Announcements
Scheme
Scheme is a Dialect of Lisp
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What are people saying about Lisp?
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– Richard Stallman, created Emacs & the first free variant of UNIX
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- "The only computer language that is beautiful."
  - Neal Stephenson, DeNero's favorite sci-fi author
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"The greatest single programming language ever designed."

– Alan Kay, co-inventor of Smalltalk and OOP (from the user interface video)
Scheme Fundamentals
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> \text{(quotient 10 2)} \\
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“quotient” names Scheme’s built-in integer division procedure (i.e., function)
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```scheme
> (quotient 10 2)
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> (quotient (+ 8 7) 5)
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    6))

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(Demo)
Special Forms
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- **if expression:**  (if <predicate> <consequent> <alternative>)
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**Evaluation:**
1. Evaluate the predicate expression
2. Evaluate either the consequent or alternative
Special Forms

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

- **if** expression:  \((\text{if } <\text{predicate}> <\text{consequent}> <\text{alternative}>)\)
- **and** and **or**:  \((\text{and } <\text{e}_1> \ldots <\text{e}_n>), (\text{or } <\text{e}_1> \ldots <\text{e}_n>)\)

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  (and <e1> ... <en>), (or <e1> ... <en>)

- Binding symbols:  
  (define <symbol> <expression>)

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(2) Evaluate either the consequent or alternative
Special Forms

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

- **if** expression:  
  \[(\text{if } \text{<predicate>} \text{<consequent>} \text{<alternative>})\]

- **and** and **or**:  
  \[(\text{and } \text{<e1> ... <en>}), (\text{or } \text{<e1> ... <en>})\]

- **Binding symbols**: \((\text{define } \text{<symbol>} \text{<expression>})\)

---

Evaluation:

1. Evaluate the predicate expression
2. Evaluate either the consequent or alternative

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> (define pi 3.14)
> (* pi 2)
6.28
Special Forms

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- **if** expression: \((\text{if } <\text{predicate}> <\text{consequent}> <\text{alternative}>)\)
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Evaluation:
(1) Evaluate the predicate expression
(2) Evaluate either the consequent or alternative

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

The symbol “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:  
  
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  \text{if } <\text{predicate}> <\text{consequent}> <\text{alternative}>
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  \[
  \text{and } <e_1> \ldots <e_n>, \text{ (or } <e_1> \ldots <e_n>)
  \]

- Binding symbols:  
  
  \[
  \text{define } <\text{symbol}> <\text{expression}>
  \]

- New procedures:  
  
  \[
  \text{define } (<\text{symbol}> <\text{formal parameters}>) <\text{body}>
  \]

\[
> \text{(define } \pi \text{ 3.14)}
> \text{(* } \pi \text{ 2)}
\]

\[
6.28
\]

**Evaluation:**

1. Evaluate the predicate expression
2. Evaluate either the consequent or alternative

---

The symbol “\(\pi\)” 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 symbols:**  
  (define <symbol> <expression>)

- **New procedures:**  
  (define (<symbol> <formal parameters>) <body>)

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

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

Evaluation:
1. Evaluate the predicate expression
2. Evaluate either the consequent or alternative

The symbol “pi” is bound to 3.14 in the global frame
A combination that is not a call expression is a special form:

- **if** expression: \((\text{if} \ <\text{predicate}> \ <\text{consequent}> \ <\text{alternative}>\)
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```
> (define pi 3.14)
> (* pi 2)
6.28

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

**Evaluation:**
1. Evaluate the predicate expression
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Special Forms

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

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- New procedures: \((\text{define} \ (<\text{symbol}> \ <\text{formal parameters}>) \ <\text{body}>))\)

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

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

Evaluation:
(1) Evaluate the predicate expression
(2) Evaluate either the consequent or alternative

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

A procedure is created and bound to the symbol “abs”
Special Forms

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

- **if** expression:  \((\text{if } \text{<predicate> } \text{<consequent> } \text{<alternative>})\)
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- Binding symbols:  \((\text{define } \text{<symbol> } \text{<expression>})\)
- New procedures:  \((\text{define } (\text{<symbol> } \text{<formal parameters>}) \text{<body>})\)

\[
> (\text{define pi 3.14})
> (* \text{pi 2})
6.28
\]
\[
> (\text{define (abs x)}
  (\text{if } (\text{< x 0})
    (- \text{x})
    \text{x}))
> (\text{abs -3})
3
\]

Evaluation:
(1) Evaluate the predicate expression
(2) Evaluate either the consequent or alternative

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

A procedure is created and bound to the symbol “abs.”
Scheme Interpreters

(Demo)
Lambda Expressions
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Lambda expressions evaluate to anonymous procedures
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(lambda (<formal-parameters>) <body>)
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Lambda Expressions

Lambda expressions evaluate to anonymous procedures

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

Two equivalent expressions:

\[
\text{(define (plus4 x) (+ x 4))}
\]

\[
\text{(define plus4 (lambda (x) (+ x 4)))}
\]
Lambda Expressions

Lambda expressions evaluate to anonymous procedures

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

Two equivalent expressions:

\[
\text{define (plus4 x) (+ x 4)}
\]

\[
\text{define plus4 (lambda (x) (+ x 4))}
\]

An operator can be a call expression too:
Lambda Expressions

Lambda expressions evaluate to anonymous procedures

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

Two equivalent expressions:

\[
\begin{align*}
\text{(define (plus4 x) (+ x 4))} \\
\text{(define plus4 (lambda (x) (+ x 4)))}
\end{align*}
\]

An operator can be a call expression too:

\[
\begin{align*}
\text{((lambda (x y z) (+ x y (square z))) 1 2 3)}
\end{align*}
\]
Lambda Expressions

Lambda expressions evaluate to anonymous procedures

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

Two equivalent expressions:

\[
\text{(define (\textit{plus4 x) (+ x 4))}
\]

\[
\text{(define plus4 (lambda (x) (+ x 4)))}
\]

An operator can be a call expression too:

\[
\text{((lambda (x y z) (+ x y (square z))) 1 2 3)}
\]

Evaluates to the \(x+y+z^2\) procedure
Lambda Expressions

Lambda expressions evaluate to anonymous procedures

\[
\lambda \text{ (formal-parameters)} \text{ body}
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Two equivalent expressions:

- \( \text{(define (plus4 x) (+ x 4))} \)
- \( \text{(define plus4 (lambda (x) (+ x 4)))} \)

An operator can be a call expression too:

\( \text{(lambda (x y z) (+ x y (square z))) 1 2 3)} \rightarrow 12 \)

Evaluates to the \( x+y+z^2 \) procedure
Pairs and Lists
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In the late 1950s, computer scientists used confusing names
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- **cons**: Two-argument procedure that creates a pair
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(cons 1 2)
Pairs and Lists

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(cons 1 2)

1 2
Pairs and Lists

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(cons 1 2)
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In the late 1950s, computer scientists used confusing names:

- **cons**: Two-argument procedure that creates a pair
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- **nil**: The empty list

\[(\text{cons } 1 \ 2)\]
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A (non-empty) list in Scheme is a pair in which the second element is **nil** or a Scheme list:

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

```
1 2
```

```
(cons 1 2)
```

```
1 2
```

```
(cons 2 nil)
```

```
2 nil
```

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

```
1 2
```

```
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```
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- **cons**: Two-argument procedure that creates a pair
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A dotted list has some value for the second element of the last pair that is not a list:

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(1 . 2)
```

Not a well-formed list!
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```scheme
> (cons 1 (cons 2 nil))  (cons 1 2)  
(1 2)  (cons 2 nil)  
> (define x (cons 1 2))  
> x  
(1 . 2)  
> (car x)  
Not a well-formed list!
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> (define x (cons 1 2))
> x
(1 . 2)
> (car x)
1
```

Not a well-formed list!
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> (cons 1 (cons 2 nil))
> (define x (cons 1 2))
> x
> (1 . 2)
> (car x)
> 1
> (cdr x)
> Not a well-formed list!
Pairs and Lists

In the late 1950s, computer scientists used confusing 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
- **nil**: The empty list

A (non-empty) list in Scheme is a pair in which the second element is `nil` or a Scheme list.

**Important!** Scheme lists are written in parentheses separated by spaces.

A dotted list has some value for the second element of the last pair that is not a list.

```scheme
> (cons 1 (cons 2 nil))
(1 2)
> (define x (cons 1 2))
> x
(1 . 2)
> (car x)
1
> (cdr x)
2
```

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

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• **cons**: Two-argument procedure that creates a pair
  
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• A (non-empty) list in Scheme is a pair in which the second element is **nil** or a Scheme list
  
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```
> (cons 1 (cons 2 nil))  
(1 2)  
> (define x (cons 1 2))  
> x  
(1 . 2)  
> (car x)  
1  
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> (cons 1 (cons 2 (cons 3 (cons 4 nil))))  
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A dotted list has some value for the second element of the last pair that is not a list.

\[
\begin{align*}
> (\text{cons} 1 \ (\text{cons} 2 \ \text{nil})) \\
& (1 \ 2) \\
> (\text{define} \ x \ (\text{cons} 1 \ 2)) \\
& x \\
& (1 . \ 2) \\
> (\text{car} \ x) \\
& 1 \\
> (\text{cdr} \ x) \\
& 2 \\
> (\text{cons} 1 \ ((\text{cons} 2 \ (\text{cons} 3 \ (\text{cons} 4 \ \text{nil})))))) \\
& (1 \ 2 \ 3 \ 4)
\end{align*}
\]
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> (cons 1 (cons 2 nil))
(1 2)
> (define x (cons 1 2))
x
(1 . 2)
> (car x)
1
> (cdr x)
2
> (cons 1 (cons 2 (cons 3 (cons 4 nil)))))
(1 2 3 4)

(Demo)
Symbolic Programming
Symbolic Programming
Symbolic Programming

Symbols normally refer to values; how do we refer to symbols?
Symbolic Programming

Symbols normally refer to values; how do we refer to symbols?

> (define a 1)
Symbolic Programming

Symbols normally refer to values; how do we refer to symbols?

> (define a 1)
> (define b 2)
Symbols normally refer to values; how do we refer to symbols?

> (define a 1)
> (define b 2)
> (list a b)
Symbolic Programming

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(1 2)
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No sign of “a” and “b” in the resulting value
Symbolic Programming

Symbols normally refer to values; how do we refer to symbols?

> (define a 1)
> (define b 2)
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Quotation is used to refer to symbols directly in Lisp.

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

Quotation is used to refer to symbols directly in Lisp.

> (list 'a 'b)
Symbolic Programming

Symbols normally refer to values; how do we refer to symbols?

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(1 2)

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

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

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Symbols are now values
Symbolic Programming

Symbols normally refer to values; how do we refer to symbols?

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

Quotation is used to refer to symbols directly in Lisp.

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

Quotation can also be applied to combinations to form lists.
Symbols normally refer to values; how do we refer to symbols?

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

Quotation is used to refer to symbols directly in Lisp.

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

Quotation can also be applied to combinations to form lists.

> (car '(a b c))
Symbolic Programming

Symbols normally refer to values; how do we refer to symbols?

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

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

Quotation is used to refer to symbols directly in 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 normally refer to values; how do we refer to symbols?

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

Quotation is used to refer to symbols directly in Lisp.

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

Quotation can also be applied to combinations to form lists.

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

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

Symbols are now values
Symbolic Programming

Symbols normally refer to values; how do we refer to symbols?

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

Quotation is used to refer to symbols directly in 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.
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Dots can be used in a quoted list to specify the second element of the final pair.

'(1 2 . 3)
Scheme Lists and Quotation

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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)))
```

![Diagram](image)
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)))

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)))

![Diagram showing the evaluation of the list expression](image)
Scheme Lists and Quotation

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

\[
> (\text{cdr (cdr (1 2 . 3))})
\]

\[
3 \hspace{2cm} 1 \hspace{0.5cm} 2 \hspace{0.5cm} 3
\]

\[
1 \hspace{2cm} 2 \hspace{0.5cm} 3
\]
Scheme Lists and Quotation

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

\[
> (\text{cdr} \ (\text{cdr} \ '(1 \ 2 \ . \ 3)))
\]

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

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

> '(1 2 . 3)
Scheme Lists and Quotation

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

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

![Diagram of a list with dots]

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

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

![Diagram of an ill-formed list]
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.

\[ \texttt{> (cdr (cdr '(1 2 . 3)))} \]
\[ 3 \]

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

\[ \texttt{> '}(1 2 . 3) \]
\[ (1 2 . 3) \]
\[ \texttt{> '}(1 2 . (3 4)) \]
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.

\[
> (\text{cdr } (\text{cdr } '(1 \ 2 \ . \ 3)))
\]

\[
\begin{array}{c}
1 \\
\rightarrow\\
2 \\
\rightarrow\\
\framebox{3}
\end{array}
\]

3

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

\[
> ' (1 \ 2 \ . \ 3)
\]

\[
\begin{array}{c}
1 \\
\rightarrow\\
2 \\
\rightarrow\\
3
\end{array}
\]

(1 2 . 3)

\[
> ' (1 \ 2 \ . \ (3 \ 4))
\]

\[
\begin{array}{c}
1 \\
\rightarrow\\
2 \\
\rightarrow\\
3 \\
\rightarrow\\
4
\end{array}
\]

(1 2 3 4)

\[
> ' (1 \ 2 \ 3 \ . \ \text{nil})
\]

\[
\begin{array}{c}
1 \\
\rightarrow\\
2 \\
\rightarrow\\
3 \\
\rightarrow\\
\text{nil}
\end{array}
\]

'(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)
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)))

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?

> (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)))
(1 2 . 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?

> (cdr '(((1 2) . (3 4) . (5))))
(3 4 5)
Scheme Lists and Quotation

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

\[
> \ (\text{cdr} \ (\text{cdr} \ '(1 \ 2 \ . \ 3)))
\]

```
(1 2 3)
```

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

\[
> \ '(1 \ 2 \ . \ 3)
(1 2 . 3)
\]

\[
> \ '(1 \ 2 \ . \ (3 \ 4))
(1 2 3 4)
\]

\[
> \ '(1 \ 2 \ 3 \ . \ \text{nil})
(1 2 3)
\]

What is the printed result of evaluating this expression?

\[
> \ (\text{cdr} \ '((1 \ 2) \ . \ (3 \ 4 \ . \ (5))))
\]

```
(3 4 5)
```
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?

> (cdr '((1 2) . (3 4 . (5))))
(3 4 5)
Scheme Lists and Quotation

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

\[
> \text{cdr (cdr '(1 2 . 3))}
\]

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?

\[
> \text{cdr '((1 2) . (3 4 . (5)))} \\
(3 4 5)
\]
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 4))
(1 2 3 4)
> '(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)
```