Recursive Objects

Recursive Objects

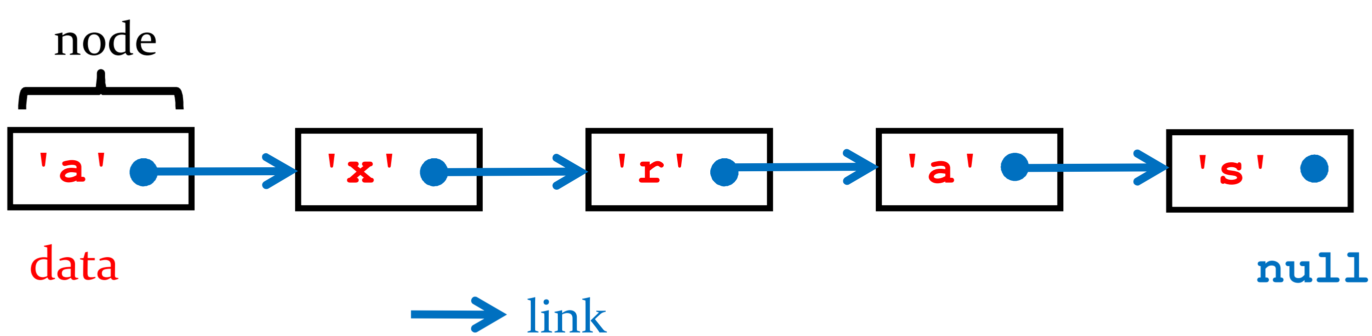
- an object that holds a reference to its own type is a recursive object
  - linked lists and trees are classic examples in computer science of objects that can be implemented recursively

Data Structures

- data structures (and algorithms) are one of the foundational elements of computer science
- a data structure is a way to organize and store data so that it can be used efficiently
  - list – sequence of elements
  - set – a group of unique elements
  - map – access elements using a key
  - many more…

Linked Lists

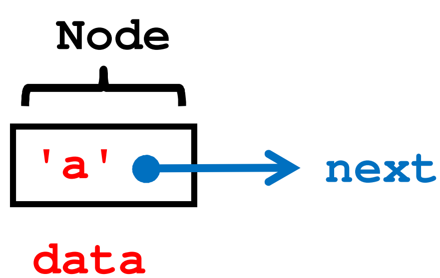
- a data structure made up of a sequence of nodes
- each node has
  - some data
  - a field that contains a reference (a *link*) to the **next** node in the sequence
- suppose we have a linked list that holds characters; a picture of our linked list would be:



UML Class Diagram

LinkedList
- size : int - head : Node
...

Node
- data : char - next : Node
...



Node

- nodes are implementation details that the client does not need to know about
  - can be private inner classes

```java
public class LinkedList {

  private static class Node {
    private char data;
    private Node next;

    public Node(char c) {
      this.data = c;
      this.next = null;
    }
  }

 // ...
}
```

LinkedList constructor

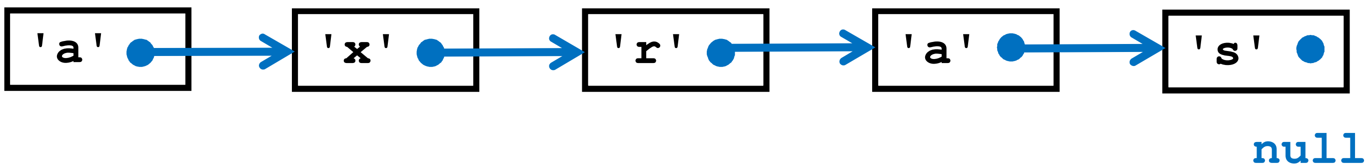
```
/**
 * Create a linked list of size 0.
 *
 */
public LinkedList() {
  this.size = 0;
  this.head = null;
}
```

Node constructor

```
/**
 * Create a node with the given character.
 *
 */
public Node(char c) {
  this.data = c;
  this.next = null;
}
```

Creating a Linked List

- to create the following linked list:




```
LinkedList t = new LinkedList();
t.add('a');
t.add('x');
t.add('r');
t.add('a');
t.add('s');
```

Add to end of list

- methods of recursive objects can often be implemented with a recursive algorithm
  - notice the word "can"; the recursive implementation is not necessarily the most efficient implementation
- adding to the end of the list can be done recursively
  - base case: at the end of the list
    - i.e., **`next`** is **`null`**
    - create new node and append it to this link
  - recursive case: current link is not the last link
    - add to the end of **`next`**

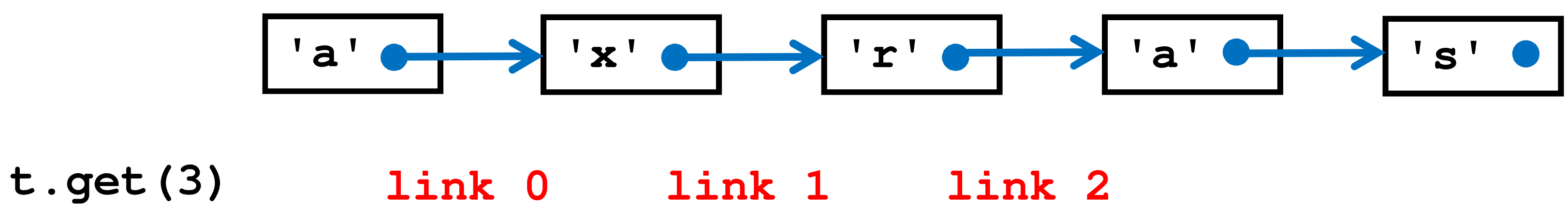
```java
/**
 * Adds the given character to the end of the list.
 *
 * @param c The character to add
 */
public void add(char c) {
  if (this.size == 0) {
    this.head = new Node(c);
  }
  else {
    LinkedList.add(c, this.head);
  }
  this.size++;
}
```

recursive method

```java
/**
 * Adds the given character to the end of the list.
 *
 * @param c The character to add
 * @param node The node at the head of the current sublist
 */
private static void add(char c, Node node) {
  if (node.next == null) {
    node.next = new Node(c);
  }
  else {
    LinkedList.add(c, node.next);
  }
}
```

Getting an Element in the List

- a client may wish to retrieve the *ith* element from a list
  - the ability to access arbitrary elements of a sequence in the same amount of time is called *random access*
  - arrays support random access; linked lists do not
- to access the *ith* element in a linked list we need to sequentially follow the first (i - 1) links



  - takes $O(n)$ time versus $O(1)$ for arrays

Getting an Element in the List

- validation?
- getting the *i*th element can be done recursively
  - base case: **`index == 0`**
    - return the value held by the current link
  - recursive case: current link is not the last link
    - get the element at **`index - 1`** starting from **`next`**

```java
/**
 * Returns the item at the specified position
 * in the list.
 *
 * @param index index of the element to return
 * @return the element at the specified position
 * @throws IndexOutOfBoundsException if the index
 *         is out of the range
 *         {@code (index < 0 || index >= list size)}
 */
public char get(int index) {
  if (index < 0 || index >= this.size) {
    throw new IndexOutOfBoundsException("Index: " + index +
                                        ", Size: " + this.size);
  }
  return LinkedList.get(index, this.head);
}
```

recursive method

```java
/**
 * Returns the item at the specified position
 * in the list.
 *
 * @param index index of the element to return
 * @param node The node at the head of the current sublist
 * @return the element at the specified position
 */
private static char get(int index, Node node) {
  if (index == 0) {
    return node.data;
  }
  return LinkedList.get(index - 1, node.next);
}
```

Setting an Element in the List

- setting the *i*th element is almost exactly the same as getting the *i*th element

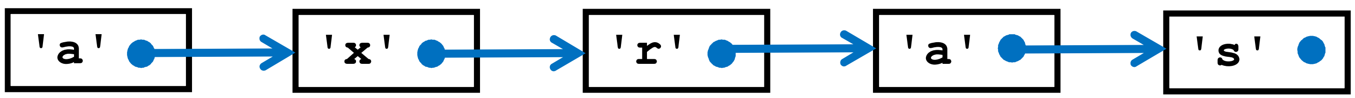
```java
/**
 * Sets the element at the specified position
 * in the list.
 *
 * @param index index of the element to set
 * @param c new value of element
 * @throws IndexOutOfBoundsException if the index
 *         is out of the range
 *         {@code (index < 0 || index >= list size)}
 */
public void set(int index, char c) {
  if (index < 0 || index >= this.size) {
    throw new IndexOutOfBoundsException("Index: " + index +
                                         ", Size: " + this.size);
  }
  LinkedList.set(index, c, this.head);
}
```

recursive method

```java
/**
 * Sets the element at the specified position
 * in the list.
 *
 * @param index index of the element to set
 * @param c new value of the element
 * @param node The node at the head of the current sublist
 */
private static void set(int index, char c, Node node) {
  if (index == 0) {
    node.data = c;
    return;
  }
  LinkedList.set(index - 1, c, node.next);
}
```

toString

- finding the string representation of a list can be done recursively



  - the string is
    `"[a, x, r, a, s]`
  - the string is
    `"[" + "a, " + toString(`*`the list['x', 'r', 'a', 's']`*`)`

toString

- base case: **`next`** is **`null`**
  - return the value of the link as a string + **`"]"`**
- recursive case: current link is not the last link
  - return the value of the link as a string + **`", "`** + the rest of the list as a string

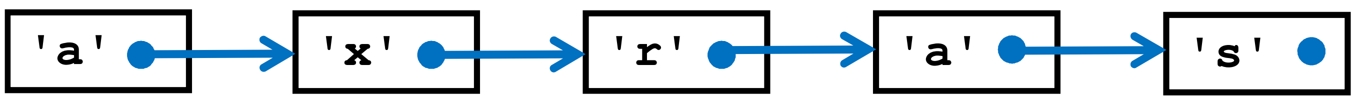
```java
public String toString() {
  if (this.size == 0) {
    return "[]";
  }
  return "[" + LinkedList.toString(this.head);
}
```

recursive method

```java
private static String toString(Node n) {
  if (n.next == null) {
    return n.data + "]";
  }
  String s = n.data + ", ";
  return s + LinkedList.toString(n.next);
}
```

Finding an element in the list

- often useful to ask if a list contains a particular element
- worst case: must visit every element of the list



  - e.g., `t.contains('z')`

Finding an element in the list

- contains can be solved recursively
  - base case: found the character we are looking for
    - i.e., node **`data`** is equal to the character we are searching for
      - return true
  - base case: at the end of the list
    - i.e., node **`next`** is **`null`**
      - return false
  - recursive case: have not found the character we are searching for and not at the end of the list
    - search the sublist starting at **`node.next`**
      - return result

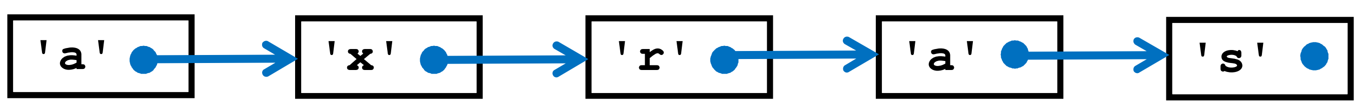
```java
/**
 * Returns <code>true</code> if this list contains the specified
   element.
 *
 * @param c element to search for
 * @return <code>true</code> if this list contains the
 * specified element
 */
public boolean contains(char c) {
  if (this.size == 0) {
       return false;
    }
  return LinkedList.contains(c, this.head);
}
```

recursive method

```java
/**
 * Returns <code>true</code> if this list contains the specified
   element.
 *
 * @param c element to search for
 * @param node the node at the head of the current sublist
 * @return <code>true</code> if this list contains the
 * specified element
 */
private static boolean contains(char c, Node node) {
  if (node.data == c) {
    return true;
  }
  if (node.next == null) {
    return false;
  }
  return LinkedList.contains(c, node.next);
}
```

Finding an element in the list

- closely related to contains is finding the index of an element in the list
- worst case: must visit every element of the list



- e.g., **`t.indexOf('s')`**

Finding an element in the list

- **`indexOf`** can be solved recursively
  - base case: found the character we are looking for
    - i.e., node **`data`** is equal to the character we are searching for
      - return 0
  - base case: at the end of the list
    - i.e., node **`next`** is **`null`**
      - return -1
  - recursive case: have not found the character we are searching for and not at the end of the list
    - search the sublist starting at **`node.next`**
      - return 1 + result

```java
/**
 * Returns the index of the first occurrence of the
 * specified element in this list, or -1 if this list
 * does not contain the element.
 *
 * @param c
 *          element to search for
 * @return the index of the first occurrence of the
 *         specified element in this list, or -1 if this
 *         list does not contain the element
 */
public int indexOf(char c) {
  if (this.size == 0) {
    return -1;
  }
  return LinkedList.indexOf(c, this.head);
}
```

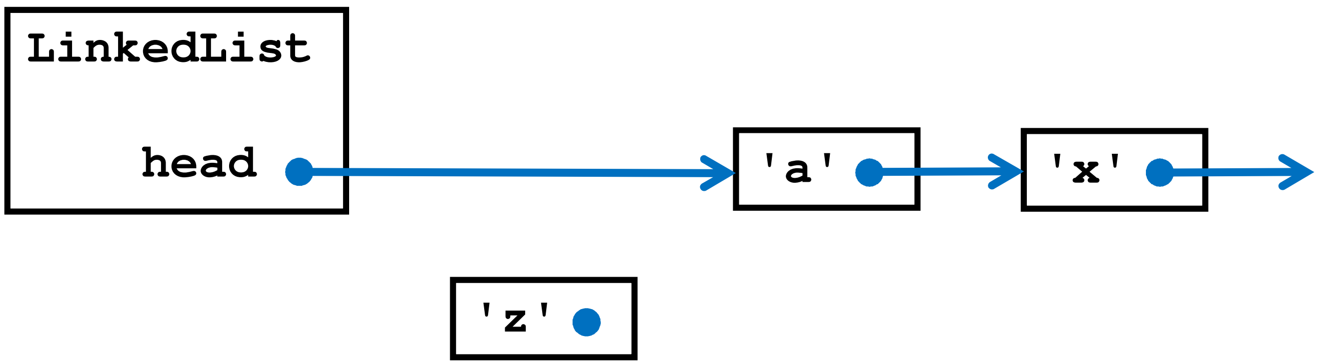
recursive method

```
private static int indexOf(char c, Node n) {
  if (n.data == c) {
    return 0;
  }
  if (n.next == null) {
    return -1;
  }
  int i = LinkedList.indexOf(c, n.next);
  if (i == -1) {
    return -1;
  }
  return 1 + i;
}
```

Recursive Objects (Part 2)

Adding to the front of the list

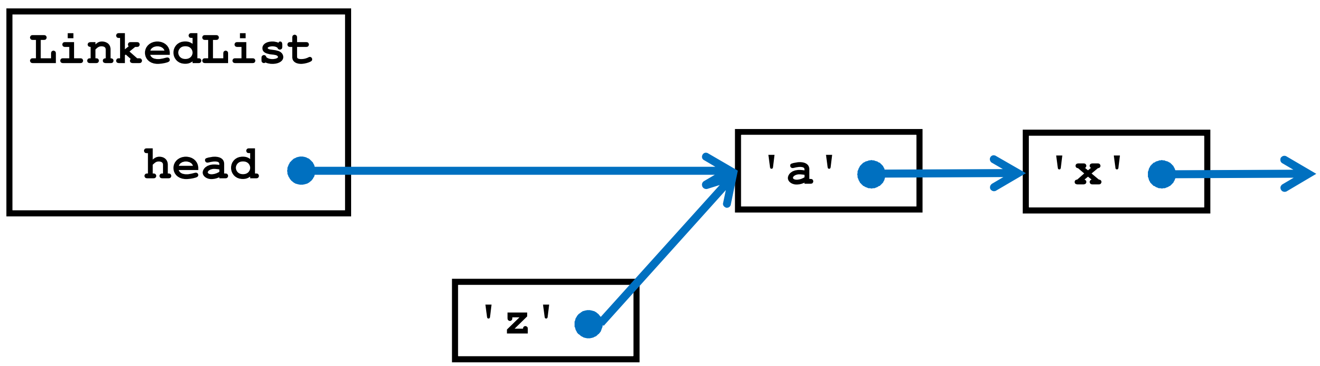
- adding to the front of the list



- `t.addFirst('z')` or `t.add(0, 'z')`

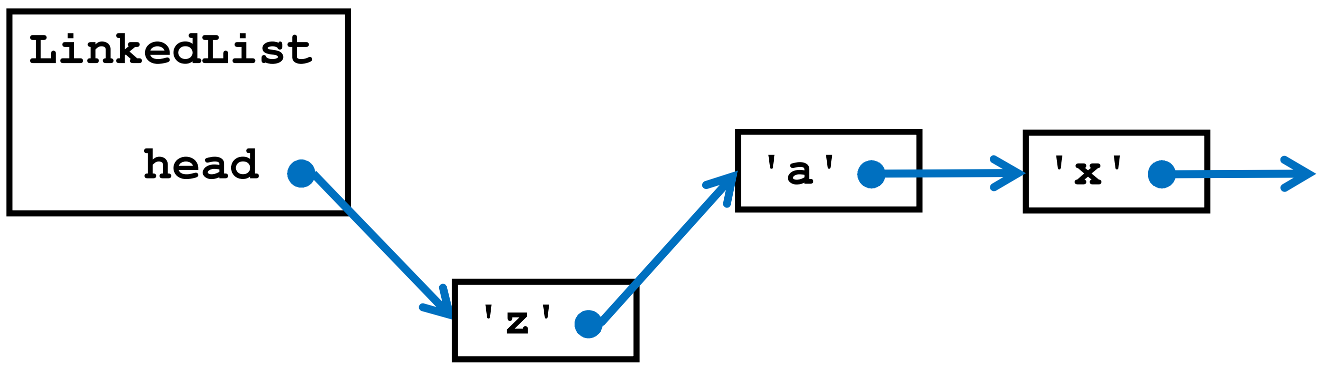
Adding to the front of the list

- must connect to the rest of the list



Adding to the front of the list

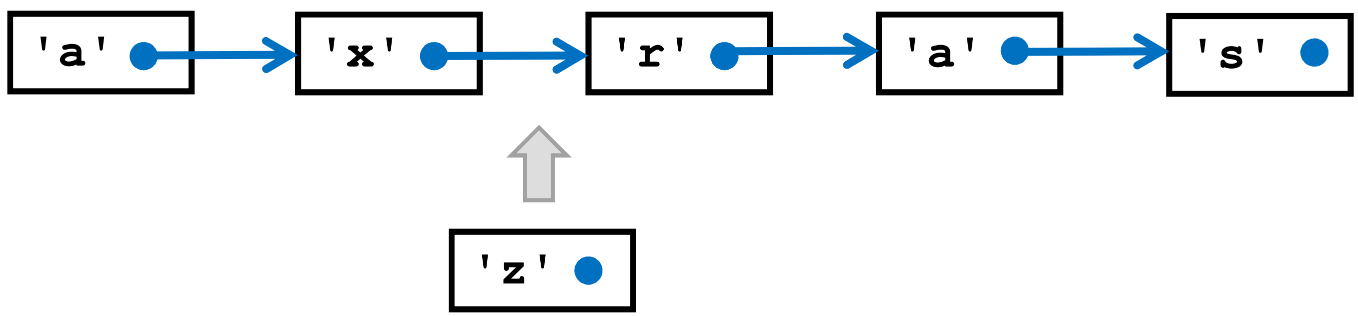
- then re-assign head of linked list



```java
/**
 * Inserts the specified element at the beginning of this list.
 *
 * @param c the character to add to the beginning of this list.
 */
public void addFirst(char c) {
  Node newNode = new Node(c);
  newNode.next = this.head;
  this.head = newNode;
  this.size++;
}
```

Adding to the middle of the list

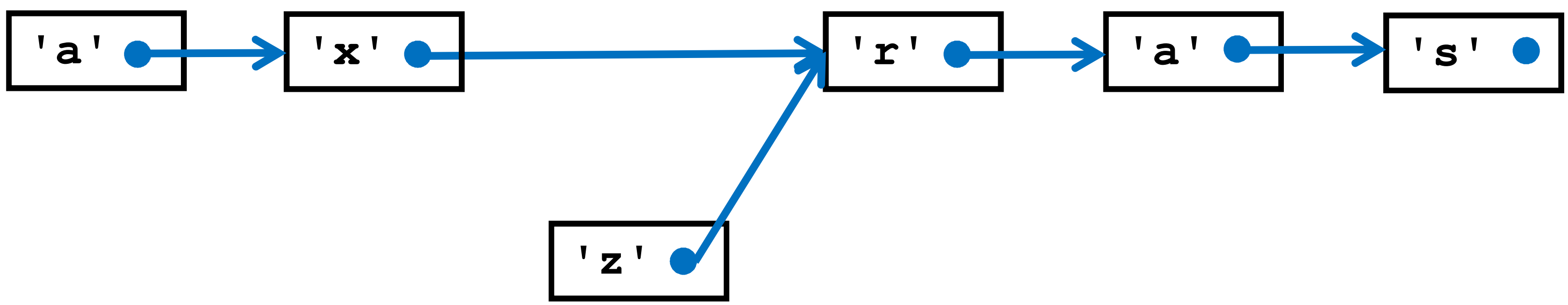
- adding to the middle of the list



- `t.add(2, 'z')`

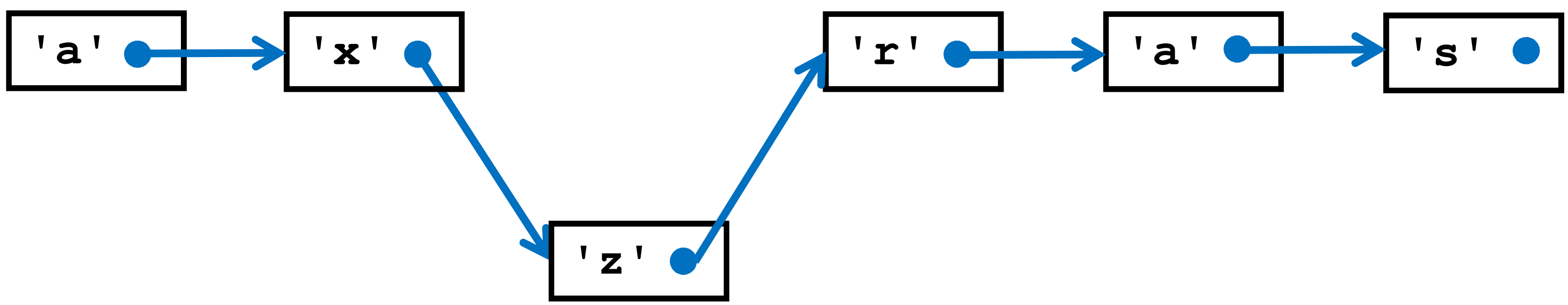
Adding to the middle of the list

- must connect to the rest of the list



Adding to the middle of the list

- then re-assign the link from the previous node



- notice that we to know the node previous to the inserted node

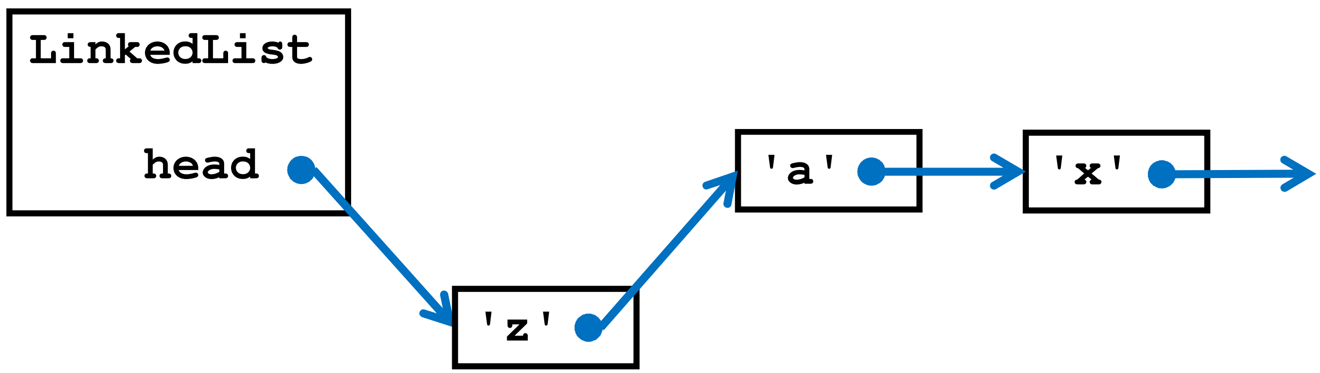
```java
/**
 * Insert an element at the specified index in the list.
 *
 * @param index the index to insert at
 * @param c the character to insert
 */
public void add(int index, char c) {
  if (index < 0 || index > this.size) {
    throw new IndexOutOfBoundsException("Index: " + index + ", Size: "
          + this.size);
  }
  if (index == 0) {
    this.addFirst(c);
  }
  else {
    LinkedList.add(index - 1, c, this.head);
    this.size++;
  }
}
```

recursive method

```java
/**
 * Insert an element at the specified index after the
 * specified node.
 *
 * @param index the index after prev to insert at
 * @param c the character to insert
 * @param prev the node to insert after
 */
private static void add(int index, char c, Node prev) {
  if (index == 0) {
    Node newNode = new Node(c);
    newNode.next = prev.next;
    prev.next = newNode;
    return;
  }
  LinkedList.add(index - 1, c, prev.next);
}
```

Removing from the front of the list

- removing from the front of the list

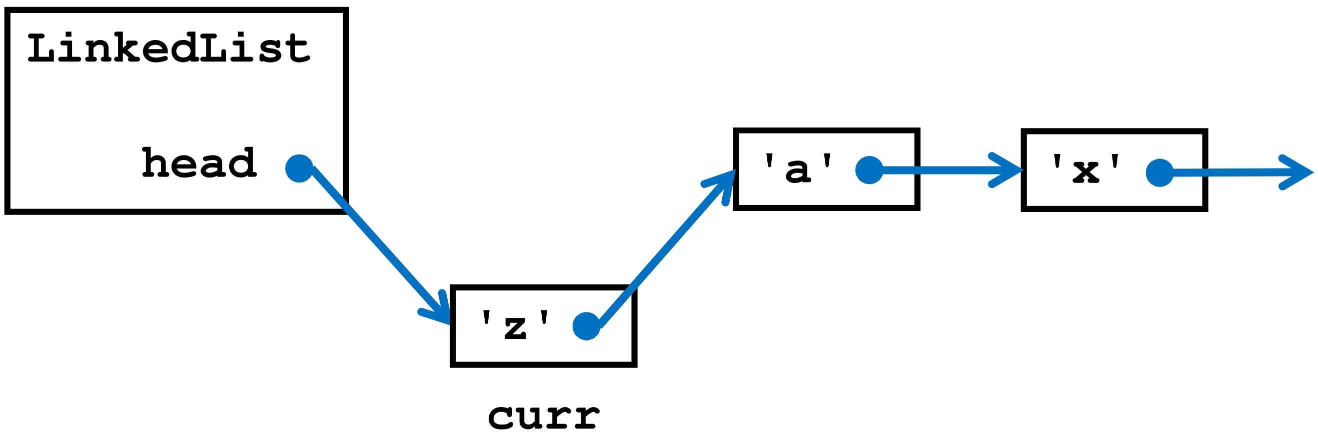


- **`t.removeFirst()`** or **`t.remove(0)`**

- also returns the element removed

Removing from the front of the list

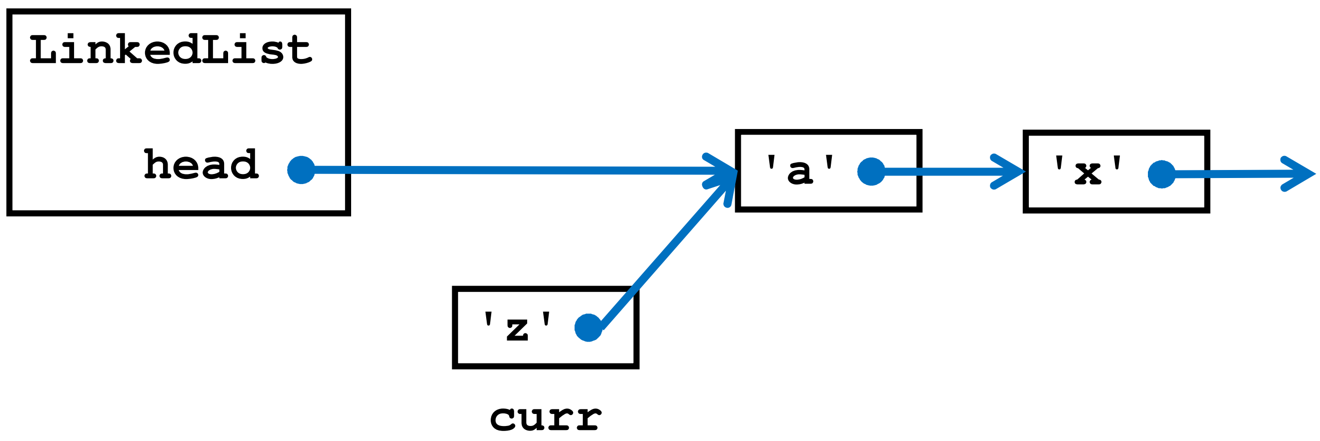
- create a reference to the node we want to remove




```
Node curr = this.head;
```

Removing from the front of the list

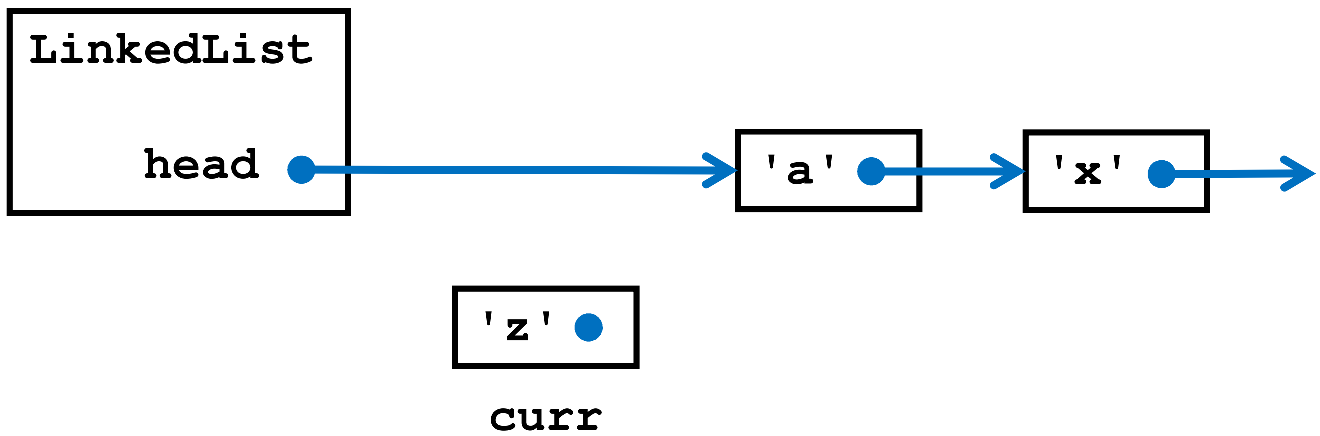
- re-assign the head node




```
this.head = curr.next;
```

Removing from the front of the list

- then remove the link from the old head node

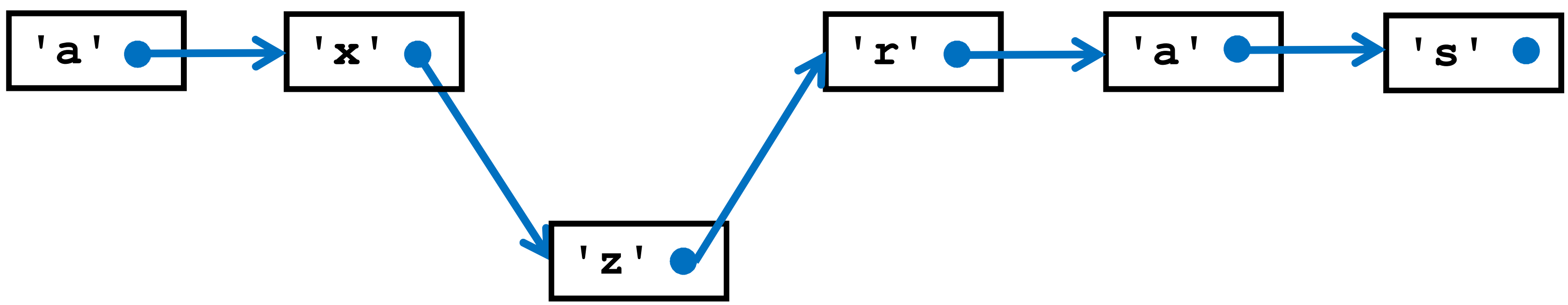



```
curr.next = null;
```

```
/**
 * Removes and returns the first element from this list.
 *
 * @return the first element from this list
 */
public char removeFirst() {
  if (this.size == 0) {
    throw new NoSuchElementException();
  }
  Node curr = this.head;
  this.head = curr.next;
  curr.next = null;
  this.size--;
  return curr.data;
}
```

Removing from the middle of the list

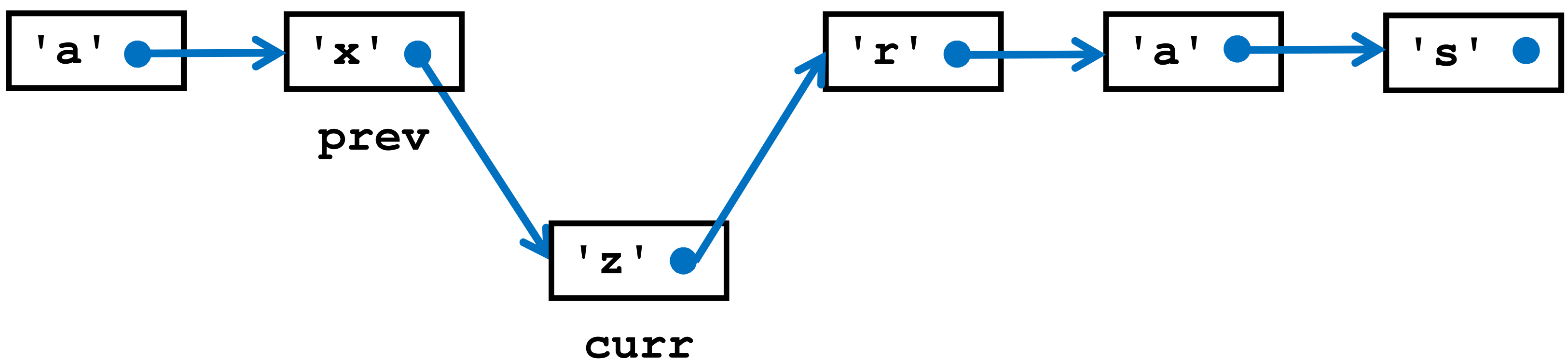
- removing from the middle of the list



- `t.remove(2)`

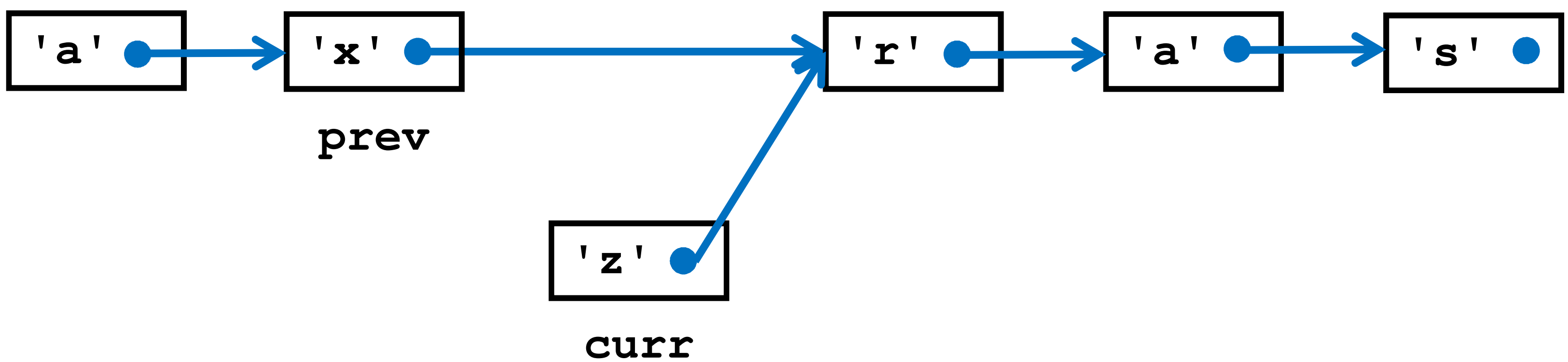
Removing from the middle of the list

- assume that we have references to the node we want to remove and its previous node



Removing from the middle of the list

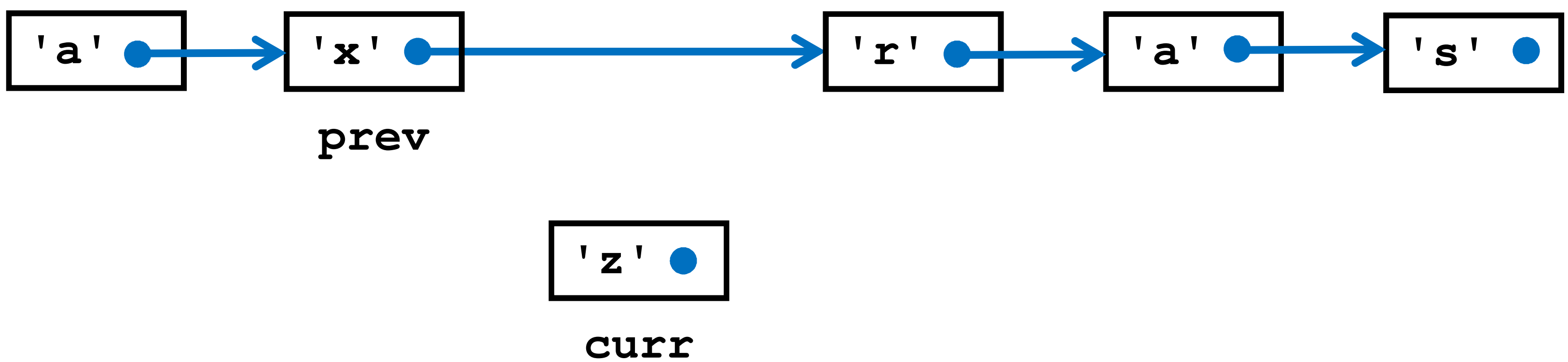
- re-assign the link from the previous node




```
prev.next = curr.next;
```

Removing from the middle of the list

- then remove the link from the current node




```
curr.next = null;
```

```java
/**
 * Removes the element at the specified position in this list
 *
 * @param index the index of the element to be removed
 * @return the element previously at the specified position
 */
public char remove(int index) {
  if (index < 0 || index >= this.size) {
    throw new IndexOutOfBoundsException("Index: " + index +
                                        ", Size: " + this.size);
  }
  if (index == 0) {
    return this.removeFirst();
  }
  else {
    char result = LinkedList.remove(index - 1, this.head, this.head.next);
    this.size--;
    return result;
  }
}
```

recursive method

```java
/**
 * Removes the element at the specified position relative to the
 * current node.
 *
 * @param index
 *          the index relative to the current node of the
 *          element to be removed
 * @param prev
 *          the node previous to the current node
 * @param curr
 *          the current node
 * @return the element previously at the specified position
 */
private static char remove(int index, Node prev, Node curr) {
  if (index == 0) {
    prev.next = curr.next;
    curr.next = null;
    return curr.data;
  }
  return LinkedList.remove(index - 1, curr, curr.next);
}
```

Implementing Iterable

- having our linked list implement **`Iterable`** would be very convenient for clients

```
// for some LinkedList t

for (Character c : t) {
  // do something with c
}
```

Iterable Interface

`public interface Iterable<T>`

Implementing this interface allows an object to be the target of the "foreach" statement.

`Iterator<T>`	**`iterator()`** Returns an iterator over a set of elements of type **`T`**.

Iterator

- to implement **`Iterable`** we need to provide an iterator object that can iterate over the elements in the list

`public interface Iterator<E>`

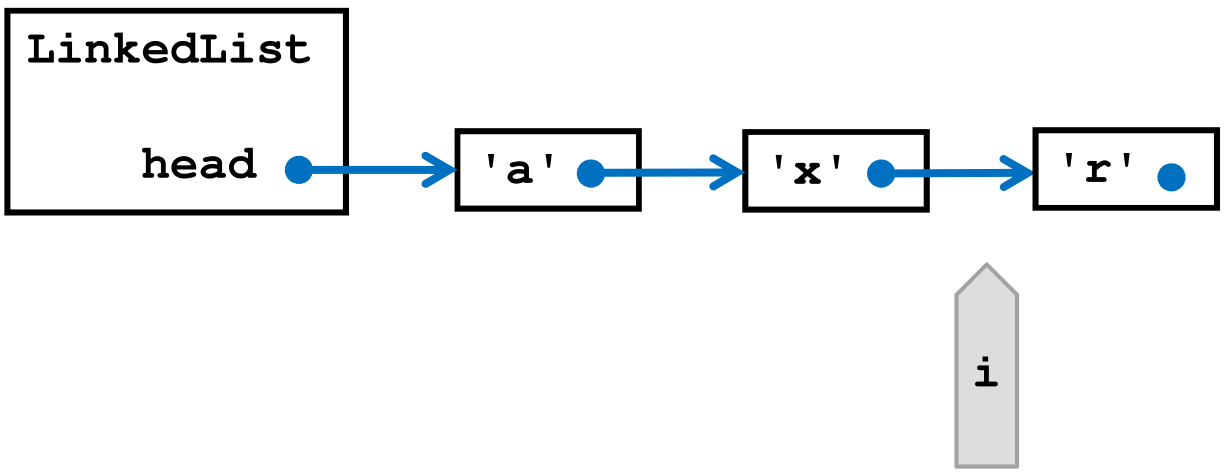
An iterator over a collection.

`boolean`	**`hasNext()`** Returns true if the iteration has more elements.
E	**`next()`** Returns the next element in the iteration.
`void`	**`remove()`** Removes from the underlying collection the last element returned by this iterator (optional operation).

Recursive Objects (Part 3)

LinkedList Iterator

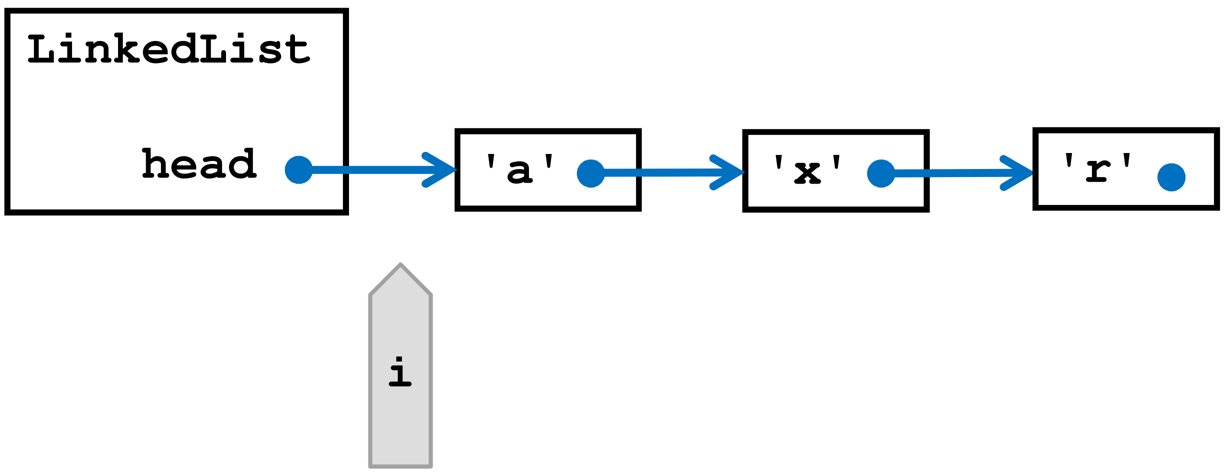
- think of the iterator as lying between elements in the list (like a cursor)



iterator between 'x' and 'r'

LinkedList Iterator

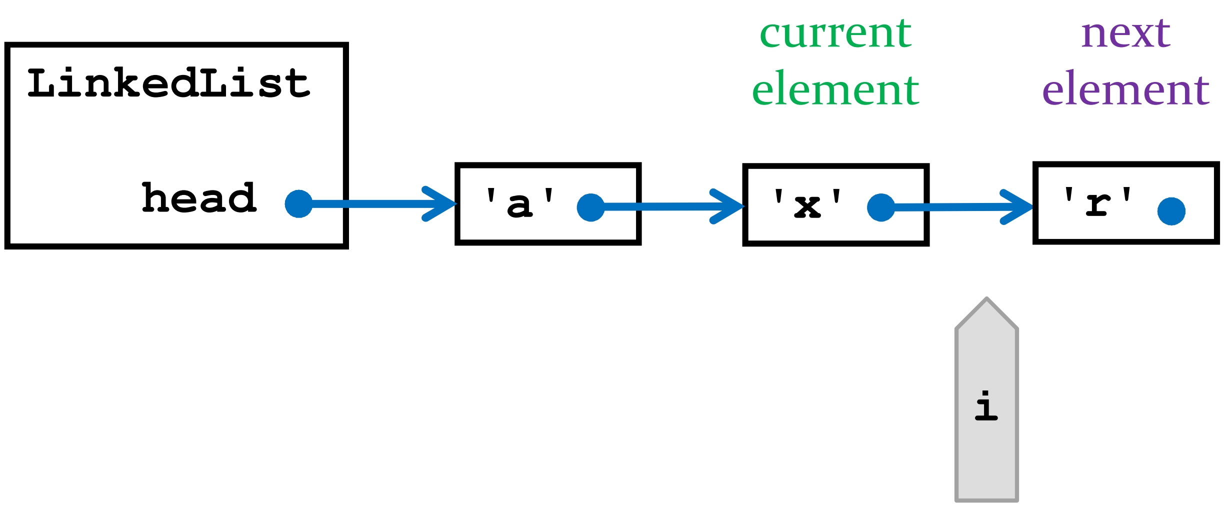
- think of the iterator as lying between elements in the list (like a cursor)



iterator at the start of the iteration
(between nothing and 'a')

LinkedList Iterator

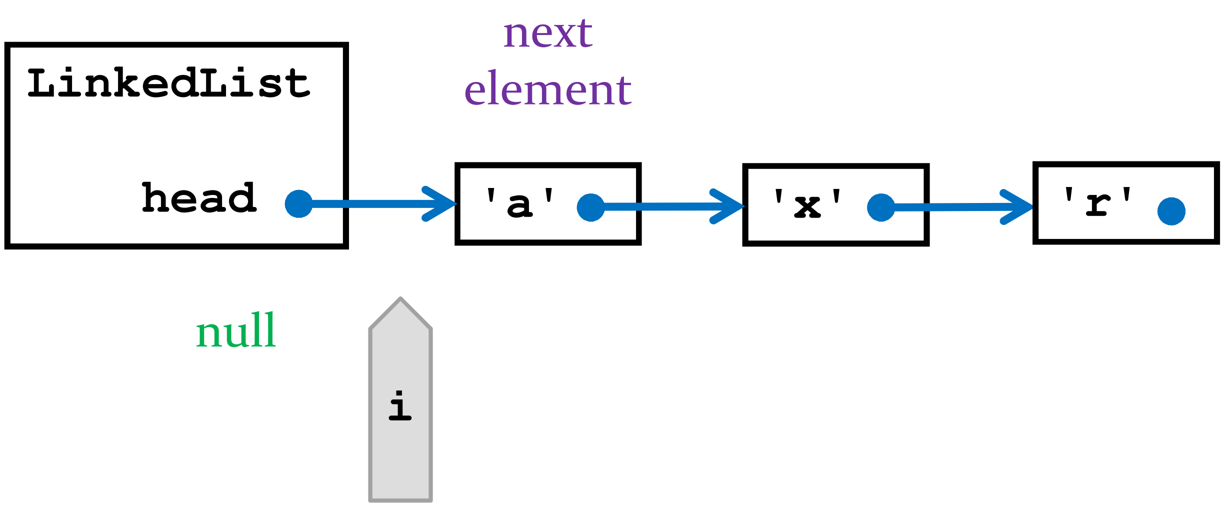
- because the iterator is between elements, there is a current element and next element of the iteration



iterator between 'x' and 'r'

LinkedList Iterator

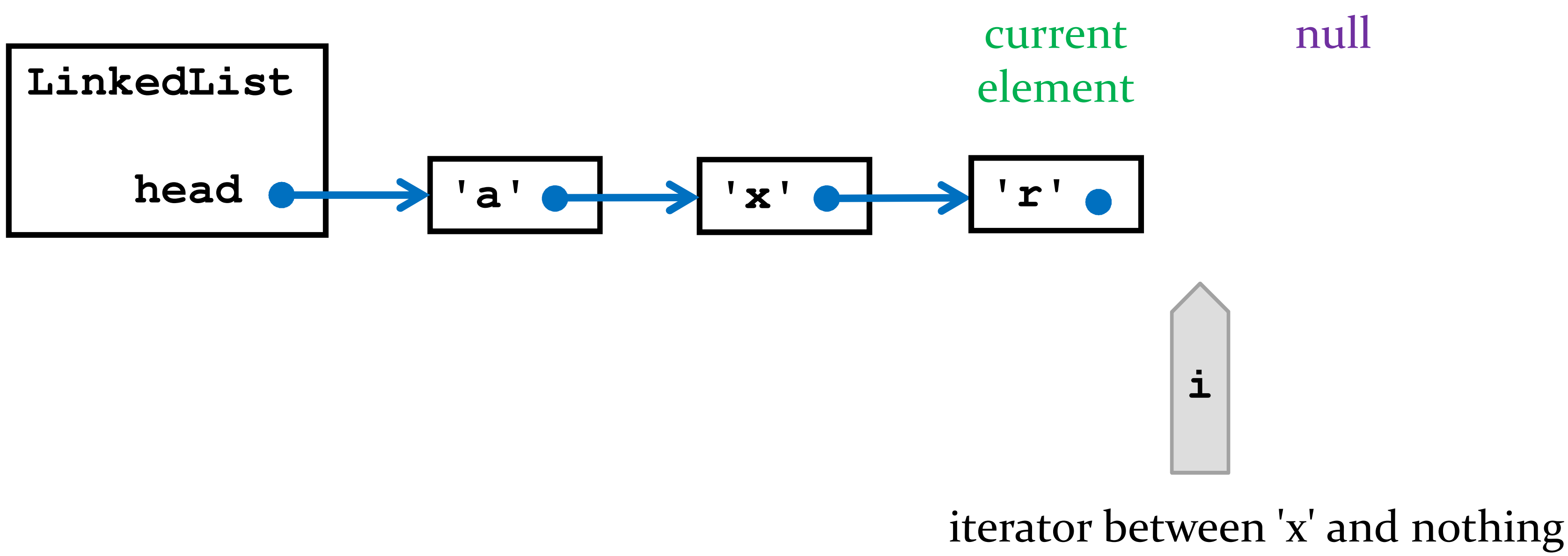
- the current element is **`null`** at the start of the iteration



iterator at the start of the iteration
(between nothing and 'a')

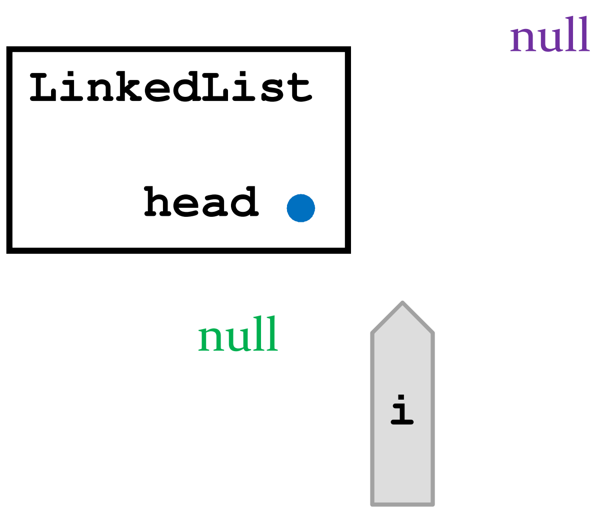
LinkedList Iterator

- the next element is **`null`** at the end of the iteration



LinkedList Iterator

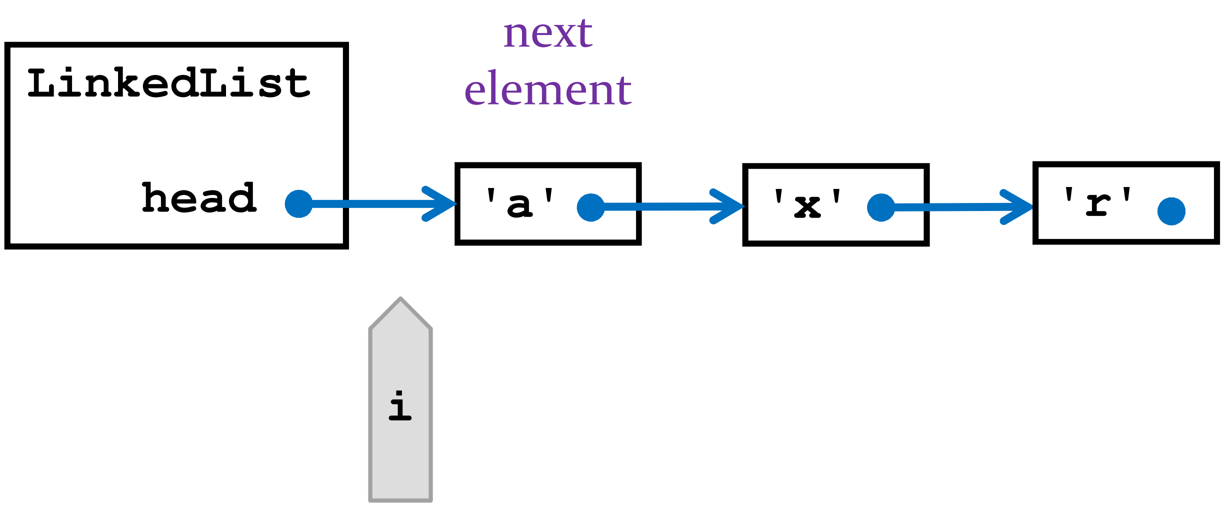
- both the current and next elements are **`null`** if the list is empty



iterator at the start of the iteration

LinkedList Iterator: hasNext

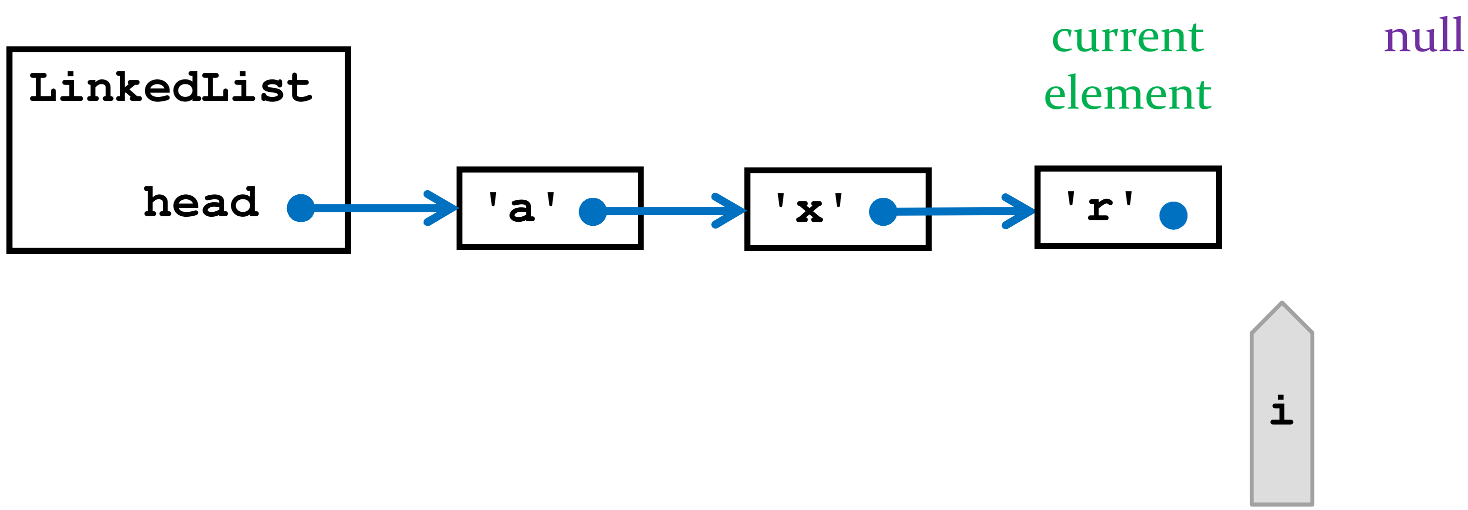
- **`hasNext()`** returns true if there is at least one more element in the iteration



`i.hasNext()` is **`true`**

LinkedList Iterator: hasNext

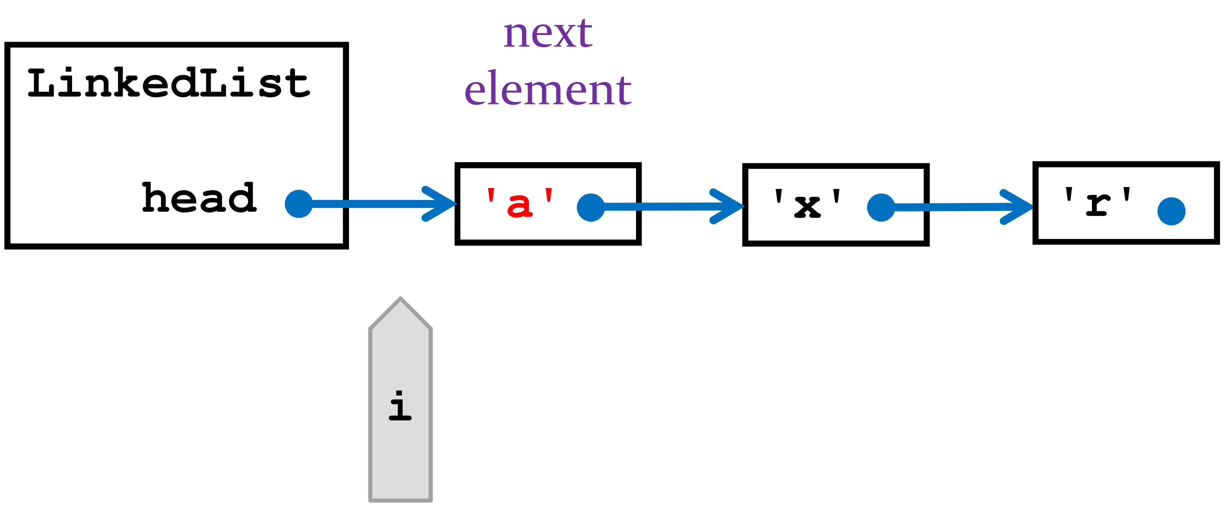
- **`hasNext()`** returns false at the end of the iteration



`i.hasNext()` is **`false`**

LinkedList Iterator: next

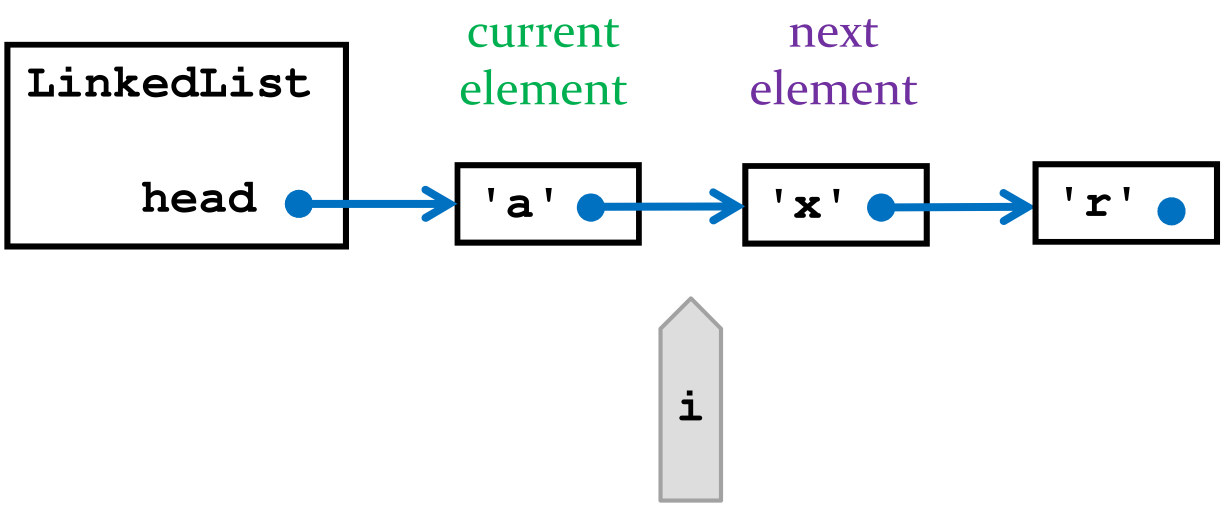
- invoking **`next()`** returns the next element...



`i.next() == 'a'` is **`true`**

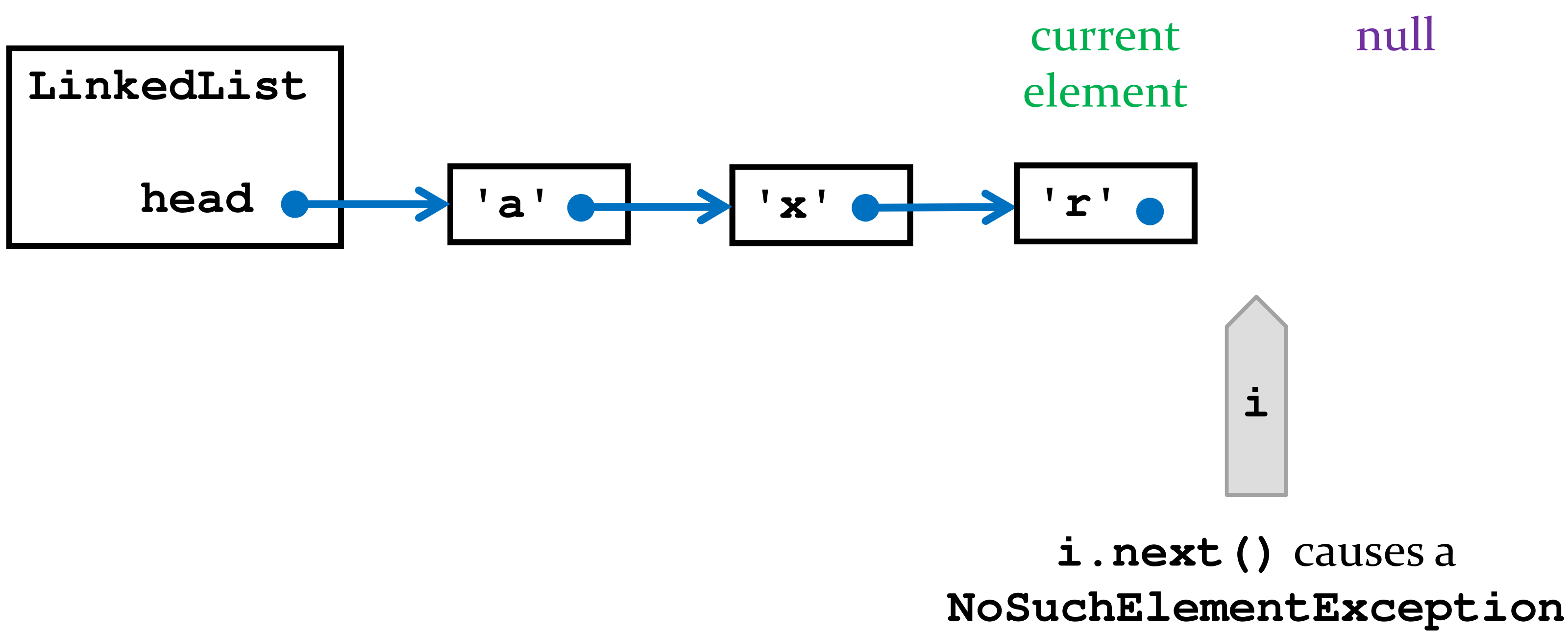
LinkedList Iterator: next

- and causes the iterator to move to its next position in the iteration



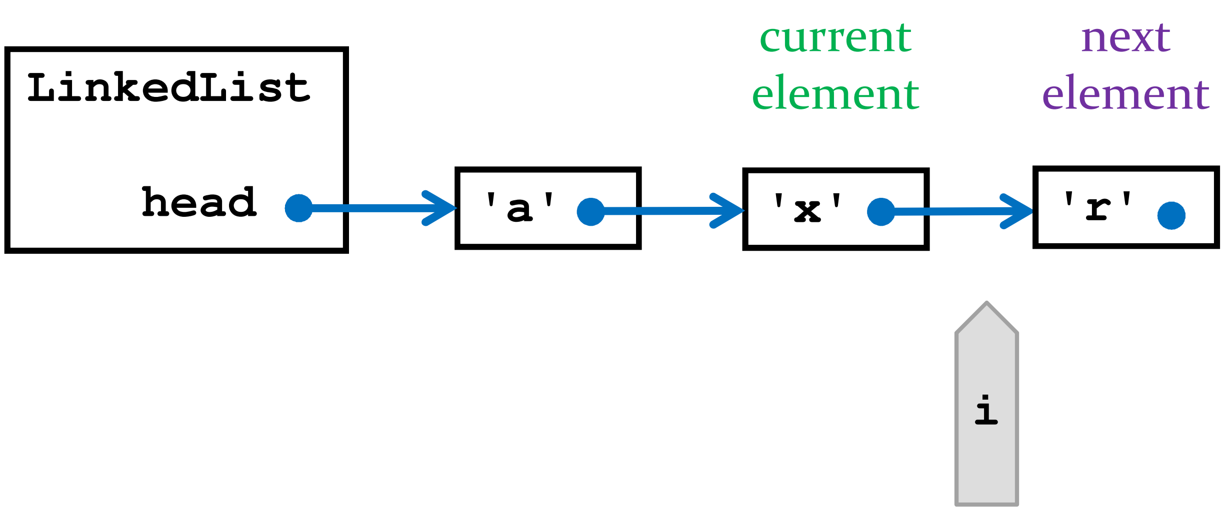
LinkedList Iterator: next

- invoking **`next()`** at the end of the iteration causes a **`NoSuchElementException`** to be thrown



LinkedList Iterator: remove

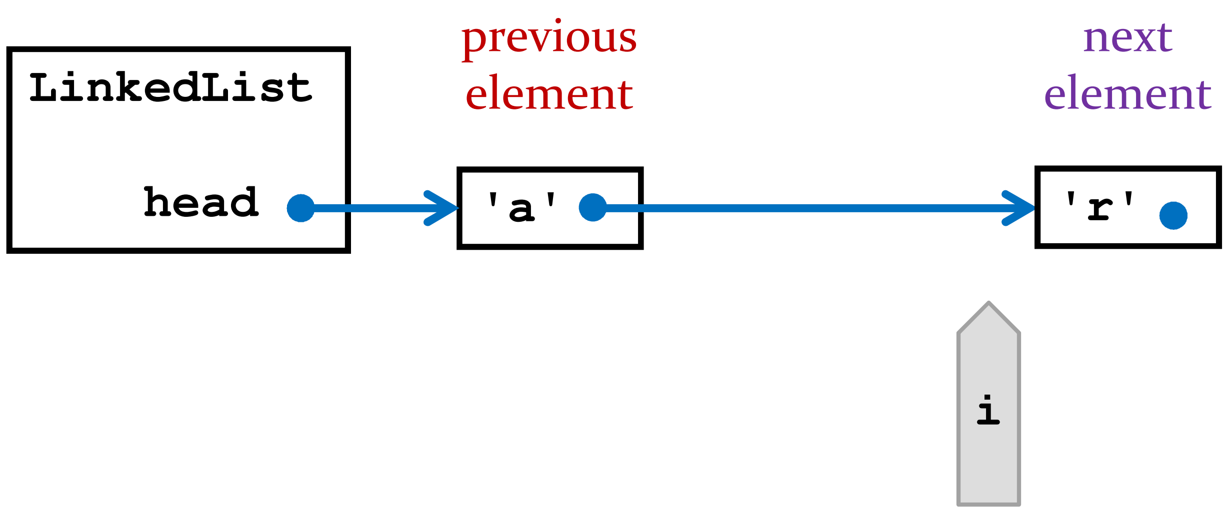
- **`remove()`** causes the element most recently returned by **`next()`** to be removed from the linked list



`i.remove()` causes 'x' to be removed

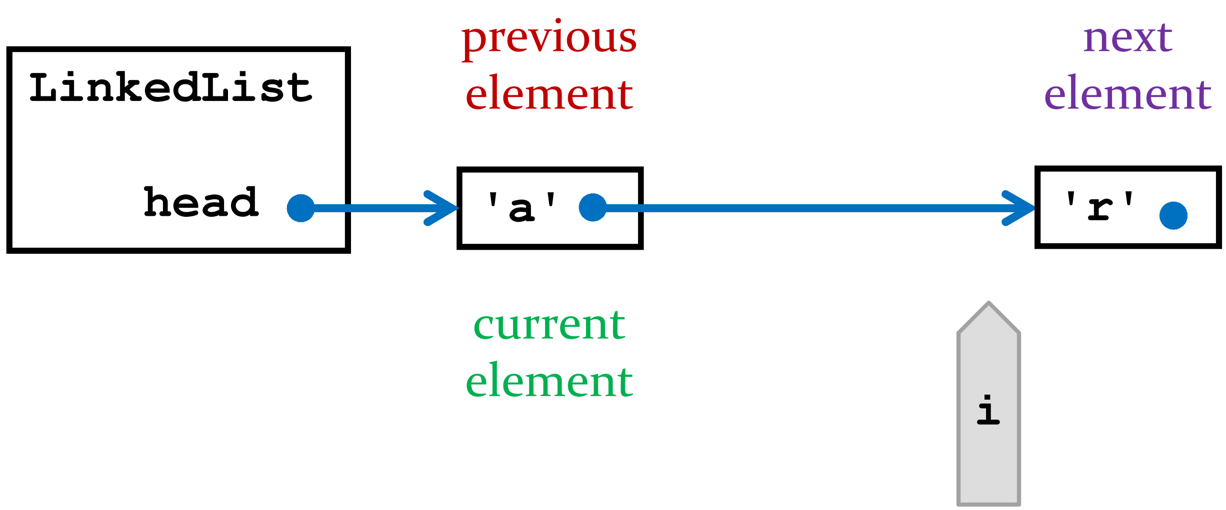
LinkedList Iterator: remove

- notice that the iterator needs to know what was the previous element of the iteration



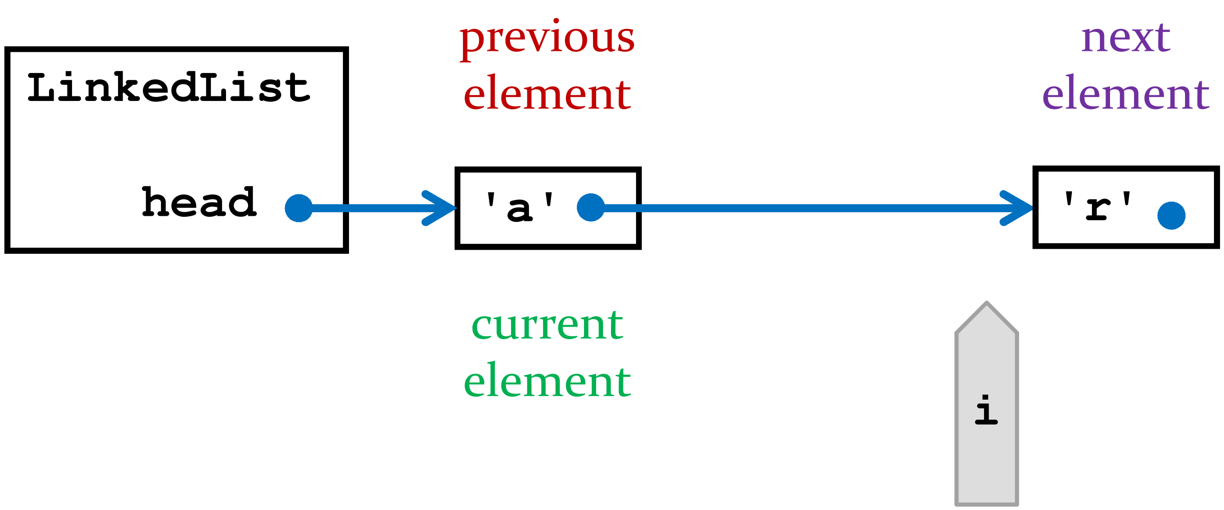
LinkedList Iterator: remove

- after removing the element the current element and previous element are the same



LinkedList Iterator: remove

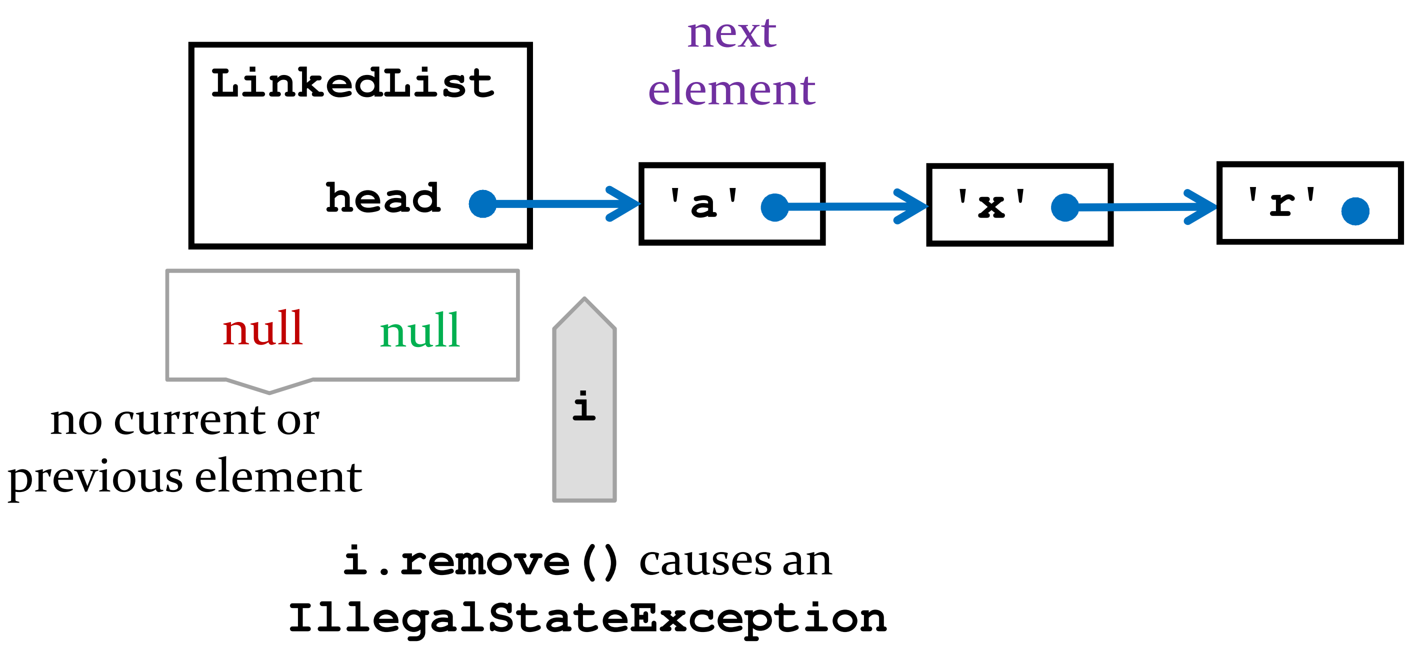
- invoking **`remove()`** a second time causes an **`IllegalStateException`** to be thrown



`i.remove()` causes an **`IllegalStateException`**

LinkedList Iterator: remove

- invoking **`remove()`** before calling **`next()`** also causes and **`IllegalStateException`** to be thrown



LinkedList Iterator: remove

- note that using an iterator and **`remove()`** is the safest way to iterate over a collection and selectively remove elements from the collection
  - called filtering

LinkedList Iterator: remove

```
// removes vowels from our LinkedList t

for (Iterator<Character> i = t.iterator();
     i.hasNext(); ) {
  char c = i.next();
  if (String.valueOf(c).matches("[aeiou]")) {
    System.out.println("removing " + c);
    i.remove();
  }
}
```

Implementation

- **`currNode`**
  - reference to the node most recently returned by **`next()`**
    - this means that **`currNode`** is **`null`** at the start of the iteration
      - requires special treatment in methods
- **`prevNode`**
  - reference to the node previous to **`currNode`**
    - needed for **`remove()`**

Implementation: Attributes and Ctor

```
private class LinkedListIterator implements
  Iterator<Character> {

  private Node currNode;
  private Node prevNode;

  public LinkedListIterator() {
    this.currNode = null;
    this.prevNode = null;
  }
```

Implementation: hasNext

```
@Override
public boolean hasNext() {
  if (this.currNode == null) {
    return head != null;
  }
  return this.currNode.next != null;
}
```

Implementation: next

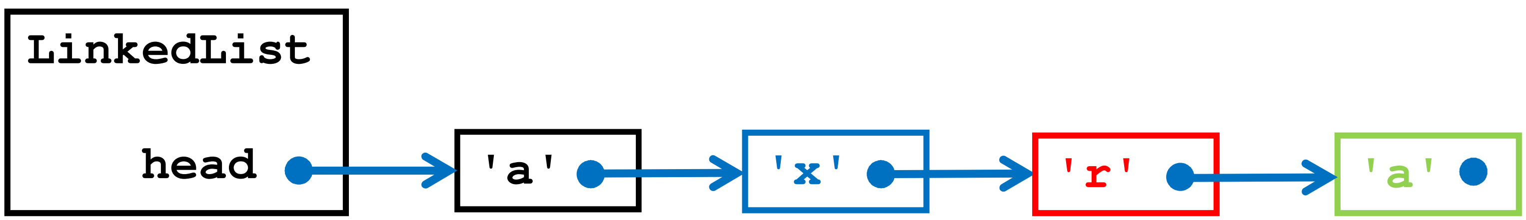
```
@Override
public Character next() {
  if (!this.hasNext()) {
    throw new NoSuchElementException();
  }
  this.prevNode = this.currNode;
  if (this.currNode == null) {
    this.currNode = head;
  }
  else {
    this.currNode = this.currNode.next;
  }
  return this.currNode.data;
}
```

Implementation: remove

```
@Override
public void remove() {
  if (this.prevNode == this.currNode) {
    throw new IllegalStateException();
  }
  if (this.currNode == head) {
    head = this.currNode.next;
  }
  else {
    this.prevNode.next = this.currNode.next;
  }
  this.currNode = this.prevNode;
  size--;
}
```

LinkedList Summary

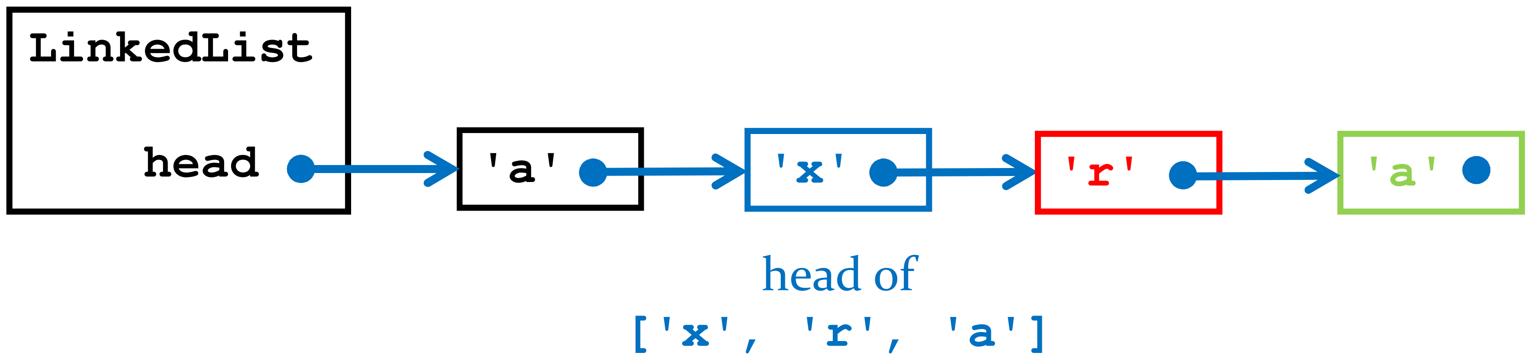
- each node can be thought of as the head of a smaller list



head of
`['a', 'x', 'r', 'a']`

LinkedList Summary

- each node can be thought of as the head of a smaller list



LinkedList Summary

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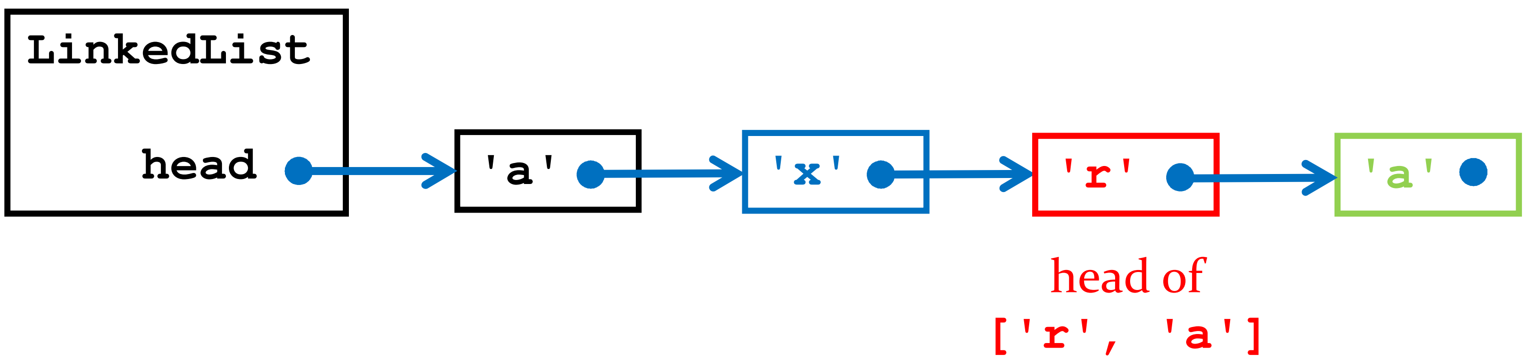
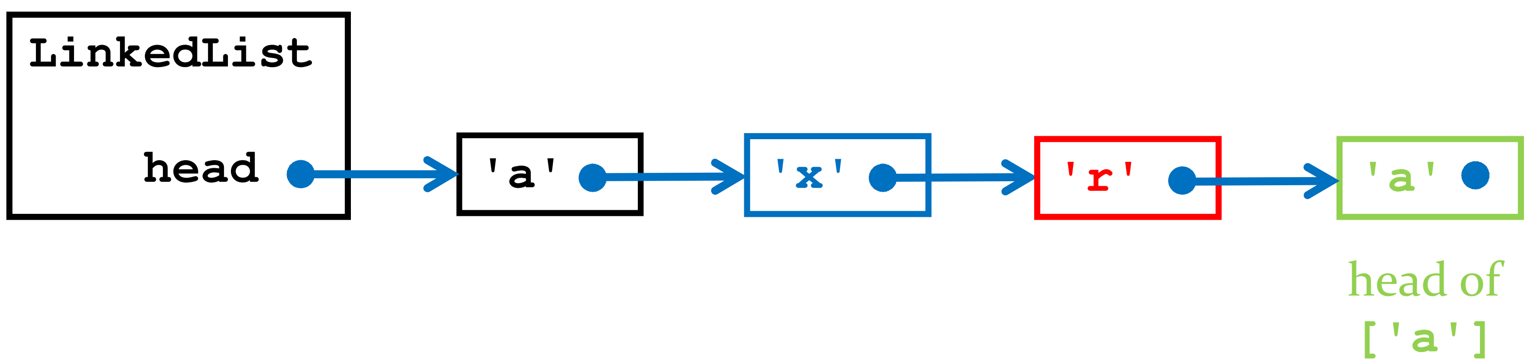


LinkedList Summary

- each node can be thought of as the head of a smaller list



LinkedList Summary

- the recursive structure of the linked list leads to recursive algorithms that operate on the list

```
private static boolean contains(char c, Node node) {
  if (node.data == c) {
    return true;
  }
  if (node.next == null) {
    return false;
  }
  return LinkedList.contains(c, node.next);
}
```

LinkedList Summary

- nodes are an implementation detail
  - the client only cares about the elements (characters) in the list
- **`Node`** is implemented as a private static inner class
  - private so that only **`LinkedList`** can use it
  - static because **`Node`** does not need access to any non-static attribute of **`LinkedList`**

LinkedList Summary

- by implementing the **`Iterable`** interface we give clients the ability to iterate over the elements of the list
- clients expect to be able to do this for most collections

```
// for some LinkedList t

for (Character c : t) {
  // do something with c
}
```

LinkedList Summary

- to implement **`Iterable`** we need to provide an iterator object that can iterate over the elements in the list

`public interface Iterator<E>`

An iterator over a collection.

`boolean`	**`hasNext()`** Returns true if the iteration has more elements.
E	**`next()`** Returns the next element in the iteration.
`void`	**`remove()`** Removes from the underlying collection the last element returned by this iterator (optional operation).