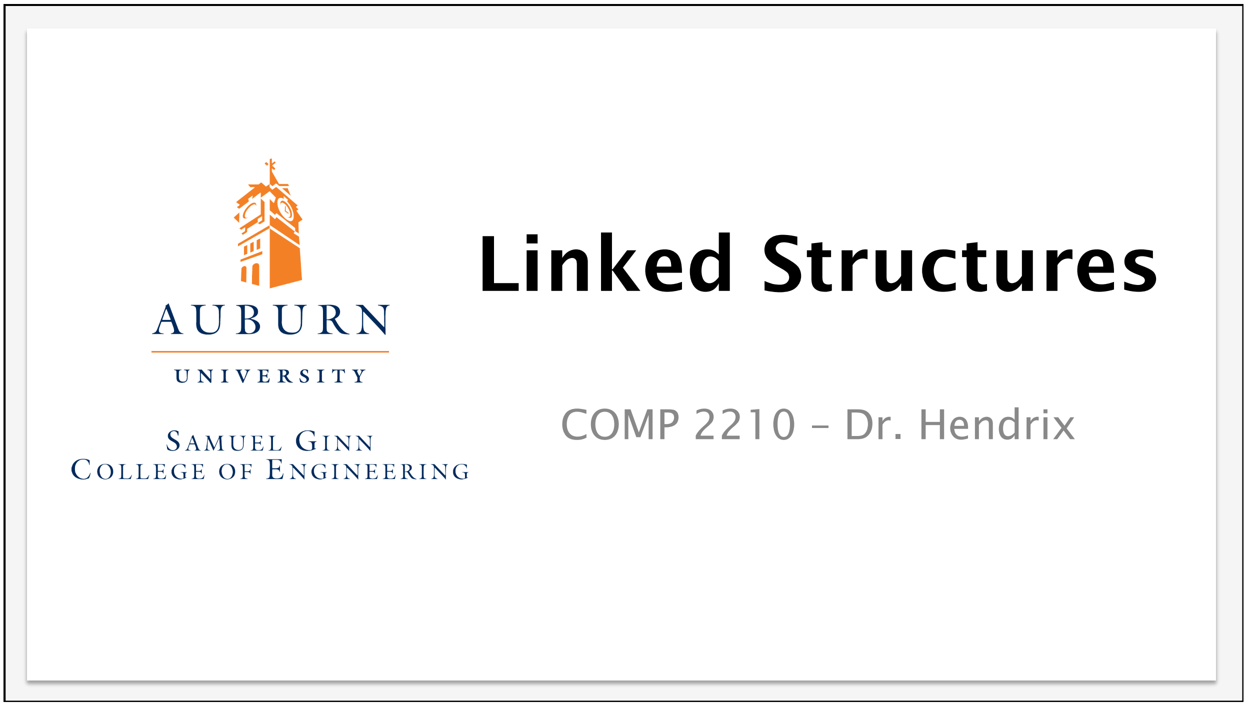

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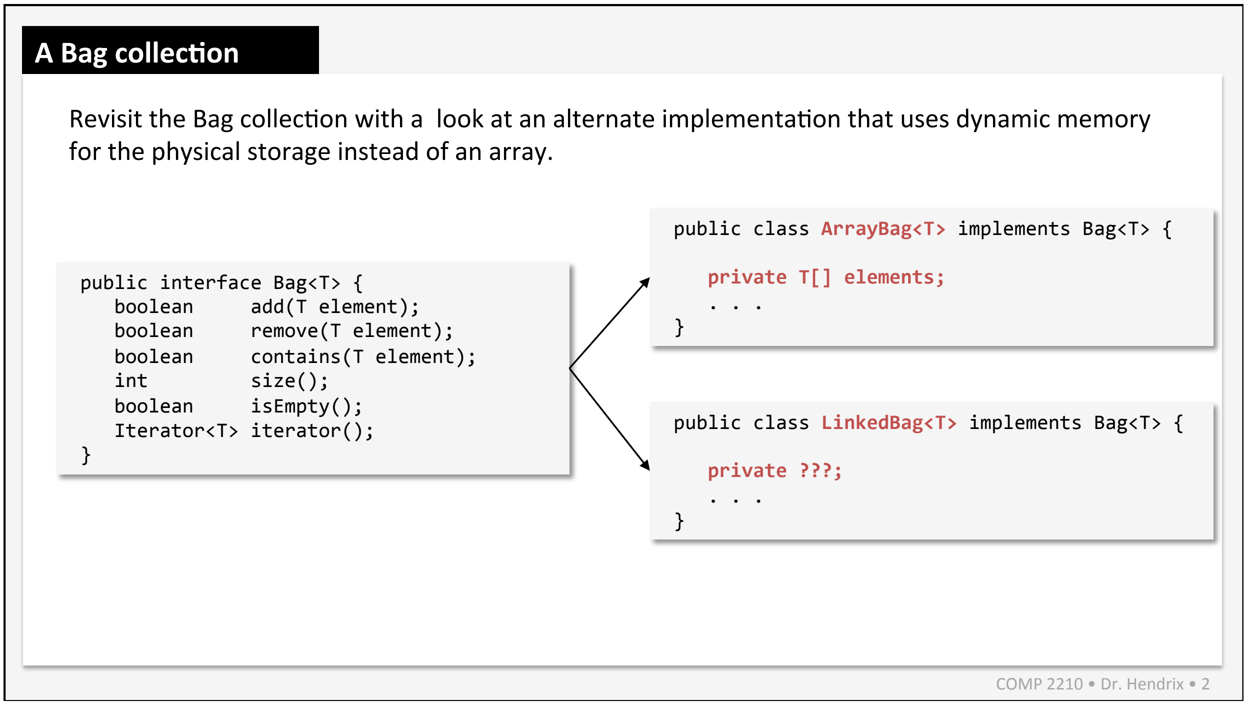
SAMUEL GINN
COLLEGE OF ENGINEERING

Linked Structures

COMP 2210 – Dr. Hendrix



A Bag collection

Revisit the Bag collection with a look at an alternate implementation that uses dynamic memory for the physical storage instead of an array.

```
public interface Bag<T> {
   boolean     add(T element);
   boolean     remove(T element);
   boolean     contains(T element);
   int         size();
   boolean     isEmpty();
   Iterator<T> iterator();
}
```

```
public class ArrayBag<T> implements Bag<T> {

   private T[] elements;
      . . .
}
```

```
public class LinkedBag<T> implements Bag<T> {

   private ???;
      . . .
}
```

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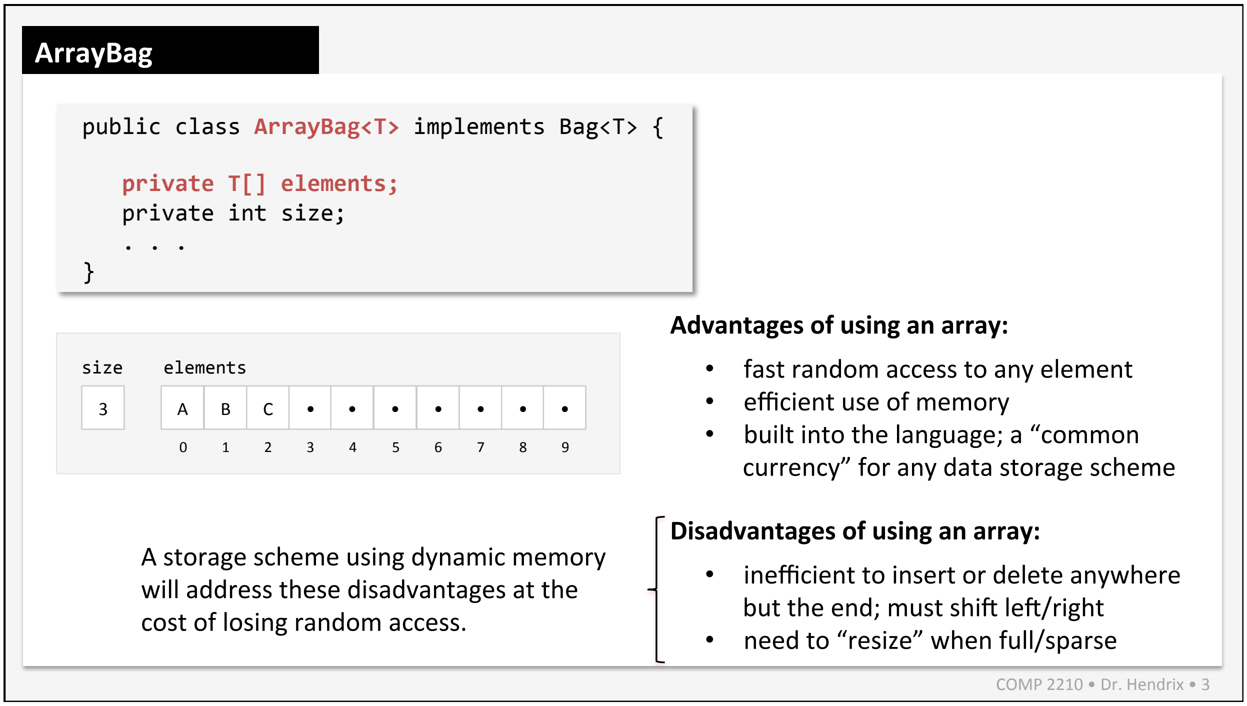


ArrayBag

```
public class ArrayBag<T> implements Bag<T> {

   private T[] elements;
   private int size;
   . . .
}
```

size

3

elements

A	B	C	•	•	•	•	•	•	•
0	1	2	3	4	5	6	7	8	9

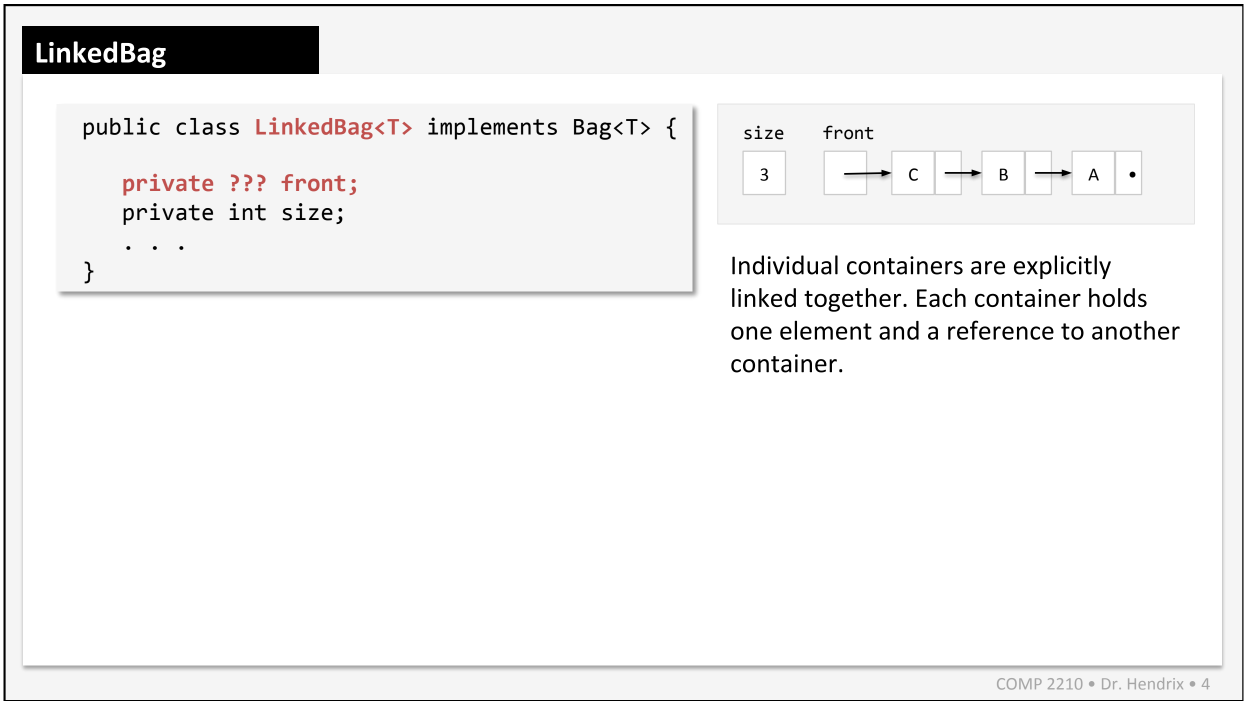
Advantages of using an array:

- fast random access to any element
- efficient use of memory
- built into the language; a “common currency” for any data storage scheme

Disadvantages of using an array:

- inefficient to insert or delete anywhere but the end; must shift left/right
- need to “resize” when full/sparse

A storage scheme using dynamic memory will address these disadvantages at the cost of losing random access.

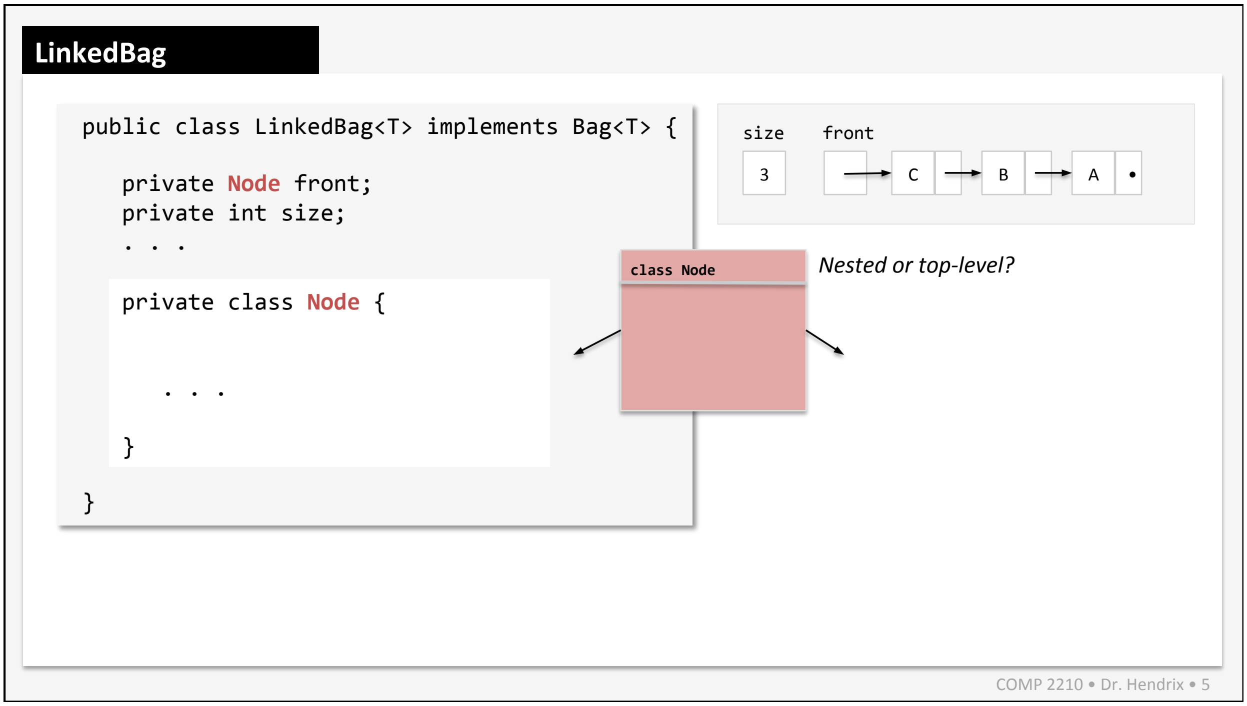


LinkedBag

```
public class LinkedBag<T> implements Bag<T> {

   private ??? front;
   private int size;
   . . .
}
```

size
3
front
C
B
A
•

Individual containers are explicitly linked together. Each container holds one element and a reference to another container.

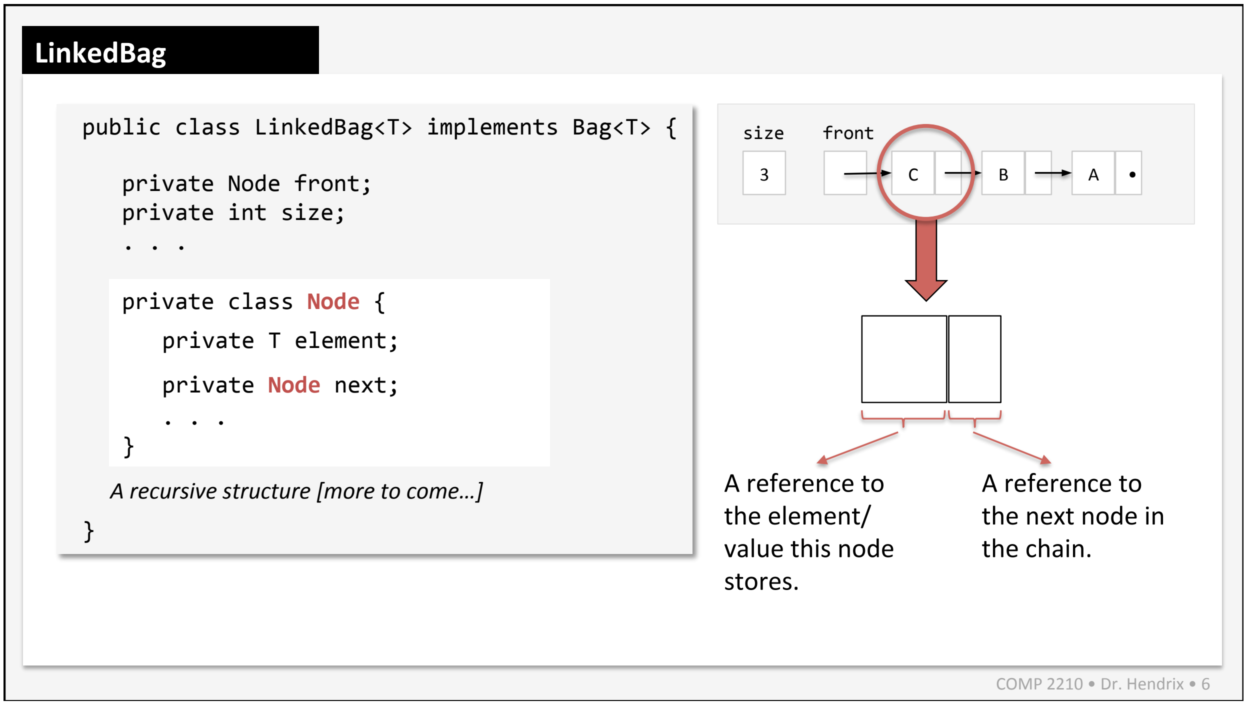


LinkedBag

```
public class LinkedBag<T> implements Bag<T> {

   private Node front;
   private int size;
   . . .

   private class Node {


      . . .

   }

}
```

size
front
3
C
B
A
•
class Node

Nested or top-level?



LinkedBag

```
public class LinkedBag<T> implements Bag<T> {

   private Node front;
   private int size;
   . . .

   private class Node {
      private T element;
      private Node next;
      . . .
   }
```

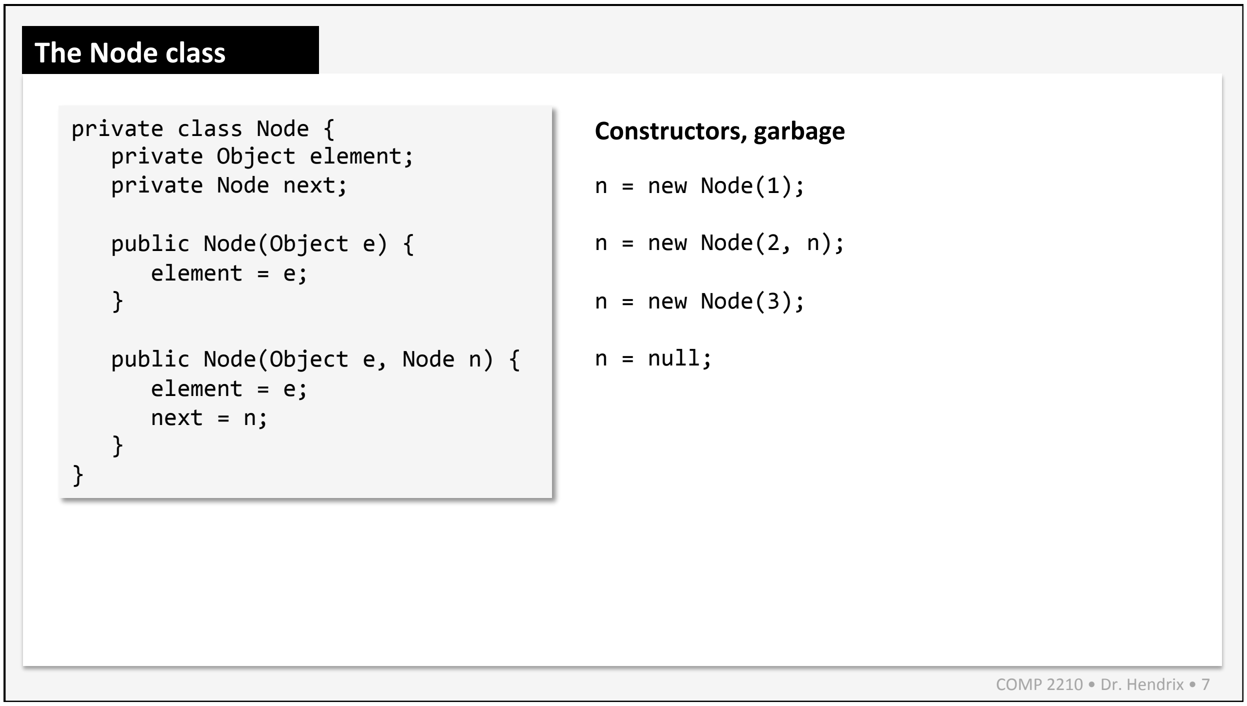
A recursive structure [more to come…]

```
}
```

size
front
3
C
B
A
•

A reference to the element/ value this node stores.

A reference to the next node in the chain.

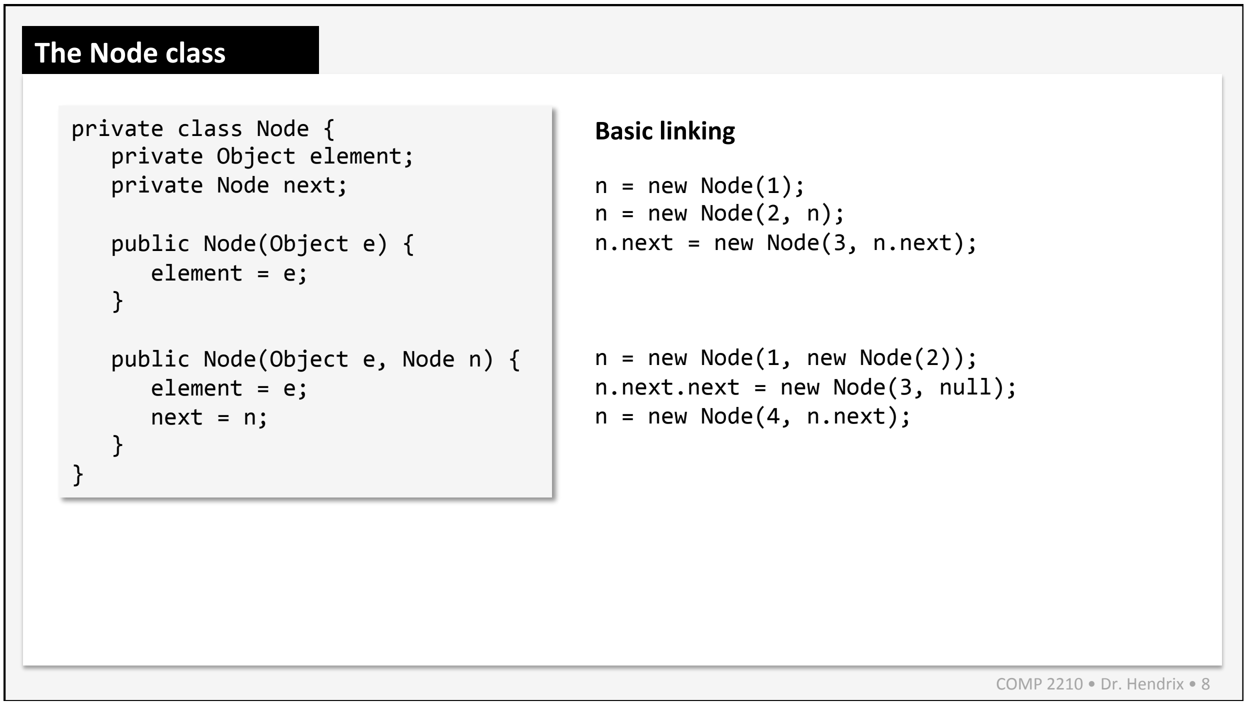


The Node class

```
private class Node {
   private Object element;
   private Node next;

   public Node(Object e) {
      element = e;
   }

   public Node(Object e, Node n) {
      element = e;
      next = n;
   }
}
```

Constructors, garbage

```
n = new Node(1);

n = new Node(2, n);

n = new Node(3);

n = null;
```



The Node class

```
private class Node {
   private Object element;
   private Node next;

   public Node(Object e) {
      element = e;
   }

   public Node(Object e, Node n) {
      element = e;
      next = n;
   }
}
```

Basic linking

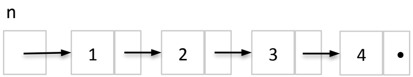
```
n = new Node(1);
n = new Node(2, n);
n.next = new Node(3, n.next);



n = new Node(1, new Node(2));
n.next.next = new Node(3, null);
n = new Node(4, n.next);
```

Participation

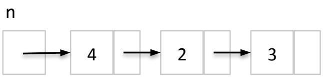
Q: Which chain of nodes is created by the following code?

```
n = new Node(1);

n.next = new Node(2, new Node(3));

n = new Node(4, n.next.next);
```

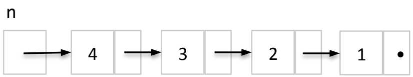
A.



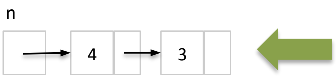
C.



B.

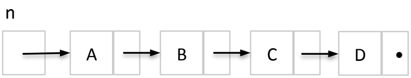


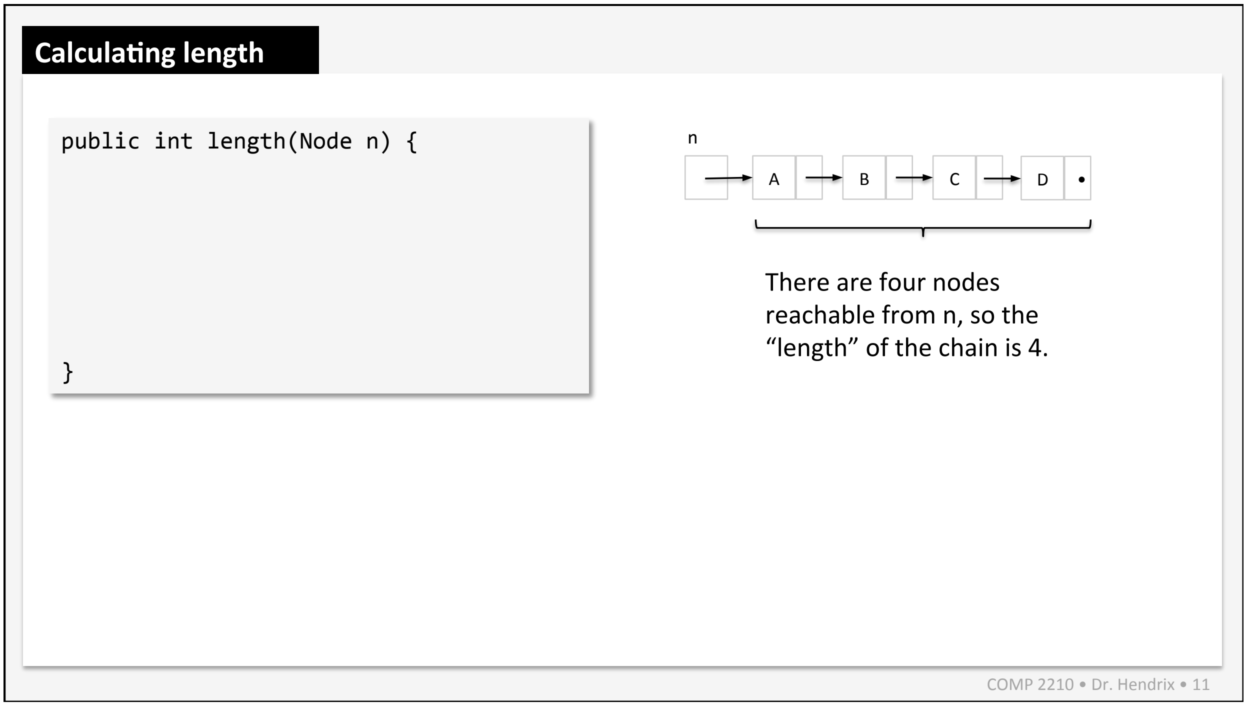
D.



Calculating length

```
public int length(Node n) {





}
```

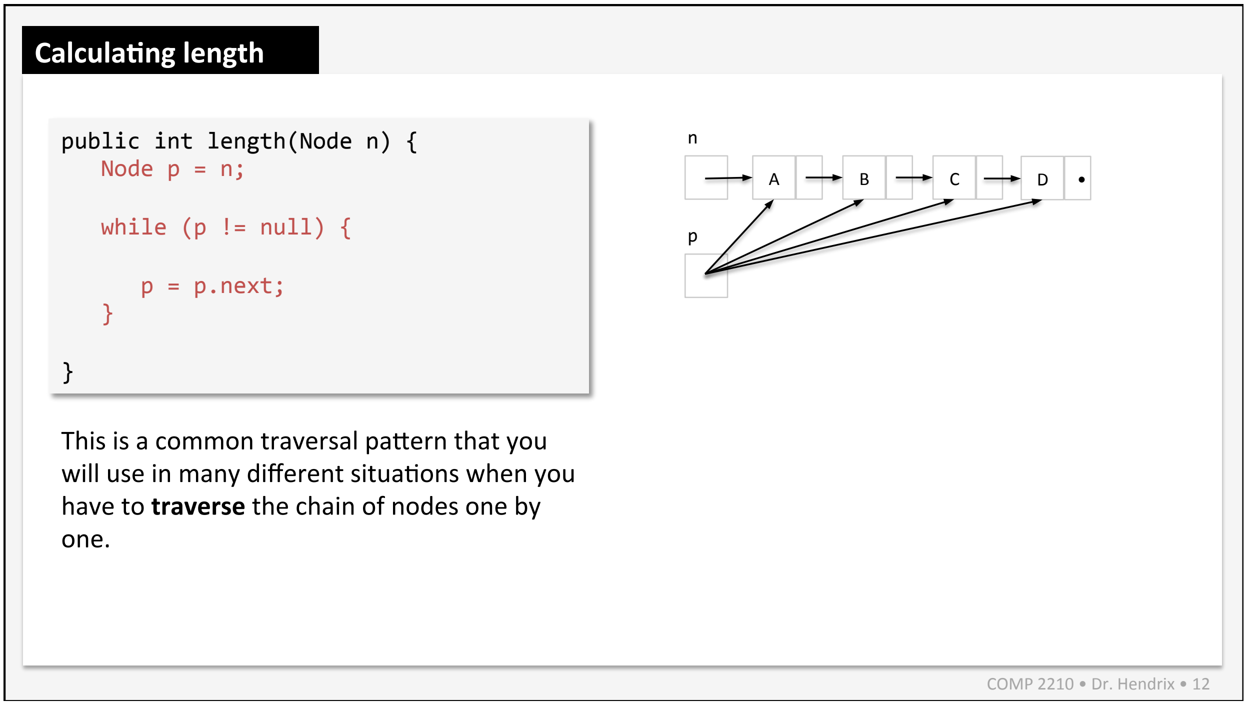




Calculating length

```
public int length(Node n) {






}
```

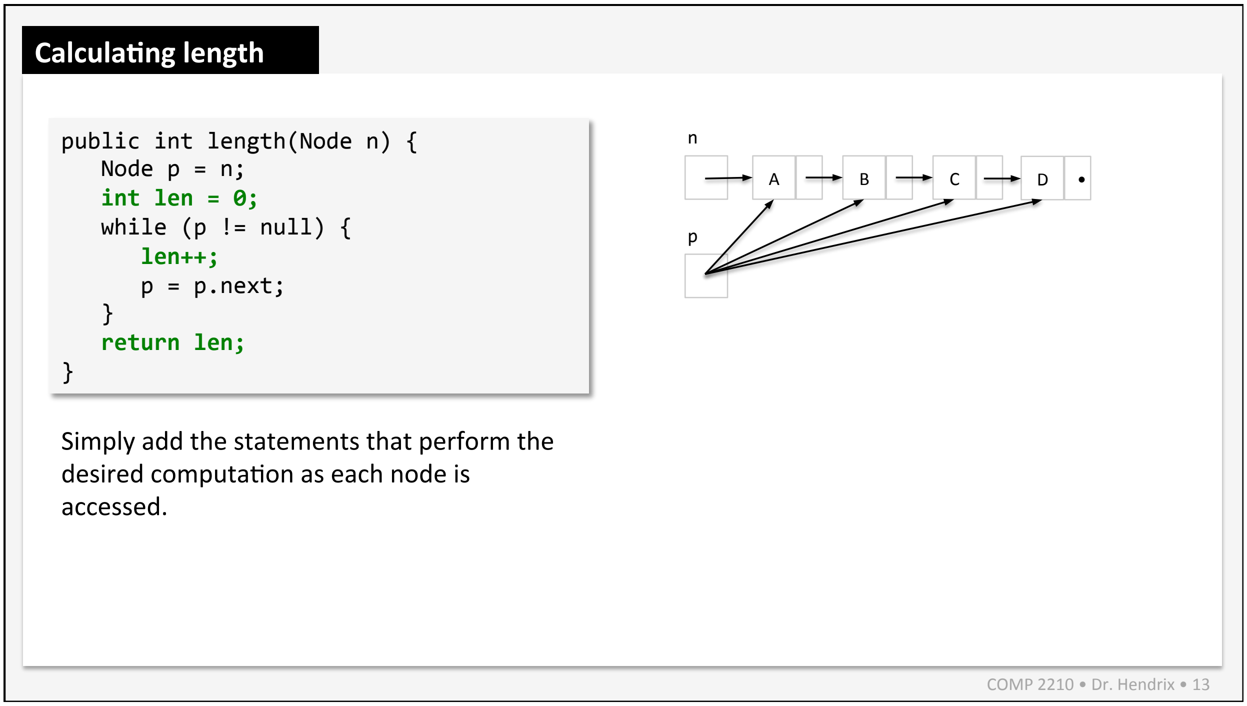
There are four nodes reachable from n, so the “length” of the chain is 4.



Calculating length

```
public int length(Node n) {
   Node p = n;

   while (p != null) {

      p = p.next;
   }

}
```

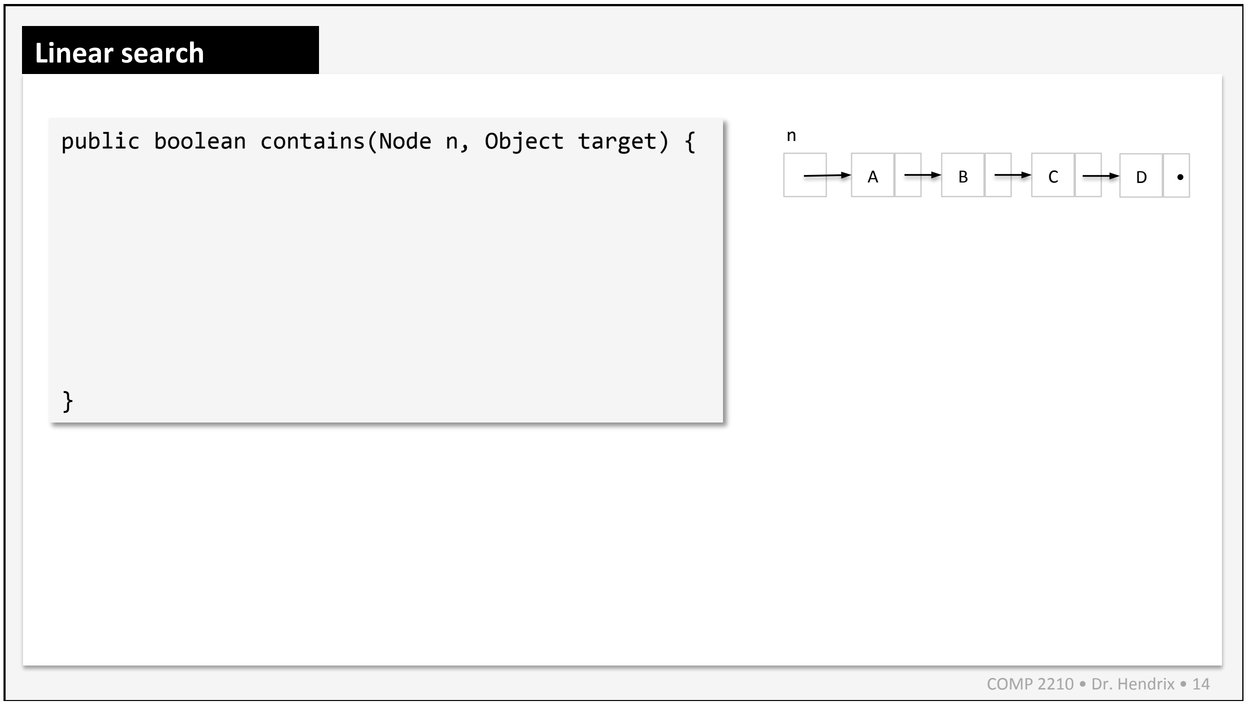
This is a common traversal pattern that you will use in many different situations when you have to **traverse** the chain of nodes one by one.



Calculating length

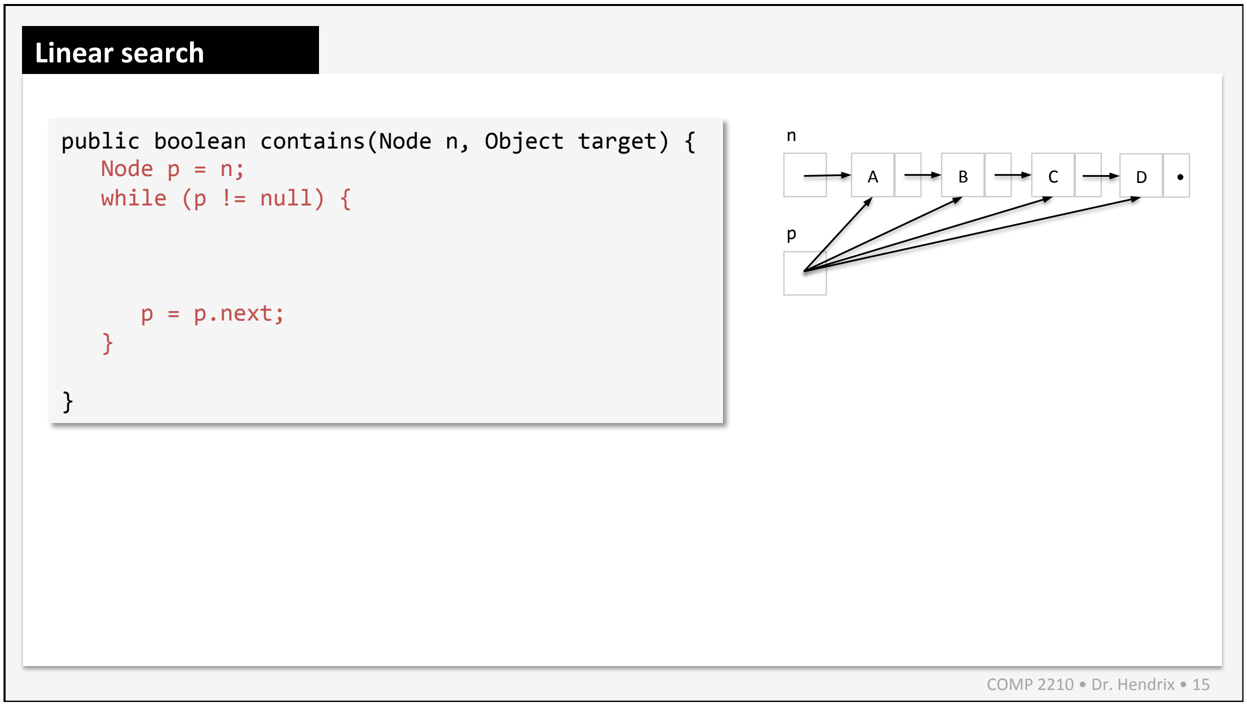
```
public int length(Node n) {
   Node p = n;
   int len = 0;
   while (p != null) {
      len++;
      p = p.next;
   }
   return len;
}
```

Simply add the statements that perform the desired computation as each node is accessed.



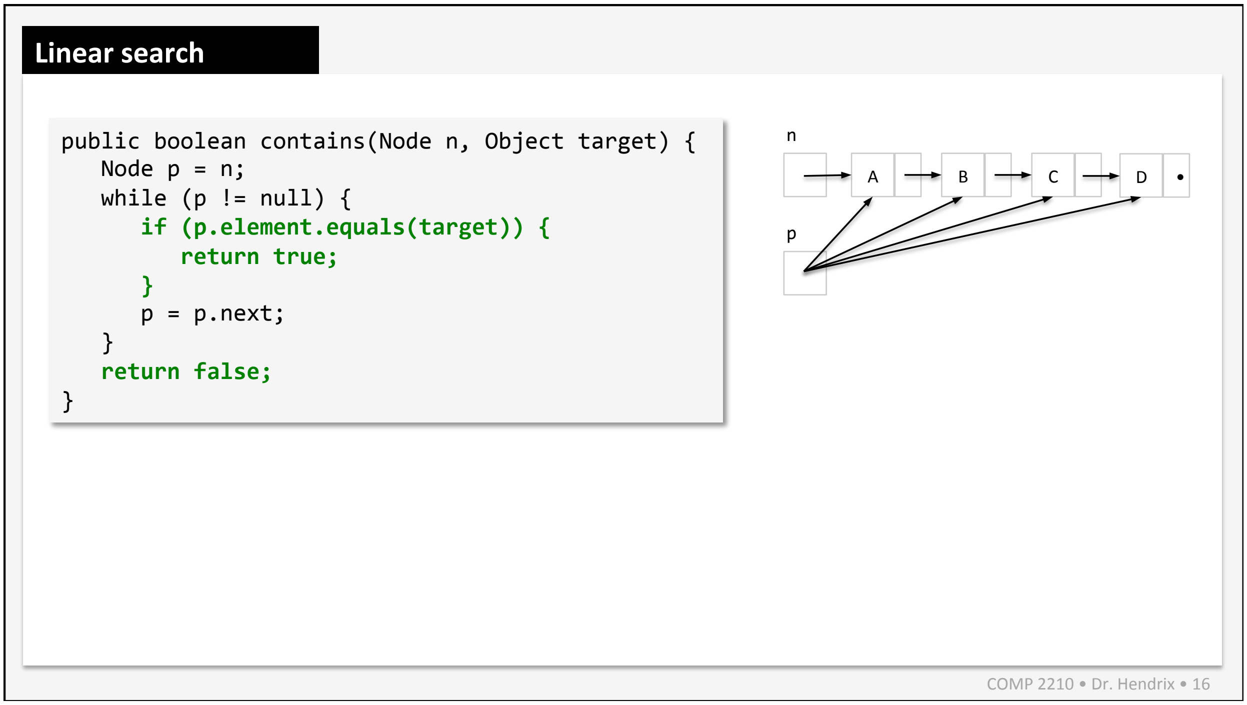
Linear search

```
public boolean contains(Node n, Object target) {










}
```



Linear search

```
public boolean contains(Node n, Object target) {
   Node p = n;
   while (p != null) {



      p = p.next;
   }

}
```

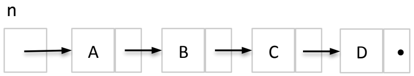


Linear search

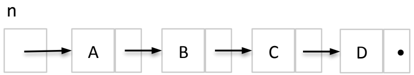
```
public boolean contains(Node n, Object target) {
   Node p = n;
   while (p != null) {
      if (p.element.equals(target)) {
         return true;
      }
      p = p.next;
   }
   return false;
}
```

Inserting nodes

Inserting a new first node

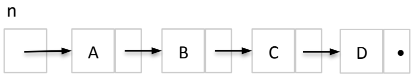


Inserting anywhere else

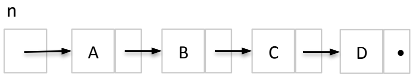


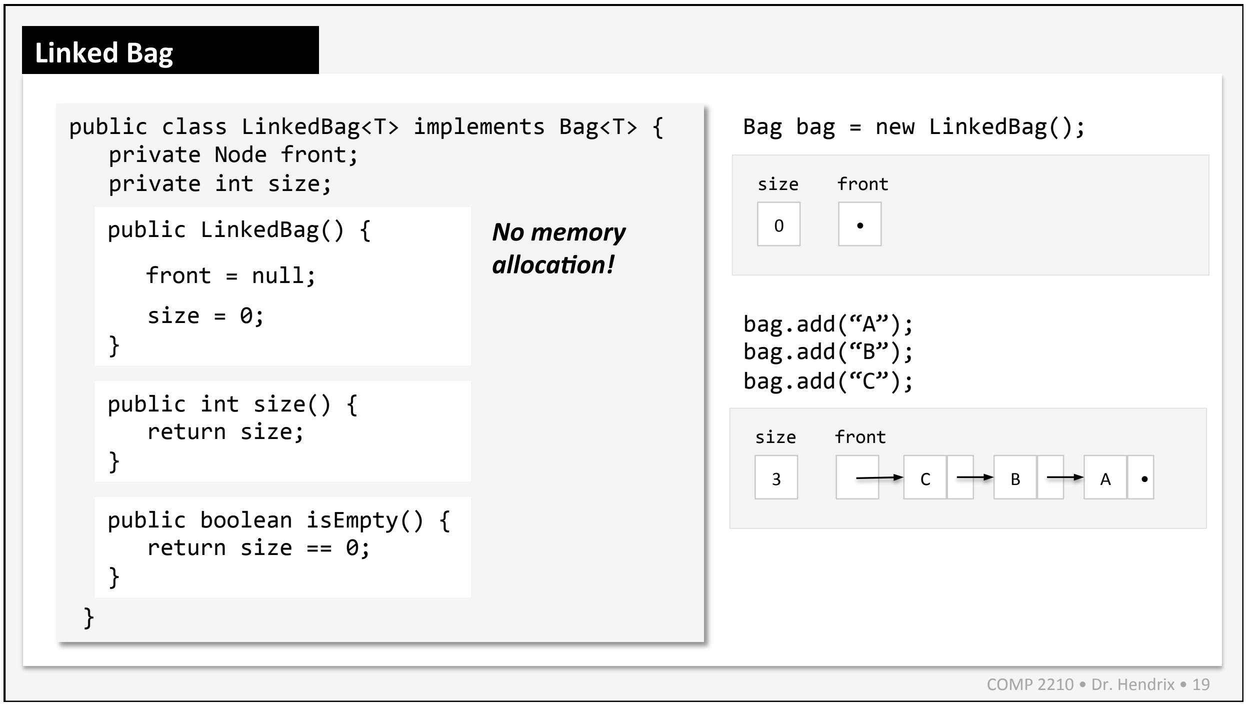
Deleting nodes

Deleting the first node



Deleting any other node





Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public LinkedBag() {
      front = null;
      size = 0;
   }

   public int size() {
      return size;
   }

   public boolean isEmpty() {
      return size == 0;
   }
 }
```

No memory allocation!

```
Bag bag = new LinkedBag();
```

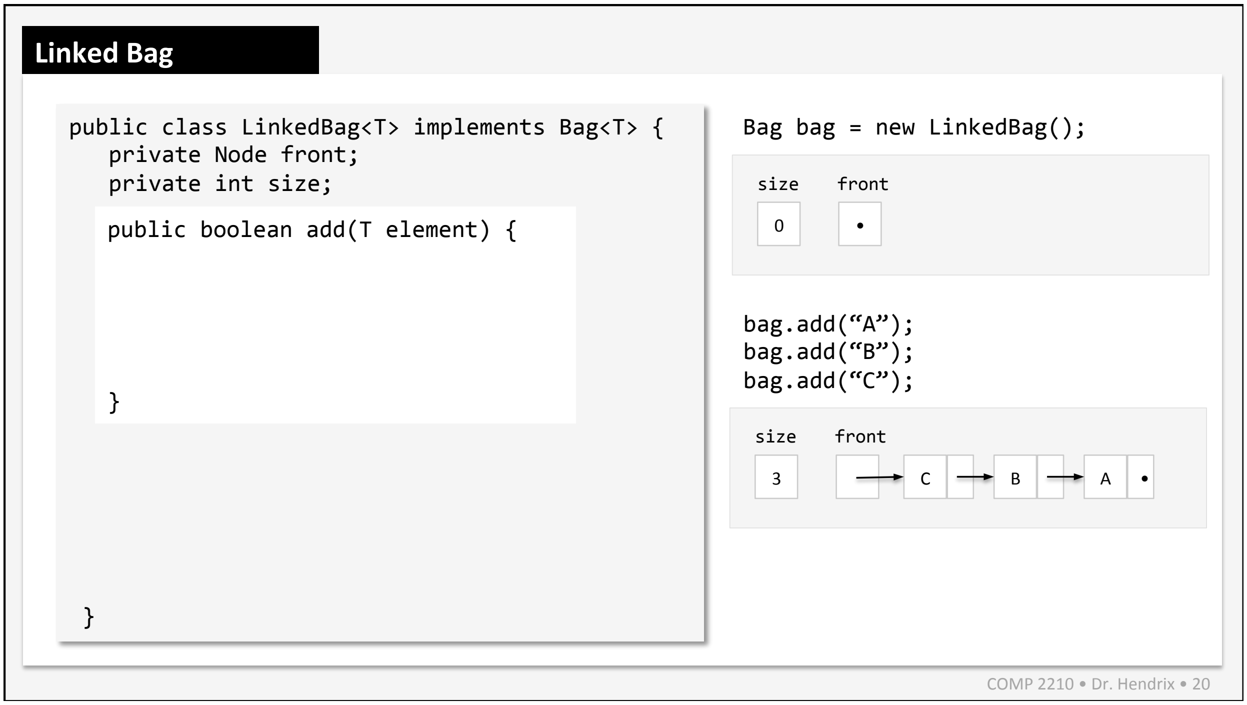
size 0

front •

```
bag.add("A");
bag.add("B");
bag.add("C");
```

size 3

front → C → B → A •



Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean add(T element) {




   }




 }
```

```
Bag bag = new LinkedBag();
```

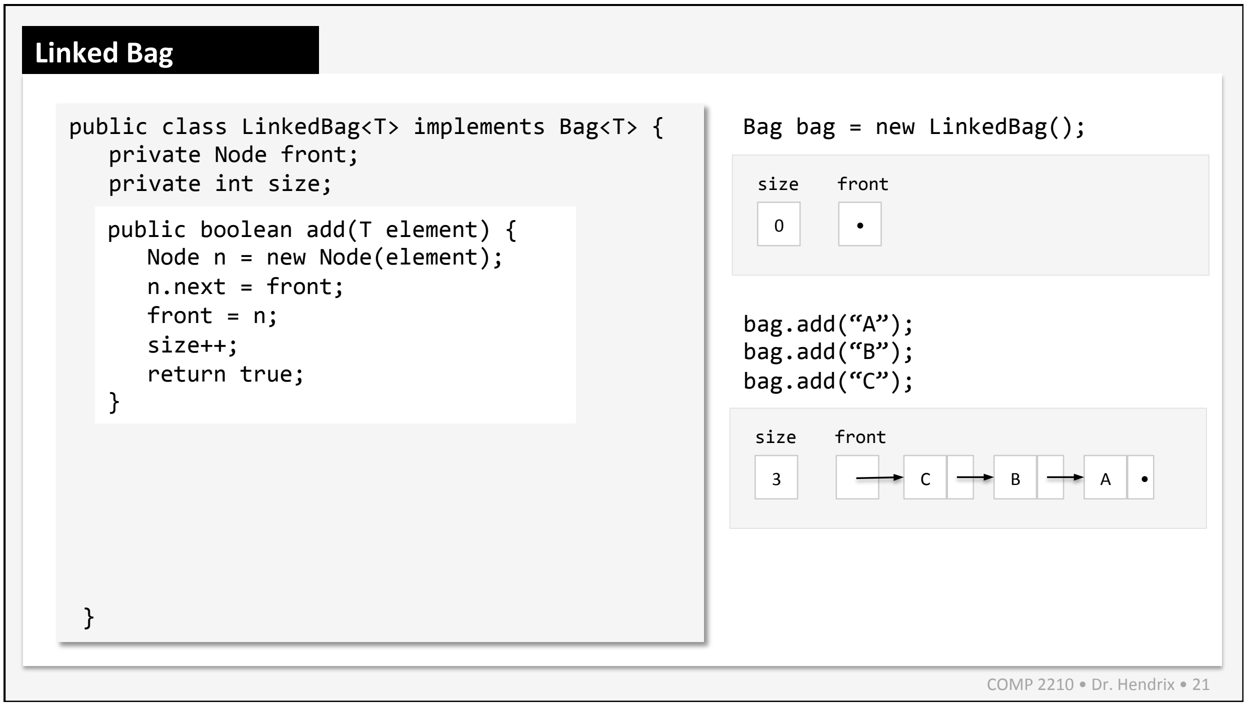
size 0

front •

```
bag.add("A");
bag.add("B");
bag.add("C");
```

size 3

front → C → B → A •



Linked Bag

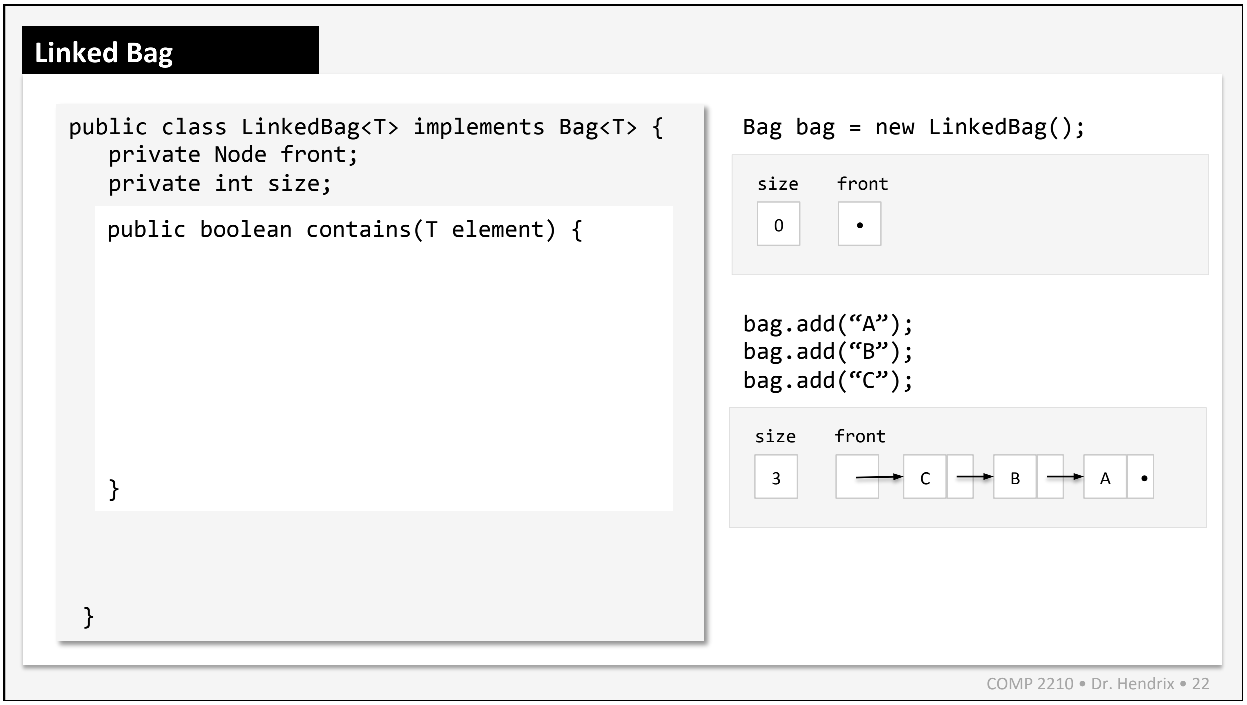
```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean add(T element) {
      Node n = new Node(element);
      n.next = front;
      front = n;
      size++;
      return true;
   }

}
```

```
Bag bag = new LinkedBag();
```

size 0 front •

```
bag.add("A");
bag.add("B");
bag.add("C");
```

size 3 front → C → B → A •



Linked Bag

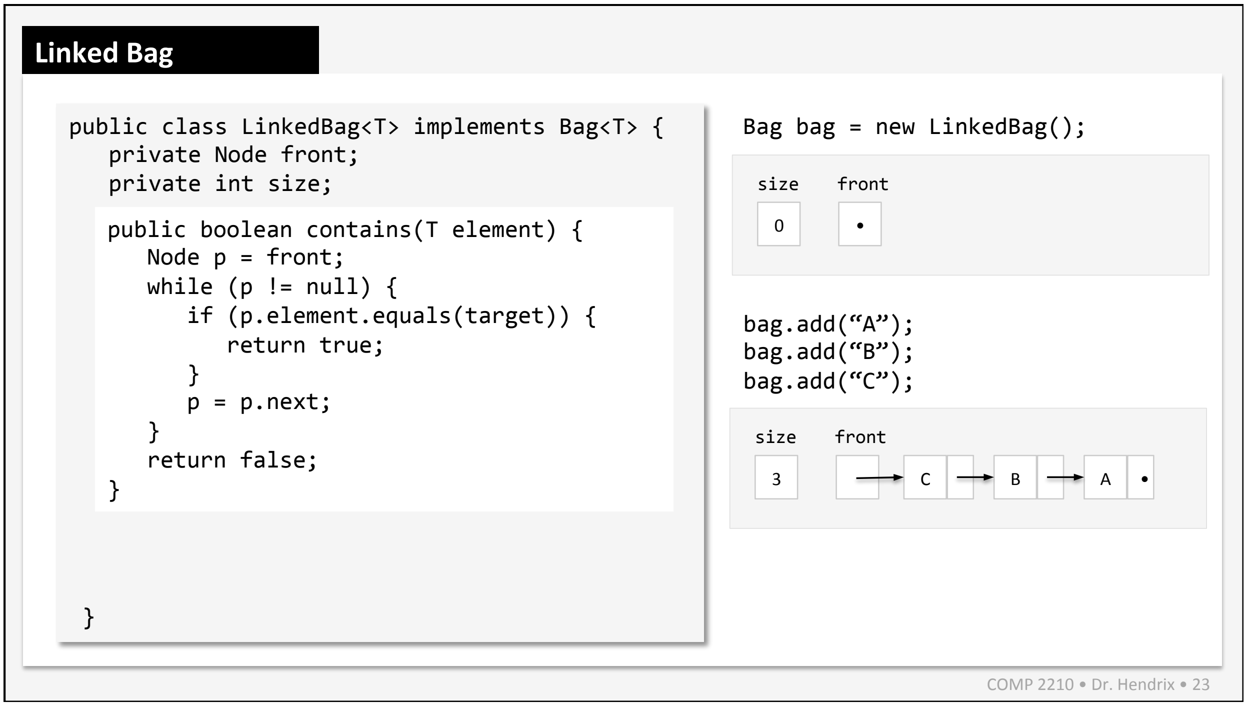
```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean contains(T element) {








   }


}
```

```
Bag bag = new LinkedBag();
```

size 0 front •

```
bag.add("A");
bag.add("B");
bag.add("C");
```

size 3 front → C → B → A •



Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean contains(T element) {
      Node p = front;
      while (p != null) {
         if (p.element.equals(target)) {
            return true;
         }
         p = p.next;
      }
      return false;
   }

}
```

```
Bag bag = new LinkedBag();
```

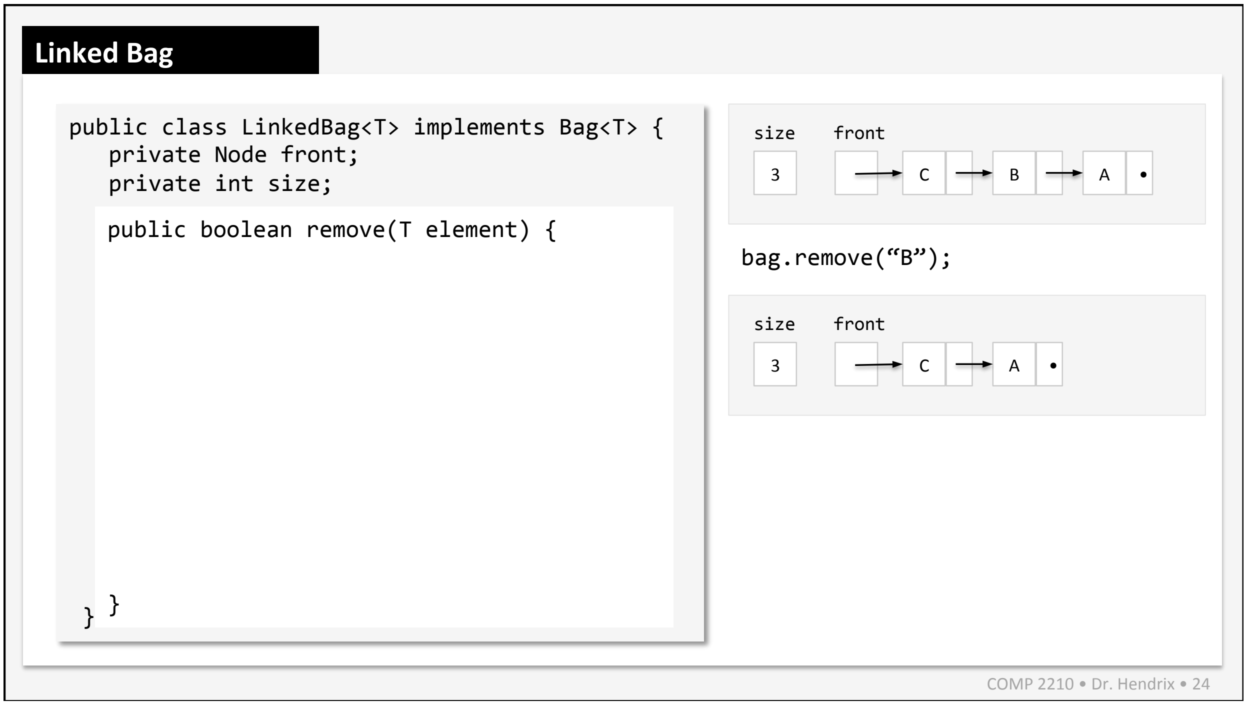
size front

0 •

```
bag.add("A");
bag.add("B");
bag.add("C");
```

size front

3 → C → B → A •



Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean remove(T element) {






   }
}
```

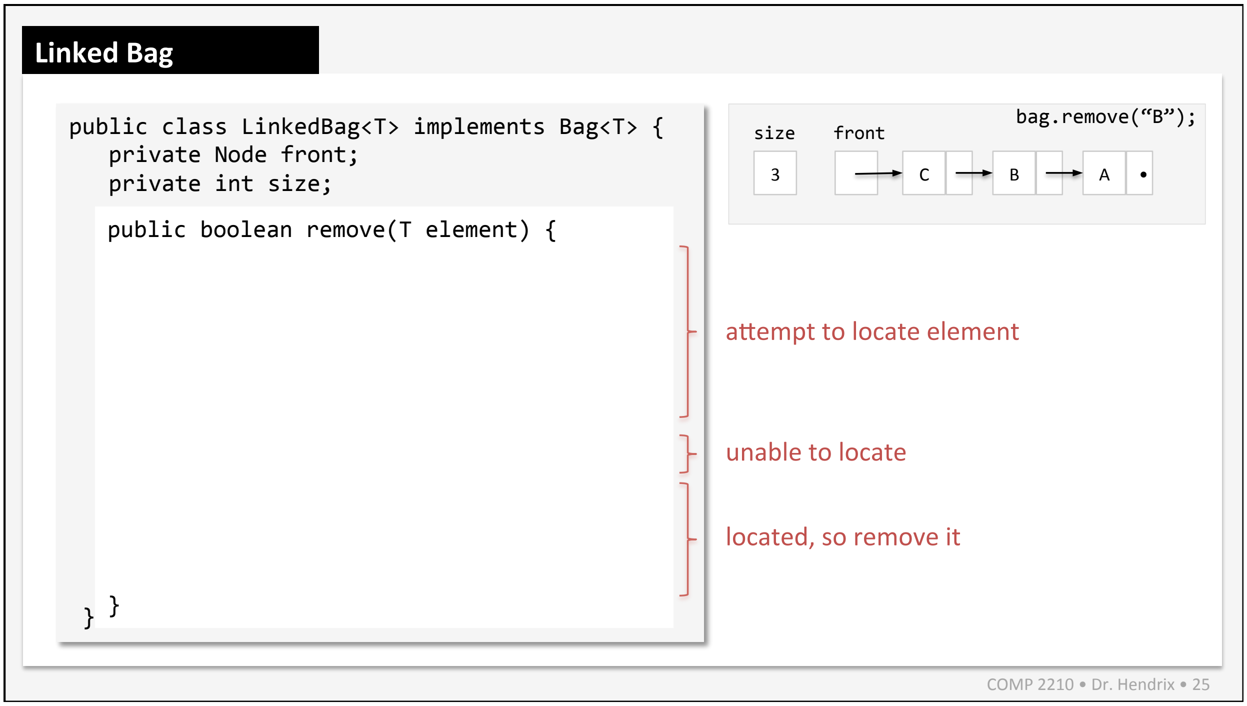
size front

3 → C → B → A •

```
bag.remove("B");
```

size front

3 → C → A •



Linked Bag

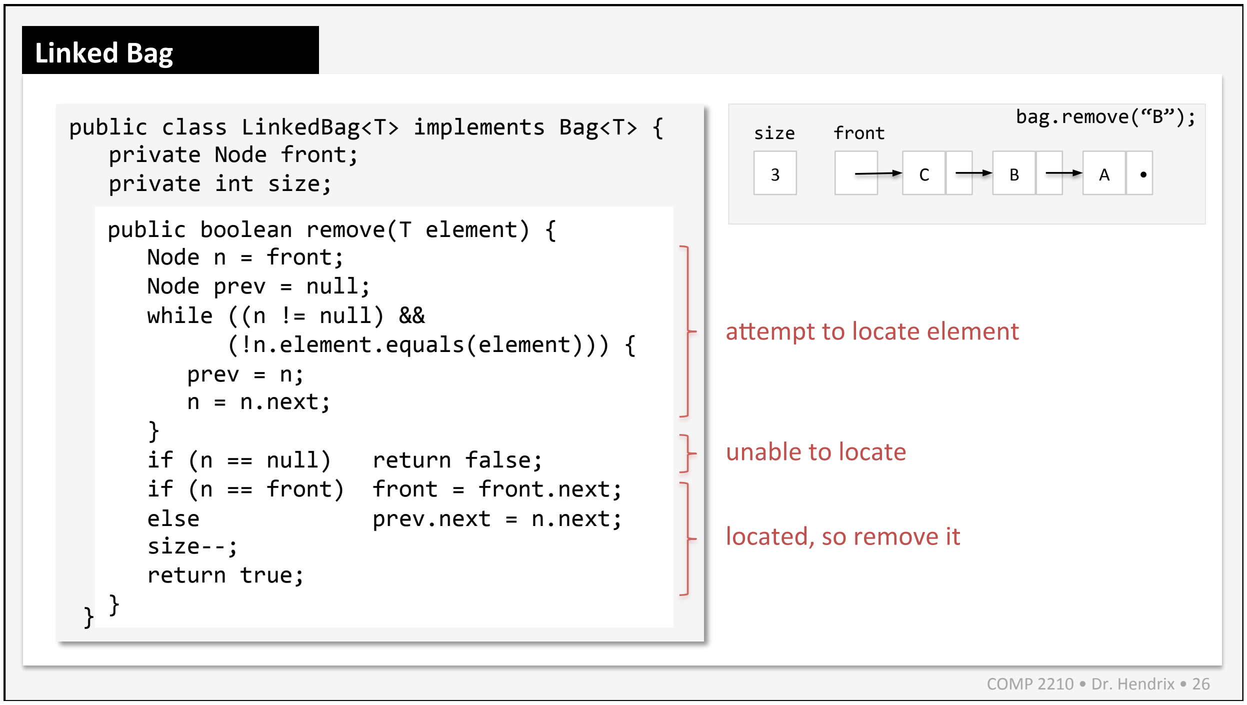
```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean remove(T element) {









   }
 }
```

bag.remove(“B”);
size
front
3
C
B
A

attempt to locate element

unable to locate

located, so remove it



Linked Bag

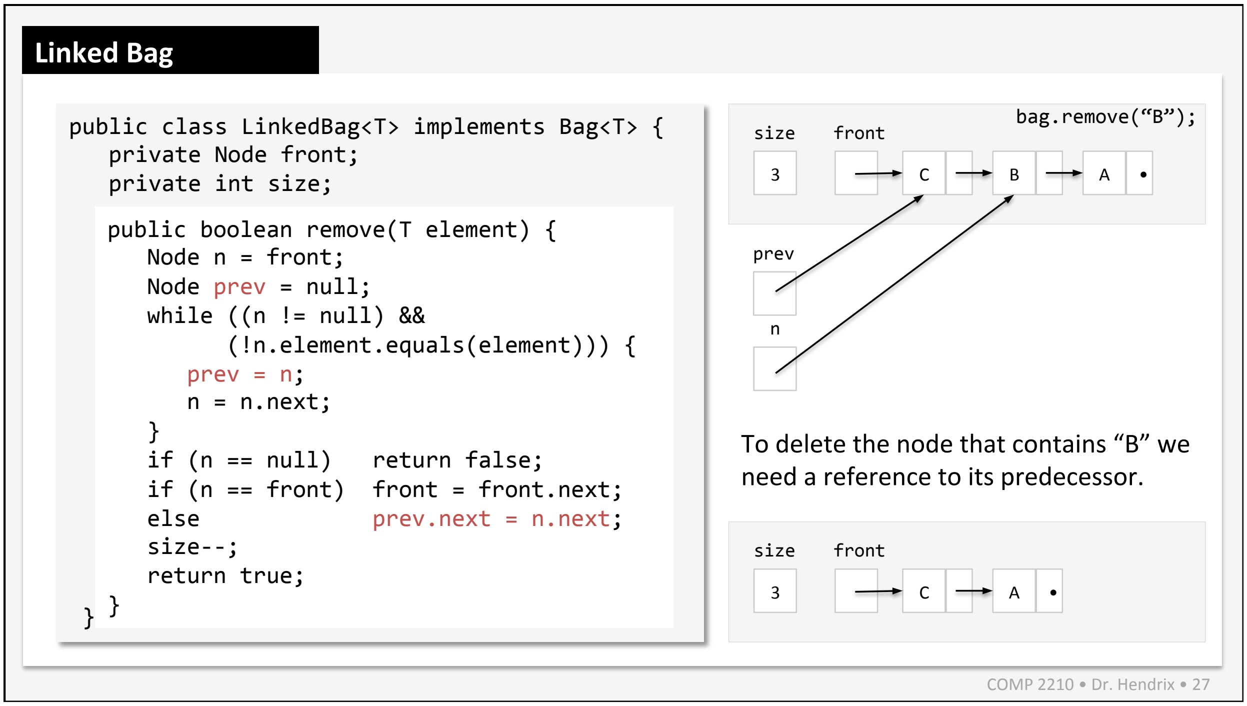
```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean remove(T element) {
      Node n = front;
      Node prev = null;
      while ((n != null) &&
            (!n.element.equals(element))) {
         prev = n;
         n = n.next;
      }
      if (n == null)   return false;
      if (n == front)  front = front.next;
      else             prev.next = n.next;
      size--;
      return true;
   }
 }
```

bag.remove(“B”);
size
front
3
C
B
A

attempt to locate element

unable to locate

located, so remove it



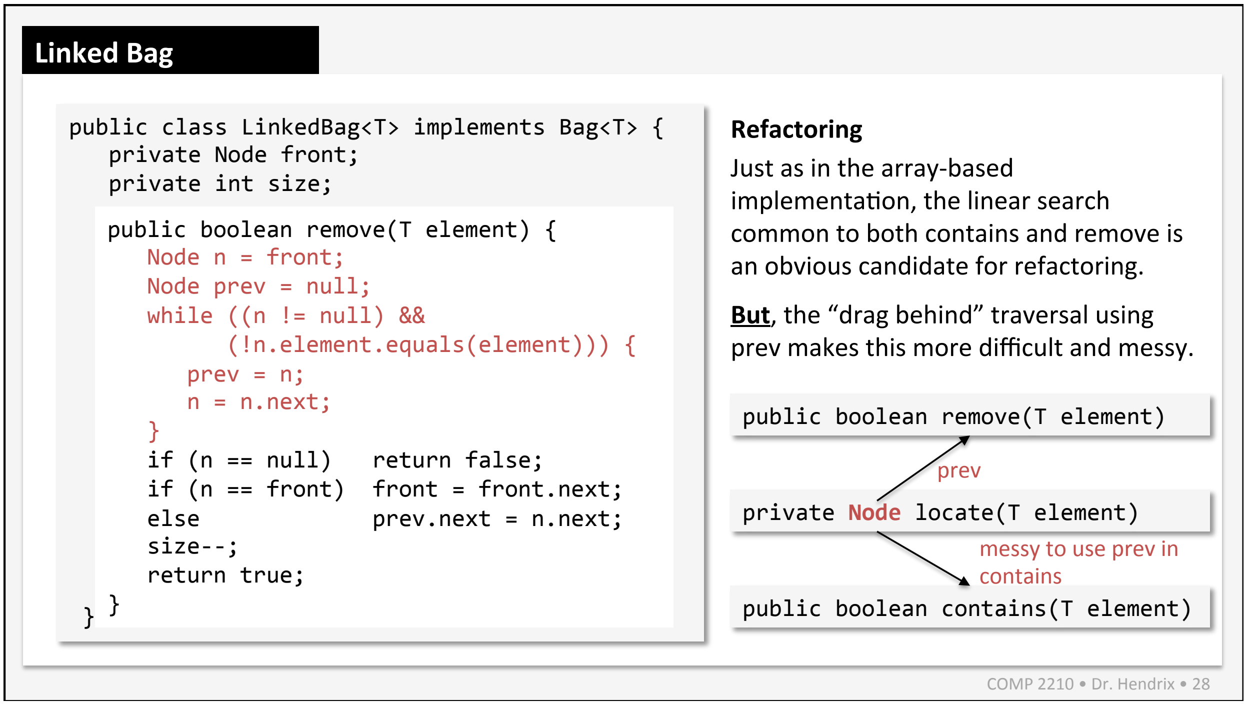
Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean remove(T element) {
      Node n = front;
      Node prev = null;
      while ((n != null) &&
            (!n.element.equals(element))) {
         prev = n;
         n = n.next;
      }
      if (n == null)    return false;
      if (n == front)   front = front.next;
      else              prev.next = n.next;
      size--;
      return true;
   }
}
```

bag.remove("B");
size
front
3
C
B
A
prev
n

To delete the node that contains "B" we need a reference to its predecessor.

size
front
3
C
A



Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean remove(T element) {
      Node n = front;
      Node prev = null;
      while ((n != null) &&
            (!n.element.equals(element))) {
         prev = n;
         n = n.next;
      }
      if (n == null)    return false;
      if (n == front)   front = front.next;
      else              prev.next = n.next;
      size--;
      return true;
   }
}
```

Refactoring

Just as in the array-based implementation, the linear search common to both contains and remove is an obvious candidate for refactoring.

But, the "drag behind" traversal using prev makes this more difficult and messy.

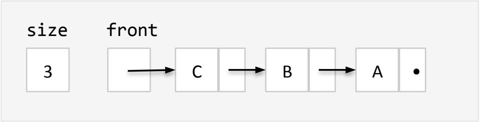
```
public boolean remove(T element)
```

```
private Node locate(T element)
```

```
public boolean contains(T element)
```

LinkedBag

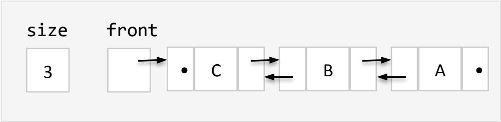
```
public class LinkedBag<T> implements Bag<T> {

   private Node front;
   private int size;
   . . .

   private class Node {
      private T element;
      private Node next;


   }

}
```



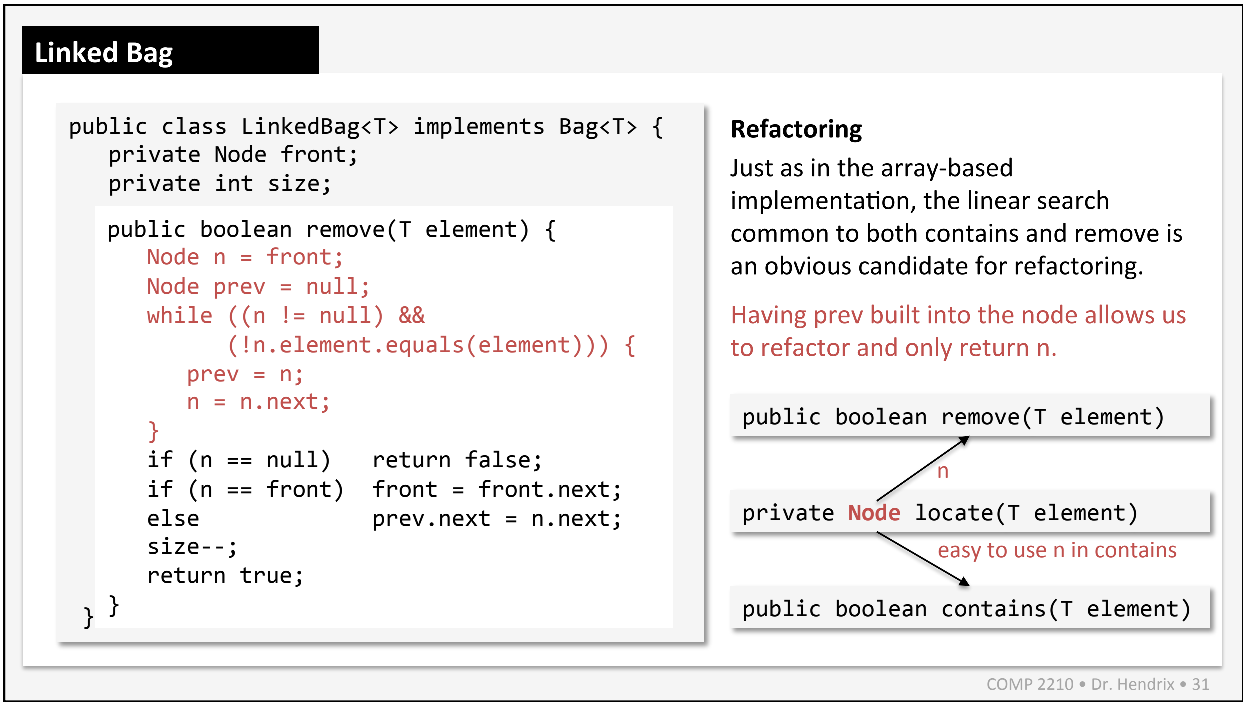
Singly linked

LinkedBag

```
public class LinkedBag<T> implements Bag<T> {

   private Node front;
   private int size;
   . . .

   private class Node {
      private T element;
      private Node next;
      private Node prev;

   }

}
```



Doubly linked



Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean remove(T element) {
      Node n = front;
      Node prev = null;
      while ((n != null) &&
            (!n.element.equals(element))) {
         prev = n;
         n = n.next;
      }
      if (n == null)   return false;
      if (n == front)  front = front.next;
      else             prev.next = n.next;
      size--;
      return true;
   }
}
```

Refactoring

Just as in the array-based implementation, the linear search common to both contains and remove is an obvious candidate for refactoring.

Having prev built into the node allows us to refactor and only return n.

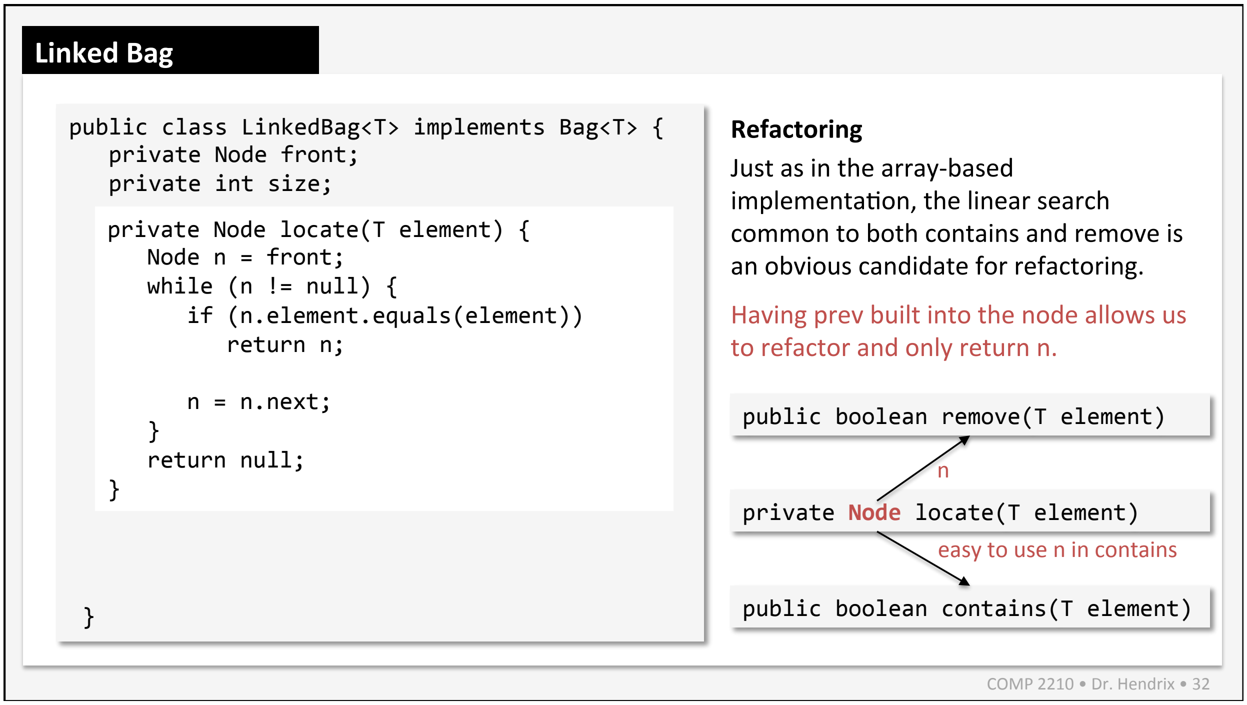
`public boolean remove(T element)`

n

`private Node locate(T element)`

easy to use n in contains

`public boolean contains(T element)`



Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   private Node locate(T element) {
      Node n = front;
      while (n != null) {
         if (n.element.equals(element))
            return n;

         n = n.next;
      }
      return null;
   }



}
```

Refactoring

Just as in the array-based implementation, the linear search common to both contains and remove is an obvious candidate for refactoring.

Having prev built into the node allows us to refactor and only return n.

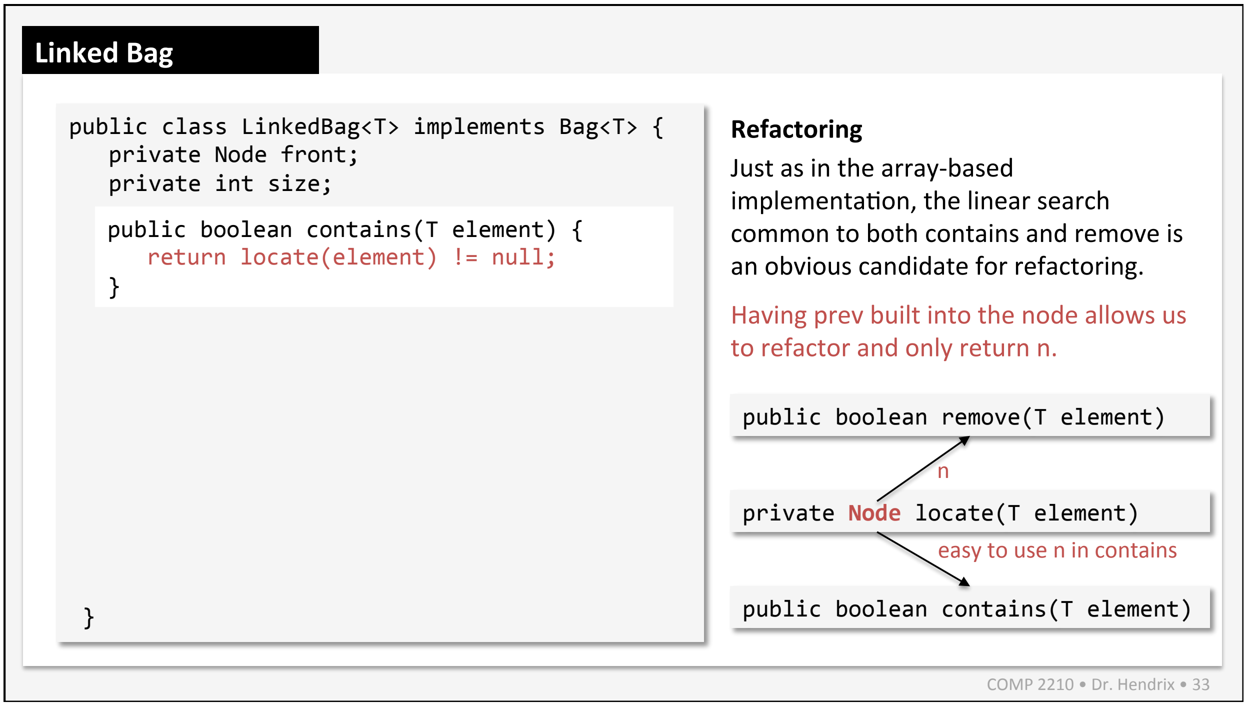
`public boolean remove(T element)`

n

`private Node locate(T element)`

easy to use n in contains

`public boolean contains(T element)`



Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean contains(T element) {
      return locate(element) != null;
   }

}
```

Refactoring

Just as in the array-based implementation, the linear search common to both contains and remove is an obvious candidate for refactoring.

Having prev built into the node allows us to refactor and only return n.

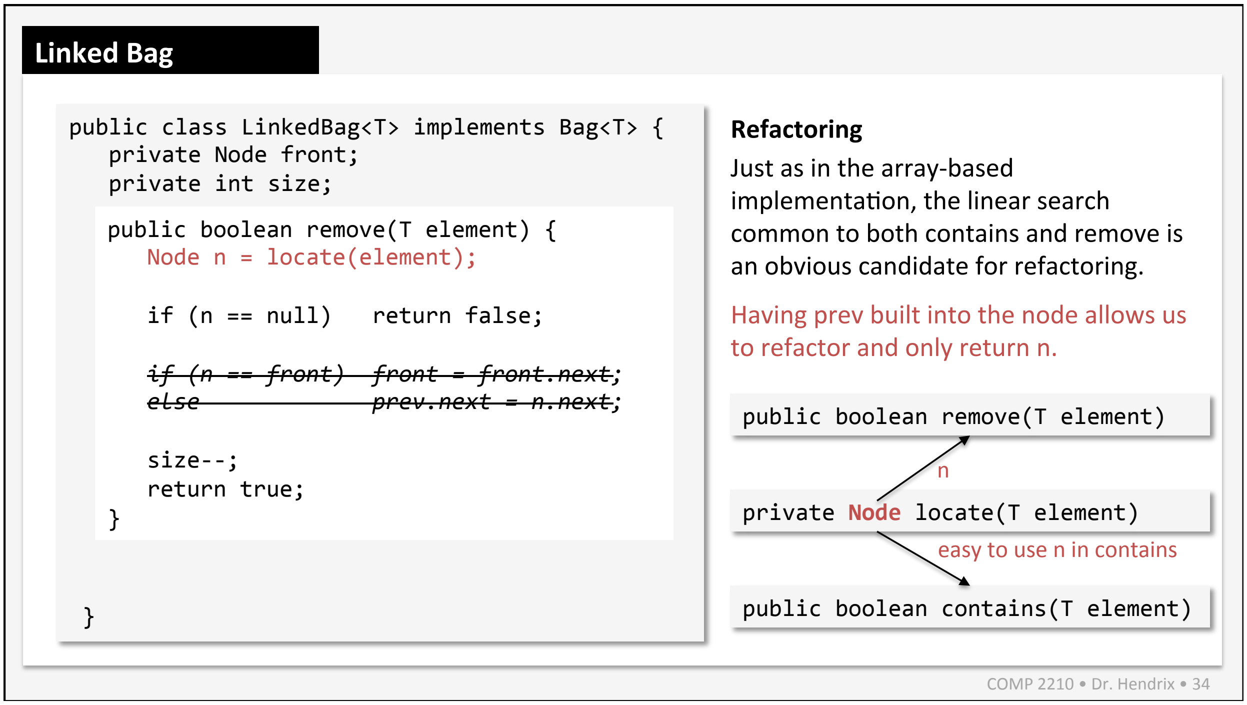
`public boolean remove(T element)`

n

`private Node locate(T element)`

easy to use n in contains

`public boolean contains(T element)`



Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean remove(T element) {
      Node n = locate(element);

      if (n == null)   return false;

      ~~if (n == front)  front = front.next;~~
      ~~else             prev.next = n.next;~~

      size--;
      return true;
   }

}
```

Refactoring

Just as in the array-based implementation, the linear search common to both contains and remove is an obvious candidate for refactoring.

Having prev built into the node allows us to refactor and only return n.

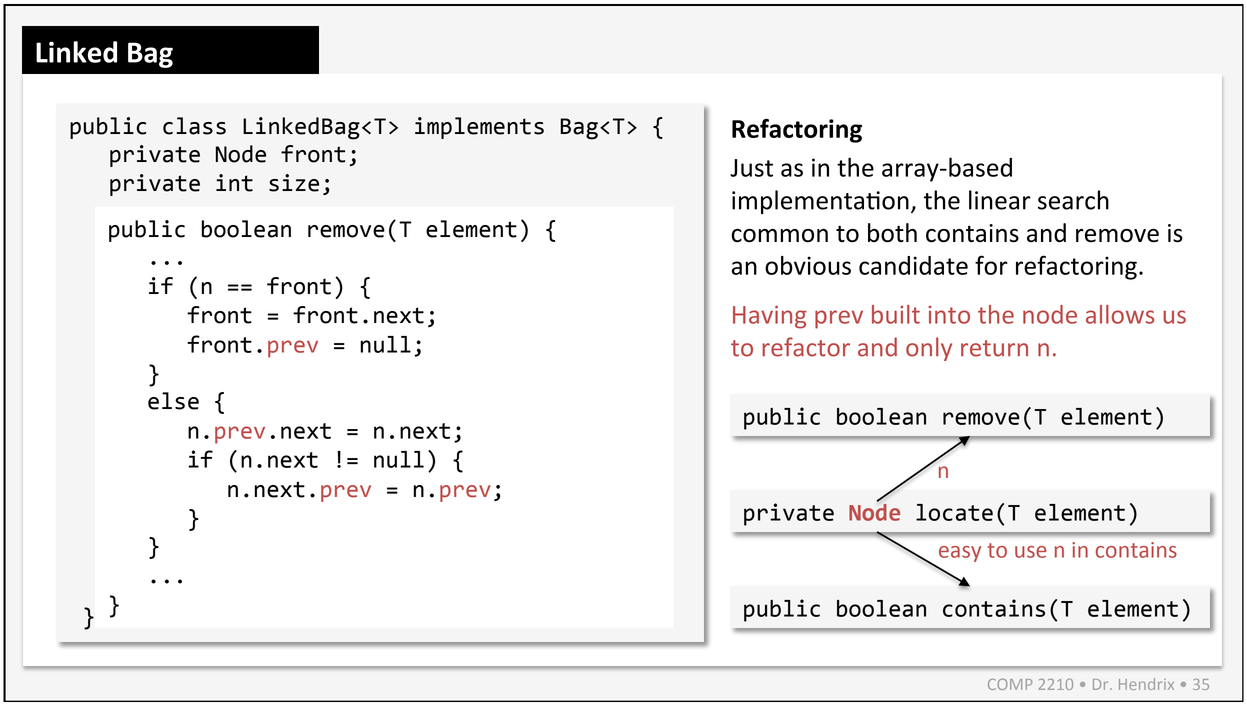
`public boolean remove(T element)`

n

`private Node locate(T element)`

easy to use n in contains

`public boolean contains(T element)`



Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean remove(T element) {
      ...
      if (n == front) {
         front = front.next;
         front.prev = null;
      }
      else {
         n.prev.next = n.next;
         if (n.next != null) {
            n.next.prev = n.prev;
         }
      }
      ...
   }
}
```

Refactoring

Just as in the array-based implementation, the linear search common to both contains and remove is an obvious candidate for refactoring.

Having prev built into the node allows us to refactor and only return n.

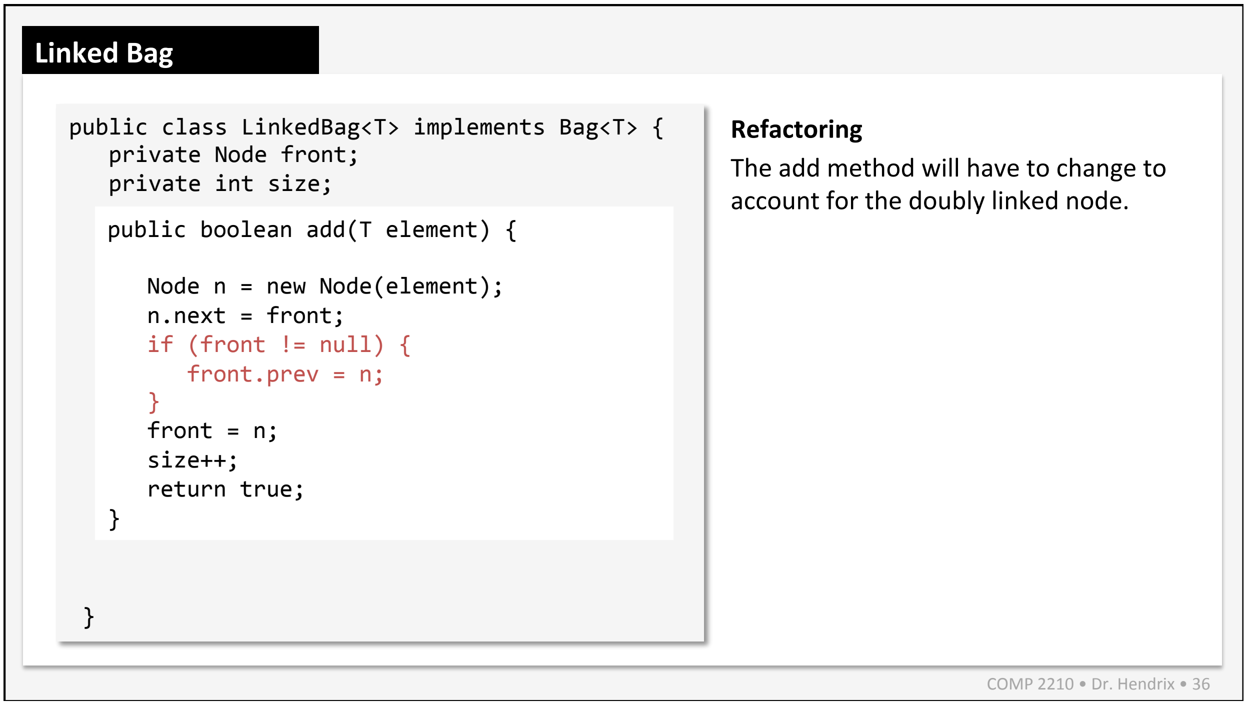
```
public boolean remove(T element)
```

n

```
private Node locate(T element)
```

easy to use n in contains

```
public boolean contains(T element)
```

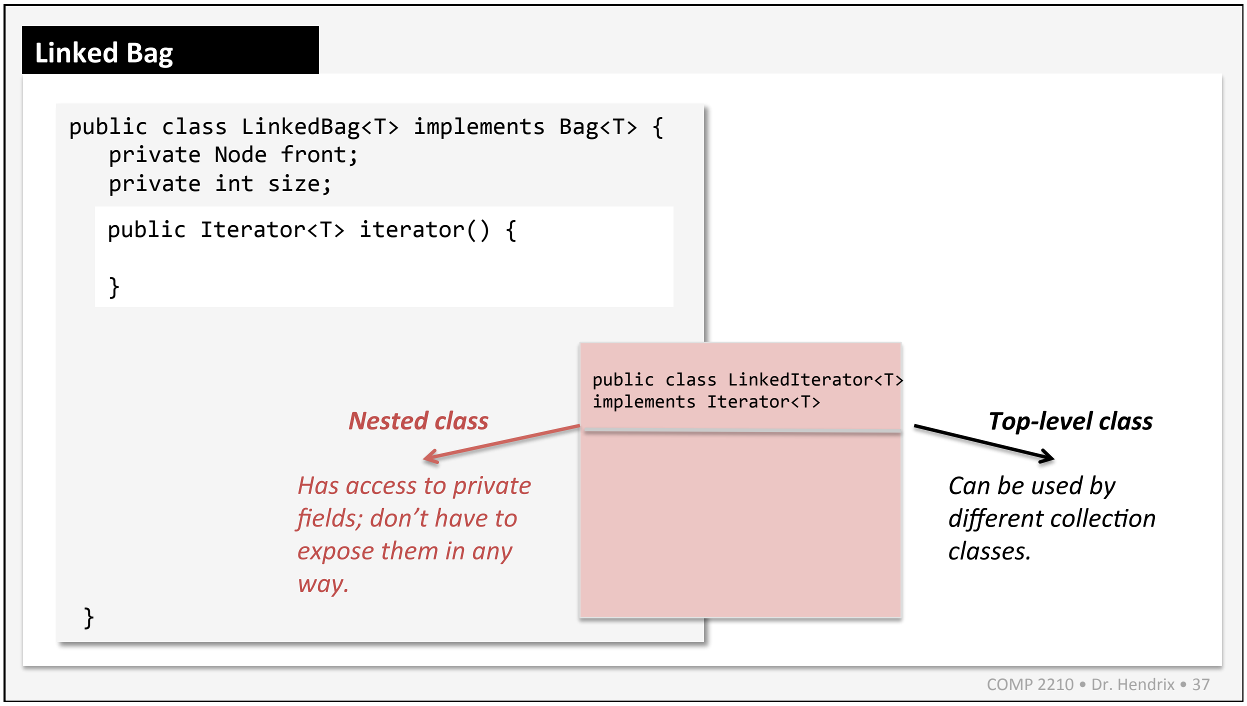


Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public boolean add(T element) {

      Node n = new Node(element);
      n.next = front;
      if (front != null) {
         front.prev = n;
      }
      front = n;
      size++;
      return true;
   }


}
```

Refactoring

The add method will have to change to account for the doubly linked node.



Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public Iterator<T> iterator() {

   }

}
```

```
public class LinkedIterator<T>
implements Iterator<T>
```

Nested class

Has access to private fields; don't have to expose them in any way.

Top-level class

Can be used by different collection classes.

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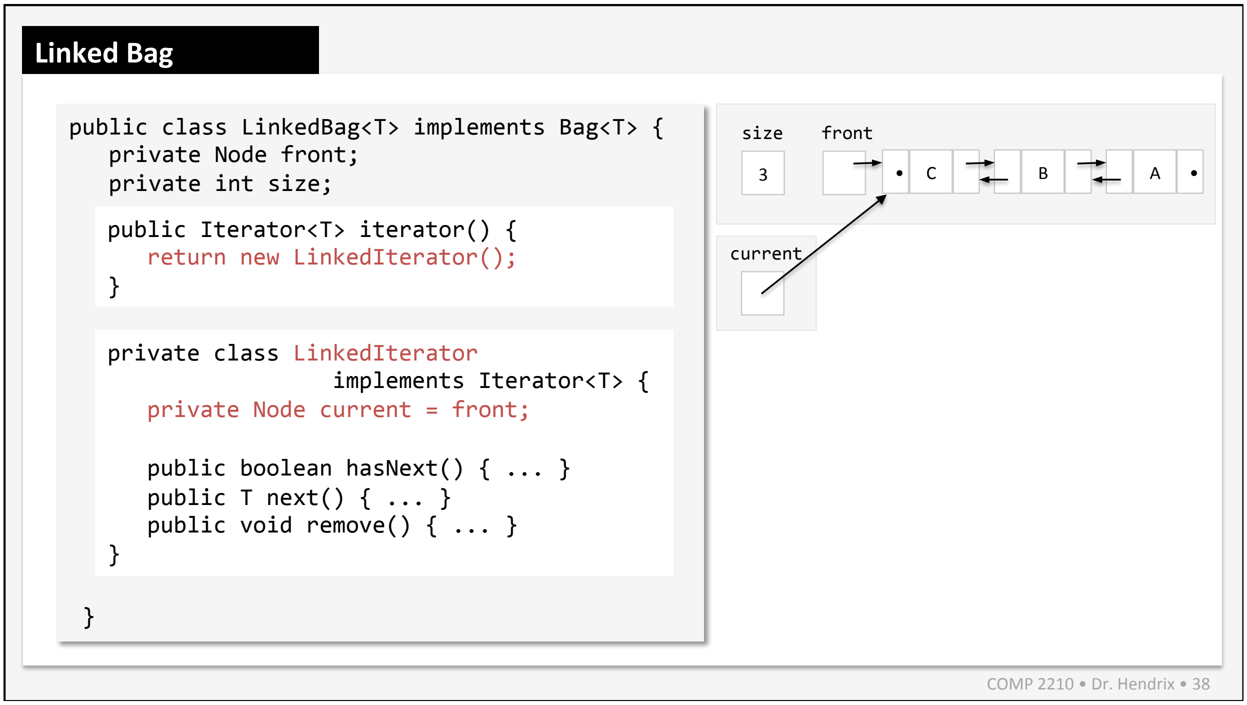

Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   public Iterator<T> iterator() {
      return new LinkedIterator();
   }

   private class LinkedIterator
                          implements Iterator<T> {
      private Node current = front;

      public boolean hasNext() { ... }
      public T next() { ... }
      public void remove() { ... }
   }

}
```

size
3
front
C
B
A
current

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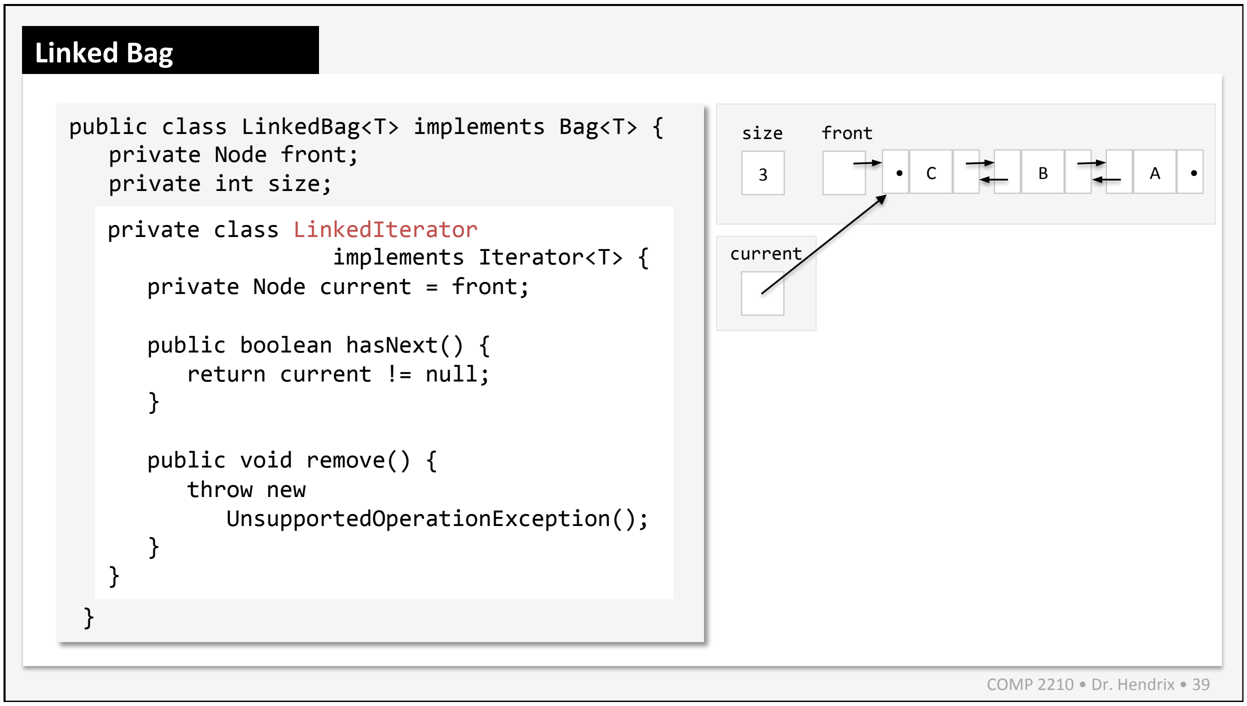

Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   private class LinkedIterator
                    implements Iterator<T> {
      private Node current = front;

      public boolean hasNext() {
         return current != null;
      }

      public void remove() {
         throw new
            UnsupportedOperationException();
      }
   }
}
```

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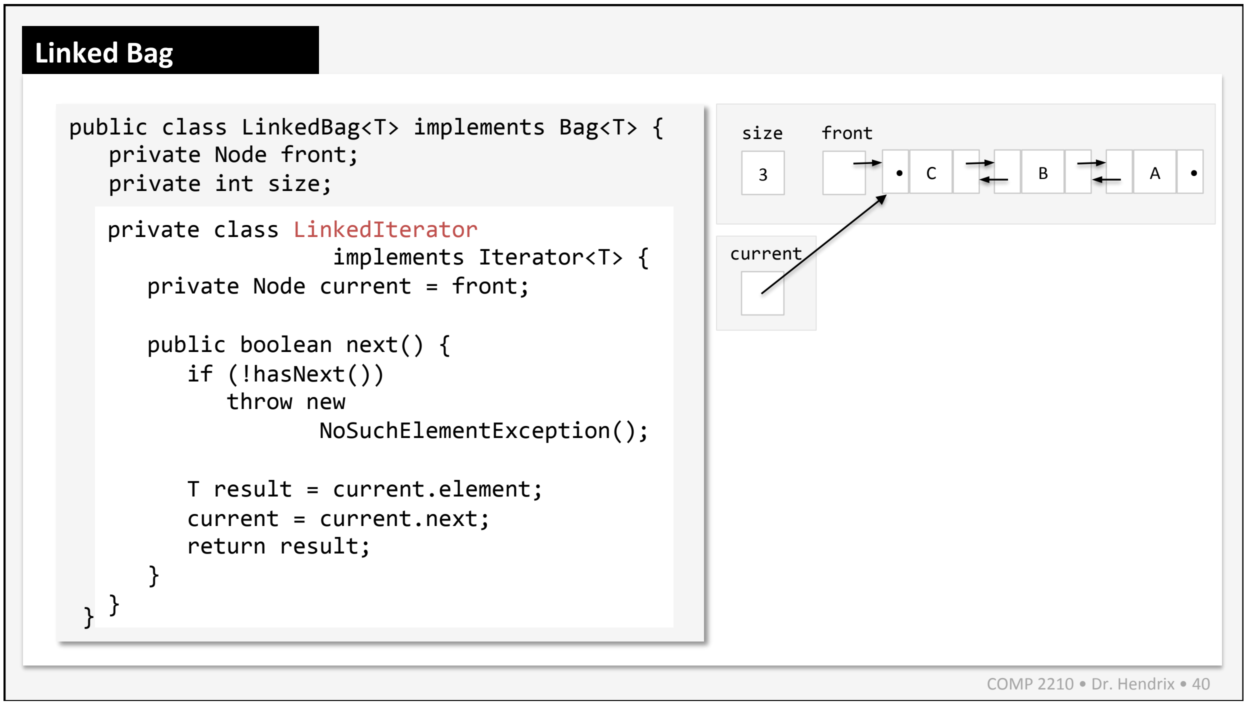

Linked Bag

```
public class LinkedBag<T> implements Bag<T> {
   private Node front;
   private int size;

   private class LinkedIterator
                    implements Iterator<T> {
      private Node current = front;

      public boolean next() {
         if (!hasNext())
            throw new
                   NoSuchElementException();

         T result = current.element;
         current = current.next;
         return result;
      }
   }
}
```

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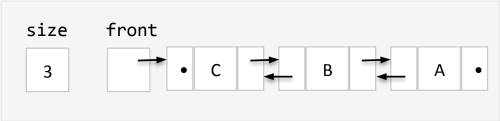
LinkedBag

```
public class LinkedBag<T> implements Bag<T> {

   private Node front;
   private int size;
   . . .
}
```



Advantages of using linked nodes:

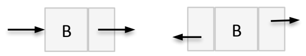
- Given a reference to a node, efficient to insert or add before or after that node; no shifting required

Disadvantages of using linked nodes:

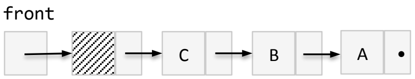
- no random access;
- less efficient use of memory
- not built in; nodes are user-created

Common variations

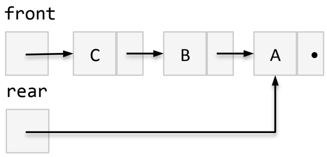
Singly linked v. Doubly linked



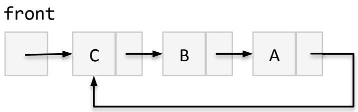
Dummy/Header nodes



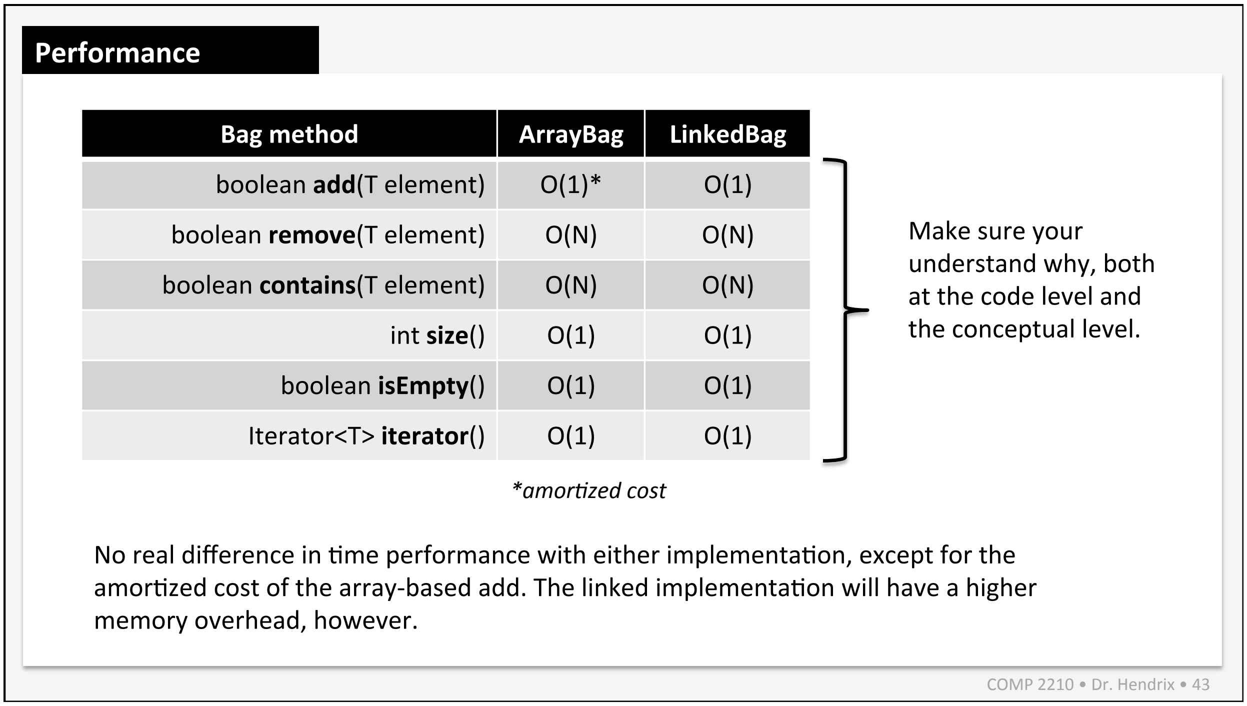
Front and rear pointers



Circular



Plus many others, and various combinations of these …



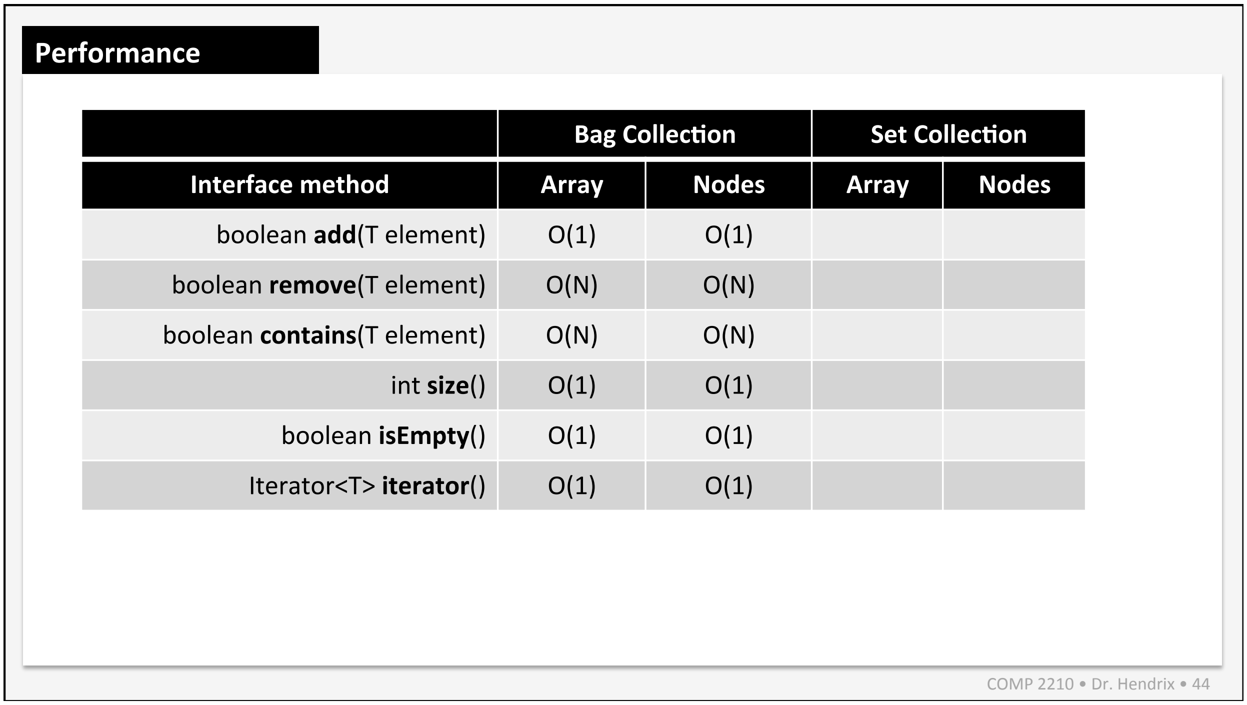
Performance

Bag method	ArrayBag	LinkedBag
boolean **add**(T element)	O(1)*	O(1)
boolean **remove**(T element)	O(N)	O(N)
boolean **contains**(T element)	O(N)	O(N)
int **size**()	O(1)	O(1)
boolean **isEmpty**()	O(1)	O(1)
Iterator<T> **iterator**()	O(1)	O(1)

Make sure your understand why, both at the code level and the conceptual level.

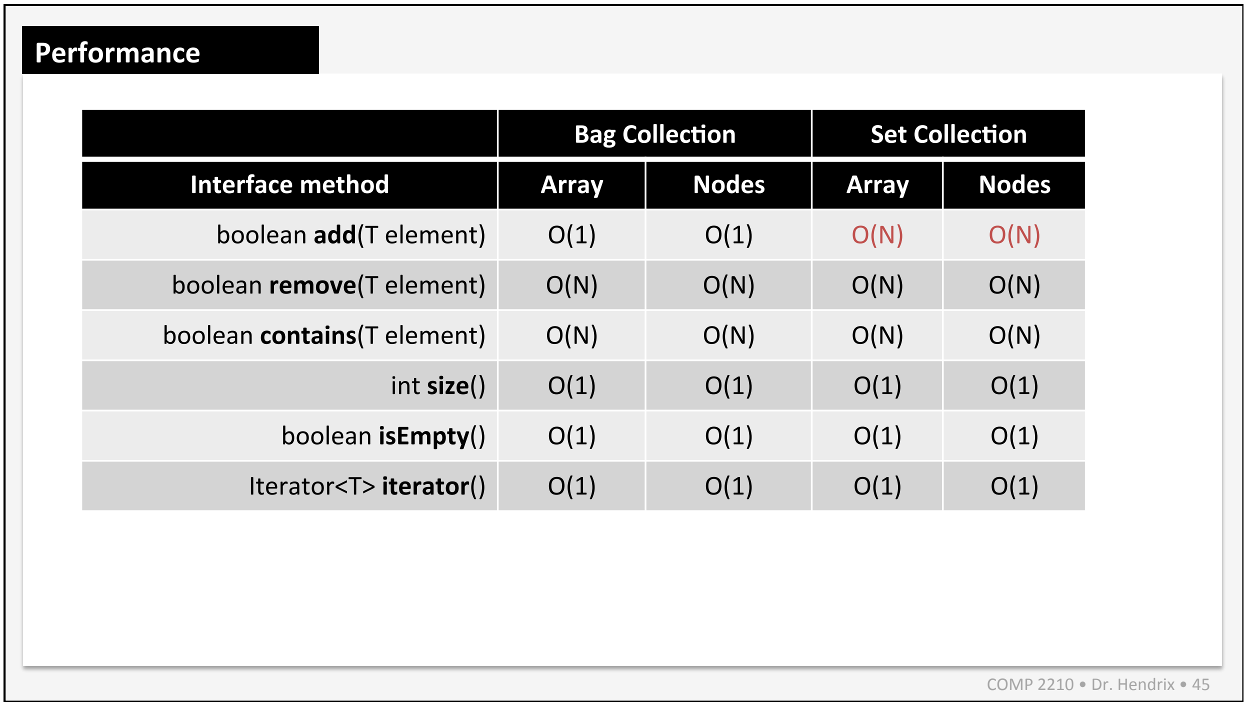
**amortized cost*

No real difference in time performance with either implementation, except for the amortized cost of the array-based add. The linked implementation will have a higher memory overhead, however.



Performance

	Bag Collection		Set Collection	
Interface method	Array	Nodes	Array	Nodes
boolean **add**(T element)	O(1)	O(1)		
boolean **remove**(T element)	O(N)	O(N)		
boolean **contains**(T element)	O(N)	O(N)		
int **size**()	O(1)	O(1)		
boolean **isEmpty**()	O(1)	O(1)		
Iterator<T> **iterator**()	O(1)	O(1)		



Performance

	Bag Collection		Set Collection	
Interface method	**Array**	**Nodes**	**Array**	**Nodes**
boolean **add**(T element)	O(1)	O(1)	O(N)	O(N)
boolean **remove**(T element)	O(N)	O(N)	O(N)	O(N)
boolean **contains**(T element)	O(N)	O(N)	O(N)	O(N)
int **size**()	O(1)	O(1)	O(1)	O(1)
boolean **isEmpty**()	O(1)	O(1)	O(1)	O(1)
Iterator<T> **iterator**()	O(1)	O(1)	O(1)	O(1)

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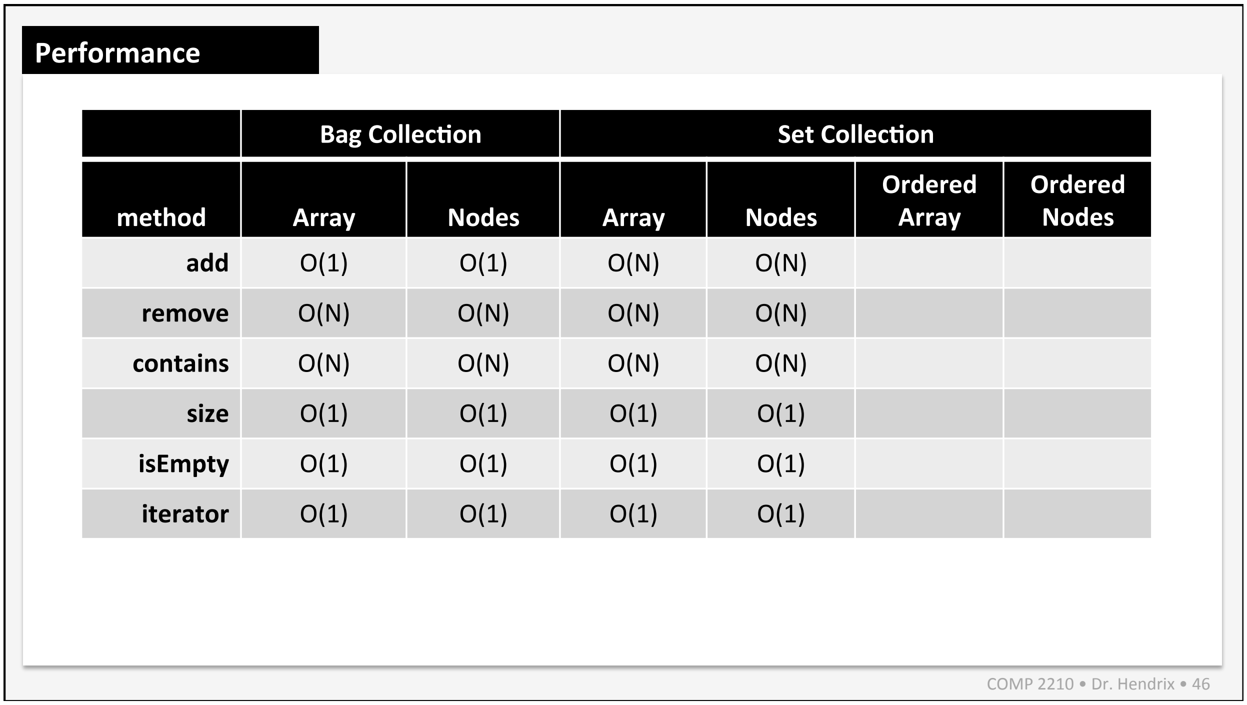

Performance

	Bag Collection		Set Collection			
method	**Array**	**Nodes**	**Array**	**Nodes**	**Ordered Array**	**Ordered Nodes**
add	O(1)	O(1)	O(N)	O(N)		
remove	O(N)	O(N)	O(N)	O(N)		
contains	O(N)	O(N)	O(N)	O(N)		
size	O(1)	O(1)	O(1)	O(1)		
isEmpty	O(1)	O(1)	O(1)	O(1)		
iterator	O(1)	O(1)	O(1)	O(1)		

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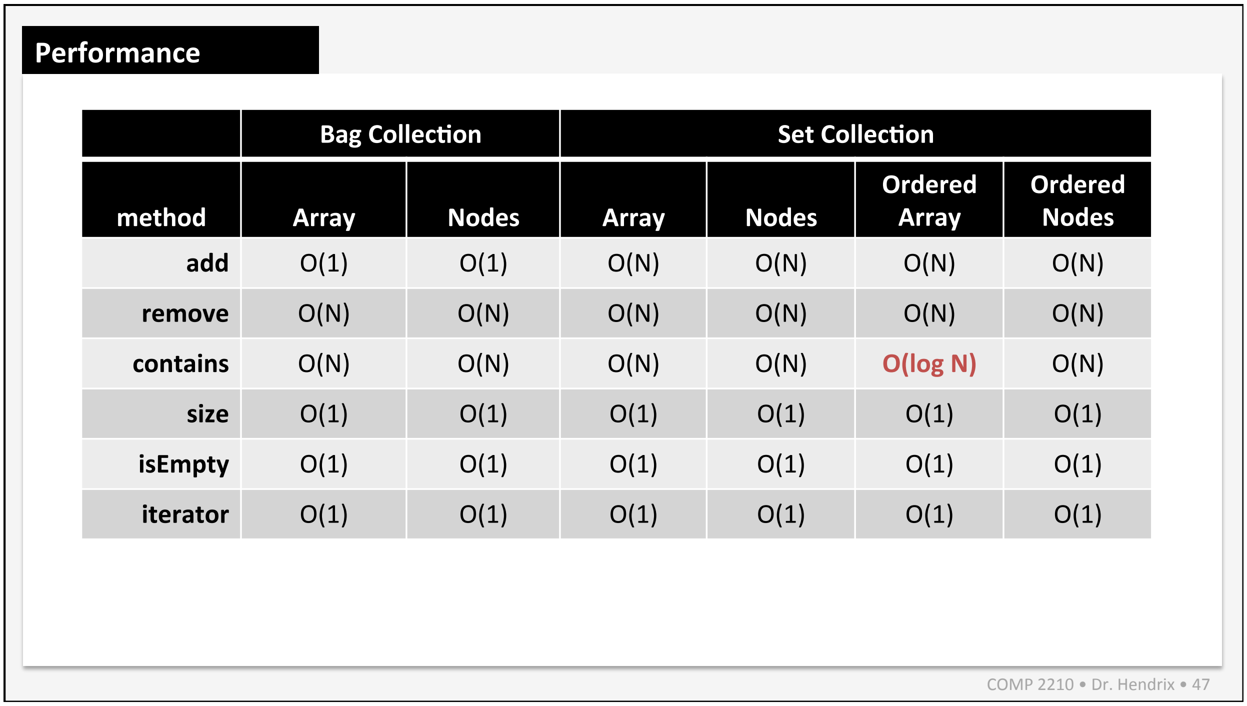

Performance

	Bag Collection		Set Collection			
method	Array	Nodes	Array	Nodes	Ordered Array	Ordered Nodes
add	O(1)	O(1)	O(N)	O(N)	O(N)	O(N)
remove	O(N)	O(N)	O(N)	O(N)	O(N)	O(N)
contains	O(N)	O(N)	O(N)	O(N)	**O(log N)**	O(N)
size	O(1)	O(1)	O(1)	O(1)	O(1)	O(1)
isEmpty	O(1)	O(1)	O(1)	O(1)	O(1)	O(1)
iterator	O(1)	O(1)	O(1)	O(1)	O(1)	O(1)

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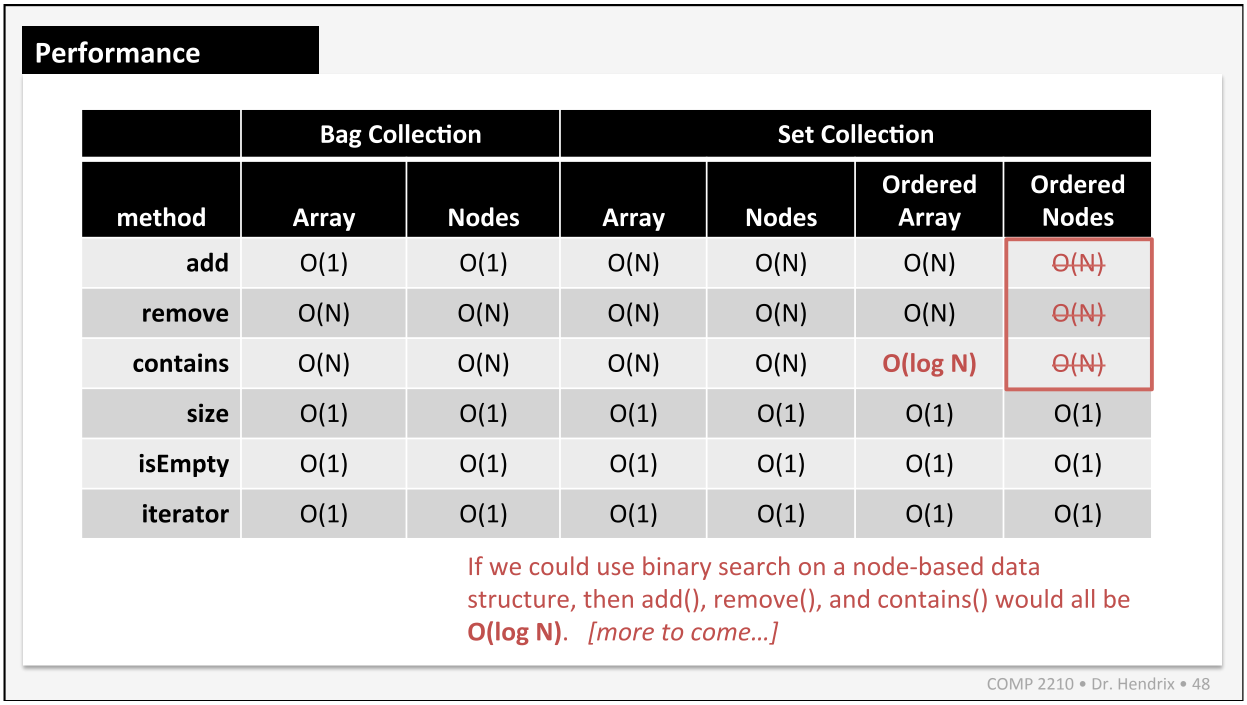

Performance

	Bag Collection		Set Collection			
method	Array	Nodes	Array	Nodes	Ordered Array	Ordered Nodes
add	O(1)	O(1)	O(N)	O(N)	O(N)	~~O(N)~~
remove	O(N)	O(N)	O(N)	O(N)	O(N)	~~O(N)~~
contains	O(N)	O(N)	O(N)	O(N)	**O(log N)**	~~O(N)~~
size	O(1)	O(1)	O(1)	O(1)	O(1)	O(1)
isEmpty	O(1)	O(1)	O(1)	O(1)	O(1)	O(1)
iterator	O(1)	O(1)	O(1)	O(1)	O(1)	O(1)

If we could use binary search on a node-based data structure, then add(), remove(), and contains() would all be **O(log N)**. *[more to come…]*

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