Lecture 10: Linked Lists

Brian Hou
July 6, 2016

Announcements

Announcements

- Project 2 is due 7/12 (+1 EC point if submitted 7/11)

Announcements

- Project 2 is due 7/12 (+1 EC point if submitted 7/11)
  - Run ok --submit to check against hidden tests

Announcements

- Project 2 is due 7/12 (+1 EC point if submitted 7/11)
  - Run ok --submit to check against hidden tests
  - Check your submission at ok.cs61a.org

Announcements

- Project 2 is due 7/12 (+1 EC point if submitted 7/11)
  - Run ok --submit to check against hidden tests
  - Check your submission at ok.cs61a.org
  - Invite your partner (watch this video)

Announcements

- Project 2 is due 7/12 (+1 EC point if submitted 7/11)
  - Run ok --submit to check against hidden tests
  - Check your submission at ok.cs61a.org
  - Invite your partner (watch this video)
- Homework 4 is due 7/7

Announcements

- Project 2 is due 7/12 (+1 EC point if submitted 7/11)
  - Run ok --submit to check against hidden tests
  - Check your submission at ok.cs61a.org
  - Invite your partner (watch this video)
- Homework 4 is due 7/7
- Quiz 3 is tomorrow at the beginning of lecture

Announcements

- Project 2 is due 7/12 (+1 EC point if submitted 7/11)
  - Run ok --submit to check against hidden tests
  - Check your submission at ok.cs61a.org
  - Invite your partner (watch this video)
- Homework 4 is due 7/7
- Quiz 3 is tomorrow at the beginning of lecture
  - If you have an alternate time or are not enrolled in the class, please arrive at 11:45 am

Announcements

- Project 2 is due 7/12 (+1 EC point if submitted 7/11)
  - Run ok --submit to check against hidden tests
  - Check your submission at ok.cs61a.org
  - Invite your partner (watch this video)
- Homework 4 is due 7/7
- Quiz 3 is tomorrow at the beginning of lecture
  - If you have an alternate time or are not enrolled in the class, please arrive at 11:45 am
- Quiz 4 is released 9 am on 7/11, due 10 am on 7/12

Announcements

- Project 2 is due 7/12 (+1 EC point if submitted 7/11)
  - Run ok --submit to check against hidden tests
  - Check your submission at ok.cs61a.org
  - Invite your partner (watch this video)
- Homework 4 is due 7/7
- Quiz 3 is tomorrow at the beginning of lecture
  - If you have an alternate time or are not enrolled in the class, please arrive at 11:45 am
- Quiz 4 is released 9 am on 7/11, due 10 am on 7/12
- **61A Potluck** on 7/8! 5 – 8 pm (or later) in Wozniak Lounge

Announcements

- Project 2 is due 7/12 (+1 EC point if submitted 7/11)
  - Run ok --submit to check against hidden tests
  - Check your submission at ok.cs61a.org
  - Invite your partner (watch this video)
- Homework 4 is due 7/7
- Quiz 3 is tomorrow at the beginning of lecture
  - If you have an alternate time or are not enrolled in the class, please arrive at 11:45 am
- Quiz 4 is released 9 am on 7/11, due 10 am on 7/12
- **61A Potluck** on 7/8! 5 – 8 pm (or later) in Wozniak Lounge
  - Bring food and board games!

Hog Contest

Roadmap

Introduction

Functions

Data

Mutability

Objects

Interpretation

Paradigms

Applications

Roadmap

Introduction

Functions

Data

Mutability

Objects

Interpretation

Paradigms

Applications

- This week (Data), the goals are:

Roadmap

Introduction

Functions

Data

Mutability

Objects

Interpretation

Paradigms

Applications

- This week (Data), the goals are:
  - To continue our journey through abstraction with *data abstraction*

Roadmap

Introduction

Functions

Data

Mutability

Objects

Interpretation

Paradigms

Applications

- This week (Data), the goals are:
  - To continue our journey through abstraction with *data abstraction*
  - To study useful data types we can construct with data abstraction

Data Abstraction

Data Abstraction

Data Abstraction

- Great programmers use data abstraction to separate:

Data Abstraction

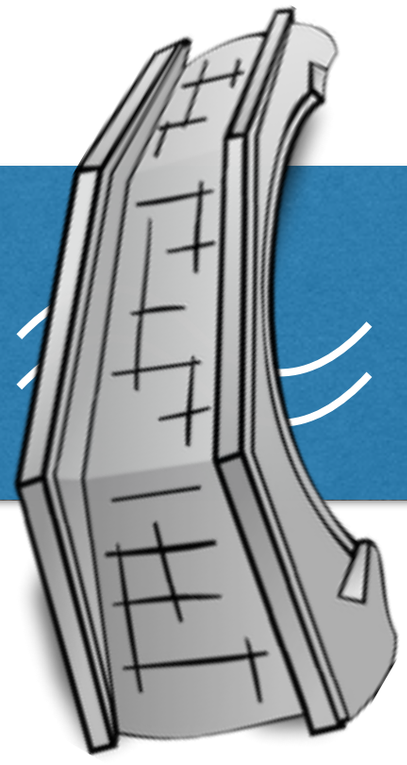
- Great programmers use data abstraction to separate:
  - How compound values are *used* (the unit)

Data Abstraction

- Great programmers use data abstraction to separate:
  - How compound values are *used* (the unit)
  - How compound values are *represented* (the parts)

Data Abstraction

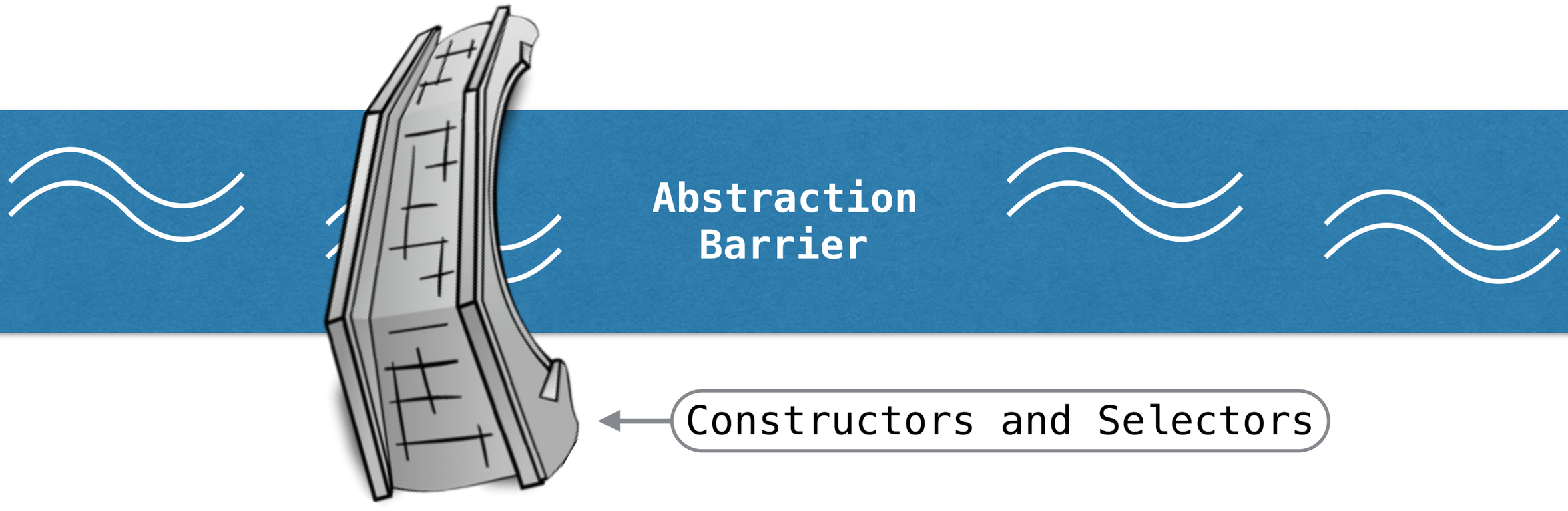
- Great programmers use data abstraction to separate:
  - How compound values are *used* (the unit)



  - How compound values are *represented* (the parts)

Data Abstraction

- Great programmers use data abstraction to separate:
  - How compound values are *used* (the unit)



  - How compound values are *represented* (the parts)

Abstraction Barrier Violations

Abstraction Barrier Violations

- Constructors and selectors provide us with abstraction, allowing us to use the data type without having to know its implementation

Abstraction Barrier Violations

- Constructors and selectors provide us with abstraction, allowing us to use the data type without having to know its implementation
- An abstraction barrier violation is when we assume knowledge about the data type implementation, rather than using constructors and selectors

Abstraction Barrier Violations

- Constructors and selectors provide us with abstraction, allowing us to use the data type without having to know its implementation
- An abstraction barrier violation is when we assume knowledge about the data type implementation, rather than using constructors and selectors

Never violate the abstraction barrier!

Sequences

The Sequence Abstraction

The Sequence Abstraction

The sequence abstraction is a collection of behaviors:

The Sequence Abstraction

The sequence abstraction is a collection of behaviors:

Length. A sequence has a finite length.

Element selection. A sequence has an element corresponding to any non-negative integer index less than its length, starting at 0.

The Sequence Abstraction

The sequence abstraction is a collection of behaviors:

> **Length.** A sequence has a finite length.
>
> **Element selection.** A sequence has an element corresponding to any non-negative integer index less than its length, starting at 0.

Lists and strings are both examples of sequences.

The Sequence Abstraction

The sequence abstraction is a collection of behaviors:

> **Length.** A sequence has a finite length.
>
> **Element selection.** A sequence has an element corresponding to any non-negative integer index less than its length, starting at 0.

Lists and strings are both examples of sequences.

We can use built-in syntax associated with this behavior.
We can also use functions.

The Sequence Abstraction (demo)

The sequence abstraction is a collection of behaviors:

> **Length.** A sequence has a finite length.
>
> **Element selection.** A sequence has an element corresponding to any non-negative integer index less than its length, starting at 0.

Lists and strings are both examples of sequences.

We can use built-in syntax associated with this behavior.
We can also use functions.

Linked Lists

Linked Lists

Linked Lists

- Another way to implement the sequence abstraction

Linked Lists

- Another way to implement the sequence abstraction
- Links have two parts

Linked Lists

- Another way to implement the sequence abstraction
- Links have two parts
  - first: the element in the link

Linked Lists

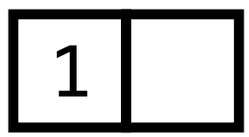
- Another way to implement the sequence abstraction
- Links have two parts
  - first: the element in the link
  - rest: the next link in the list

Linked Lists

- Another way to implement the sequence abstraction
- Links have two parts
  - first: the element in the link
  - rest: the next link in the list
- This is a recursive definition: the rest of a linked list is another linked list

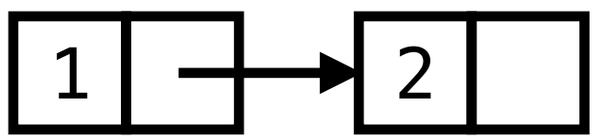
Linked Lists

- Another way to implement the sequence abstraction
- Links have two parts
  - first: the element in the link
  - rest: the next link in the list
- This is a recursive definition: the rest of a linked list is another linked list



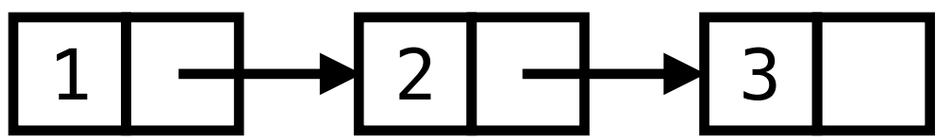
Linked Lists

- Another way to implement the sequence abstraction
- Links have two parts
  - first: the element in the link
  - rest: the next link in the list
- This is a recursive definition: the rest of a linked list is another linked list



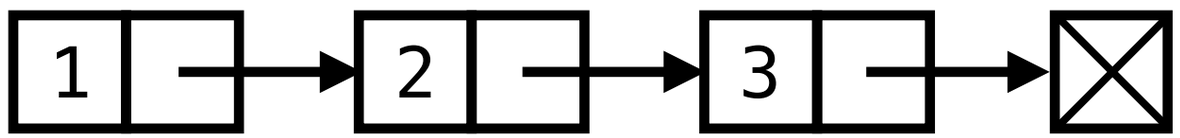
Linked Lists

- Another way to implement the sequence abstraction
- Links have two parts
  - first: the element in the link
  - rest: the next link in the list
- This is a recursive definition: the rest of a linked list is another linked list



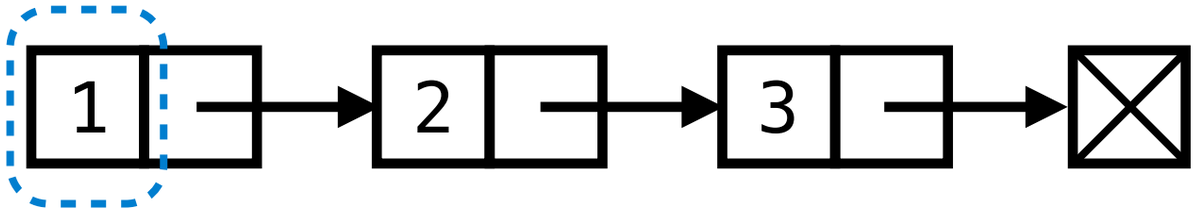
Linked Lists

- Another way to implement the sequence abstraction
- Links have two parts
  - first: the element in the link
  - rest: the next link in the list
- This is a recursive definition: the rest of a linked list is another linked list



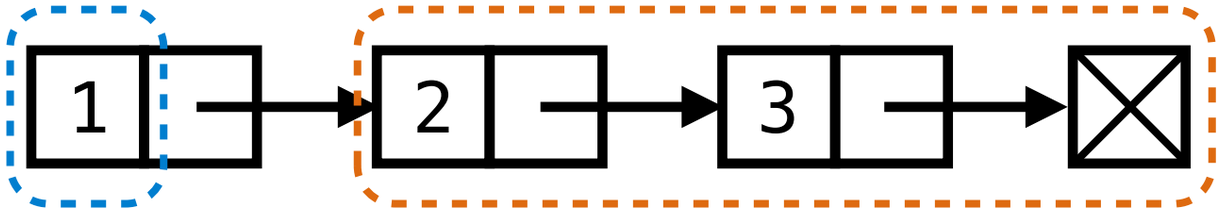
Linked Lists

- Another way to implement the sequence abstraction
- Links have two parts
  - first: the element in the link
  - rest: the next link in the list
- This is a recursive definition: the rest of a linked list is another linked list



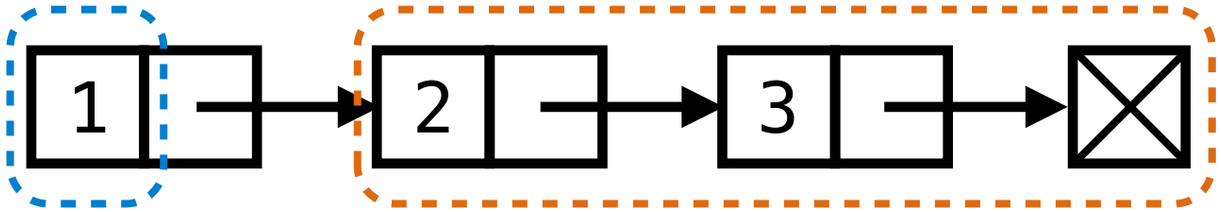
Linked Lists

- Another way to implement the sequence abstraction
- Links have two parts
  - `first`: the element in the link
  - `rest`: the next link in the list
- This is a recursive definition: the rest of a linked list is another linked list



Linked Lists

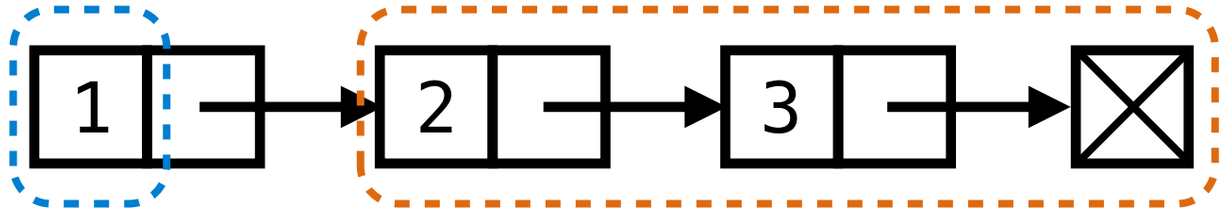
- Another way to implement the sequence abstraction
- Links have two parts
  - `first`: the element in the link
  - `rest`: the next link in the list
- This is a recursive definition: the rest of a linked list is another linked list



- This data structure has many names:

Linked Lists

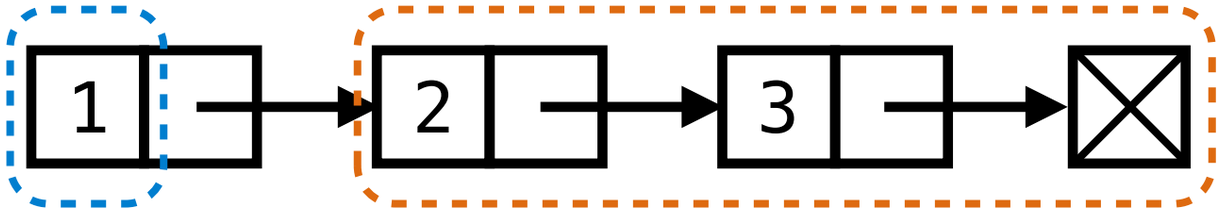
- Another way to implement the sequence abstraction
- Links have two parts
  - `first`: the element in the link
  - `rest`: the next link in the list
- This is a recursive definition: the rest of a linked list is another linked list



- This data structure has many names:
  - Linked list (C, Java)
  - List (Lisp)
  - Forward list (C++)

Linked Lists

- Another way to implement the sequence abstraction
- Links have two parts
  - `first`: the element in the link
  - `rest`: the next link in the list
- This is a recursive definition: the rest of a linked list is another linked list



- This data structure has many names:
  - Linked list (C, Java)
  - List (Lisp)
  - Forward list (C++)
  - Linky Listys (TAs)

Linked List Abstraction

Linked List Abstraction

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
```

Linked List Abstraction

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
```

```
def first(s):
    """Return the first element of a linked
    list S."""
def rest(s):
    """Return the rest of the elements of a
    linked list S."""
```

Linked List Abstraction

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
```

```
def first(s):
    """Return the first element of a linked
    list S."""
def rest(s):
    """Return the rest of the elements of a
    linked list S."""
```

If a linked list `s` is constructed from a first element `h` and a linked list `t`, then

Linked List Abstraction

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
```

```
def first(s):
    """Return the first element of a linked
    list S."""
def rest(s):
    """Return the rest of the elements of a
    linked list S."""
```

If a linked list `s` is constructed from a first element `h` and a linked list `t`, then

- `first(s)` returns `h`, which is an element of the sequence

Linked List Abstraction

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
```

```
def first(s):
    """Return the first element of a linked
    list S."""
def rest(s):
    """Return the rest of the elements of a
    linked list S."""
```

If a linked list `s` is constructed from a first element `h` and a linked list `t`, then

- `first(s)` returns `h`, which is an element of the sequence
- `rest(s)` returns `t`, which is a linked list

Implementing Linked Lists (v1)

Implementing Linked Lists (v1)

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
```

Implementing Linked Lists (v1)

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
```

```
def first(s):
    """Return the first element of a linked
    list S."""

def rest(s):
    """Return the rest of the elements of a
    linked list S."""
```

Implementing Linked Lists (v1)

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
    return [first, rest]
```

```
def first(s):
    """Return the first element of a linked
    list S."""

def rest(s):
    """Return the rest of the elements of a
    linked list S."""
```

Implementing Linked Lists (v1)

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
    return [first, rest]
```

```
def first(s):
    """Return the first element of a linked
    list S."""
    return s[0]

def rest(s):
    """Return the rest of the elements of a
    linked list S."""
```

Implementing Linked Lists (v1)

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
    return [first, rest]
```

```
def first(s):
    """Return the first element of a linked
    list S."""
    return s[0]

def rest(s):
    """Return the rest of the elements of a
    linked list S."""
    return s[1]
```

Implementing Linked Lists (v1) (demo)

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
    return [first, rest]
```

```
def first(s):
    """Return the first element of a linked
    list S."""
    return s[0]

def rest(s):
    """Return the rest of the elements of a
    linked list S."""
    return s[1]
```

Linked Lists are Sequences

Linked Lists are Sequences (demo)

Linked Lists are Sequences (demo)

```
def len_link(s):
    """Return the length of the linked list."""
    length = 0
    while s != empty:
        s, length = rest(s), length + 1
    return length
```

Linked Lists are Sequences (demo)

```
def len_link(s):
    """Return the length of the linked list."""
    length = 0
    while s != empty:
        s, length = rest(s), length + 1
    return length

def getitem_link(s, i):
    """Return the element at index i."""
    while i > 0:
        s, i = rest(s), i - 1
    return first(s)
```

Linked Lists are Sequences (demo)

```
def len_link(s):
    """Return the length of the linked list."""
    length = 0
    while s != empty:
        s, length = rest(s), length + 1
    return length

def getitem_link(s, i):
    """Return the element at index i."""
    while i > 0:
        s, i = rest(s), i - 1
    return first(s)
```

Never violate the abstraction barrier!

Linked Lists are Recursive

Linked Lists are Recursive (demo)

Linked Lists are Recursive (demo)

```
def len_link(s):
    """Return the length of the linked list."""
    if s == empty:
        return 0
    else:
        return 1 + len_link(rest(s))
```

Linked Lists are Recursive (demo)

```
def len_link(s):
    """Return the length of the linked list."""
    if s == empty:
        return 0
    else:
        return 1 + len_link(rest(s))

def getitem_link(s, i):
    """Return the element at index i."""
    if i == 0:
        return first(s)
    else:
        return getitem_link(rest(s), i - 1)
```

Linked Lists are Recursive (demo)

```
def len_link(s):
    """Return the length of the linked list."""
    if s == empty:
        return 0
    else:
        return 1 + len_link(rest(s))

def getitem_link(s, i):
    """Return the element at index i."""
    if i == 0:
        return first(s)
    else:
        return getitem_link(rest(s), i - 1)
```

Never violate the abstraction barrier!

Break!

Linked List Processing

Sequences as Containers

Sequences as Containers (demo)

Sequences as Containers (demo)

```
def contains(s, elem):
    """Return whether ELEM is in the sequence S.
    >>> contains([1, 2, 3], 1)
    True
    >>> contains([1, 2, 3], 4)
    False
    """
    for x in s:
        if x == elem:
            return True
    return False
```

Linked Lists as Containers (demo)

Linked Lists as Containers (demo)

```
def contains_link(s, elem):
    """Return whether ELEM is in the sequence S.
    >>> contains_link(link(1, link(2, link(3, empty))), 1)
    True
    >>> contains_link(link(1, link(2, link(3, empty))), 4)
    False
    """
    if s == empty:
        return False
    if first(s) == elem:
        return True
    else:
        return contains(rest(s), elem)
```

Linked List Examples

Counting Partitions

```
def count_partitions(n, m):
    if n == 0:
        return 1
    elif n < 0:
        return 0
    elif m == 0:
        return 0
    else:
        with_m = count_partitions(n-m, m)
        without_m = count_partitions(n, m-1)
        return with_m + without_m
```

Enumerating Partitions

Enumerating Partitions (demo)

Enumerating Partitions (demo)

```
def partitions(n, m):
```

Enumerating Partitions (demo)

```
def partitions(n, m):
    if n == 0:
```

Enumerating Partitions (demo)

```
def partitions(n, m):
    if n == 0:
        return link(empty, empty)
```

Enumerating Partitions (demo)

```
def partitions(n, m):
    if n == 0:
        return link(empty, empty)
    elif n < 0 or m == 0:
```

Enumerating Partitions (demo)

```
def partitions(n, m):
    if n == 0:
        return link(empty, empty)
    elif n < 0 or m == 0:
        return empty
```

Enumerating Partitions (demo)

```
def partitions(n, m):
    if n == 0:
        return link(empty, empty)
    elif n < 0 or m == 0:
        return empty
    else:
```

Enumerating Partitions (demo)

```
def partitions(n, m):
    if n == 0:
        return link(empty, empty)
    elif n < 0 or m == 0:
        return empty
    else:
        with_m = partitions(n-m, m)
```

Enumerating Partitions (demo)

```
def partitions(n, m):
    if n == 0:
        return link(empty, empty)
    elif n < 0 or m == 0:
        return empty
    else:
        with_m = partitions(n-m, m)
        without_m = partitions(n, m-1)
```

Enumerating Partitions (demo)

```
def partitions(n, m):
    if n == 0:
        return link(empty, empty)
    elif n < 0 or m == 0:
        return empty
    else:
        with_m = partitions(n-m, m)
        without_m = partitions(n, m-1)
        add_m = lambda s: link(m, s)
```

Enumerating Partitions (demo)

```
def partitions(n, m):
    if n == 0:
        return link(empty, empty)
    elif n < 0 or m == 0:
        return empty
    else:
        with_m = partitions(n-m, m)
        without_m = partitions(n, m-1)
        add_m = lambda s: link(m, s)
        with_m = map_link(add_m, with_m)
```

Enumerating Partitions (demo)

```
def partitions(n, m):
    if n == 0:
        return link(empty, empty)
    elif n < 0 or m == 0:
        return empty
    else:
        with_m = partitions(n-m, m)
        without_m = partitions(n, m-1)
        add_m = lambda s: link(m, s)
        with_m = map_link(add_m, with_m)
        return extend(with_m, without_m)
```

Break?

Other Linked List Implementations

Implementing Linked Lists (v1)

```
def link(first, rest):
    """Construct a linked list from its first
    element and the rest of the linked list."""
    return [first, rest]
```

```
def first(s):
    """Return the first element of a linked
    list S."""
    return s[0]

def rest(s):
    """Return the rest of the elements of a
    linked list S."""
    return s[1]
```

Implementing Linked Lists (v2)

Implementing Linked Lists (v2)

```
def link(first, rest):
```

Implementing Linked Lists (v2)

```
def link(first, rest):


```

```
def first(s):


def rest(s):
```

Implementing Linked Lists (v2)

```
def link(first, rest):
    def dispatch(msg):
```

```
def first(s):

def rest(s):
```

Implementing Linked Lists (v2)

```
def link(first, rest):
    def dispatch(msg):
        if msg == 'first':
```

```
def first(s):

def rest(s):
```

Implementing Linked Lists (v2)

```
def link(first, rest):
    def dispatch(msg):
        if msg == 'first':
            return first
```

```
def first(s):

def rest(s):
```

Implementing Linked Lists (v2)

```
def link(first, rest):
    def dispatch(msg):
        if msg == 'first':
            return first
        elif msg == 'rest':
```

```
def first(s):


def rest(s):
```

Implementing Linked Lists (v2)

```
def link(first, rest):
    def dispatch(msg):
        if msg == 'first':
            return first
        elif msg == 'rest':
            return rest
```

```
def first(s):


def rest(s):
```

Implementing Linked Lists (v2)

```
def link(first, rest):
    def dispatch(msg):
        if msg == 'first':
            return first
        elif msg == 'rest':
            return rest
    return dispatch
```

```
def first(s):


def rest(s):

```

Implementing Linked Lists (v2)

```
def link(first, rest):
    def dispatch(msg):
        if msg == 'first':
            return first
        elif msg == 'rest':
            return rest
    return dispatch
```

```
def first(s):
    return s('first')

def rest(s):

```

Implementing Linked Lists (v2)

```
def link(first, rest):
    def dispatch(msg):
        if msg == 'first':
            return first
        elif msg == 'rest':
            return rest
    return dispatch
```

```
def first(s):
    return s('first')

def rest(s):
    return s('rest')
```

Implementing Linked Lists (v2) (demo)

```
def link(first, rest):
    def dispatch(msg):
        if msg == 'first':
            return first
        elif msg == 'rest':
            return rest
    return dispatch
```

```
def first(s):
    return s('first')

def rest(s):
    return s('rest')
```

Implementing Linked Lists (v2) (demo)

```
def link(first, rest):
    def dispatch(msg):
        if msg == 'first':
            return first
        elif msg == 'rest':
            return rest
    return dispatch
```

```
def first(s):
    return s('first')

def rest(s):
    return s('rest')
```

Implementing Linked Lists (v3)

```
def link(first, rest):
    def dispatch(msg):
        if msg == 'brian':
            return first
        elif msg == 'marvin':
            return rest
    return dispatch
```

```
def first(s):
    return s('brian')

def rest(s):
    return s('marvin')
```

Summary

- Linked lists are one implementation of the sequence abstraction
- Linked lists are composed of two parts:
  - first: the element in the link
  - rest: the next link in the list (may be empty)
- Data abstraction means that the implementation details of the first and rest selectors are unnecessary
- We can use functions to implement linked lists
  - We can use lists to implement dictionaries
  - Therefore, we can use functions to implement dictionaries