



CS61A Lecture 30

Amir Kamil
UC Berkeley
April 1, 2013

Announcements



- HW9 due Wednesday

- Ants extra credit due Wednesday
 - See Piazza for submission instructions

- Hog revisions out, due next Monday

Scheme Is a Dialect of Lisp



Scheme Is a Dialect of Lisp



“The greatest single programming language ever designed.”

-Alan Kay, co-inventor of Smalltalk and OOP

Scheme Is a Dialect of Lisp



“The greatest single programming language ever designed.”

-Alan Kay, co-inventor of Smalltalk and OOP

“The only computer language that is beautiful.”

-Neal Stephenson, sci-fi author

Scheme Is a Dialect of Lisp



“The greatest single programming language ever designed.”

-Alan Kay, co-inventor of Smalltalk and OOP

“The only computer language that is beautiful.”

-Neal Stephenson, sci-fi author

“The most powerful programming language is Lisp. If you don't know Lisp (or its variant, Scheme), you don't appreciate what a powerful language is. Once you learn Lisp you will see what is missing in most other languages.”

-Richard Stallman, founder of the Free Software movement

Scheme Is a Dialect of Lisp



“The greatest single programming language ever designed.”

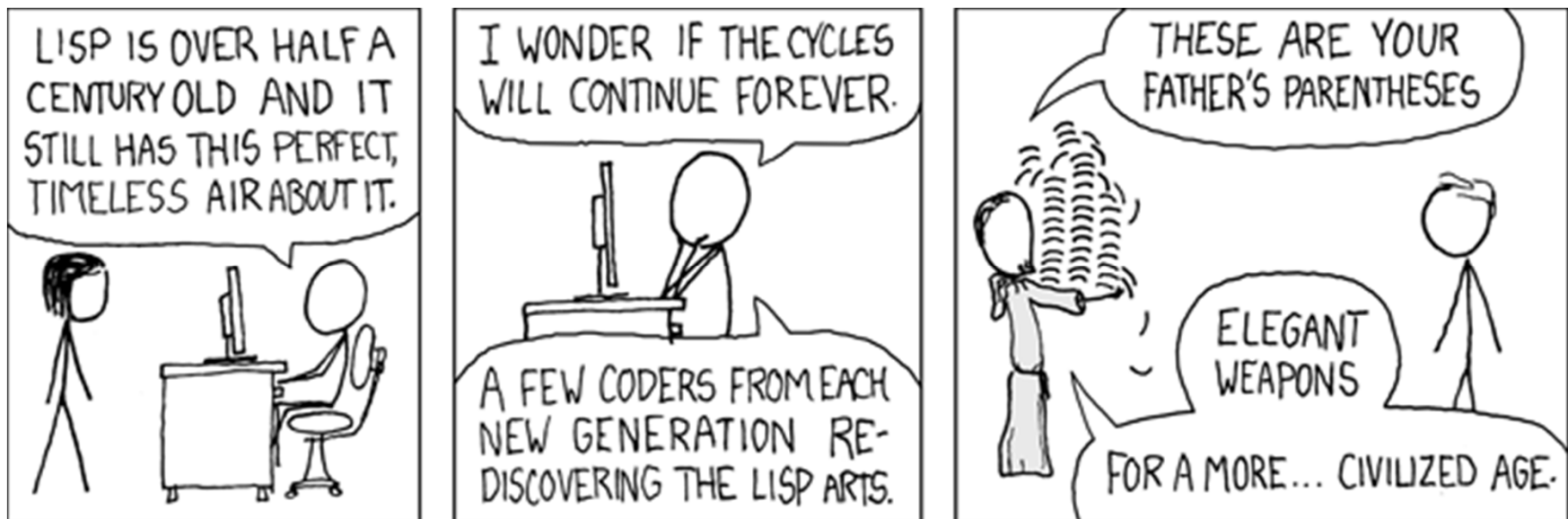
-Alan Kay, co-inventor of Smalltalk and OOP

“The only computer language that is beautiful.”

-Neal Stephenson, sci-fi author

“The most powerful programming language is Lisp. If you don't know Lisp (or its variant, Scheme), you don't appreciate what a powerful language is. Once you learn Lisp you will see what is missing in most other languages.”

-Richard Stallman, founder of the Free Software movement



Scheme Fundamentals



Scheme Fundamentals



Scheme programs consist of expressions, which can be:

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

> `(quotient 10 2)`

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
```

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
> (quotient (+ 8 7) 5)
```


Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
> (quotient (+ 8 7) 5)
3
```

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
> (quotient (+ 8 7) 5)
3
> (+ (* 3
      (+ (* 2 4)
          (+ 3 5)))
      (+ (- 10 7)
          6))
```

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
> (quotient (+ 8 7) 5)
3
> (+ (* 3
      (+ (* 2 4)
          (+ 3 5)))
      (+ (- 10 7)
          6))
```

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
> (quotient (+ 8 7) 5)
3
> (+ (* 3
      (+ (* 2 4)
          (+ 3 5)))
      (+ (- 10 7)
          6))
```

“quotient” names Scheme’s built-in integer division procedure (i.e., function)

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
> (quotient (+ 8 7) 5)
3
> (+ (* 3
      (+ (* 2 4)
          (+ 3 5)))
      (+ (- 10 7)
          6))
```

“quotient” names Scheme’s built-in integer division procedure (i.e., function)

Combinations can span multiple lines (spacing doesn’t matter)

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
> (quotient (+ 8 7) 5)
3
> (+ (* 3
      (+ (* 2 4)
          (+ 3 5)))
      (+ (- 10 7)
          6))
```

“quotient” names Scheme’s built-in integer division procedure (i.e., function)

Combinations can span multiple lines (spacing doesn’t matter)

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
> (quotient (+ 8 7) 5)
3
> (+ (+ (* 3
         (+ (* 2 4)
             (+ 3 5)))
      (+ (- 10 7)
          6)))
```

“quotient” names Scheme’s built-in integer division procedure (i.e., function)

Combinations can span multiple lines (spacing doesn’t matter)

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
> (quotient (+ 8 7) 5)
3
> (+ (+ (* 3
         (+ (* 2 4)
             (+ 3 5)))
      (+ (- 10 7)
          6)))
```

“quotient” names Scheme’s built-in integer division procedure (i.e., function)

Combinations can span multiple lines (spacing doesn’t matter)

Scheme Fundamentals



Scheme programs consist of expressions, which can be:

- Primitive expressions: `2`, `3.3`, `true`, `+`, `quotient`, ...
- Combinations: `(quotient 10 2)`, `(not true)`, ...

Numbers are self-evaluating; symbols are bound to values

Call expressions have an operator and 0 or more operands

```
> (quotient 10 2)
5
> (quotient (+ 8 7) 5)
3
> (+ (* 3
      (+ (* 2 4)
          (+ 3 5)))
      (+ (- 10 7)
          6))
```

“quotient” names Scheme’s built-in integer division procedure (i.e., function)

Combinations can span multiple lines (spacing doesn’t matter)

Special Forms



Special Forms



A combination that is not a call expression is a *special form*:

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: (`if` <predicate> <consequent> <alternative>)

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: (`if` `<predicate>` `<consequent>` `<alternative>`)
- **And** and **or**: (`and` `<e1>` ... `<en>`), (`or` `<e1>` ... `<en>`)

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>), (or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: (`if` <predicate> <consequent> <alternative>)
- **And** and **or**: (`and` <e₁> ... <e_n>), (`or` <e₁> ... <e_n>)
- Binding names: (`define` <name> <expression>)
- New procedures: (`define` (<name> <formal parameters>) <body>)

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: (`if` `<predicate>` `<consequent>` `<alternative>`)
- **And** and **or**: (`and` `<e1>` ... `<en>`), (`or` `<e1>` ... `<en>`)
- Binding names: (`define` `<name>` `<expression>`)
- New procedures: (`define` (`<name>` `<formal parameters>`) `<body>`)

> (define pi 3.14)

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`
- New procedures: `(define (<name> <formal parameters>) <body>)`

```
> (define pi 3.14)
```

The name “pi” is bound to 3.14 in the global frame

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`
- New procedures: `(define (<name> <formal parameters>) <body>)`

```
> (define pi 3.14)
> (* pi 2)
```

The name “pi” is bound to 3.14 in the global frame

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`
- New procedures: `(define (<name> <formal parameters>) <body>)`

```
> (define pi 3.14)
> (* pi 2)
6.28
```

The name “pi” is bound to 3.14 in the global frame

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`
- New procedures: `(define (<name> <formal parameters>) <body>)`

```
> (define pi 3.14)
> (* pi 2)
6.28
```

The name “pi” is bound to 3.14 in the global frame

```
> (define (abs x)
```

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`
- New procedures: `(define (<name> <formal parameters>) <body>)`

```
> (define pi 3.14)
> (* pi 2)
6.28
```

The name “pi” is bound to 3.14 in the global frame

```
> (define (abs x)
      (if (< x 0)
```

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`
- New procedures: `(define (<name> <formal parameters>) <body>)`

```
> (define pi 3.14)
> (* pi 2)
6.28
```

The name “pi” is bound to 3.14 in the global frame

```
> (define (abs x)
  (if (< x 0)
      (- x)
```

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`
- New procedures: `(define (<name> <formal parameters>) <body>)`

```
> (define pi 3.14)
> (* pi 2)
6.28
```

The name “pi” is bound to 3.14 in the global frame

```
> (define (abs x)
  (if (< x 0)
      (- x)
      x))
```

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`
- New procedures: `(define (<name> <formal parameters>) <body>)`

```
> (define pi 3.14)
> (* pi 2)
6.28
```

The name “pi” is bound to 3.14 in the global frame

```
> (define (abs x)
  (if (< x 0)
      (- x)
      x))
```

A procedure is created and bound to the name “abs”

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`
- New procedures: `(define (<name> <formal parameters>) <body>)`

```
> (define pi 3.14)
> (* pi 2)
6.28
```

The name “pi” is bound to 3.14 in the global frame

```
> (define (abs x)
      (if (< x 0)
          (- x)
          x))
> (abs -3)
```

A procedure is created and bound to the name “abs”

Special Forms



A combination that is not a call expression is a *special form*:

- **If** expression: `(if <predicate> <consequent> <alternative>)`
- **And** and **or**: `(and <e1> ... <en>)`, `(or <e1> ... <en>)`
- Binding names: `(define <name> <expression>)`
- New procedures: `(define (<name> <formal parameters>) <body>)`

```
> (define pi 3.14)
> (* pi 2)
6.28
```

The name “pi” is bound to 3.14 in the global frame

```
> (define (abs x)
      (if (< x 0)
          (- x)
          x))
> (abs -3)
3
```

A procedure is created and bound to the name “abs”

Lambda Expressions



Lambda expressions evaluate to anonymous procedures

Lambda Expressions



Lambda expressions evaluate to anonymous procedures

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

Lambda Expressions



Lambda expressions evaluate to anonymous procedures

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



Lambda Expressions



Lambda expressions evaluate to anonymous procedures

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



Two equivalent expressions:

```
(define (plus4 x) (+ x 4))
```

```
(define plus4 (lambda (x) (+ x 4)))
```

Lambda Expressions



Lambda expressions evaluate to anonymous procedures

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



Two equivalent expressions:

```
(define (plus4 x) (+ x 4))
```

```
(define plus4 (lambda (x) (+ x 4)))
```

An operator can be a combination too:

Lambda Expressions



Lambda expressions evaluate to anonymous procedures

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



Two equivalent expressions:

```
(define (plus4 x) (+ x 4))
```

```
(define plus4 (lambda (x) (+ x 4)))
```

An operator can be a combination too:

```
((lambda (x y z) (+ x y (square z))) 1 2 3)
```


Lambda Expressions



Lambda expressions evaluate to anonymous procedures

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



Two equivalent expressions:

```
(define (plus4 x) (+ x 4))
```

```
(define plus4 (lambda (x) (+ x 4)))
```

An operator can be a combination too:

```
((lambda (x y z) (+ x y (square z))) 1 2 3)
```

Evaluates to the
add-x-&-y-&-z² procedure

Pairs



Pairs



We can implement pairs functionally:

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

- **cons:** Two-argument procedure that **creates a pair**

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

- **cons:** Two-argument procedure that **creates a pair**
- **car:** Procedure that returns the **first element** of a pair

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

- **cons:** Two-argument procedure that **creates a pair**
- **car:** Procedure that returns the **first element** of a pair
- **cdr:** Procedure that returns the **second element** of a pair

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

- **cons:** Two-argument procedure that **creates a pair**
- **car:** Procedure that returns the **first element** of a pair
- **cdr:** Procedure that returns the **second element** of a pair

A pair is represented by a dot between the elements, all in parens

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

- **cons:** Two-argument procedure that **creates a pair**
- **car:** Procedure that returns the **first element** of a pair
- **cdr:** Procedure that returns the **second element** of a pair

A pair is represented by a dot between the elements, all in parens

```
> (cons 1 2)
```

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

- **cons:** Two-argument procedure that **creates a pair**
- **car:** Procedure that returns the **first element** of a pair
- **cdr:** Procedure that returns the **second element** of a pair

A pair is represented by a dot between the elements, all in parens

```
> (cons 1 2)  
(1 . 2)
```

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

- **cons**: Two-argument procedure that **creates a pair**
- **car**: Procedure that returns the **first element** of a pair
- **cdr**: Procedure that returns the **second element** of a pair

A pair is represented by a dot between the elements, all in parens

```
> (cons 1 2)  
(1 . 2)  
> (car (cons 1 2))
```

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

- **cons**: Two-argument procedure that **creates a pair**
- **car**: Procedure that returns the **first element** of a pair
- **cdr**: Procedure that returns the **second element** of a pair

A pair is represented by a dot between the elements, all in parens

```
> (cons 1 2)  
(1 . 2)  
> (car (cons 1 2))  
1
```

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

- **cons**: Two-argument procedure that **creates a pair**
- **car**: Procedure that returns the **first element** of a pair
- **cdr**: Procedure that returns the **second element** of a pair

A pair is represented by a dot between the elements, all in parens

```
> (cons 1 2)  
(1 . 2)  
> (car (cons 1 2))  
1  
> (cdr (cons 1 2))
```

Pairs



We can implement pairs functionally:

```
(define (pair x y) (lambda (m) (if (= m 0) x y)))  
(define (first p) (p 0))  
(define (second p) (p 1))
```

Scheme also has built-in pairs that use weird names:

- **cons**: Two-argument procedure that **creates a pair**
- **car**: Procedure that returns the **first element** of a pair
- **cdr**: Procedure that returns the **second element** of a pair

A pair is represented by a dot between the elements, all in parens

```
> (cons 1 2)  
(1 . 2)  
> (car (cons 1 2))  
1  
> (cdr (cons 1 2))  
2
```

Recursive Lists



Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- `nil` is the empty list

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- **nil** is the empty list
- A non-empty Scheme list is a pair in which the second element is **nil** or a Scheme list

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- **nil** is the empty list
- A non-empty Scheme list is a pair in which the second element is **nil** or a Scheme list

Scheme lists are written as space-separated combinations

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- **nil** is the empty list
- A non-empty Scheme list is a pair in which the second element is **nil** or a Scheme list

Scheme lists are written as space-separated combinations

```
> (define x (cons 1 (cons 2 (cons 3 (cons 4 nil)))))
```

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- **nil** is the empty list
- A non-empty Scheme list is a pair in which the second element is **nil** or a Scheme list

Scheme lists are written as space-separated combinations

```
> (define x (cons 1 (cons 2 (cons 3 (cons 4 nil)))))  
> x
```

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- **nil** is the empty list
- A non-empty Scheme list is a pair in which the second element is **nil** or a Scheme list

Scheme lists are written as space-separated combinations

```
> (define x (cons 1 (cons 2 (cons 3 (cons 4 nil)))))  
> x  
(1 2 3 4)
```


Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- **nil** is the empty list
- A non-empty Scheme list is a pair in which the second element is **nil** or a Scheme list

Scheme lists are written as space-separated combinations

```
> (define x (cons 1 (cons 2 (cons 3 (cons 4 nil)))))  
> x  
(1 2 3 4)  
> (cdr x)
```

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- **nil** is the empty list
- A non-empty Scheme list is a pair in which the second element is **nil** or a Scheme list

Scheme lists are written as space-separated combinations

```
> (define x (cons 1 (cons 2 (cons 3 (cons 4 nil)))))  
> x  
(1 2 3 4)  
> (cdr x)  
(2 3 4)
```

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- **nil** is the empty list
- A non-empty Scheme list is a pair in which the second element is **nil** or a Scheme list

Scheme lists are written as space-separated combinations

```
> (define x (cons 1 (cons 2 (cons 3 (cons 4 nil)))))  
> x  
(1 2 3 4)  
> (cdr x)  
(2 3 4)  
> (cons 1 (cons 2 (cons 3 4)))
```

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- **nil** is the empty list
- A non-empty Scheme list is a pair in which the second element is **nil** or a Scheme list

Scheme lists are written as space-separated combinations

```
> (define x (cons 1 (cons 2 (cons 3 (cons 4 nil)))))  
> x  
(1 2 3 4)  
> (cdr x)  
(2 3 4)  
> (cons 1 (cons 2 (cons 3 4)))  
(1 2 3 . 4)
```

Recursive Lists



A recursive list can be represented as a pair in which the second element is a recursive list or the empty list

Scheme lists are recursive lists:

- **nil** is the empty list
- A non-empty Scheme list is a pair in which the second element is **nil** or a Scheme list

Scheme lists are written as space-separated combinations

```
> (define x (cons 1 (cons 2 (cons 3 (cons 4 nil)))))  
> x  
(1 2 3 4)  
> (cdr x)  
(2 3 4)  
> (cons 1 (cons 2 (cons 3 4)))  
(1 2 3 . 4)
```

Not a well-formed list!

Symbolic Programming



Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

> (define a 1)

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

- > (define a 1)
- > (define b 2)

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

- > (define a 1)
- > (define b 2)
- > (list a b)

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

No sign of "a" and "b" in the resulting value

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

No sign of "a" and "b" in the resulting value

Quotation prevents something from being evaluated by Lisp

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

No sign of "a" and "b" in the resulting value

Quotation prevents something from being evaluated by Lisp

```
> (list 'a 'b)
```

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

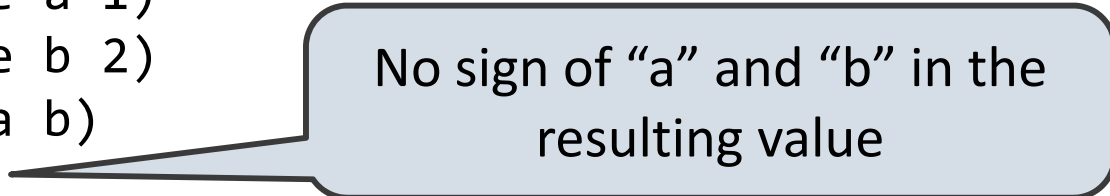
No sign of "a" and "b" in the resulting value

Quotation prevents something from being evaluated by Lisp

```
> (list 'a 'b)
(a b)
```

Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```



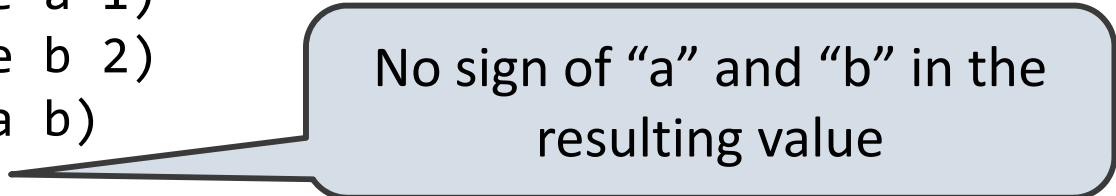
No sign of “a” and “b” in the resulting value

Quotation prevents something from being evaluated by Lisp

```
> (list 'a 'b)
(a b)
> (list 'a b)
```


Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```



No sign of “a” and “b” in the resulting value

Quotation prevents something from being evaluated by Lisp

```
> (list 'a 'b)
(a b)
> (list 'a b)
(a 2)
```

Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

No sign of "a" and "b" in the resulting value

Quotation prevents something from being evaluated by Lisp

```
> (list 'a 'b)
(a b)
> (list 'a b)
(a 2)
```

Symbols are now values

Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

No sign of "a" and "b" in the resulting value

Quotation prevents something from being evaluated by Lisp

```
> (list 'a 'b)
(a b)
> (list 'a b)
(a 2)
```

Symbols are now values

Quotation can also be applied to combinations to form lists

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

No sign of "a" and "b" in the resulting value

Quotation prevents something from being evaluated by Lisp

```
> (list 'a 'b)
(a b)
> (list 'a b)
(a 2)
```

Symbols are now values

Quotation can also be applied to combinations to form lists

```
> (car '(a b c))
```

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

No sign of "a" and "b" in the resulting value

Quotation prevents something from being evaluated by Lisp

```
> (list 'a 'b)
(a b)
> (list 'a b)
(a 2)
```

Symbols are now values

Quotation can also be applied to combinations to form lists

```
> (car '(a b c))
a
```

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

No sign of "a" and "b" in the resulting value

Quotation prevents something from being evaluated by Lisp

```
> (list 'a 'b)
(a b)
> (list 'a b)
(a 2)
```

Symbols are now values

Quotation can also be applied to combinations to form lists

```
> (car '(a b c))
a
> (cdr '(a b c))
```

Symbolic Programming



Symbols are normally evaluated to produce values; how do we refer to symbols?

```
> (define a 1)
> (define b 2)
> (list a b)
(1 2)
```

No sign of "a" and "b" in the resulting value

Quotation prevents something from being evaluated by Lisp

```
> (list 'a 'b)
(a b)
> (list 'a b)
(a 2)
```

Symbols are now values

Quotation can also be applied to combinations to form lists

```
> (car '(a b c))
a
> (cdr '(a b c))
(b c)
```

Scheme Lists and Quotation



Scheme Lists and Quotation



Dots can be used in a quoted list to specify the second element of the final pair

Scheme Lists and Quotation



Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))
```

Scheme Lists and Quotation



Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

Scheme Lists and Quotation



Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists

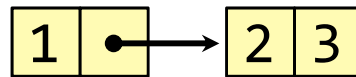
Scheme Lists and Quotation



Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists



Scheme Lists and Quotation



Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)
```

A diagram illustrating the internal structure of a cons cell. It consists of two adjacent yellow boxes. The first box contains the number '1'. The second box contains a black dot followed by an arrow pointing to the right. This arrow points to another yellow box containing the number '2'. To the right of this second box is a third yellow box containing the number '3'. This represents a cons cell where the first element is 1 and the rest of the list is a cons cell with 2 and 3.

Scheme Lists and Quotation

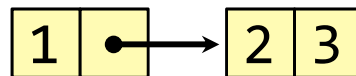


Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)  
(1 2 . 3)
```



Scheme Lists and Quotation

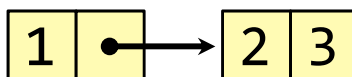


Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)  
(1 2 . 3)  
> '(1 2 . (3 4))
```



Scheme Lists and Quotation

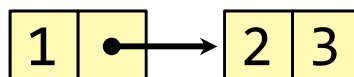


Dots can be used in a quoted list to specify the second element of the final pair

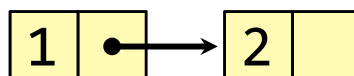
```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)  
(1 2 . 3)
```



```
> '(1 2 . (3 4))
```



Scheme Lists and Quotation

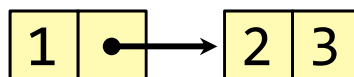


Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

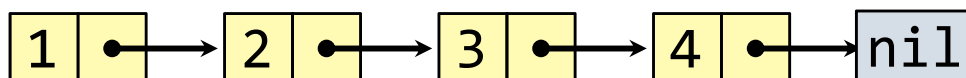
However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)
```



```
(1 2 . 3)
```

```
> '(1 2 . (3 4))
```



Scheme Lists and Quotation

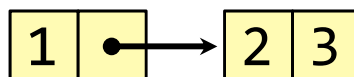


Dots can be used in a quoted list to specify the second element of the final pair

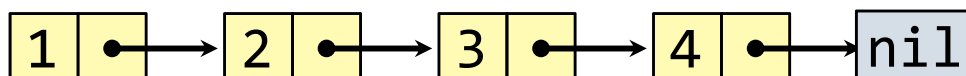
```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)  
(1 2 . 3)
```



```
> '(1 2 . (3 4))  
(1 2 3 4)
```



Scheme Lists and Quotation

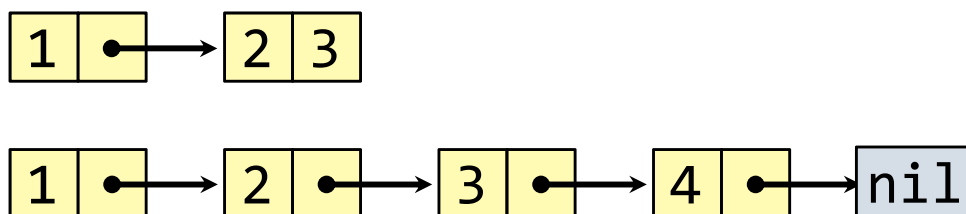


Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)  
(1 2 . 3)  
> '(1 2 . (3 4))  
(1 2 3 4)  
> '(1 2 3 . nil)
```



Scheme Lists and Quotation

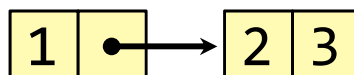


Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

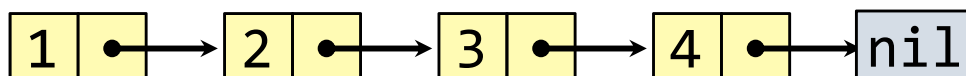
However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)
```



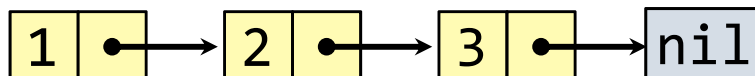
```
(1 2 . 3)
```

```
> '(1 2 . (3 4))
```



```
(1 2 3 4)
```

```
> '(1 2 3 . nil)
```



Scheme Lists and Quotation

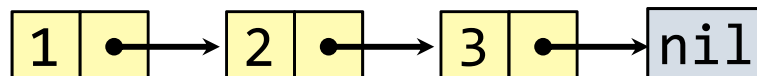
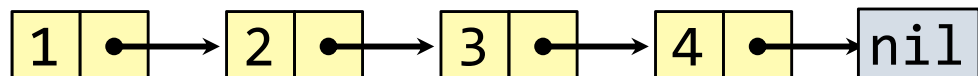
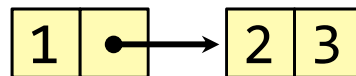


Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)  
(1 2 . 3)  
> '(1 2 . (3 4))  
(1 2 3 4)  
> '(1 2 3 . nil)  
(1 2 3)
```



Scheme Lists and Quotation

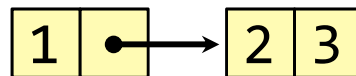


Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

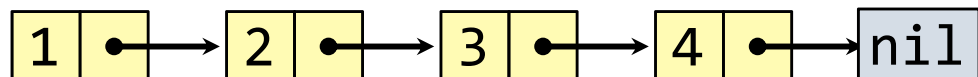
However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)
```



```
(1 2 . 3)
```

```
> '(1 2 . (3 4))
```



```
(1 2 3 4)
```

```
> '(1 2 3 . nil)
```



```
(1 2 3)
```

What is the printed result of evaluating this expression?

Scheme Lists and Quotation



Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)          1 | • → 2 | 3  
(1 2 . 3)  
> '(1 2 . (3 4))    1 | • → 2 | • → 3 | • → 4 | • → nil  
(1 2 3 4)  
> '(1 2 3 . nil)    1 | • → 2 | • → 3 | • → nil  
(1 2 3)
```

What is the printed result of evaluating this expression?

```
> (cdr '((1 2) . (3 4 . (5))))
```


Scheme Lists and Quotation



Dots can be used in a quoted list to specify the second element of the final pair

```
> (cdr (cdr '(1 2 . 3)))  
3
```

However, dots appear in the output only of ill-formed lists

```
> '(1 2 . 3)          (1 | • | → 2 | 3 |)  
(1 2 . 3)  
> '(1 2 . (3 4))    (1 | • | → 2 | • | → 3 | • | → 4 | • | → nil |)  
(1 2 3 4)  
> '(1 2 3 . nil)    (1 | • | → 2 | • | → 3 | • | → nil |)  
(1 2 3)
```

What is the printed result of evaluating this expression?

```
> (cdr '((1 2) . (3 4 . (5))))  
(3 4 5)
```