Introduction

Important submission note: For full credit:

- submit with Part I complete by **Friday 4/6** (worth 1 pt),
- submit again with Part II complete by **Thursday 4/12** (worth 1 pt), and
- submit the entire project by **Tuesday 4/17**. You will get an extra credit point for submitting the entire project by Monday 4/16.

The Scheme project involves writing an interpreter for the Scheme language which is no small task! Start working on the project *now*! There are many parts and students often get stuck throughout the project so It's best to solve these problems early while there's still plenty of time. Remember that you can ask questions about the project in lab and office hours too!

We've also written a language specification and primitive procedure reference for the CS 61A subset of Scheme that you'll be building in this project. Reading the entirety of either of these documents should not be necessary, but we'll point out useful sections from the documentation in each part of the project.

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 byproducts of implementation decisions in interpreters and compilers. The subset of the language used in this project is described in the functional programming section of Composing Programs. Since we only include a subset of the language, your interpreter will not exactly match the behavior of other interpreters.

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.

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, 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.

Download starter files

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

- `scheme.py`: the Scheme evaluator
- `scheme_reader.py`: the Scheme syntactic analyzer
- `questions.scm`: a collection of functions written in Scheme
- `tests.scm`: a collection of test cases written in Scheme
- `scheme_tokens.py`: a tokenizer for Scheme
- `scheme_primitives.py`: definitions for primitive Scheme procedures
- `buffer.py`: a Buffer implementation, used in `scheme_reader.py`
- `ucb.py`: utility functions for 61A
- `ok`: the autograder
- `tests`: a directory of tests used by `ok`
- `mytests.rst`: A space for you to add your custom tests in Python; see section on adding your own tests

In Parts I and II, you will develop the interpreter in several stages:

- Reading Scheme expressions
- Symbol evaluation
- Calling built-in procedures
- Definitions
- Lambda expressions and procedure definition
- Calling user-defined procedures

- Evaluation of special forms

In Part III, you will implement Scheme procedures.

Logistics

This is a 17-day project. You may work with one other partner. You should not share your code with students who are not your partner or copy from anyone else's solutions. In the end, you will submit one project for both partners.

Remember that you can earn an additional bonus point by submitting the project at least 24 hours before the deadline.

The project is worth 31 points. 27 points are assigned for correctness, 1 point for submitting Part I by the first checkpoint, 1 point for submitting Part II by the second checkpoint, and 2 points for writing your own tests (Problem 0).

You will turn in the following files:

- `scheme_reader.py`
- `scheme.py`
- `questions.scm`
- `tests.scm`

You do not need to modify or turn in any other files to complete the project. To submit the project, run the following command:

```
python3 ok --submit
```

You will be able to view your submissions on the Ok dashboard.

For the functions that we ask you to complete, there may be some initial code that we provide. If you would rather not use that code, feel free to delete it and start from scratch. You may also add new function definitions as you see fit.

However, please do **not** modify any other functions. Doing so may result in your code failing our autograder tests. Also, please do not change any function signatures (names, argument order, or number of arguments).

Throughout this project, you should be testing the correctness of your code. It is good practice to test often, so that it is easy to isolate any problems. However, you should not be testing *too* often, to allow yourself time to think through problems.

We have provided an **autograder** called `ok` to help you with testing your code and tracking your progress. The first time you run the autograder, you will be asked to **log in with your Ok account using your web browser**. Please do so. Each time you run `ok`, it will back up your work and progress on our servers.

The primary purpose of `ok` is to test your implementations, but there are two things you should be aware of.

First, some of the test cases are *locked*. To unlock tests, run the following command from your terminal:

```
python3 ok -u
```

This command will start an interactive prompt that looks like:

```
=====================================================
===================
Assignment: Scheme Interpreter
Ok, version ...
=====================================================
===================


~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~~~~
Unlocking tests

At each "? ", type what you would expect the output
to be.
Type exit() to quit
```

```
---------------------------------------------------------------------
-----------------
Question 0 > Suite 1 > Case 1
(cases remaining: 1)

>>> Code here
?
```

At the `?`, you can type what you expect the output to be. If you are correct, then this test case will be available the next time you run the autograder.

The idea is to understand *conceptually* what your program should do first, before you start writing any code.

Once you have unlocked some tests and written some code, you can check the correctness of your program using the tests that you have unlocked:

```
python3 ok
```

Most of the time, you will want to focus on a particular question. Use the `-q` option as directed in the problems below.

We recommend that you submit **after you finish each problem**. Only your last submission will be graded. It is also useful for us to have more backups of your code in case you run into a submission issue.

The `tests` folder is used to store autograder tests, so **do not modify it**. You may lose all your unlocking progress if you do. If you need to get a fresh copy, you can download the zip archive and copy it over, but you will need to start unlocking from scratch.

If you do not want us to record a backup of your work or information about your progress, use the `--local`option when invoking `ok`. With this option, no information will be sent to our course servers.

Custom Ok tests

Adding your own **Python** tests is entirely optional, and you will not submit your `mytests.rst` file. This is different from the **required** tests in `tests.scm`.
While the tests you write in `tests.scm` (see Problem 0) will test the *correctness* of your interpreter, they may not be of much use while you're still implementing basic features. Moreover, directly testing the implementation of the interpreter can be very useful in fixing some bugs.

We highly recommend that you add your own tests as you work through the project. It's a really helpful way to speed up the debugging process and improve your understanding of the code.

The course staff has also made an instructional video summarizing the information below.

Adding tests

Adding tests is easy. Directly edit the `mytests.rst` file included with the Scheme project. We provide a sample structure to start from, but the test format is actually quite flexible. Here are some simple rules to follow:

- Follow standard Python doctest format. This is what we mostly use for the Ok tests, so feel free to use those as examples.
- For the most part, you may use whitespace as you'd like, but we recommend keeping it organized for your own sake.
- Generally, smaller, simpler tests will be more useful than larger, more complex tests.

You may also find our debugging guide helpful. If you're stuck on a particularly tricky `Ok` test case, a good first step would be to break it up into small parts and test them out yourself in `mytests.rst`.

Running tests

To run all your tests in `mytests.rst` with verbose results:

```
python3 ok -t -v
```
If you put your tests in a different file or split your tests up into multiple files:

```
python3 ok -t your_new_filename.rst
```
To run just the tests from suite 1 case 1 in `mytests.rst`:

```
python3 ok -t --suite 1 --case 1
```
You might have noticed that there's a "test coverage" percentage for your tests (note that coverage statistics are only returned when running all tests). This is a measure of your test's code coverage. If you're interested, you can find more information in our reference guide.

Interpreter details

Scheme features

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

```
scm> 2
2
scm> (+ 2 3)
5
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 call to a primitive function) and the third (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. Various dialects of Scheme are more or less permissive about identifiers (which serve as symbols and variable names).

Our rule is that:

An identifier is a sequence of letters (a-z and A-Z), digits, and characters in `!$%&*/:<=>?@^_~-+.` that do not form a valid integer or floating-point numeral.

Our version of Scheme is case-insensitive: two identifiers are considered identical if they match except possibly in the capitalization of letters. They are internally represented and printed in lower case:

```
scm> 'Hello
hello
```

Turtle Graphics. In addition to standard Scheme procedures, we include procedure calls to the Python `turtle`package. This will come in handy for the contest.

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.

Implementation overview

Here is a brief overview of each of the Read-Eval-Print Loop components in our interpreter. Please read this before beginning the project!

- **Read**: This step parses user input (a string of Scheme code) into our interpreter's internal Python representation of Scheme expressions (e.g. Pairs).

    - *Lexical analysis* has already been implemented for you in the `tokenize_lines` function in `scheme_tokens.py`. This function returns a `Buffer` (from `buffer.py`) of tokens. You do not need to read or understand the code for this step.
    - *Syntactic analysis* happens in `scheme_reader.py`, in the `scheme_read` and `read_tail` functions. Together, these mutually recursive functions parse Scheme tokens into our interpreter's internal Python representation of Scheme expressions. You will complete both functions.
- **Eval**: This step evaluates Scheme expressions (represented in Python) to obtain values. Code for this step is in the main `scheme.py` file.
    - *Eval* happens in the `scheme_eval` function. If the expression being evaluated is a special form, the corresponding `do_?_form` function is called. You will fill in part of `scheme_eval`, as well as several of the`do_?_form` functions.
    - *Apply* happens in the `scheme_apply` function. `scheme_apply` calls the `apply` method of a primitive procedure, or it creates a new frame in which to evaluate the body of a user-defined procedure. In this case, the `apply` method calls `eval_all` which calls `scheme_eval`, resulting in a mutually recursive eval-apply loop.
- **Print**: This step prints the `__str__` representation of the obtained value.
- **Loop**: The step is handled by the `read_eval_print_loop` function in `scheme.py`. You do not need to understand the entire implementation.

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, but some might just be errors in user programs. programs. The former should be fixed by debugging your interpreter 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 the interpreter

To start an interactive Scheme interpreter session, 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> true
True
```

To exit the Scheme interpreter, press `Ctrl-d` or evaluate the `exit` procedure (after completing problems 3 and 4):

```
scm> (exit)
```

Part 0: Testing Your Interpreter

The `tests.scm` file contains a long list of sample Scheme expressions and their expected values. Many of these examples are from Chapters 1 and 2 of Structure and Interpretation of Computer

Programs, the textbook from which Composing Programs is adapted.

Problem 0 (2 pt)

Write tests as you go to verify that your interpreter works correctly. You will get full credit only if your custom tests are different than the provided OK tests, the provided tests.scm tests, and other Scheme assignments in this class. We recommend that you test how multiple features of your interpreter interact together. Quality is better than quantity. A few unique tests are sufficient for full credit, but there is no harm in writing more. Note that your interpreter will not be able to evaluate any expressions until you complete Problem 5, so you should wait until then to try running your custom tests.

Writing Tests. A test is written as a Scheme expression and the corresponding expected output:

```
<expr>
; expect <value>
```

Here are two examples:

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

The first example above tests if your interpreter correctly evaluates `(+ 1 2)`. Specifically, the test will pass if your interpreter returns `3` as the value of that expression. The second example tests for a Scheme error (but not the specific error message). You should follow this format for your own tests.

Running Tests. You can compare the output of your interpreter to the expected output by running the following command:

```
python3 ok -q tests.scm
```

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**. However, your interpreter doesn't know how to `exit` until Problems 3 and 4 are completed; all tests will run until then.

Part I: The Reader

Important submission note: For full credit:

- submit with Part I complete by **Friday 4/6** (worth 1 pt),
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- submit the entire project by **Tuesday 4/17**. You will get an extra credit point for submitting the entire project by Monday 4/16.

All changes in this part should be made in `scheme_reader.py`.

The first part of this project deals with reading and parsing user input. Our reader will parse Scheme code into Python values with the following representations:

Input Example	Scheme Data Type	Our Internal Representation
`scm> 1`	Numbers	Python's built-in `int` and `float` values
`scm> x`	Symbols	Python's built-in `string` values
`scm> #t`	Booleans (`#t`, `#f`)	Python's built-in `True`, `False` values
`scm> (+ 2 3)`	Pairs	Instances of the `Pair` class, defined in `scheme_reader.py`

`scm> nil`	`nil`	The `nil` object, defined in `scheme_reader.py`

If you haven't already, make sure to read the Implementation overview section above to understand how the reader is broken up into parts.

In our implementation, we store tokens ready to be parsed in `Buffer` instances. For example, a buffer containing the input `(+ (2 . 3))` would have the tokens `'('`, `'+'`, `'('`, `2`, `'.'`, `3`, `')'`, and `')'`. See the doctests in `buffer.py` for more examples. You do not have to understand the code in this file.

You will write the parsing functionality, which consists of two mutually recursive functions `scheme_read` and `read_tail`. These functions each take in a single parameter, `src`, which is an instance of `Buffer`.

There are two methods defined in `buffer.py` that you'll use to interact with `src`:

- `src.remove_front()`: mutates `src` by removing the **first** token in `src` and returns it. For the sake of simplicity, if we imagine `src` as a Python list such as `[4, '.', 3, ')']`, `src.remove_front()` will return `4`, and `src` will be left with `['.', 3, ')']`.
- `src.current()`: returns the **first** token in `src` without removing it. For example, if `src` currently contains the tokens `[4, '.', 3, ')']`, then `src.current()` will return `4` but `src` will remain the same.

Problem 1 (2 pt)

First, implement `scheme_read` and `read_tail` so that they can parse list expressions and primitive expressions. We'll take care of dotted pairs in Problem 2. The expected behavior is as follows:

- `scheme_read` removes enough tokens from `src` to form a single expression and returns that expression in the correct internal representation (see above table).

- `read_tail` expects to read the rest of a list or pair, assuming the open parenthesis of that list or pair has already been removed by `scheme_read`. It will read expressions (and thus remove tokens) until the matching closing parenthesis `)` is seen. This list of expressions is returned as nested instances of the `Pair` class.

In short, `scheme_read` returns the next single complete expression in the buffer and `read_tail` returns the rest of a list or pair in the buffer. Both functions mutate the buffer, removing the tokens that have already been processed.

The behavior of both functions depends on the first token currently in `src`. They should be implemented as follows:

`scheme_read`:

- If the current token is the string `"nil"`, return the `nil` object.
- If the current token is `(`, the expression is a pair or list. Call `read_tail` on the rest of `src` and return its result.
- If the current token is `'`, the rest of the buffer should be processed as a quoted expression. You don't have to worry about this until Problem 7.
- If the next token is not a delimiter, then it must be self-evaluating. Return it. **(provided)**
- If none of the above cases apply, raise an error. **(provided)**

`read_tail`:

- If there are no more tokens, then the list is missing a close parenthesis and we should raise an error. **(provided)**
- If the token is `)`, then we've reached the end of the list or pair. Remove this token from the buffer and return the `nil` object.
- If the token is `.`, the current expression is a dotted pair. Implement this in Problem 2.
- If none of the above cases apply, the `src` is at the beginning of an expression. Then:
    1. Read the next complete expression in the buffer. (Hint:

   Which function can we use to read an complete expression?)
2. Read the rest of the original expression (i.e. not including the one found in step 1) until the matching closing parenthesis. (Hint: Which function can we use to read the rest of a list?)
3. Return the results as a `Pair` instance.

Test your understanding and implementation before moving on:

```
python3 ok -q 01 -u
python3 ok -q 01
```

Problem 2 (1 pt)

Now, complete the `read_tail` function by adding support for dotted pairs. To clarify, here is how we define lists vs. dotted pairs:

- A list denotes a linked sequence of pairs in which the `second` attribute of the final pair is `nil`. For example, `(1 2 3)` should be converted to `Pair(1, Pair(2, Pair(3, nil)))`.
- A dotted pair denotes a sequence of pairs in which the `second` attribute of the final pair may be any Scheme value. For example, `(1 2 . 3)` should be converted to `Pair(1, Pair(2, 3))`

In the case of calling `scheme_read` on input "`(1 2 . 3)`", `read_tail` 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))`.

A dotted pair must have exactly one item after the dot; anything else is a syntax error. You should fill in `read_tail` so that if there is only one expression after the dot, return it. Otherwise, raise a `SyntaxError` with an appropriate error message. Don't forget to remove the close parenthesis!

Hint: In order to verify that only one element follows a dot, read the expression after the `'.'` and then check if the next token is a closing parenthesis.

Test your understanding and implementation before moving on:

```
python3 ok -q 02 -u
python3 ok -q 02
```

Now that your parser is complete, you should also test it as follows:

- Run the doctests for `scheme_reader.py`

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

- Test interactively by running `python3 scheme_reader.py`. Every time you type in a value into the prompt, both the `str` and `repr` values of the parsed expression are printed. You can try the following inputs:

  ```
  read> 42
  str : 42
  repr: 42
  read> nil
  str : ()
  repr: nil
  read> (1 (2 3) (4 (5)))
  str : (1 (2 3) (4 (5)))
  repr: Pair(1, Pair(Pair(2, Pair(3, nil)),
  Pair(Pair(4, Pair(Pair(5, nil), nil)), nil)))
  read> (1 (9 8) . 7)
  str : (1 (9 8) . 7)
  repr: Pair(1, Pair(Pair(9, Pair(8, nil)), 7))
  read> (hi there . (cs . (student)))
  str : (hi there cs student)
  repr: Pair('hi', Pair('there', Pair('cs',
  ```

```
    Pair('student', nil))))
```

Once you have completed Part I, make sure you submit using OK to receive full credit for the first checkpoint.

```
python3 ok --submit
```

Part II: The Evaluator

Important submission note: For full credit:

- submit with Part I complete by **Friday 4/6** (worth 1 pt),
- submit again with Part II complete by **Thursday 4/12** (worth 1 pt), and
- submit the entire project by **Tuesday 4/17**. You will get an extra credit point for submitting the entire project by Monday 4/16. All changes in this part should be made in `scheme.py`.

In the starter implementation given to you, the evaluator can only evaluate self-evaluating expressions: numbers, booleans, and `nil`.

Read the first two sections of `scheme.py`, called Eval/Apply and Environments.

- `scheme_eval` evaluates a Scheme expression in the given environment. This function is nearly complete but is missing the logic for call expressions.
- When evaluating a special form, `scheme_eval` redirects evaluation to an appropriate `do_XXX_form` function found in the Special Forms section in `scheme.py`.
- `scheme_apply` applies a procedure to some arguments. This function is complete.
- The `.apply` methods in subclasses of `Procedure` and the `make_call_frame` function assist in applying built-in and user-defined procedures.
- The `Frame` class implements an environment frame.
- The `LambdaProcedure` class (in the Procedures section)

represents user-defined procedures.

These are all of the essential components of the interpreter; the rest of `scheme.py` defines special forms and input/output behavior.

Test your understanding of how these components fit together by unlocking the tests for `eval_apply`.

```
python3 ok -q eval_apply -u
```

Some Core Functionality

Problem 3 (1 pt)

Implement the `define` and `lookup` methods of the `Frame` class. Each `Frame` object has the following instance attributes:

- `bindings` is a dictionary representing the bindings in the frame. It maps Scheme symbols (represented as Python strings) to Scheme values.
- `parent` is the parent `Frame` instance. The parent of the Global Frame is `None`.

`define` takes a symbol (represented by a Python string) and value and binds the value to that symbol in the frame.

`lookup` takes a symbol and returns the value bound to that name in the first `Frame` of the environment in which that name is found. Recall that an *environment* is defined as a frame, its parent frame, and all its ancestor frames, including the Global Frame. Therefore, if the name is not found in the `bindings` dictionary in the current frame and the frame has a parent frame, continue lookup in the parent frame. If the name is not found in the current frame and there is no parent frame, raise a `SchemeError` **(provided)**.

Test your understanding and implementation before moving on:

```
python3 ok -q 03 -u
python3 ok -q 03
```

After you complete this problem, you can open your Scheme interpreter (with `python3 scheme.py`). You should be able to look up built-in procedure names:

```
scm> +
#[+]
scm> odd?
#[odd?]
scm> display
#[display]
```

However, your Scheme interpreter will still not be able to call these procedures. Let's fix that.

Problem 4 (1 pt)

To be able to call primitive procedures, such as `+`, you need to complete the `apply` method in the class `PrimitiveProcedure`. Primitive procedures are applied by calling a corresponding Python function that implements the procedure. For example, the `+` procedure in Scheme is implemented as the `add` function in Python.

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.

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.

The `apply` method of `PrimitiveProcedure` takes a list of argument values and the current environment. Note that `args` is a Scheme list represented as a `Pair` object. Your implementation should do the following:

- Convert the Scheme list to a Python list of arguments. **(provided)**

- If `self.use_env` is `True`, then add the current environment `env` as the last argument to this Python list.
- Call `self.fn` on all of those arguments using `*args` notation.
- If calling the function results in a `TypeError` exception being raised, then the wrong number of arguments were passed. Use a `try`/`except` block to intercept the exception and raise an appropriate `SchemeError` in its place.

Test your understanding and implementation before moving on:

```
python3 ok -q 04 -u
python3 ok -q 04
```

Problem 5 (1 pt)

`scheme_eval` evaluates a Scheme expression in a given environment. Most of `scheme_eval` has already been implemented for you. It currently looks up names in the current environment, returns self-evaluating expressions (like numbers) and evaluates special forms.

Implement the missing part of `scheme_eval`, which evaluates a call expression. To evaluate a call expression, we do the following:

1. Evaluate the operator (which should evaluate to an instance of `Procedure`)
2. Evaluate all of the operands
3. Apply the procedure on the evaluated operands

You'll have to recursively call `scheme_eval` in the first two steps. Here are some other functions/methods you should use:

- The `check_procedure` function raises an error if the provided argument is not a Scheme procedure. You can use this to check that your operator indeed evaluates to a procedure.
- The `map` method of `Pair` can apply a one-argument function to every item in a Scheme list.
- The `scheme_apply` function applies a Scheme procedure to some arguments.

Test your understanding and implementation before moving on:

```
python3 ok -q 05 -u
python3 ok -q 05
```

Your interpreter should now be able to evaluate primitive procedure calls, giving you the functionality of the Calculator language and more.

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

Hint: A solution to this problem was projected in Lecture 27 (Video; Berkeley login required). You should try to solve the problem yourself, but it's not cheating to use the solution from lecture.

Now would be a good time to start adding tests to `tests.scm`. For each new problem you complete from now on, add a few tests to the top of `tests.scm` to verify the behavior of your implementation. Remember, these are worth points! See Problem 0.

Problem 6 (1 pt)

Next, we'll implement defining variables. Recall that the `define` special form in Scheme can be used to define both names and procedures:

```
scm> (define a 3)   ; Defining a name
a
scm> (define (foo x) x)   ; Defining a procedure
foo
```

The type of the first operand tells us what is being defined:

- If it is a symbol, e.g. `a`, then the expression is defining a name
- If it is a list, e.g. `(foo x)`, then the expression is defining a procedure.

Read the Scheme Specifications to understand the behavior of the `define` special form! This problem only provides the behavior for binding expressions, not procedures, to names.
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
```

Test your understanding and implementation before moving on:

```
python3 ok -q 06 -u
python3 ok -q 06
```

You should now be able to give names to values and evaluate the resulting symbols. Note that `eval` takes a quoted expression and evaluates it (you can think of it as "removing" the quotes):

```
scm> (eval (define tau 6.28))
6.28
scm> (eval 'tau)
6.28
scm> tau
6.28
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 7 (1 pt)

To complete the core functionality, let's implement quoting in our interpreter. In Scheme, you can quote expressions in two ways: with the `quote` special form or with the symbol `'`. Recall that the `quote` special form returns its operand expression without evaluating it:

```
scm> (quote hello)
hello
scm> '(cons 1 2)  ; Equivalent to (quote (cons 1
2))
(cons 1 2)
```

Read the Scheme Specifications to understand the behavior of the `quote` special form.

Let's take care of the `quote` special form first. Implement the `do_quote_form` function so that it simply returns the unevaluated operand to the special form.

After completing this function, you should be able to evaluate quoted expressions. Try out some of the following in your interpreter!

```
scm> (quote a)
a
scm> (quote (1 . 2))
(1 . 2)
scm> (quote (1 (2 three . (4 . 5))))
(1 (2 three 4 . 5))
scm> (car (quote (a b)))
a
```

Next, complete your implementation of `scheme_read` in `scheme_reader.py` by handling the `'` case.

First, notice that `'<expression>` translates to `(quote <expression>)`. That means that we need to wrap the expression following `'` (which you can get by recursively calling `scheme_read`) into a quote special form, which, like all special forms, is really just a list.

For example, `'bagel` should be represented as `Pair('quote', Pair('bagel', nil))`.

After completing your `scheme_read` implementation, the following quoted expressions should now work as well.

```
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
```

Test your understanding and implementation before moving on:

```
python3 ok -q 07 -u
python3 ok -q 07
```

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

- Evaluate atoms, which include numbers, booleans, nil, and symbols,
- Evaluate the `quote` special form,
- Define symbols, and
- Call primitive procedures, for example evaluating `(+ (- 4 2) 5)`.

User-Defined Procedures

User-defined procedures are represented as instances of the `LambdaProcedure` class. 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 Scheme list of expressions; the body of the procedure.
- `env` is the environment in which the procedure was **defined**.

Problem 8 (1 pt)

Read the Scheme Specifications to understand the behavior of the `begin` special form!

Change the `eval_all` function (which is called from `do_begin_form`) to complete the implementation of the `begin`special form. A `begin` expression is evaluated by evaluating all sub-expressions in order. The value of the `begin`expression is the value of the final sub-expression.

```
scm> (begin (+ 2 3) (+ 5 6))
11
scm> (define x (begin (display 3) (newline) (+ 2
3)))
3
x
scm> (+ x 3)
8
scm> (begin (print 3) '(+ 2 3))
3
(+ 2 3)
```

If `eval_all` is passed an empty list of expressions (`nil`), then it should return the Python value `None`, which represents an undefined Scheme value.

Test your understanding and implementation before moving on:

```
python3 ok -q 08 -u
python3 ok -q 08
```

Problem 9 (1 pt)

Read the Scheme Specifications to understand the behavior of the `lambda` special form!

Implement the `do_lambda_form` function, which creates a `LambdaProcedure` instance. While you cannot call a user-defined procedure yet, you can verify that you have created the procedure correctly by typing a lambda expression into the interpreter prompt:

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

In Scheme, it is legal to place more than one expression in the body of a procedure (there must be at least one expression).
The `body` attribute of a `LambdaProcedure` instance is a Scheme list of body expressions.

Test your understanding and implementation before moving on:

```
python3 ok -q 09 -u
python3 ok -q 09
```

Problem 10 (2 pt)

Read the Scheme Specifications to understand the behavior of the `define` special form! In this problem, we'll finish defining the `define` form for procedures.

Currently, your Scheme interpreter is able to bind symbols to 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 named 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.

Test your understanding and implementation before moving on:

```
python3 ok -q 10 -u
python3 ok -q 10
```
You should now find that defined procedures evaluate to `LambdaProcedure` instances.

```
scm> (define (square x) (* x x))
square
scm> square
(lambda (x) (* x x))
```
Problem 11 (2 pt)

Implement the `make_child_frame` method of the `Frame` class, which:

- Creates a new `Frame` instance, the parent of which is `self`. **(provided)**
- If the number of argument values does not match with the number of formal parameters, raises a `SchemeError`.
- Binds formal parameters to their corresponding argument values in the newly created frame.

Test your understanding and implementation before moving on:

```
python3 ok -q 11 -u
python3 ok -q 11
```
Problem 12 (1 pt)

Implement the `make_call_frame` method in `LambdaProcedure`, which is needed by `scheme_apply`. It should create a new `Frame` instance using the `make_child_frame` method of the appropriate parent frame, binding formal parameters to argument values.

Since lambdas are lexically scoped, your new frame should be a child of the frame in which the lambda is defined. The `env` provided as an argument to `make_call_frame` is instead the frame in which the procedure is called, which will be useful when you implement dynamically scoped procedures in problem 16.

Test your understanding and implementation before moving on:

```
python3 ok -q 12 -u
python3 ok -q 12
```

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

- Create procedures using `lambda` expressions,
- Define named procedures using `define` expressions, and
- Call user-defined procedures.

Now is an excellent time to revisit the tests in `tests.scm` and ensure that you pass the tests that involve definition (Sections 1.1.2 and 1.1.4). To get the 2 points for Problem 0, remember to add a few of your own tests at the top.

To run your tests, run the command:

```
  python3 ok -q tests.scm
```

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 `False` is a false value. All other values (including `0` and `nil`) are true values. You can test whether a value is a true or false value using the provided Python functions `scheme_truep` and `scheme_falsep`, defined in `scheme_primitives.py`.

Note: Scheme traditionally uses `#f` to indicate the false Boolean value. In our interpreter, that is equivalent to `false` or `False`. Similarly, `true`, `True`, and `#t` are all equivalent. However when unlocking tests, use `#t`and `#f`.

To get you started, we've provided an implementation of the `if` special form in the `do_if_form` function. Make sure you understand that implementation before starting the following questions.

Problem 13 (2 pt)

Read the Scheme Specifications to understand the behavior of the `and` and `or` special forms!

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 a false value, then `#f` is returned. Otherwise, it should return the value of the last sub-expression. If there are no sub-expressions in an `and` expression, it evaluates to `#t`.

```
scm> (and)
#t
scm> (and 4 5 6)  ; all operands are true values
6
scm> (and 4 5 (+ 3 3))
6
scm> (and True False 42 (/ 1 0))  ; short-
circuiting behavior of and
#f
```

For `or`, evaluate each sub-expression from left to right. If any sub-expression evaluates to a true value, return that value. Otherwise, return `#f`. If there are no sub-expressions in an `or` expression, it evaluates to `#f`.

```
scm> (or)
```

```
#f
scm> (or 5 2 1)  ; 5 is a true value
5
scm> (or False (- 1 1) 1)  ; 0 is a true value in
Scheme
0
scm> (or 4 True (/ 1 0))  ; short-circuiting
behavior of or
4
```

Test your understanding and implementation before moving on:

```
python3 ok -q 13 -u
python3 ok -q 13
```

Problem 14 (2 pt)

Read the Scheme Specifications to understand the behavior of the `cond` special form!

Fill in the missing parts of `do_cond_form` so that it returns the value of the first result sub-expression corresponding to a true predicate, or the result sub-expression corresponding to `else`. Some special cases:

- When the true predicate does not have a corresponding result sub-expression, return the predicate value.
- When a result sub-expression of a `cond` case has multiple expressions, evaluate them all and return the value of the last expression. (*Hint*: Use `eval_all`.)

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 (+ 40 2))
           (else 'wat 0))
42
```
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 `None`.

```
scm> (cond (False 1) (False 2))
scm>
```
Test your understanding and implementation before moving on:

```
python3 ok -q 14 -u
python3 ok -q 14
```
Problem 15 (2 pt)

Read the Scheme Specifications to understand the behavior of the `let` special form!

The `let` special form binds symbols to values locally, giving them their initial values. For example:

```
scm> (define x 5)
x
scm> (define y 'bye)
y
scm> (let ((x 42)
           (y (* x 10)))  ; x refers to the global
value of x, not 42
       (list x y))
(42 50)
scm> (list x y)
(5 bye)
```
Implement `make_let_frame`, which returns a child frame of `env` that

binds the symbol in each element of `bindings` to the value of its corresponding expression. The `bindings` scheme list contains pairs that each contain a symbol and a corresponding expression.

You may find the following functions and methods useful:

- `check_form`: this function can be used to check the structure of each binding.
- `check_formals`: this function checks that formal parameters are a Scheme list of symbols for which each symbol is distinct.
- `make_child_frame`: this method (which you implemented in Problem 11) takes a `Pair` of formal parameters (symbols) and a `Pair` of values, and returns a new frame with all the symbols bound to the corresponding values.

Test your understanding and implementation before moving on:

```
python3 ok -q 15 -u
python3 ok -q 15
```

Problem 16 (1 pt)

Read the Scheme Specifications to understand the behavior of the `mu` special form!

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**. Most of the `MuProcedure` class has been provided for you.

Complete the `MuProcedure` class so that when a call on such a procedure is executed, it is dynamically scoped. 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
```

Looking at `LambdaProcedure` should give you a clue about what needs to be done to `MuProcedure` to complete it. Test your understanding and implementation before moving on:

```
python3 ok -q 16 -u
python3 ok -q 16
```

Congratulations! Your Scheme interpreter implementation is now complete!

The autograder tests for the interpreter are *not* comprehensive, so you may have uncaught bugs in your implementation. You should have been adding tests to the top of `tests.scm` as you did each problem, which will help you discover bugs on your own. **Writing these tests is worth 2 points of the project.**

To run your tests, run the command:

```
  python3 ok -q tests.scm
```

Make sure to remove all of the `(exit)` commands, so that all the tests are run! We've provided 115 tests (not counting the extra credit tests), so if you don't see at least that many tests passed, you haven't removed all the `(exit)` commands. (Of course, you should have many more than that, since you've been writing your own as well.)
One you have completed Part II, make sure you submit using OK to receive full credit for the second checkpoint.

```
python3 ok --submit
```

Part III: 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 the `questions.scm` file.

In addition, for this part of the project, you may find the primitive procedure reference very helpful if you ever have a question about the behavior of a built-in Scheme procedure, like the difference between `pair?`and `list?`.
The autograder tests for the interpreter are *not* comprehensive, so you may have uncaught bugs in your implementation. Therefore, you may find it useful to test your code for these questions in the staff interpreter or the web interpreter and then try it in your own interpreter once you are confident your Scheme code is working.

Problem 17 (1 pt)

Implement the `enumerate` procedure, which takes in a list of values and returns a list of two-element lists, where the first element is the index of the value, and the second element is the value itself.

```
scm> (enumerate '(3 4 5 6))
((0 3) (1 4) (2 5) (3 6))
scm> (enumerate '())
()
```
Test your implementation before moving on:

```
python3 ok -q 17
```
Problem 18 (2 pt)

Implement the `list-change` procedure, which lists all of the ways to make change for a positive integer `total`amount of money, using a list of currency denominations, which is sorted in descending order. The resulting list of ways of making change should also be returned in descending order.

To make change for 10 with the denominations (25, 10, 5, 1), we get the possibliites:

```
10
5, 5
5, 1, 1, 1, 1, 1
1, 1, 1, 1, 1, 1, 1, 1, 1, 1
```

To make change for 5 with the denominations (4, 3, 2, 1), we get the possibilities:

```
4, 1
3, 2
3, 1, 1
2, 2, 1
2, 1, 1, 1
1, 1, 1, 1, 1
```

You may find that implementing a helper function, `cons-all`, will be useful for this problem. To implement `cons-all`, use the built-in map procedure. `cons-all` takes in an element `first` and a list of lists `rests`, and adds `first` to the beginning of each list in `rests`:

```
scm> (cons-all 1 '((2 3) (2 4) (3 5)))
((1 2 3) (1 2 4) (1 3 5))
```

You may also find the built-in append procedure useful.

Test your implementation before moving on:

```
python3 ok -q 18
```

Problem 19 (2 pt)

In Scheme, source code is data. Every non-primitive expression is written as a Scheme list, so we can write procedures that manipulate other programs just as we write procedures that manipulate lists.

Rewriting programs can be useful: we can write an interpreter that only handles a small core of the language, and then write a procedure that converts other special forms into the core language before a program is passed to the interpreter.

For example, the `let` special form is equivalent to a call expression that begins with a `lambda` expression. Both create a new frame extending the current environment and evaluate a body within that new environment. Feel free to revisit Problem 15 as a refresher on how the `let` form works.

```
(let ((a 1) (b 2)) (+ a b))
;; Is equivalent to:
((lambda (a b) (+ a b)) 1 2)
```

These expressions can be represented by the following diagrams:

Let	Lambda

Use this rule to implement a procedure called `let-to-lambda` that rewrites all `let` special forms into `lambda`expressions. If we quote a `let` expression and pass it into this procedure, an equivalent `lambda` expression should be returned: pass it into this procedure:

```
scm> (let-to-lambda '(let ((a 1) (b 2)) (+ a b)))
((lambda (a b) (+ a b)) 1 2)
scm> (let-to-lambda '(let ((a 1)) (let ((b a)) b)))
((lambda (a) ((lambda (b) b) a)) 1)
```

In order to handle all programs, `let-to-lambda` must be aware of Scheme syntax. Since Scheme expressions are recursively nested, `let-to-lambda` must also be recursive. In fact, the structure of `let-to-lambda` is somewhat similar to that of `scheme_eval`--but in Scheme! As a reminder, atoms include numbers, booleans, nil, and symbols.

```
(define (let-to-lambda expr)
  (cond ((atom?   expr) <rewrite atoms>)
        ((quoted? expr) <rewrite quoted 
expressions>)
        ((lambda? expr) <rewrite lambda 
expressions>)
        ((define? expr) <rewrite define 
expressions>)
        ((let?    expr) <rewrite let expressions>)
        (else           <rewrite other 
expressions>)))
```
Hint: You may want to implement `zip` at the top of `questions.scm` and also use the built-in `map` procedure.

```
scm> (zip '((1 2) (3 4) (5 6)))
((1 3 5) (2 4 6))
scm> (zip '((1 2)))
((1) (2))
scm> (zip '())
(() ())
```
Test your understanding and implementation before moving on:

```
python3 ok -q 19 -u
python3 ok -q 19
```
Note: We used `let` while defining `let-to-lambda`. What if we want to run `let-to-lambda` on an interpreter that does not recognize `let`? We can pass `let-to-lambda` to itself to rewrite itself into an *equivalent program without* `let`:

```
;; The let-to-lambda procedure
(define (let-to-lambda expr)
  ...)

;; A list representing the let-to-lambda procedure
```

```
(define let-to-lambda-code
  '(define (let-to-lambda expr)
     ...))

;; An let-to-lambda procedure that does not use
'let'!
(define let-to-lambda-without-let
  (let-to-lambda let-to-lambda-code))
```

Part IV: Extra Credit

Note: During regular Office Hours and Project Parties, the staff will prioritize helping students with required questions. We will not be offering help with either extra credit problems unless the queue is empty.

Problem 20 (2 pt)

Complete the function `optimize_tail_calls` in `scheme.py`. It returns an alternative to `scheme_eval` that is properly tail recursive. That is, the interpreter will allow an unbounded number of active tail calls in constant space.

The `Thunk` class represents a thunk, an expression that needs to be evaluated in an environment.
When `scheme_optimized_eval` receives a non-atomic expression in a `tail` context, then it returns an `Thunk` instance. Otherwise, it should repeatedly call `original_scheme_eval` until the result is a value, rather than a `Thunk`.

A successful implementation will require changes to several other functions, including some functions that we provided for you. All expressions throughout your interpreter that are in a tail context should be evaluated by calling `scheme_eval` with `True` as a third argument. Your goal is to determine which expressions are in a tail context throughout your code.

Once you finish, uncomment the following line in `scheme.py` to use your implementation:

```
scheme_eval = optimize_tail_calls(scheme_eval)
```

Test your implementation before moving on:

```
python3 ok -q 20
```

Problem 21 (1 pt)

Macros allow the language itself to be extended by the user. Simple macros can be provided with the `define-macro` special form. This must be used like a procedure definition, and it creates a procedure just like `define`. However, this procedure has a special evaluation rule: it is applied to its arguments without first evaluating them. Then the result of this application is evaluated.

This final evaluation step takes place in the caller's frame, as if the return value from the macro was literally pasted into the code in place of the macro.

Here is a simple example:

```
scm> (define (map f lst) (if (null? lst) nil (cons
(f (car lst)) (map f (cdr lst)))))
scm> (define-macro (for formal iterable body)
....     (list 'map (list 'lambda (list formal)
body) iterable))
scm> (for i '(1 2 3)
....     (print (* i i)))
1
4
9
(None None None)
```

The code above defines a macro `for` that acts as a `map` except that it doesn't need a lambda around the body.

In order to implement `define-macro`, implement complete the implementation for `do_define_macro`, which should create a `MacroProcedure` and bind it to the given name as in `do_define_form`. Then, update `scheme_eval` so that calls to macro procedures are evaluated correctly.

Hint: Use the `apply_macro` method in the `MacroProcedure` class to apply a *macro to the operands in its call expression. This procedure is written to* interact well with tail call optimization.

Test your implementation before moving on:

```
python3 ok -q 21
```

Conclusion

Congratulations! You have just implemented an interpreter for an entire language! We've implemented a significant subset of Scheme in this project, but your interpreter can be extended with even more features! If you enjoyed this project, we have some suggestions in the extension instructions.