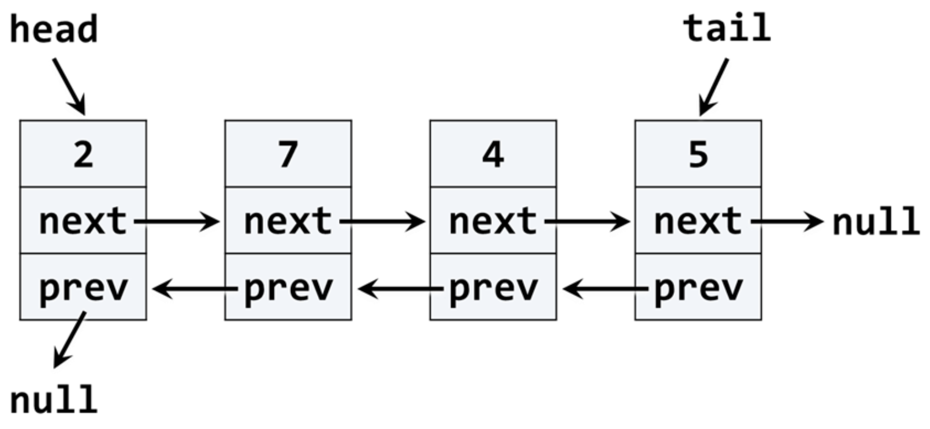
Exercises: Implement Doubly Linked List in C#

This document defines the **in-class exercises** assignments for the "Data Structures" course @ Software University. You have to implement a **doubly linked list** in C# – a data structure that holds **nodes**, where each node knows its **next** and **previous** nodes:



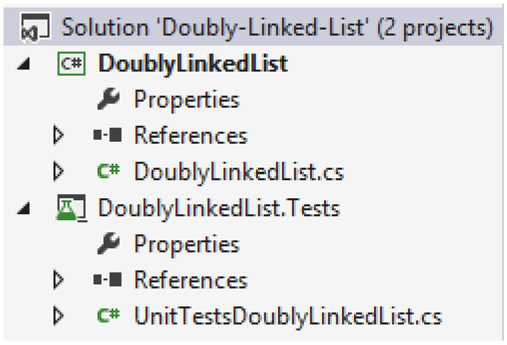
Problem 1. Learn about Doubly Linked List in Wikipedia

Before starting, get familiar with the concept of doubly linked list: https://en.wikipedia.org/wiki/Doubly_linked_list.

The typical operations over a doubly linked list are **add** / **remove** element at **both ends** and **traverse**. By definition, the doubly linked list has a **head** (list start) and a **`tail`** (list end). Let's start coding!

Problem 2. DoublyLinkedList<T> – Project Skeleton

You are given a **Visual Studio project skeleton** (unfinished project) holding the **`DoublyLinkedList<T>`** class. The project holds the following assets:

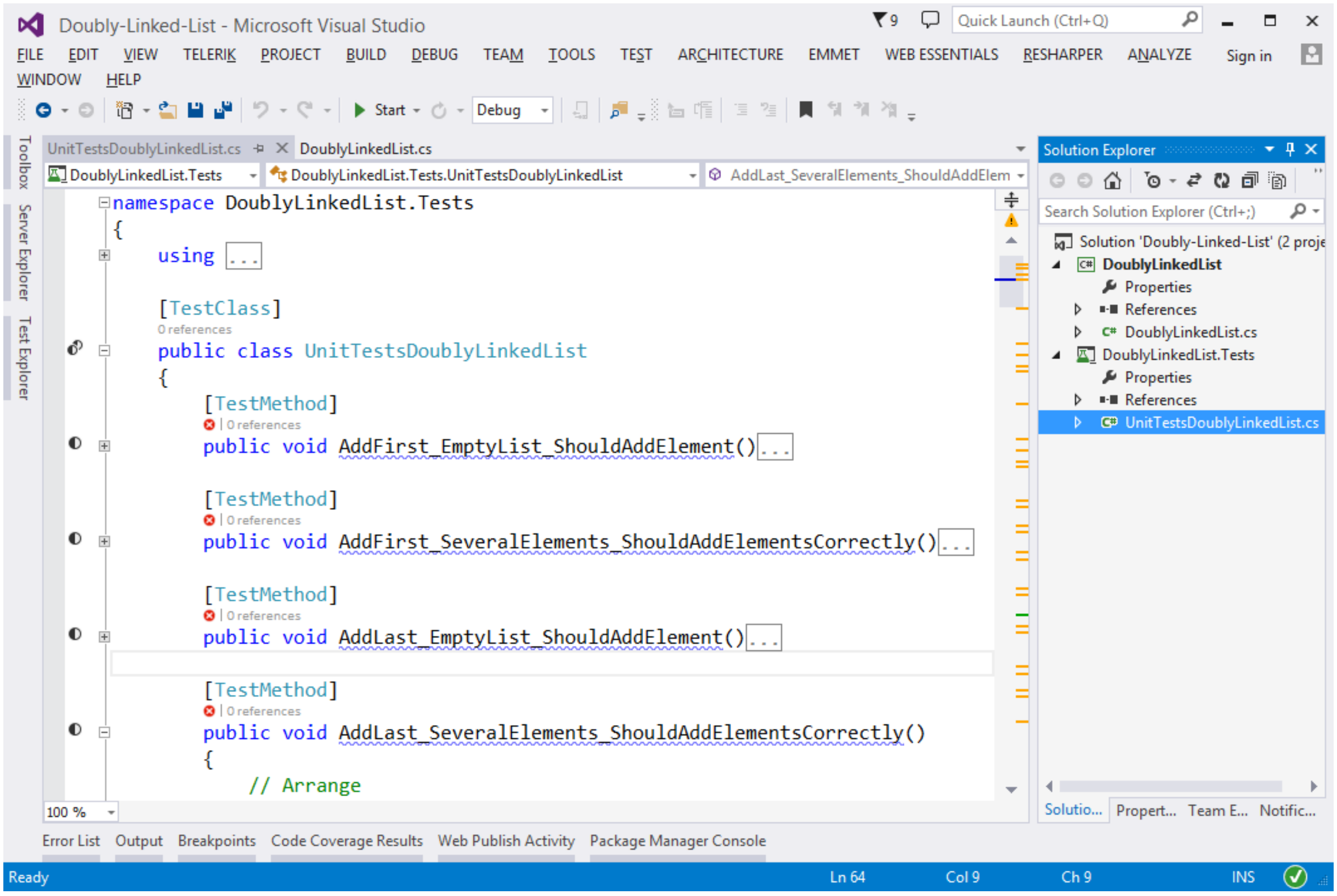


The project skeleton opens correctly in **Visual Studio 2013** but can be open in other Visual Studio versions as well and also can run in **SharpDevelop** and **Xamarin Studio**.

The main class stays in the file **`DoublyLinkedList.cs`**:

```
public class DoublyLinkedList<T> : IEnumerable<T>
{
    public int Count { … }
    public void AddFirst(T element) { … }
    public void AddLast(T element) { … }
    public T RemoveFirst() { … }
    public T RemoveLast() { … }
    public void ForEach(Action<T> action) { … }
    public IEnumerator<T> GetEnumerator() { … }
    IEnumerator IEnumerable.GetEnumerator() { … }
    public T[] ToArray() { … }
}
```

The project comes with **unit tests** covering the entire functionality of the doubly linked list (see the class **`UnitTestsDoublyLinkedList`**):

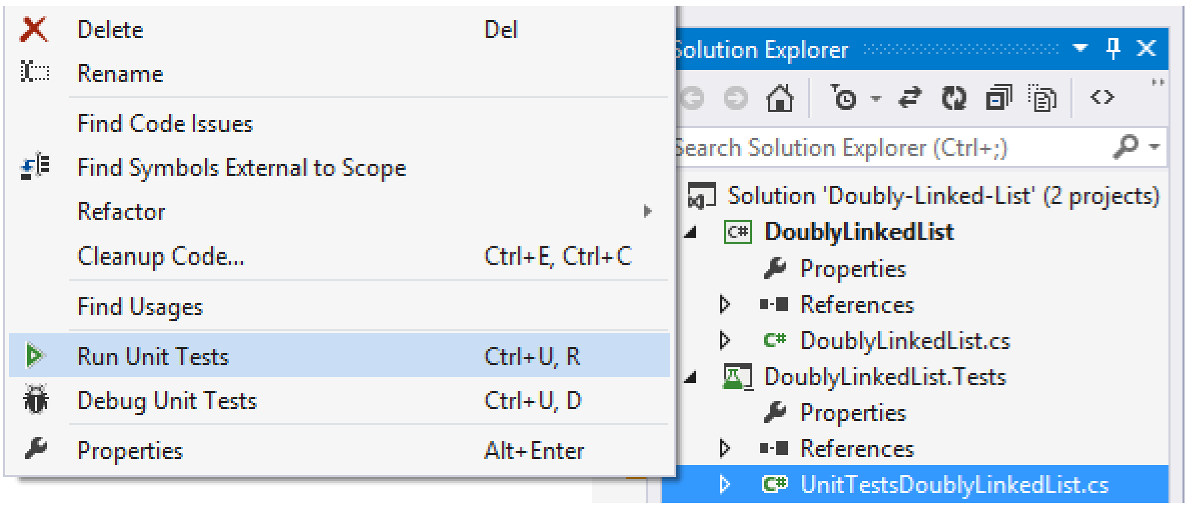


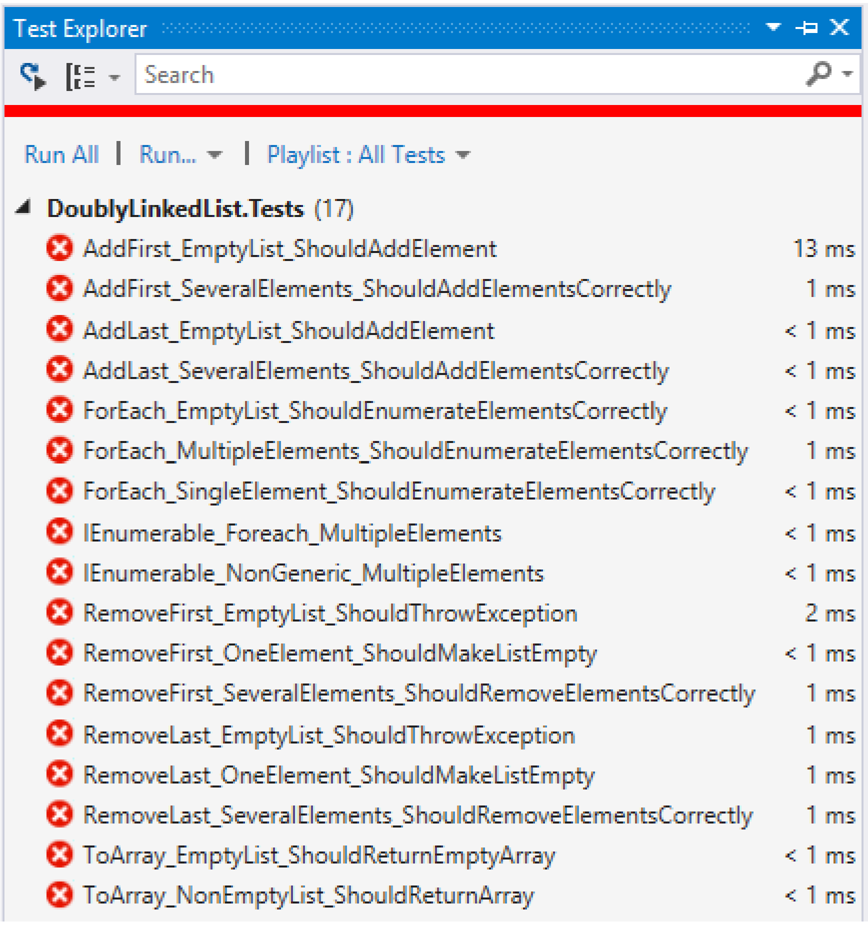
```
namespace DoublyLinkedList.Tests
{
    using ...

    [TestClass]
    public class UnitTestsDoublyLinkedList
    {
        [TestMethod]
        public void AddFirst_EmptyList_ShouldAddElement()...

        [TestMethod]
        public void AddFirst_SeveralElements_ShouldAddElementsCorrectly()...

        [TestMethod]
        public void AddLast_EmptyList_ShouldAddElement()...

        [TestMethod]
        public void AddLast_SeveralElements_ShouldAddElementsCorrectly()
        {
            // Arrange
```

Doubly-Linked-List - Microsoft Visual Studio
Solution Explorer
Solution 'Doubly-Linked-List' (2 projects)
DoublyLinkedList
Properties
References
DoublyLinkedList.cs
DoublyLinkedList.Tests
Properties
References
UnitTestsDoublyLinkedList.cs

Problem 3. Run the Unit Tests to Ensure All of Them Fail

Run the unit tests from the **`DoublyLinkedList.Tests`** project. Right click on the file "**`UnitTestsDoublyLinkedList.cs`**" in Solution Explorer and select **[Run Unit Tests]**:





```
DoublyLinkedList.Tests (17)
AddFirst_EmptyList_ShouldAddElement                          13 ms
AddFirst_SeveralElements_ShouldAddElementsCorrectly           1 ms
AddLast_EmptyList_ShouldAddElement                          < 1 ms
AddLast_SeveralElements_ShouldAddElementsCorrectly          < 1 ms
ForEach_EmptyList_ShouldEnumerateElementsCorrectly          < 1 ms
ForEach_MultipleElements_ShouldEnumerateElementsCorrectly     1 ms
ForEach_SingleElement_ShouldEnumerateElementsCorrectly      < 1 ms
IEnumerable_Foreach_MultipleElements                        < 1 ms
IEnumerable_NonGeneric_MultipleElements                     < 1 ms
RemoveFirst_EmptyList_ShouldThrowException                    2 ms
RemoveFirst_OneElement_ShouldMakeListEmpty                  < 1 ms
RemoveFirst_SeveralElements_ShouldRemoveElementsCorrectly     1 ms
RemoveLast_EmptyList_ShouldThrowException                     1 ms
RemoveLast_OneElement_ShouldMakeListEmpty                     1 ms
RemoveLast_SeveralElements_ShouldRemoveElementsCorrectly      1 ms
ToArray_EmptyList_ShouldReturnEmptyArray                    < 1 ms
ToArray_NonEmptyList_ShouldReturnArray                      < 1 ms
```

This is quite normal. We have unit tests, but the code covered by these tests is missing. Let's write it.

Problem 4. Implement ListNode<T>

The first step when implementing a linked / doubly linked list is to understand that we need **two classes**:

- **`ListNode<T>`** class to hold a single list node (its value + next node + previous node)
- **`DoublyLinkedList<T>`** to hold the entire list (its head + tail + operations)

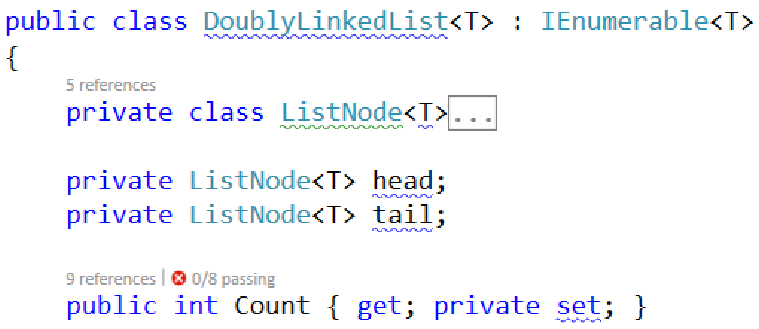
Now, let's write the **list node class**. It should hold a **`Value`** and a reference to its previous and next node. It can be inner class, because we will need it only internally from the doubly linked list class:

```
public class DoublyLinkedList<T> : IEnumerable<T>
{
    3 references
    private class ListNode<T>
    {
        1 reference
        public T Value { get; private set; }

        0 references
        public ListNode<T> NextNode { get; set; }

        0 references
        public ListNode<T> PrevNode { get; set; }

        0 references
        public ListNode(T value)
        {
            this.Value = value;
        }
    }
```

The class **ListNode<T>** is called **recursive data structure**, because it references itself recursively. It uses the **generic argument T** to avoid later specialization for any data type, e.g. **int**, **string** or **DateTime**. The **generic classes in C#** work similarly to **templates in C++** and **generic types in Java**.

Problem 5. Implement Head, Tail and Count

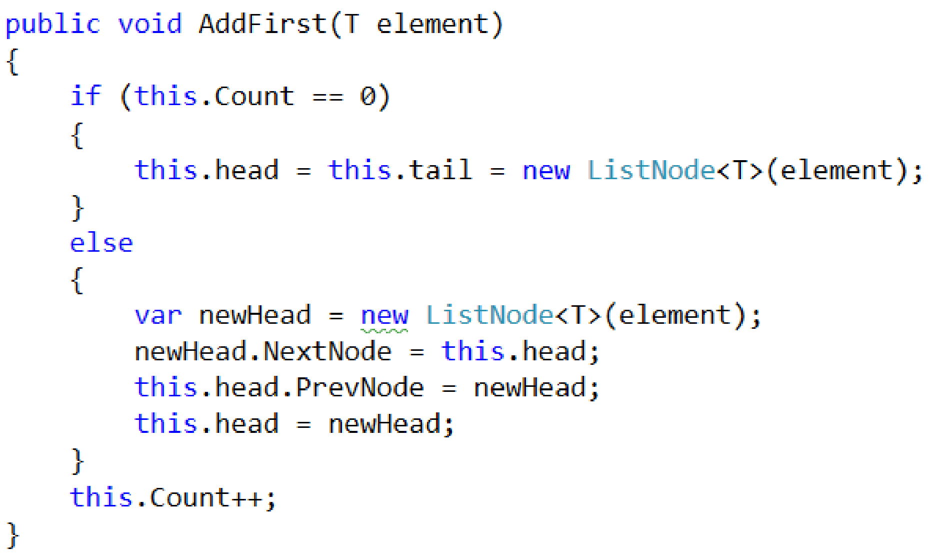
Now, let's define the **head** and **tail** of the doubly linked list:



```
public class DoublyLinkedList<T> : IEnumerable<T>
{
    5 references
    private class ListNode<T>...

    private ListNode<T> head;
    private ListNode<T> tail;

    9 references | 0/8 passing
    public int Count { get; private set; }
```

Problem 6. Implement AddFirst(T) Method

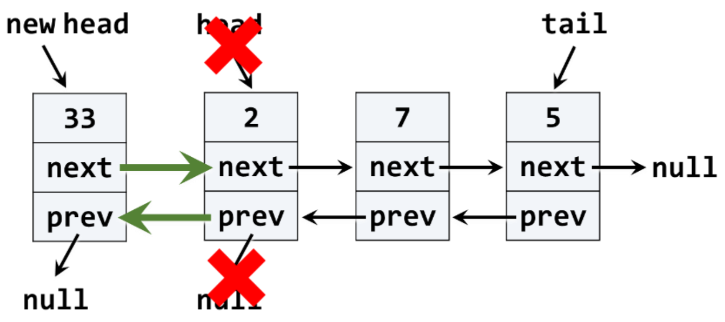
Next, implement the **AddFirst(T element)** method:



```
public void AddFirst(T element)
{
    if (this.Count == 0)
    {
        this.head = this.tail = new ListNode<T>(element);
    }
    else
    {
        var newHead = new ListNode<T>(element);
        newHead.NextNode = this.head;
        this.head.PrevNode = newHead;
        this.head = newHead;
    }
    this.Count++;
}
```

Adding an element at the start of the list (before its head) has **two scenarios** (considered in the above code):

- **Empty list** → add the new element as **head** and **tail** in the same time.
- **Non-empty list** → add the new element as **new head** and redirect the **old head** as second element, just after the new head.



The above graphic visualizes the process of inserting a new node at the start (**head**) of the list. The **red** arrows denote the removed pointers from the old head. The **green** arrows denote the new pointers to the new head.

Problem 7. Implement ForEach(Action) Method

We have a doubly linked list. We can add elements to it. But we cannot see what's inside, because the list still does not have a method to traverse its elements (pass through each of them, one by one). Now let's define the **`ForEach(Action<T>)`** method. In programming such a method is known as **"visitor"** pattern. It takes as an argument a function (action) to be invoked for each of the elements of the list. The algorithm behind this method is simple: start from **head** and pass to the next element until the last element is reached (its next element is **`null`**). A sample implementation is given below:

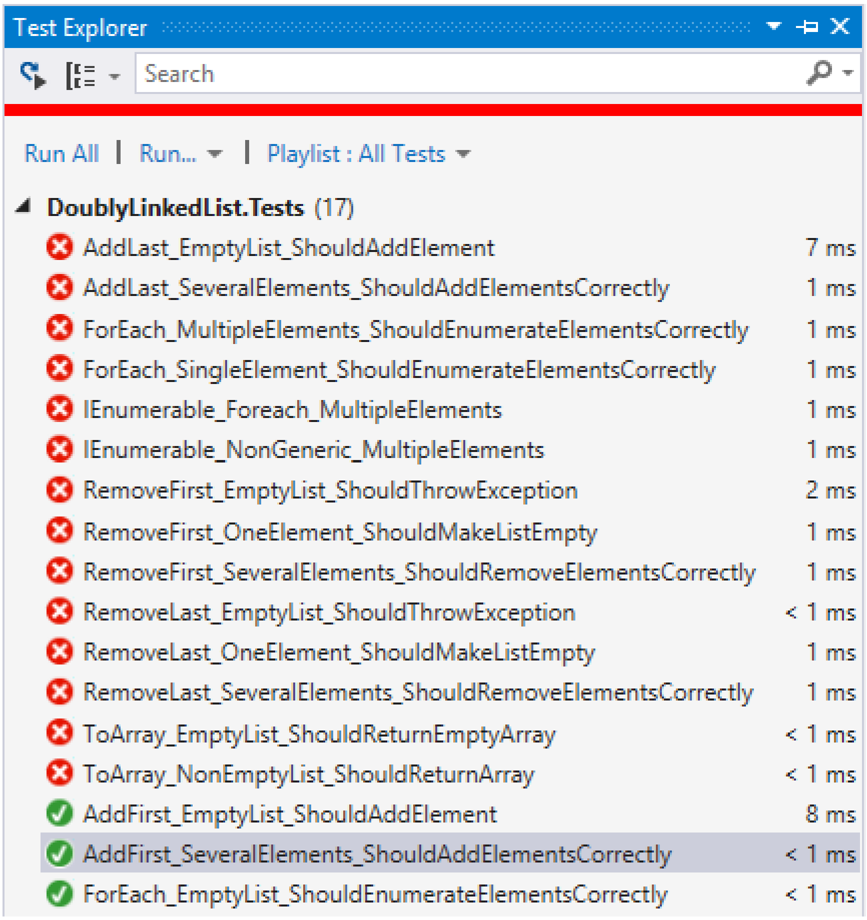
```
public void ForEach(Action<T> action)
{
    var currentNode = this.head;
    while (currentNode != null)
    {
        action(currentNode.Value);
        currentNode = currentNode.NextNode;
    }
}
```

Problem 8. Run the Unit Tests

Now we have the methods **`AddFirst(T)`** and **`ForEach(Action<T>)`**. We are ready to run the unit tests to ensure they are correctly implemented. Most of the **unit tests** create a doubly linked list, add / remove elements from it and then check whether the elements in the list are as expected. For example, let's examine this unit test:

```
[TestMethod]
✓ | 0 references
public void AddFirst_SeveralElements_ShouldAddElementsCorrectly()
{
    // Arrange
    var list = new DoublyLinkedList<int>();

    // Act
    list.AddFirst(10);
    list.AddFirst(5);
    list.AddFirst(3);

    // Assert
    Assert.AreEqual(3, list.Count);

    var items = new List<int>();
    list.ForEach(items.Add);
    CollectionAssert.AreEqual(items, new List<int>() { 3, 5, 10 });
}
```

If we **run the unit tests**, some of them will now pass:



DoublyLinkedList.Tests (17)

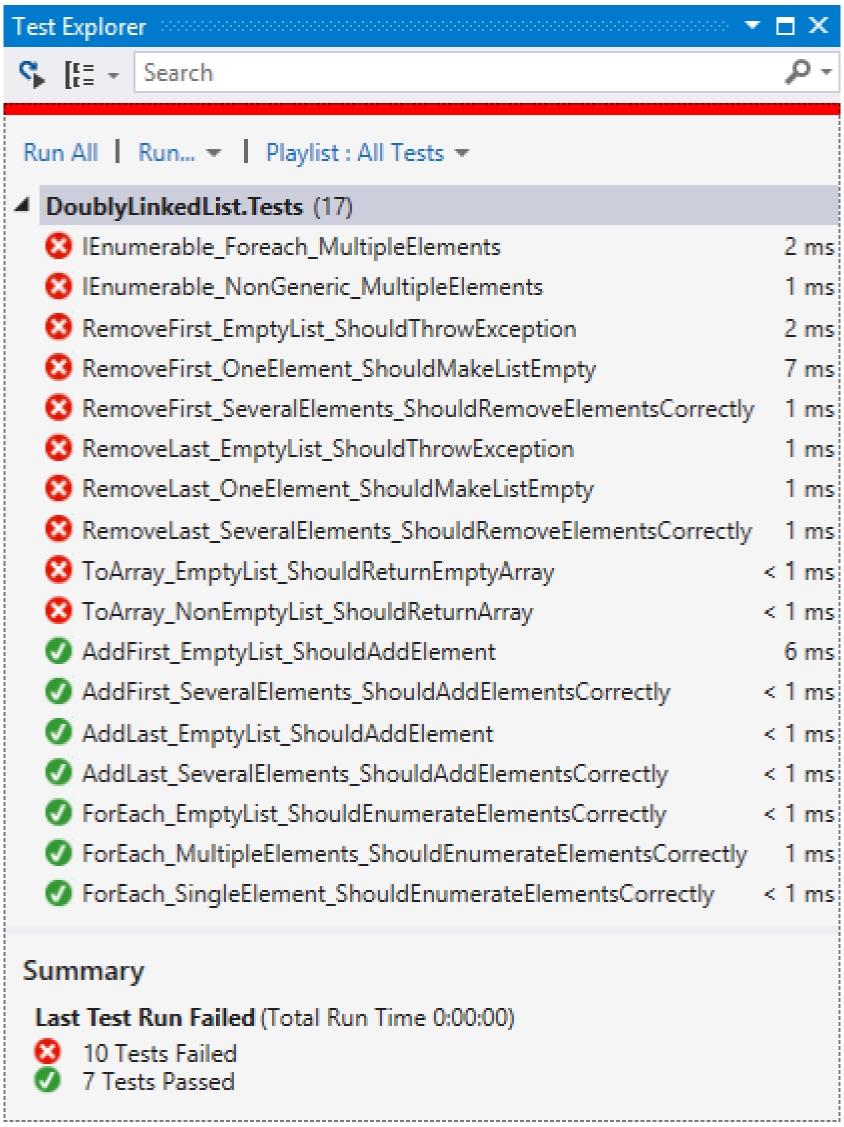
✗	AddLast_EmptyList_ShouldAddElement	7 ms
✗	AddLast_SeveralElements_ShouldAddElementsCorrectly	1 ms
✗	ForEach_MultipleElements_ShouldEnumerateElementsCorrectly	1 ms
✗	ForEach_SingleElement_ShouldEnumerateElementsCorrectly	1 ms
✗	IEnumerable_Foreach_MultipleElements	1 ms
✗	IEnumerable_NonGeneric_MultipleElements	1 ms
✗	RemoveFirst_EmptyList_ShouldThrowException	2 ms
✗	RemoveFirst_OneElement_ShouldMakeListEmpty	1 ms
✗	RemoveFirst_SeveralElements_ShouldRemoveElementsCorrectly	1 ms
✗	RemoveLast_EmptyList_ShouldThrowException	< 1 ms
✗	RemoveLast_OneElement_ShouldMakeListEmpty	1 ms
✗	RemoveLast_SeveralElements_ShouldRemoveElementsCorrectly	1 ms
✗	ToArray_EmptyList_ShouldReturnEmptyArray	< 1 ms
✗	ToArray_NonEmptyList_ShouldReturnArray	< 1 ms
✓	AddFirst_EmptyList_ShouldAddElement	8 ms
✓	AddFirst_SeveralElements_ShouldAddElementsCorrectly	< 1 ms
✓	ForEach_EmptyList_ShouldEnumerateElementsCorrectly	< 1 ms

Problem 9. Implement AddLast(T) Method

Next, implement the **`AddLast(T element)`** method for appending a new element as the list **`tail`**. It should be very similar to the **`AddFirst(T element)`** method. The logic inside it exactly the same, but we append the new element at the **`tail`** instead of at the **head**. The code below is intentionally blurred. Write it yourself!

```
public void AddLast(T element)
{
    if (this.Count == 0)
    {
        this.head = this.tail = new ListNode<T>(element);
    }
    else
    {
        var newTail = new ListNode<T>(element);
        newTail.PrevNode = this.tail;
        this.tail.NextNode = newTail;
        this.tail = newTail;
    }
    this.Count++;
}
```

Now **run the unit tests** again. You should have several more passed (green) tests:



```
DoublyLinkedList.Tests (17)
✗ IEnumerable_Foreach_MultipleElements                              2 ms
✗ IEnumerable_NonGeneric_MultipleElements                           1 ms
✗ RemoveFirst_EmptyList_ShouldThrowException                        2 ms
✗ RemoveFirst_OneElement_ShouldMakeListEmpty                        7 ms
✗ RemoveFirst_SeveralElements_ShouldRemoveElementsCorrectly         1 ms
✗ RemoveLast_EmptyList_ShouldThrowException                         1 ms
✗ RemoveLast_OneElement_ShouldMakeListEmpty                         1 ms
✗ RemoveLast_SeveralElements_ShouldRemoveElementsCorrectly          1 ms
✗ ToArray_EmptyList_ShouldReturnEmptyArray                        < 1 ms
✗ ToArray_NonEmptyList_ShouldReturnArray                          < 1 ms
✓ AddFirst_EmptyList_ShouldAddElement                               6 ms
✓ AddFirst_SeveralElements_ShouldAddElementsCorrectly             < 1 ms
✓ AddLast_EmptyList_ShouldAddElement                              < 1 ms
✓ AddLast_SeveralElements_ShouldAddElementsCorrectly              < 1 ms
✓ ForEach_EmptyList_ShouldEnumerateElementsCorrectly              < 1 ms
✓ ForEach_MultipleElements_ShouldEnumerateElementsCorrectly         1 ms
✓ ForEach_SingleElement_ShouldEnumerateElementsCorrectly          < 1 ms

Summary
Last Test Run Failed (Total Run Time 0:00:00)
✗ 10 Tests Failed
✓ 7 Tests Passed
```

Problem 10. Implement RemoveFirst() Method

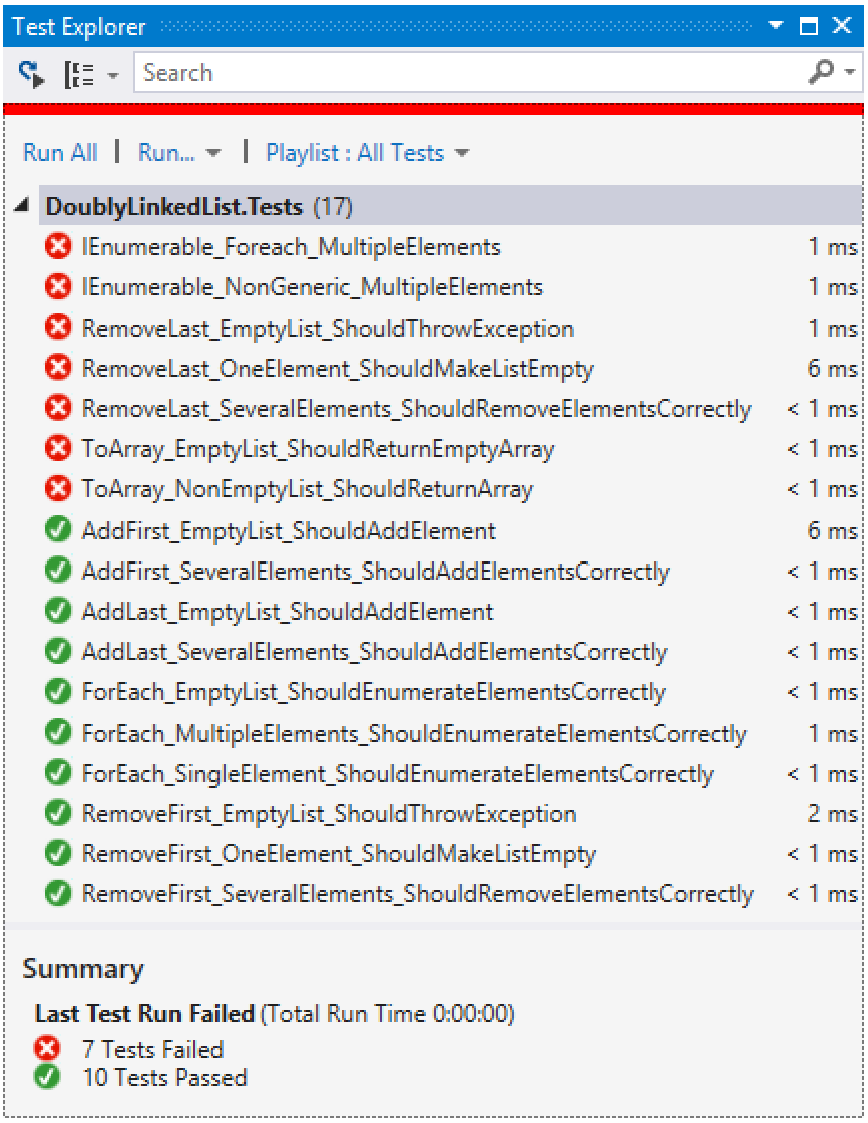
Next, let's implement the method **`RemoveFirst()` → T**. It should **remove the first element** from the list and move its **head** to point to the second element. The removed element should be returned as a result from the method. In case of empty list, the method should throw an exception. We have to consider the following three cases:

- **Empty list** → throw and exception.
- **Single element in the list** → make the list empty (**head** == **`tail`** == **`null`**).
- **Multiple elements in the list** → remove the first element and redirect the head to point to the second element (**head** = **`head.NextNode`**).

A sample implementation of **`RemoveFirst()`** method is given below:

```
public T RemoveFirst()
{
    if (this.Count == 0)
    {
        throw new InvalidOperationException("List empty");
    }

    var firstElement = this.head.Value;
    this.head = this.head.NextNode;
    if (this.head != null)
    {
        this.head.PrevNode = null;
    }
    else
    {
        this.tail = null;
    }

    this.Count--;
    return firstElement;
}
```

Run the **unit tests** to ensure the method is correctly implemented:



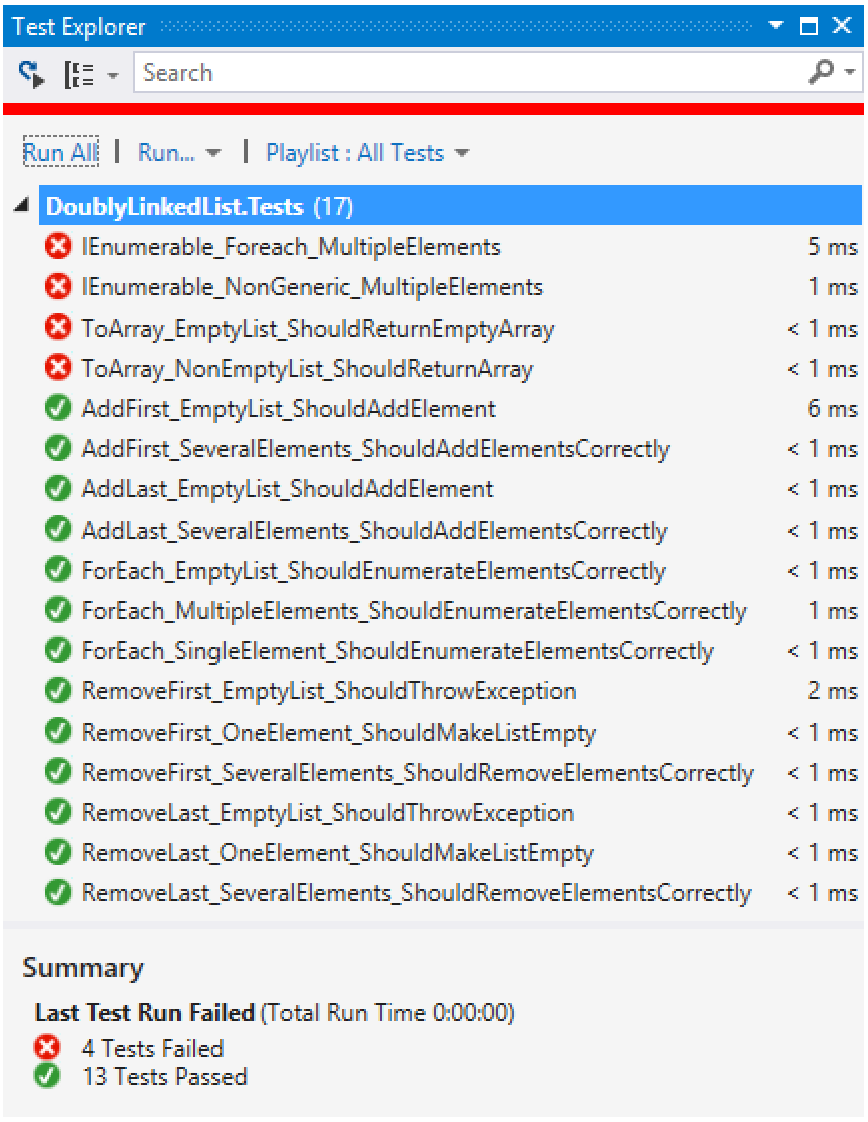
```
DoublyLinkedList.Tests (17)
✗ IEnumerable_Foreach_MultipleElements                                   1 ms
✗ IEnumerable_NonGeneric_MultipleElements                                1 ms
✗ RemoveLast_EmptyList_ShouldThrowException                              1 ms
✗ RemoveLast_OneElement_ShouldMakeListEmpty                              6 ms
✗ RemoveLast_SeveralElements_ShouldRemoveElementsCorrectly             < 1 ms
✗ ToArray_EmptyList_ShouldReturnEmptyArray                             < 1 ms
✗ ToArray_NonEmptyList_ShouldReturnArray                               < 1 ms
✓ AddFirst_EmptyList_ShouldAddElement                                    6 ms
✓ AddFirst_SeveralElements_ShouldAddElementsCorrectly                  < 1 ms
✓ AddLast_EmptyList_ShouldAddElement                                   < 1 ms
✓ AddLast_SeveralElements_ShouldAddElementsCorrectly                   < 1 ms
✓ ForEach_EmptyList_ShouldEnumerateElementsCorrectly                   < 1 ms
✓ ForEach_MultipleElements_ShouldEnumerateElementsCorrectly              1 ms
✓ ForEach_SingleElement_ShouldEnumerateElementsCorrectly               < 1 ms
✓ RemoveFirst_EmptyList_ShouldThrowException                             2 ms
✓ RemoveFirst_OneElement_ShouldMakeListEmpty                           < 1 ms
✓ RemoveFirst_SeveralElements_ShouldRemoveElementsCorrectly            < 1 ms

Summary
Last Test Run Failed (Total Run Time 0:00:00)
✗ 7 Tests Failed
✓ 10 Tests Passed
```

Problem 11. Implement RemoveLast() Method

Next, let's implement the method **`RemoveLast()` → T**. It should **remove the last element** from the list and move its **`tail`** to point to the element before the last. It is very similar to the method **`RemoveFirst()`**, so you are free to implement it yourself. The code below is intentionally blurred:

```
public T RemoveLast()
{
    if (this.Count == 0)
    {
        throw new InvalidOperationException("List empty");
    }

    var lastElement = this.tail.Value;
    this.tail = this.tail.PrevNode;
    if (this.tail != null)
    {
        this.tail.NextNode = null;
    }
    else
    {
        this.head = null;
    }

    this.Count--;
    return lastElement;
}
```

Now **run the unit tests** once again to ensure your code is correct:



```
DoublyLinkedList.Tests (17)
✗ IEnumerable_Foreach_MultipleElements                              5 ms
✗ IEnumerable_NonGeneric_MultipleElements                           1 ms
✗ ToArray_EmptyList_ShouldReturnEmptyArray                        < 1 ms
✗ ToArray_NonEmptyList_ShouldReturnArray                          < 1 ms
✓ AddFirst_EmptyList_ShouldAddElement                               6 ms
✓ AddFirst_SeveralElements_ShouldAddElementsCorrectly             < 1 ms
✓ AddLast_EmptyList_ShouldAddElement                              < 1 ms
✓ AddLast_SeveralElements_ShouldAddElementsCorrectly              < 1 ms
✓ ForEach_EmptyList_ShouldEnumerateElementsCorrectly              < 1 ms
✓ ForEach_MultipleElements_ShouldEnumerateElementsCorrectly         1 ms
✓ ForEach_SingleElement_ShouldEnumerateElementsCorrectly          < 1 ms
✓ RemoveFirst_EmptyList_ShouldThrowException                        2 ms
✓ RemoveFirst_OneElement_ShouldMakeListEmpty                      < 1 ms
✓ RemoveFirst_SeveralElements_ShouldRemoveElementsCorrectly       < 1 ms
✓ RemoveLast_EmptyList_ShouldThrowException                       < 1 ms
✓ RemoveLast_OneElement_ShouldMakeListEmpty                       < 1 ms
✓ RemoveLast_SeveralElements_ShouldRemoveElementsCorrectly        < 1 ms

Summary
Last Test Run Failed (Total Run Time 0:00:00)
✗ 4 Tests Failed
✓ 13 Tests Passed
```

Problem 12. Implement ToArray() Method

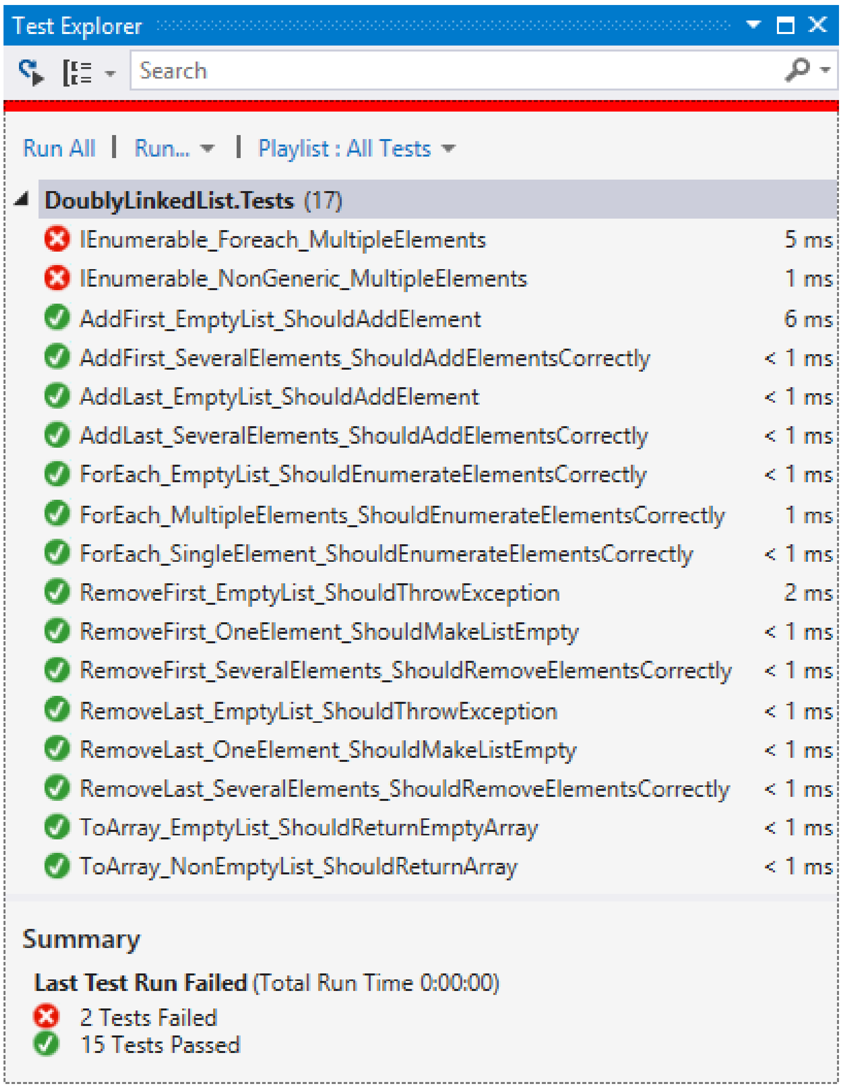
Now, implement the next method: **`ToArray()`** → **`T[]`**. It should copy all elements of the linked list to an array of the same size. You could use the following steps to implement this method:

- Allocate an array **`T[]`** of size **`this.Count`**.
- Pass through all elements of the list (from **head** to **`tail`**) and fill them to **`T[0]`**, **`T[1]`**, …, **`T[Count-1]`**.
- Return the array as result.

Write yourself the blurred code in the method **`ToArray()`**:

```
public T[] ToArray()
{
    var arr = new T[this.Count];
    int index = 0;
    var currentNode = this.head;
    while (currentNode != null)
    {
        arr[index++] = currentNode.Value;
        currentNode = currentNode.NextNode;
    }
    return arr;
}
```

Again, **run the unit tests**, to ensure your code is correct:



```
Test Explorer
Search
Run All | Run... | Playlist : All Tests
DoublyLinkedList.Tests (17)
IEnumerable_Foreach_MultipleElements                           5 ms
IEnumerable_NonGeneric_MultipleElements                        1 ms
AddFirst_EmptyList_ShouldAddElement                            6 ms
AddFirst_SeveralElements_ShouldAddElementsCorrectly          < 1 ms
AddLast_EmptyList_ShouldAddElement                           < 1 ms
AddLast_SeveralElements_ShouldAddElementsCorrectly           < 1 ms
ForEach_EmptyList_ShouldEnumerateElementsCorrectly           < 1 ms
ForEach_MultipleElements_ShouldEnumerateElementsCorrectly      1 ms
ForEach_SingleElement_ShouldEnumerateElementsCorrectly       < 1 ms
RemoveFirst_EmptyList_ShouldThrowException                     2 ms
RemoveFirst_OneElement_ShouldMakeListEmpty                   < 1 ms
RemoveFirst_SeveralElements_ShouldRemoveElementsCorrectly    < 1 ms
RemoveLast_EmptyList_ShouldThrowException                    < 1 ms
RemoveLast_OneElement_ShouldMakeListEmpty                    < 1 ms
RemoveLast_SeveralElements_ShouldRemoveElementsCorrectly     < 1 ms
ToArray_EmptyList_ShouldReturnEmptyArray                     < 1 ms
ToArray_NonEmptyList_ShouldReturnArray                       < 1 ms

Summary
Last Test Run Failed (Total Run Time 0:00:00)
2 Tests Failed
15 Tests Passed
```

Problem 13. Implement IEnumerable<T>

Collection classes in C# and .NET Framework (like arrays, lists and sets) implement the system interface **IEnumerable<T>** to enable the **foreach** iteration over their elements. The C# keyword **foreach** calls internally the following method:

```
public IEnumerator<T> GetEnumerator()
{
    // TODO: implement me
}
```

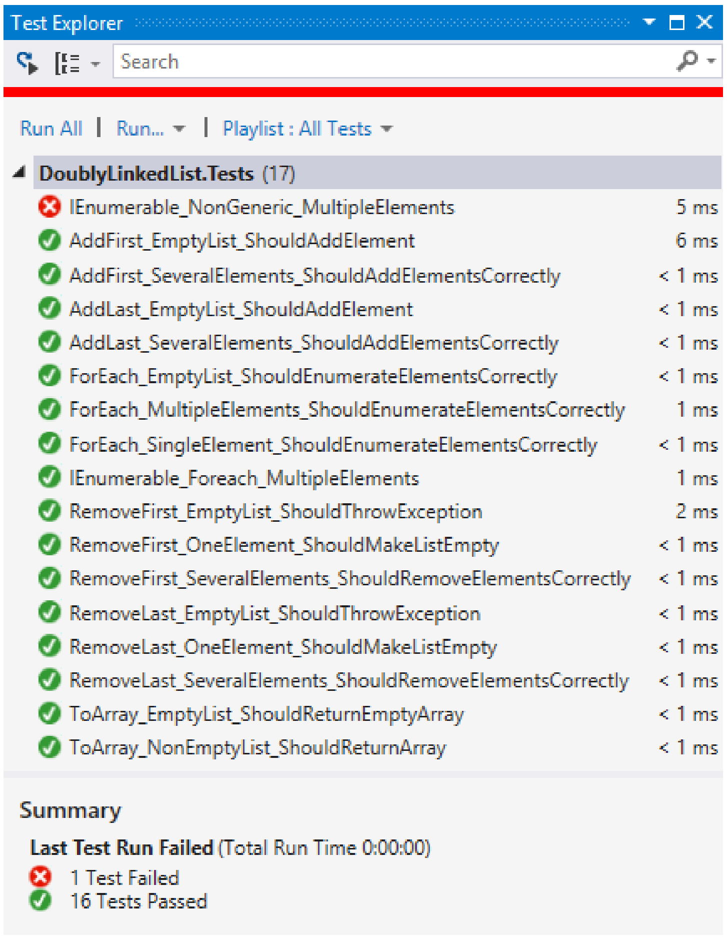
This method returns **IEnumerator<T>**, which can move to the next element and read the current element. In programming, this is known as **"iterator"** pattern (**enumerator**).

We will use the "**yield return**" C# statement to simplify the implementation of the iterator:

```
public IEnumerator<T> GetEnumerator()
{
    var currentNode = this.head;
    while (currentNode != null)
    {
        yield return currentNode.Value;
        currentNode = currentNode.NextNode;
    }
}
```

The above code will enable using the **DoublyLinkedList<T>** in **foreach** loops.

Now, we have added the iterator over the list elements, so let's **run the unit tests** again:

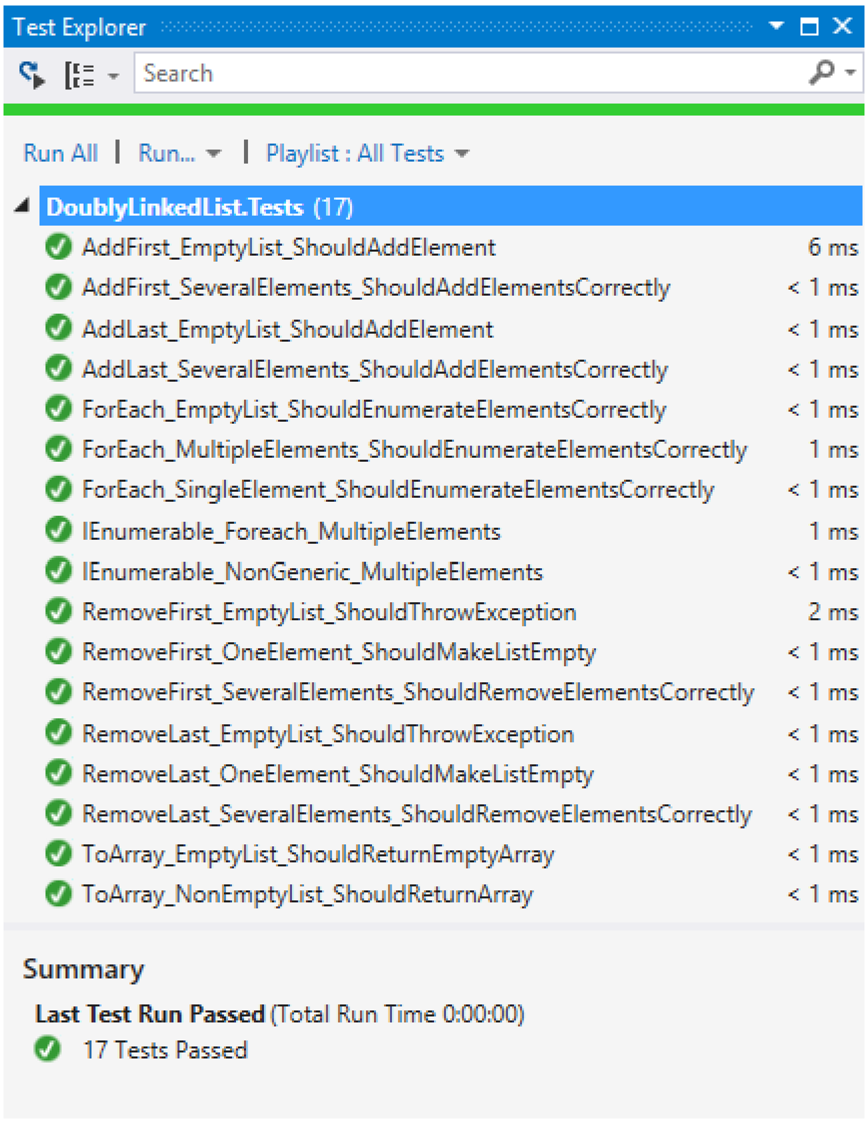


```
DoublyLinkedList.Tests (17)
✗ IEnumerable_NonGeneric_MultipleElements                        5 ms
✓ AddFirst_EmptyList_ShouldAddElement                            6 ms
✓ AddFirst_SeveralElements_ShouldAddElementsCorrectly          < 1 ms
✓ AddLast_EmptyList_ShouldAddElement                           < 1 ms
✓ AddLast_SeveralElements_ShouldAddElementsCorrectly           < 1 ms
✓ ForEach_EmptyList_ShouldEnumerateElementsCorrectly           < 1 ms
✓ ForEach_MultipleElements_ShouldEnumerateElementsCorrectly      1 ms
✓ ForEach_SingleElement_ShouldEnumerateElementsCorrectly       < 1 ms
✓ IEnumerable_Foreach_MultipleElements                           1 ms
✓ RemoveFirst_EmptyList_ShouldThrowException                     2 ms
✓ RemoveFirst_OneElement_ShouldMakeListEmpty                   < 1 ms
✓ RemoveFirst_SeveralElements_ShouldRemoveElementsCorrectly    < 1 ms
✓ RemoveLast_EmptyList_ShouldThrowException                    < 1 ms
✓ RemoveLast_OneElement_ShouldMakeListEmpty                    < 1 ms
✓ RemoveLast_SeveralElements_ShouldRemoveElementsCorrectly     < 1 ms
✓ ToArray_EmptyList_ShouldReturnEmptyArray                     < 1 ms
✓ ToArray_NonEmptyList_ShouldReturnArray                       < 1 ms

Summary
Last Test Run Failed (Total Run Time 0:00:00)
✗ 1 Test Failed
✓ 16 Tests Passed
```

We have all but one unit tests passed. The last unimplemented method is the **non-generic enumerator**:

```
IEnumerator IEnumerable.GetEnumerator()
{
    return this.GetEnumerator();
}
```

Finally, **run the unit tests** to ensure all of them pass correctly:



```
DoublyLinkedList.Tests (17)
AddFirst_EmptyList_ShouldAddElement                              6 ms
AddFirst_SeveralElements_ShouldAddElementsCorrectly            < 1 ms
AddLast_EmptyList_ShouldAddElement                             < 1 ms
AddLast_SeveralElements_ShouldAddElementsCorrectly             < 1 ms
ForEach_EmptyList_ShouldEnumerateElementsCorrectly             < 1 ms
ForEach_MultipleElements_ShouldEnumerateElementsCorrectly        1 ms
ForEach_SingleElement_ShouldEnumerateElementsCorrectly         < 1 ms
IEnumerable_Foreach_MultipleElements                             1 ms
IEnumerable_NonGeneric_MultipleElements                        < 1 ms
RemoveFirst_EmptyList_ShouldThrowException                       2 ms
RemoveFirst_OneElement_ShouldMakeListEmpty                     < 1 ms
RemoveFirst_SeveralElements_ShouldRemoveElementsCorrectly      < 1 ms
RemoveLast_EmptyList_ShouldThrowException                      < 1 ms
RemoveLast_OneElement_ShouldMakeListEmpty                      < 1 ms
RemoveLast_SeveralElements_ShouldRemoveElementsCorrectly       < 1 ms
ToArray_EmptyList_ShouldReturnEmptyArray                       < 1 ms
ToArray_NonEmptyList_ShouldReturnArray                         < 1 ms

Summary
Last Test Run Passed (Total Run Time 0:00:00)
17 Tests Passed
```

Congratulations! You have implemented your doubly linked list.