61A Lecture 27

Wednesday, November 5
Announcements
Announcements

• Homework 7 due Wednesday 11/5 @ 11:59pm
Announcements

• Homework 7 due Wednesday 11/5 @ 11:59pm
• Project 1 composition revisions due Wednesday 11/5 @ 11:59pm
Announcements

• Homework 7 due Wednesday 11/5 @ 11:59pm
• Project 1 composition revisions due Wednesday 11/5 @ 11:59pm
  ▪ Copy hog.py to an instructional server and run: submit proj1revision
Announcements

• Homework 7 due Wednesday 11/5 @ 11:59pm
• Project 1 composition revisions due Wednesday 11/5 @ 11:59pm
  ▪ Copy hog.py to an instructional server and run: submit proj1revision
• Quiz 2 released Wednesday 11/5 & due Thursday 11/6 @ 11:59pm
Announcements

• Homework 7 due Wednesday 11/5 @ 11:59pm
• Project 1 composition revisions due Wednesday 11/5 @ 11:59pm
  ▪ Copy hog.py to an instructional server and run: submit proj1revision
• Quiz 2 released Wednesday 11/5 & due Thursday 11/6 @ 11:59pm
  ▪ Open note, open interpreter, closed classmates, closed Internet
Announcements

• Homework 7 due Wednesday 11/5 @ 11:59pm
• Project 1 composition revisions due Wednesday 11/5 @ 11:59pm
  ▪ Copy hog.py to an instructional server and run: submit proj1revision
• Quiz 2 released Wednesday 11/5 & due Thursday 11/6 @ 11:59pm
  ▪ Open note, open interpreter, closed classmates, closed Internet
• Midterm survey due Monday 11/10 @ 11:59pm (Thanks!)
Announcements

• Homework 7 due Wednesday 11/5 @ 11:59pm
• Project 1 composition revisions due Wednesday 11/5 @ 11:59pm
  ▪ Copy hog.py to an instructional server and run: submit proj1revision
• Quiz 2 released Wednesday 11/5 & due Thursday 11/6 @ 11:59pm
  ▪ Open note, open interpreter, closed classmates, closed Internet
• Midterm survey due Monday 11/10 @ 11:59pm (Thanks!)
• Project 4 due Thursday 11/20 @ 11:59pm (Big!)
Interpreting Scheme
The Structure of an Interpreter
The Structure of an Interpreter

Eval

Apply
The Structure of an Interpreter

Base cases: Eval

Apply
The Structure of an Interpreter

Base cases:
- Primitive values (numbers)
The Structure of an Interpreter

Base cases:
• Primitive values (numbers)

Recursive calls:
The Structure of an Interpreter

Base cases:
• Primitive values (numbers)

Recursive calls:
• Eval(operator, operands) of call expressions
The Structure of an Interpreter

Base cases:
- Primitive values (numbers)

Recursive calls:
- Eval(operator, operands) of call expressions
- Apply(procedure, arguments)
The Structure of an Interpreter

Base cases:
• Primitive values (numbers)

Recursive calls:
• Eval(operator, operands) of call expressions
• Apply(procedure, arguments)

Base cases:
• Built-in primitive procedures
The Structure of an Interpreter

Base cases:
• Primitive values (numbers)
• Look up values bound to symbols

Recursive calls:
• Eval(operator, operands) of call expressions
• Apply(procedure, arguments)

Base cases:
• Built-in primitive procedures
The Structure of an Interpreter

Base cases:
- Primitive values (numbers)
- Look up values bound to symbols

Recursive calls:
- Eval(operator, operands) of call expressions
- Apply(procedure, arguments)

Base cases:
- Built-in primitive procedures
The Structure of an Interpreter

**Eval**

Base cases:
- Primitive values (numbers)
- Look up values bound to symbols

Recursive calls:
- Eval(operator, operands) of call expressions
- Apply(procedure, arguments)
- Eval(sub-expressions) of special forms

**Apply**

Base cases:
- Built-in primitive procedures
The Structure of an Interpreter

Eval

Base cases:
• Primitive values (numbers)
• Look up values bound to symbols

Recursive calls:
• Eval(operator, operands) of call expressions
• Apply(procedure, arguments)
• Eval(sub-expressions) of special forms

Apply

Base cases:
• Built-in primitive procedures

Recursive calls:
• Eval(body) of user-defined procedures
The Structure of an Interpreter

Base cases:  
- Primitive values (numbers)  
- Look up values bound to symbols

Recursive calls:  
- Eval(operator, operands) of call expressions  
- Apply(procedure, arguments)  
- Eval(sub-expressions) of special forms

Base cases:  
- Built-in primitive procedures

Recursive calls:  
- Eval(body) of user-defined procedures
The Structure of an Interpreter

**Eval**

Base cases:
- Primitive values (numbers)
- Look up values bound to symbols

Recursive calls:
- Eval(operator, operands) of call expressions
- Apply(procedure, arguments)
- Eval(sub-expressions) of special forms

Requires an environment for symbol lookup

**Apply**

Base cases:
- Built-in primitive procedures

Recursive calls:
- Eval(body) of user-defined procedures
The Structure of an Interpreter

**Eval**

Base cases:
- Primitive values (numbers)
- Look up values bound to symbols

Recursive calls:
- Eval(operator, operands) of call expressions
- Apply(procedure, arguments)
- Eval(sub-expressions) of special forms

**Apply**

Base cases:
- Built-in primitive procedures

Recursive calls:
- Eval(body) of user-defined procedures

Requires an environment for symbol lookup

Creates a new environment each time a user-defined procedure is applied
Special Forms
Scheme Evaluation
Scheme Evaluation

The scheme_eval function dispatches on expression form:
Scheme Evaluation

The scheme_eval function dispatches on expression form:
- Symbols are looked up in the current environment
Scheme Evaluation

The scheme_eval function dispatches on expression form:

- Symbols are looked up in the current environment
- Self-evaluating expressions are returned as values
Scheme Evaluation

The scheme_eval function dispatches on expression form:
• Symbols are looked up in the current environment
• Self-evaluating expressions are returned as values
• All other legal expressions are represented as Scheme lists, called combinations
Scheme Evaluation

The scheme_eval function dispatches on expression form:
• Symbols are looked up in the current environment
• Self-evaluating expressions are returned as values
• All other legal expressions are represented as Scheme lists, called combinations

(if <predicate> <consequent> <alternative>)
Scheme Evaluation

The scheme_eval function dispatches on expression form:

- Symbols are looked up in the current environment
- Self-evaluating expressions are returned as values
- All other legal expressions are represented as Scheme lists, called combinations

```
(if <predicate> <consequent> <alternative>)
```

```
(lambda (<formal-parameters>) <body>)
```
Scheme Evaluation

The scheme_eval function dispatches on expression form:
- Symbols are looked up in the current environment
- Self-evaluating expressions are returned as values
- All other legal expressions are represented as Scheme lists, called combinations

```
(if <predicate> <consequent> <alternative>)
(lambda (<formal-parameters>) <body>)
(define <name> <expression>)
```
Scheme Evaluation

The scheme_eval function dispatches on expression form:

- Symbols are looked up in the current environment
- Self-evaluating expressions are returned as values
- All other legal expressions are represented as Scheme lists, called combinations

\[
\text{(if <predicate> <consequent> <alternative>)}
\]

\[
\text{(lambda (<formal-parameters>) <body>)}
\]

\[
\text{(define <name> <expression>)}
\]

\[
\text{(<operator> <operand 0> ... <operand k>)}
\]
Scheme Evaluation

The `scheme_eval` function dispatches on expression form:

- Symbols are looked up in the current environment
- Self-evaluating expressions are returned as values
- All other legal expressions are represented as Scheme lists, called combinations

```
(if <predicate> <consequent> <alternative>)
(lambda (<formal-parameters>) <body>)
(define <name> <expression>)
(<operator> <operand 0> ... <operand k>)
```

Special forms are identified by the first list element
Scheme Evaluation

The scheme_eval function dispatches on expression form:

- Symbols are looked up in the current environment
- Self-evaluating expressions are returned as values
- All other legal expressions are represented as Scheme lists, called combinations

```
(if <predicate> <consequent> <alternative>)
(lambda (<formal-parameters>) <body>)
(define <name> <expression>)
(<operator> <operand 0> ... <operand k>)
```

Special forms are identified by the first list element.
Scheme Evaluation

The scheme_eval function dispatches on expression form:

- Symbols are looked up in the current environment
- Self-evaluating expressions are returned as values
- All other legal expressions are represented as Scheme lists, called combinations

\[(\text{if} \ <\text{predicate}> \ <\text{consequent}> \ <\text{alternative}>)]\]

\[(\text{lambda} \ (<\text{formal-parameters}>) \ <\text{body}>)\]

\[(\text{define} \ <\text{name}> \ <\text{expression}>)\]

\[(<\text{operator}> \ <\text{operand} \ 0> \ ... \ <\text{operand} \ k>)\]

Special forms are identified by the first list element

Any combination that is not a known special form is a call expression
Scheme Evaluation

The scheme_eval function dispatches on expression form:

- Symbols are looked up in the current environment
- Self-evaluating expressions are returned as values
- All other legal expressions are represented as Scheme lists, called combinations

```
(define (demo s) (if (null? s) '(3) (cons (car s) (demo (cdr s)))))
```
Scheme Evaluation

The scheme_eval function dispatches on expression form:

- Symbols are looked up in the current environment
- Self-evaluating expressions are returned as values
- All other legal expressions are represented as Scheme lists, called combinations

\[
\text{(if } \text{<predicate}> \text{ <consequent>} \text{ <alternative>)}
\]

\[
\text{(lambda } \text{(<formal-parameters>)} \text{ <body>)}
\]

\[
\text{(define } \text{<name> } \text{<expression>)}
\]

\[
\text{(<operator> } \text{<operand 0> ... <operand k>)}
\]

Any combination that is not a known special form is a call expression

\[
\text{(define (demo } \text{s)} \text{ (if } \text{(null? } \text{s)} \text{'(3) (cons (car } \text{s)} \text{(demo (cdr } \text{s)}))} \text{))}
\]

\[
\text{(demo (list 1 2))}
\]
Logical Forms
Logical Special Forms
Logical forms may only evaluate some sub-expressions.
Logical Special Forms

Logical forms may only evaluate some sub-expressions.

- **If** expression: \( \text{if} \ <\text{predicate}> \ <\text{consequent}> \ <\text{alternative}> \)
Logical Special Forms

Logical forms may only evaluate some sub-expressions.

- **If** expression: $(\text{if }<\text{predicate}> <\text{consequent}> <\text{alternative}>)$
- **And** and **or**: $(\text{and } <\text{e}_1> ... <\text{e}_n>), \ (\text{or } <\text{e}_1> ... <\text{e}_n>)$
Logical Special Forms

Logical forms may only evaluate some sub-expressions.

• **If** expression: \((\text{if} <\text{predicate}> <\text{consequent}> <\text{alternative}>)\)

• **And** and **or**: \((\text{and} <e_1> \ldots <e_n>), \quad (\text{or} <e_1> \ldots <e_n>)\)

• **Cond** expression: \((\text{cond} (<p_1> <e_1>) \ldots (<p_n> <e_n>) \text{ (else } <e>))\)
Logical Special Forms

Logical forms may only evaluate some sub-expressions.

- **If** expression: \((\text{if} \ <\text{predicate}> \ <\text{consequent}> \ <\text{alternative}>)\)
- **And** and **or**: \((\text{and} \ <\text{e}1> \ ... \ <\text{e}n>), \ (\text{or} \ <\text{e}1> \ ... \ <\text{e}n>))\)
- **Cond** expression: \((\text{cond} \ (<\text{p}1> \ <\text{e}1>) \ ... \ (<\text{p}n> \ <\text{e}n>) \ (\text{else} \ <\text{e}>)\))

The value of an if expression is the value of a sub-expression:
Logical Special Forms

Logical forms may only evaluate some sub–expressions.

- **If** expression: \((\text{if} \ <\text{predicate}> \ <\text{consequent}> \ <\text{alternative}>)\)
- **And** and **or**: \((\text{and} \ <\text{e}_1> \ ... \ <\text{e}_n>), \ (\text{or} \ <\text{e}_1> \ ... \ <\text{e}_n>)\)
- **Cond** expression: \((\text{cond} \ (<p_1> \ <e_1>) \ ... \ (<p_n> \ <e_n>) \ (\text{else} \ <e>))\)

The value of an if expression is the value of a sub–expression:

- Evaluate the predicate.
Logical Special Forms

Logical forms may only evaluate some sub-expressions.

- **If** expression: \((\text{if} \ <\text{predicate}> \ <\text{consequent}> \ <\text{alternative}>)\)
- **And** and **or**: \((\text{and} \ <e1> \ ... \ <en>), \quad (\text{or} \ <e1> \ ... \ <en>)\)
- **Cond** expression: \((\text{cond} \ (<p1> <e1>) \ ... \ (<pn> <en>) \ (\text{else} \ <e>))\)

The value of an if expression is the value of a sub-expression:

- Evaluate the predicate.
- Choose a sub-expression: <consequent> or <alternative>. 
Logical Special Forms

Logical forms may only evaluate some sub-expressions.

- **If** expression: \((\text{if } \text{<predicate>} \text{ <consequent>} \text{ <alternative>})\)
- **And** and **or**: \((\text{and } \text{<e}_1\ldots\text{ <en>}), \text{ (or } \text{<e}_1\ldots\text{ <en>})\)
- **Cond** expression: \((\text{cond } (<p_1> \text{ <e}_1>) \ldots (<p_n> \text{ <en>}) \text{ (else } \text{<e>}))\)

The value of an if expression is the value of a sub-expression:

- Evaluate the predicate.
- Choose a sub-expression: <consequent> or <alternative>.
- Evaluate that sub-expression in place of the whole expression.
Logical Special Forms

Logical forms may only evaluate some sub-expressions.

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And and or:** `(and <e1> ... <en>), (or <e1> ... <en>)`
- **Cond** expression: `(cond (<p1> <e1>) ... (<pn> <en>) (else <e>))`

The value of an if expression is the value of a sub-expression:

- Evaluate the predicate.
- Choose a sub-expression: `<consequent>` or `<alternative>`.
- Evaluate that sub-expression in place of the whole expression.
Logical Special Forms

Logical forms may only evaluate some sub-expressions.

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And and or:** `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- **Cond** expression: `(cond (<p1> <e1>) ... (<pn> <en>) (else <e>))`

The value of an if expression is the value of a sub-expression:

- Evaluate the predicate.
- Choose a sub-expression: `<consequent>` or `<alternative>`.
- Evaluate that sub-expression in place of the whole expression.
Logical Special Forms

Logical forms may only evaluate some sub-expressions.

- **If** expression:  \( (\text{if } <\text{predicate}> <\text{consequent}> <\text{alternative}>) \)
- **And** and **or**:  \( (\text{and } <e1> ... <en>), (\text{or } <e1> ... <en>) \)
- **Cond** expression:  \( (\text{cond } (<p1> <e1>) ... (<pn> <en>) (\text{else } <e>)) \)

The value of an if expression is the value of a sub-expression:

- Evaluate the predicate.
- Choose a sub-expression: \(<\text{consequent}>\) or \(<\text{alternative}>\).
- Evaluate that sub-expression in place of the whole expression.
Quotation
Quotation

The quote special form evaluates to the quoted expression, which is not evaluated
Quotation

The quote special form evaluates to the quoted expression, which is not evaluated

(quote <expression>)
Quotation

The quote special form evaluates to the quoted expression, which is not evaluated

(quote <expression>) (quote (+ 1 2))

evaluates to the
three-element Scheme list

(+ 1 2)
The quote special form evaluates to the quoted expression, which is not evaluated.

\[
\text{quote <expression>} \quad (\text{quote } (+ 1 2))
\]

Evaluates to the three-element Scheme list

\[
(+ 1 2)
\]

The <expression> itself is the value of the whole quote expression.
Quotation

The quote special form evaluates to the quoted expression, which is not evaluated

\[
\text{(quote <expression>)} \quad \text{(quote (+ 1 2))}
\]

The <expression> itself is the value of the whole quote expression

'\text{<expression>} is shorthand for (quote <expression>)}
Quotation

The quote special form evaluates to the quoted expression, which is not evaluated:

\[
\text{(quote <expression>)} \quad \text{(quote (+ 1 2))} \quad \text{(quote (1 2))}
\]

The <expression> itself is the value of the whole quote expression:

'expression is shorthand for (quote <expression>)

\[
\text{(quote (1 2))} \quad \text{is equivalent to} \quad \text{'(1 2)}
\]
Quotation

The quote special form evaluates to the quoted expression, which is not evaluated

\[(quote \text{<expression>}) \quad (quote (+ 1 2))\]

\text{The \text{<expression>} itself is the value of the whole quote expression}

\text{<expression>} is shorthand for \(quote \text{<expression>}\)

\[(quote (1 2)) \quad \text{is equivalent to} \quad '(1 2)\]

The scheme_read parser converts shorthand \' to a combination that starts with quote
Quotation

The quote special form evaluates to the quoted expression, which is not evaluated

\[
(\text{quote } <\text{expression}>) \quad (\text{quote } (+ 1 2))
\]

\[
\text{evaluates to the three-element Scheme list}
\]

The \(<\text{expression}>\) itself is the value of the whole quote expression

\'<\text{expression}>\ is shorthand for (quote \(<\text{expression}>\))

\[
(\text{quote } (1 2)) \quad \text{is equivalent to} \quad '(1 2)
\]

The scheme_read parser converts shorthand \' to a combination that starts with quote

\[
(\text{Demo})
\]
Lambda Expressions
Lambda Expressions
Lambda Expressions

Lambda expressions evaluate to user-defined procedures.
Lambda Expressions

Lambda expressions evaluate to user-defined procedures.

\[
\text{(lambda (formal-parameters) body)}
\]
Lambda Expressions

Lambda expressions evaluate to user-defined procedures.

\[
\text{lambda} \ (<\text{formal-parameters}>\) \ <\text{body}>
\]

\[
\text{lambda} \ (x) \ (\ast \ x \ x)
\]
Lambda Expressions

Lambda expressions evaluate to user-defined procedures.

\[(\text{lambda} \ (<\text{formal-parameters}>\)) \ (<\text{body}>\))\]

\[(\text{lambda} \ (x) \ (* \ x \ x))\]

class LambdaProcedure:
    def __init__(self, formals, body, env):
        self.formals = formals
        self.body = body
        self.env = env
Lambda Expressions

Lambda expressions evaluate to user-defined procedures.

```
(lambda (<formal-parameters>) <body>)
```

```
(lambda (x) (* x x))
```

```python
class LambdaProcedure:
    def __init__(self, formals, body, env):
        self.formals = formals  # A scheme list of symbols
        self.body = body
        self.env = env
```
Lambda Expressions

Lambda expressions evaluate to user-defined procedures.

\(\texttt{(lambda (formal-parameters) \text{body})}\)

\(\texttt{(lambda (x) (* x x))}\)

class LambdaProcedure:
    def __init__(self, formals, body, env):
        self.formals = formals  # A scheme list of symbols
        self.body = body  # A scheme expression
        self.env = env
**Lambda Expressions**

Lambda expressions evaluate to user-defined procedures.

```
(lambda (<formal-parameters>) <body>)
```

```
(lambda (x) (* x x))
```

class LambdaProcedure:
```python
def __init__(self, formals, body, env):
    self.formals = formals  # A scheme list of symbols
    self.body = body        # A scheme expression
    self.env = env          # A Frame instance
```
Frames and Environments
Frames and Environments

A frame represents an environment by having a parent frame
Frames and Environments

A frame represents an environment by having a parent frame.

Frames are Python instances with methods `lookup` and `define`.
Frames and Environments

A frame represents an environment by having a parent frame.

Frames are Python instances with methods lookup and define.

In Project 4, Frames do not hold return values.
Frames and Environments

A frame represents an environment by having a parent frame.

Frames are Python instances with methods lookup and define.

In Project 4, Frames do not hold return values.

\[
\begin{array}{|c|}
\hline
\text{g: Global frame} \\
\hline
y & 3 \\
\hline
z & 5 \\
\hline
\end{array}
\]
Frames and Environments

A frame represents an environment by having a parent frame

Frames are Python instances with methods lookup and define

In Project 4, Frames do not hold return values

\[
g: \text{Global frame} \\
\begin{array}{ll}
y & 3 \\
z & 5 \\
\end{array}
\]

\[
f1: [parent=g] \\
\begin{array}{ll}
x & 2 \\
z & 4 \\
\end{array}
\]
Frames and Environments

A frame represents an environment by having a parent frame.

Frames are Python instances with methods lookup and define.

In Project 4, Frames do not hold return values.

<table>
<thead>
<tr>
<th>g: Global frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>y</td>
</tr>
<tr>
<td>z</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>f1: [parent=g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
</tr>
<tr>
<td>z</td>
</tr>
</tbody>
</table>

(Demo)
Define Expressions
Define Expressions
Define Expressions

Define binds a symbol to a value in the first frame of the current environment.
Define Expressions

Define binds a symbol to a value in the first frame of the current environment.

\[(\text{define} \ <\text{name}> \ <\text{expression}>\)]
Define Expressions

Define binds a symbol to a value in the first frame of the current environment.

(define <name> <expression>)

1. Evaluate the <expression>
Define Expressions

Define binds a symbol to a value in the first frame of the current environment.

\[(\text{define } <\text{name}> <\text{expression}>)\]

1. Evaluate the <expression>

2. Bind <name> to its value in the current frame
Define Expressions

Define binds a symbol to a value in the first frame of the current environment.

\[
\text{(define <name> <expression>)}
\]

1. Evaluate the \(<\text{expression}>\)

2. Bind \(<\text{name}>\) to its value in the current frame

\[
\text{(define x (+ 1 2))}
\]
Define Expressions

Define binds a symbol to a value in the first frame of the current environment.

\[
\text{(define } \text{name} \text{ } \text{expression})
\]

1. Evaluate the <expression>
2. Bind <name> to its value in the current frame

\[
\text{(define } x \text{ } (+ 1 2))
\]

Procedure definition is shorthand of define with a lambda expression
Define Expressions

Define binds a symbol to a value in the first frame of the current environment.

\[(\text{define} \ <\text{name}> \ <\text{expression}>)]

1. Evaluate the \(<\text{expression}>\)

2. Bind \(<\text{name}>\) to its value in the current frame

\[(\text{define} \ x \ (+ \ 1 \ 2))]\]

Procedure definition is shorthand of define with a lambda expression

\[(\text{define} \ (<\text{name}> \ <\text{formal parameters}>)) \ <\text{body}>)]
Define Expressions

Define binds a symbol to a value in the first frame of the current environment.

```
(define <name> <expression>)
```

1. Evaluate the `<expression>`
2. Bind `<name>` to its value in the current frame

```
(define x (+ 1 2))
```

Procedure definition is shorthand of define with a lambda expression

```
(define (<name> <formal parameters>) <body>)
```

```
(define <name> (lambda (<formal parameters>) <body>))
```
Applying User-Defined Procedures
Applying User-Defined Procedures

To apply a user-defined procedure, create a new frame in which formal parameters are bound to argument values, whose parent is the env attribute of the procedure.
Applying User-Defined Procedures

To apply a user-defined procedure, create a new frame in which formal parameters are bound to argument values, whose parent is the `env` attribute of the procedure.

Evaluate the body of the procedure in the environment that starts with this new frame.
Applying User-Defined Procedures

To apply a user-defined procedure, create a new frame in which formal parameters are bound to argument values, whose parent is the \texttt{env} attribute of the procedure.

Evaluate the body of the procedure in the environment that starts with this new frame.

\begin{verbatim}
(define (demo s) (if (null? s) '(3) (cons (car s) (demo (cdr s))))
\end{verbatim}
Applying User-Defined Procedures

To apply a user-defined procedure, create a new frame in which formal parameters are bound to argument values, whose parent is the `env` attribute of the procedure.

Evaluate the body of the procedure in the environment that starts with this new frame:

```
(define (demo s) (if (null? s) '(3) (cons (car s) (demo (cdr s)))))
```
Applying User-Defined Procedures

To apply a user-defined procedure, create a new frame in which formal parameters are bound to argument values, whose parent is the `env` attribute of the procedure.

Evaluate the body of the procedure in the environment that starts with this new frame.

```
(define (demo s) (if (null? s) '(3) (cons (car s) (demo (cdr s)))))
(demo (list 1 2))
```
Applying User-Defined Procedures

To apply a user-defined procedure, create a new frame in which formal parameters are bound to argument values, whose parent is the `env` attribute of the procedure.

Evaluate the body of the procedure in the environment that starts with this new frame.

```
(define (demo s) (if (null? s) '(3) (cons (car s) (demo (cdr s)))))
(demo (list 1 2))
```
Applying User-Defined Procedures

To apply a user-defined procedure, create a new frame in which formal parameters are bound to argument values, whose parent is the env attribute of the procedure.

Evaluate the body of the procedure in the environment that starts with this new frame.

\[
\text{define (demo s) (if (null? s) '(3) (cons (car s) (demo (cdr s)))})}}
\]

\[
\text{(demo (list 1 2))}
\]
Applying User-Defined Procedures

To apply a user-defined procedure, create a new frame in which formal parameters are bound to argument values, whose parent is the env attribute of the procedure.

Evaluate the body of the procedure in the environment that starts with this new frame.

\[
\text{(define (demo s) (if (null? s) '(3) (cons (car s) (demo (cdr s)))))}
\]

\[
\text{(demo (list 1 2))}
\]
Applying User-Defined Procedures

To apply a user-defined procedure, create a new frame in which formal parameters are bound to argument values, whose parent is the `env` attribute of the procedure.

Evaluate the body of the procedure in the environment that starts with this new frame.

```scheme
(define (demo s) (if (null? s) '(3) (cons (car s) (demo (cdr s)))))
(demo (list 1 2))
```
apply[fn;x;a] =
    [atom[fn] -> [eq[fn;CAR] -> caar[x];
                  eq[fn;CDR] -> cdar[x];
                  eq[fn;CONS] -> cons[car[x];cadr[x]];]
    eq[fn;ATOM] -> atom[car[x]];]
    eq[fn;EQ] -> eq[car[x];cadr[x]];]
T -> apply[eval[fn;a];x;a]];}

substitute[fn] = [atom[fn] ->
    eq[car[fn];LAMBDA] -> ev[principal[fn];pairlis[cadr[fn];x;a]];]
substitute[fn] = [atom[fn] ->
    eq[car[fn];LABEL] -> apply[caddr[fn];x;cons[cons[cadr[fn];
                                      caddr[fn]]];a]];]

atom[car[e]] ->
    [eq[car[e];QUOTE] -> cadr[e];
    eq[car[e];COND] -> evcon[cdr[e];a];
    T -> apply[car[e];evlis[cdr[e];a];a]];]

T -> apply[car[e];evlis[cdr[e];a];a]]