evaluated. As a result, a `MuProcedure` does not need to store an environment as an instance attribute. It can refer to names in the environment from which it was called.

```
scm> (define f (mu (x) (+ x y)))
f
scm> (define g (lambda (x y) (f (+ x x))))
g
scm> (g 3 7)
13
```

Your Scheme interpreter implementation is now complete. You should have been adding tests to the top of [tests.scm] as you did each problem. These tests will be evaluated as part of your composition score for the project.

Part 3: Write Some Scheme

Not only is your Scheme interpreter itself a tree-recursive program, but it is flexible enough to evaluate *other* recursive programs. Implement the following procedures in Scheme in [questions.scm].

Problem 18 (2 pt). Implement the `merge` procedure, which takes in a comparator and two sorted list arguments and combines them into one sorted list. A comparator is a function that compares two values. For example:

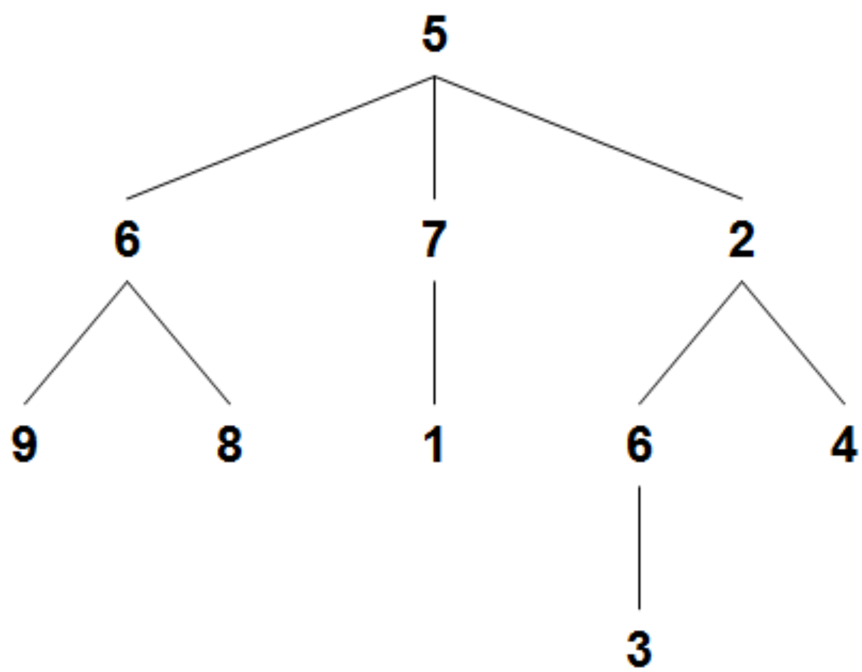
```
scm> (merge < '(1 4 6) '(2 5 8))
(1 2 4 5 6 8)
scm> (merge > '(6 4 1) '(8 5 2))
(8 6 5 4 2 1)
```

Problem 19 (2 pt). Implement the `list-partitions` procedure, which lists all of the ways to partition a positive integer `total` into at most `max-pieces` pieces that are all less than or equal to a positive integer `max-value`. *Hint*: Define a helper function to construct partitions.

The number `5` has 4 partitions using pieces up to a `max-value` of `3` and a `max-pieces` of `4`:

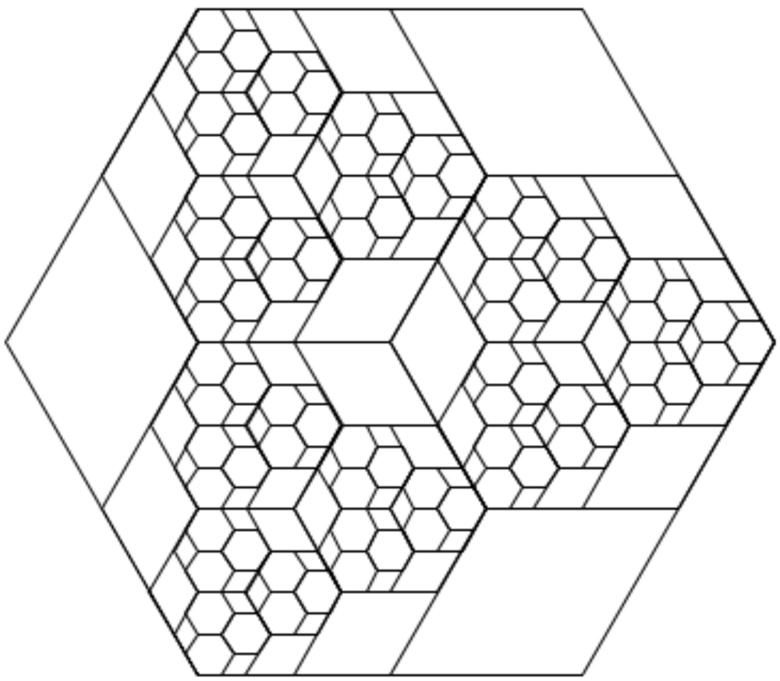
```
3, 2 (two pieces)
3, 1, 1 (three pieces)
2, 2, 1 (three pieces)
2, 1, 1, 1 (four pieces)
```

Problem 20 (2 pt). You have been given the definition to an abstract implementation of trees. Use it to implement `tree-sums`, which is a function that returns a list of all possible sums of nodes, when traversing from root to leaf. For example, the following tree when passed through `tree-sums` will return `(20 19 13 16 11)`:

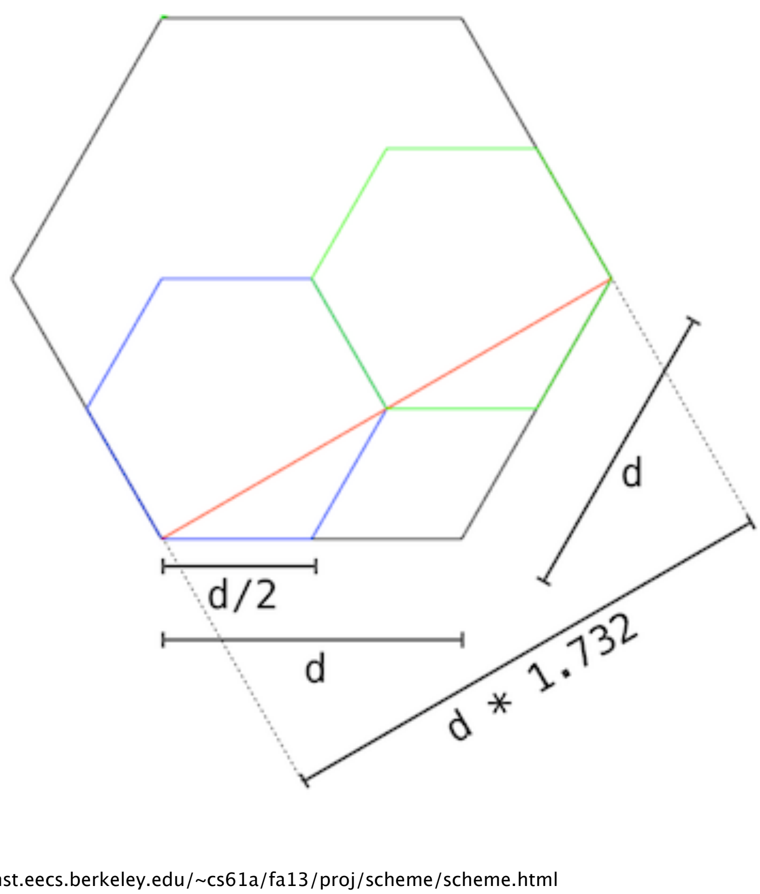


Problem 21 (0 pt). Implement the `hax` procedure that draws the following recursive

illustration when passed two arguments, a side length `d` and recursive depth `k`. The example below is drawn from `(hax 200 4)`.



To see how this illustration is constructed, consider this annotated version that gives the relative lengths of lines of the component shapes in the figure.



Extra Credit

Problem 22 (3 pt). Complete the function `scheme_optimized_eval` in [scheme.py](). This alternative to `scheme_eval` is properly tail recursive. That is, the interpreter will allow an unbounded number of active tail calls in constant space.

Instead of recursively calling `scheme_eval` for tail calls and logical special forms, and `let`, replace the current `expr` and `env` with different expressions and environments. For call expressions, this change only applies to calling user-defined procedures.

Once you finish, uncomment the line `scheme_eval = scheme_optimized_eval` in `scheme.py`.

Congratulations! You have finished the final project for 61A! Assuming your tests are good and you've passed them all, consider yourself a proper computer scientist!

Now, get some sleep. You've earned it!

Contest: Recursive Art

We've added a number of primitive drawing procedures that are collectively called "turtle graphics". The *turtle* represents the state of the drawing module, which has a position, an orientation, a pen state (up or down), and a pen color. The `tscheme_x` functions in `scheme_primitives.py` are the implementations of these procedures, and show their parameters with a brief description of each. The Python documentation of the turtle module contains more detail.

Contest. Create a visualization of an iterative or recursive process of your choosing, using turtle graphics. Your implementation must be written entirely in Scheme using the interpreter you have built. However, you may add primitive procedures to interface with Python's `turtle` or `math` modules. Other than that *all computation must be done in Scheme*. If you do add new primitives, then make sure to submit `scheme_primitives.py` in addition to `contest.scm`.

Prizes will be awarded for the winning entry in each of the following categories, as well as 3 extra credit points.

- **Featherweight.** At most 256 tokens of Scheme, not including comments and delimiters.
- **Heavyweight.** At most 2013 tokens of Scheme, not including comments and delimiters.

Entries (code and results) will be posted online, and winners will be selected by popular vote as part of a future homework. The voting instructions will read:

> Please vote for your favorite entry in this semester's 61A Recursion Exposition contest. The winner should exemplify the principles of elegance, beauty, and abstraction that are prized in the Berkeley computer science curriculum. As an academic community, we should strive to recognize and reward merit and achievement (translation: please don't just vote for your friends).

To improve your chance of success, you are welcome to include a title and descriptive haiku in the comments of your entry, which will be included in the voting.

Entries that do not construct an image iteratively or recursively may be disqualified. This includes just drawing a preexisting image, even if the drawing function is iterative or recursive.

Submission instructions will be posted on the course website.

Extra for Experts

We have implemented a significant subset of Scheme in this project, but our interpreter can be extended with more features by following the extension instructions.