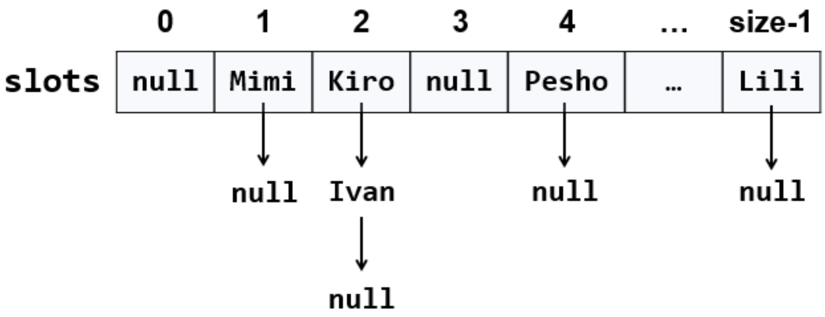
Exercises: Implement Hash Table with Chaining

This document defines the **in-class exercises** assignments for the ["Data Structures" course @ Software University](#).

You have to implement a **hash table** that uses **chaining in a linked list** as collision resolution strategy:



The hash table will hold its **elements** (key-value pairs) in a class **KeyValue<TKey, TValue>**. The hash table will consist of **slots**, each holding a **linked list of key-value pairs**: **LinkedList<KeyValue<TKey, TValue>>**.

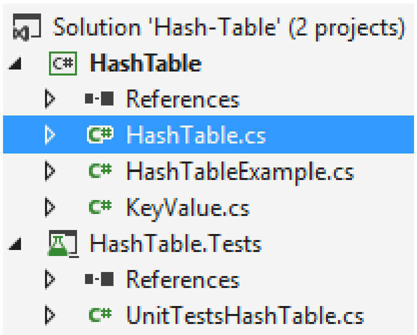
Problem 1. Learn about Hash Tables in Wikipedia

Before starting, get familiar with the concept of **hash table**: https://en.wikipedia.org/wiki/Hash_table. Note that there are many collision resolution strategies like chaining and open addressing. We will use one of the simplest strategies: **chaining** elements with collisions in a linked list.

The typical **operations** over a hash table are **add** or **replace**, **find** and **remove**. Additional operations are **enumerate all elements**, **enumerate all keys**, **enumerate all values** and **get count**. Let's start coding!

Problem 2. HashTable<TKey, TValue> – Project Skeleton

You are given a **Visual Studio project skeleton** (unfinished project) holding the class **KeyValue<TKey, TValue>**, the unfinished class **HashTable<TKey, TValue>** and **unit tests** for its entire functionality. The project holds the following assets:

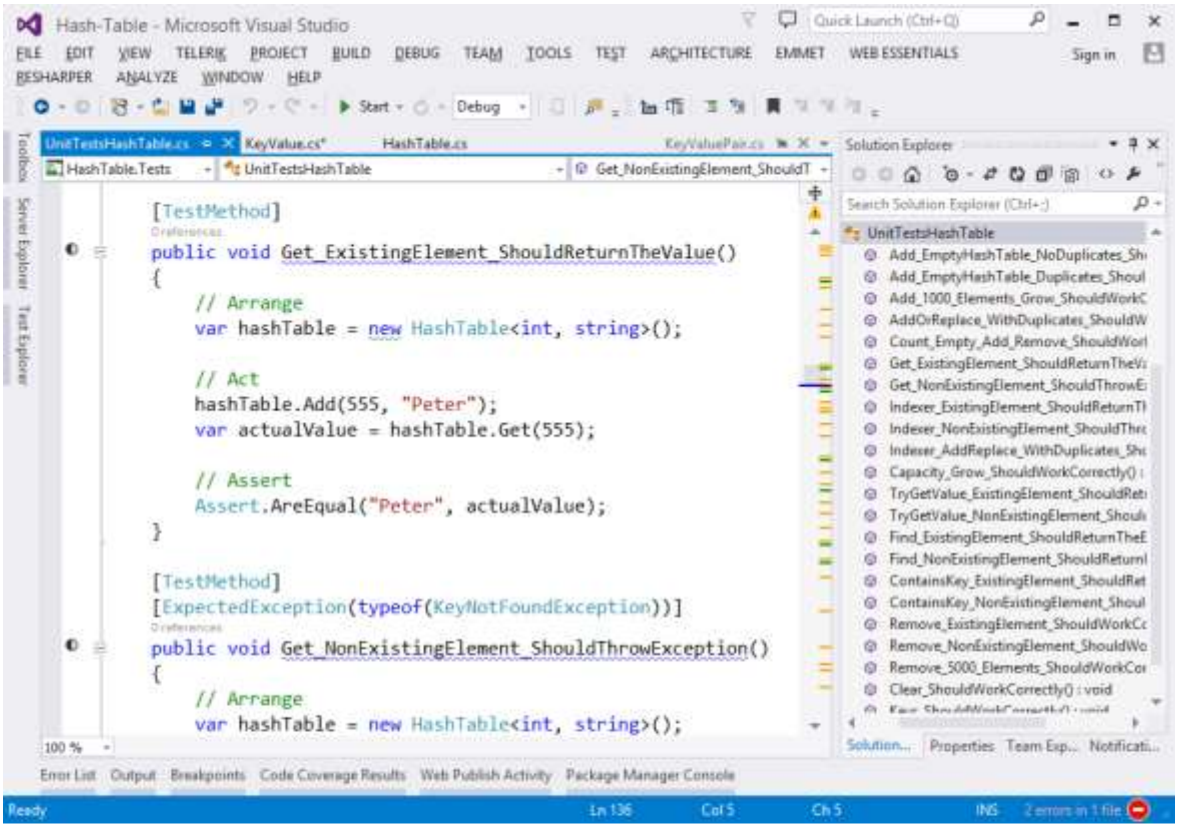


The project skeleton opens correctly in **Visual Studio 2013** but can be open in other Visual Studio versions as well and also can run in **SharpDevelop** and **Xamarin Studio**. Your goal is to implement the missing functionality in order to finish the project.

First, let's take a look at the **KeyValue<TKey, TValue>** class. It holds a **key-value pair** of parameterized types **TKey** and **TValue**. To enable comparing key-value pairs, the class implements **Equals(…)** and **GetHashCode()**. It also has **ToString()** method to enable printing it on the console and view it inside the Visual Studio debugger. Note that this class is different than the .NET structure **System.Collections.Generic.KeyValuePair<TKey, TValue>**. First, our class is mutable (can modify the key and value), and second, it is class, not structure, so it can have a **null** value (missing value). The **KeyValue<TKey, TValue>** class comes out-of-the-box with the project skeleton, so you don't have to change it:

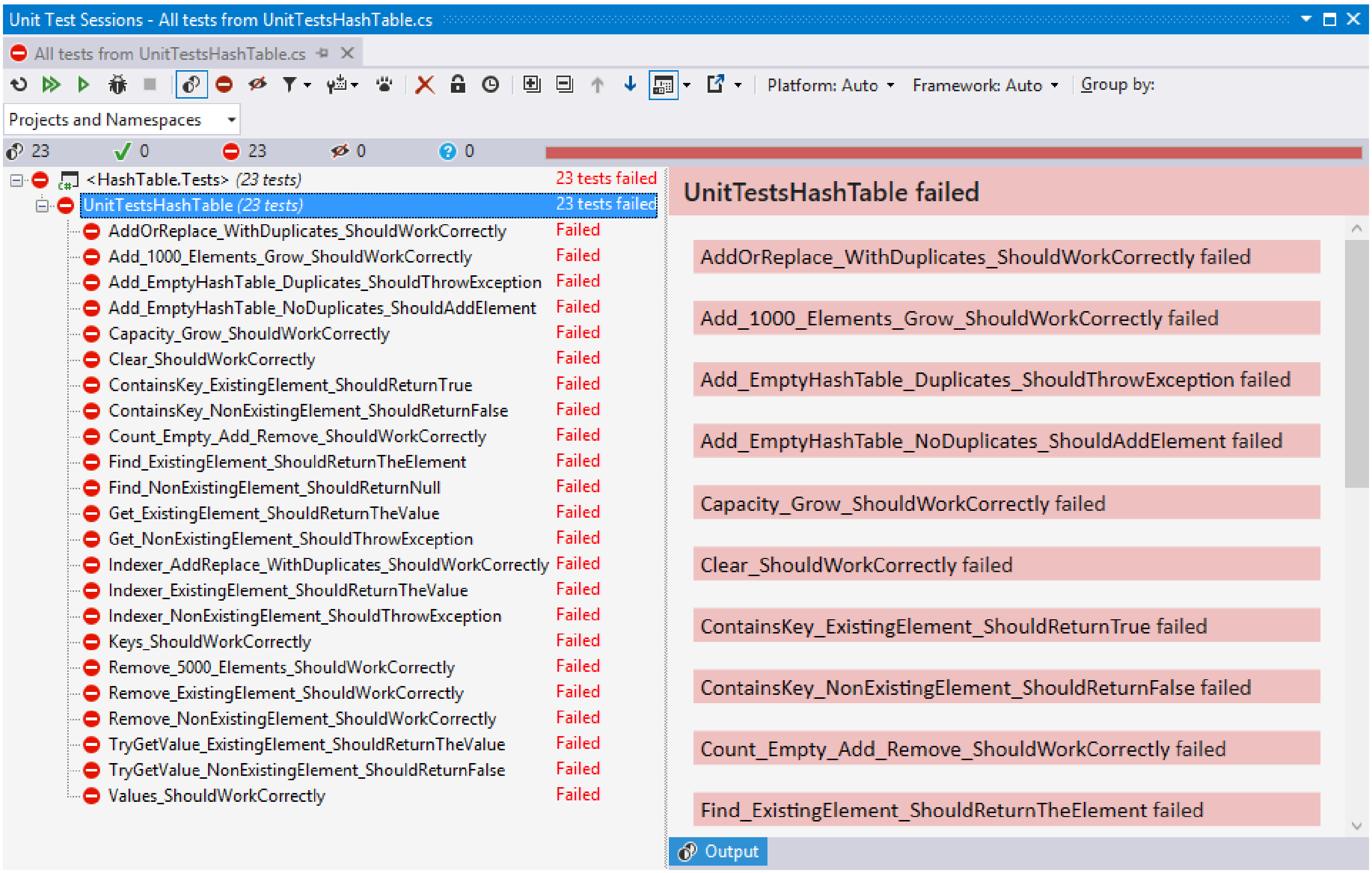
```
public class KeyValue<TKey, TValue>
{
    6 references
    public TKey Key { get; set; }
    6 references
    public TValue Value { get; set; }

    10 references
    public KeyValue(TKey key, TValue value)
    {
        this.Key = key;
        this.Value = value;
    }

    0 references
    public override bool Equals(object other)...

    2 references
    public override int GetHashCode()...

    1 reference
    private int CombineHashCodes(int h1, int h2)...

    1 reference
    public override string ToString()...
}
```

The project comes also with **unit tests** covering the entire functionality of the hash table (see the class **UnitTestsHashTable**):



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

Run the unit tests from the **HashTable.Tests** project. All of them should fail:



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

Problem 4. Define the Hash Table Internal Data

The first step is to define the inner **data** that holds the hash table elements:

- **`LinkedList<KeyValue<TKey, TValue>>[] slots`** – an array that holds the slots in the hash table
  - Each slot is either empty (**`null`**) or holds a **linked list** of elements with the same hash code
- **`int Count`** – holds the number of elements in the hash table
- **`int Capacity`** – holds the number of slots in the hash table
- Thus, the hash table **fill factor** can be calculated by **`Count / Capacity`**

The code might look like this:

```
public class HashTable<TKey, TValue> : IEnumerable<KeyValue<TKey, TValue>>
{
    private LinkedList<KeyValue<TKey, TValue>>[] slots;

    17 references | 0/5 passing
    public int Count { get; private set; }

    3 references | 0/1 passing
    public int Capacity
    {
        get
        {
            return this.slots.Length;
        }
    }
```

Problem 5. Implement the Hash Table Constructor

Now, let's implement the hash table **constructor**. Its purpose is to allocate the slots that will hold the hash table elements. The hash table constructor has two forms:

- Parameterless constructor – should allocate 16 slots (16 is the default initial hash table capacity)
- Constructor with parameter **`capacity`** – allocates the specified capacity in the underlying array (slots)

The code might look like the sample below (note that we have combined the above described two constructors in a single constructor through a default parameter value). We also introduced the constant **`InitialCapacity`** to hold the initial hash table capacity (16 elements):

```
public const int InitialCapacity = 16;

24 references | 0/23 passing
public HashTable(int capacity = InitialCapacity)
{
    this.slots = new LinkedList<KeyValue<TKey, TValue>>[capacity];
    this.Count = 0;
}
```

Problem 6. Implement the Add(key, value) Method

Now, we are ready to implement the most important method **`Add(key, value)`** that inserts a new element in the hash table. It should take into account several things:

- Detect **collisions** and resolve them through **chaining** the elements in a linked list.
- Detect **duplicated keys** and throw an exception.
- **Grow** the hash table if needed (resize to double capacity when the fill factor is too high).

The **`Add(key, value)`** method might look like this:

```
public void Add(TKey key, TValue value)
{
    GrowIfNeeded();
    int slotNumber = this.FindSlotNumber(key);
    if (this.slots[slotNumber] == null)
    {
        this.slots[slotNumber] = new LinkedList<KeyValue<TKey, TValue>>();
    }
    foreach (var element in this.slots[slotNumber])
    {
        if (element.Key.Equals(key))
        {
            throw new ArgumentException("Key already exists: " + key);
        }
    }
    var newElement = new KeyValue<TKey, TValue>(key, value);
    this.slots[slotNumber].AddLast(newElement);
    this.Count++;
}
```

How it works? First, if the hash table is full, **grow** it (resize its capacity to 2 times bigger capacity). This will be discussed later. We can leave the **`GrowIfNeeded()`** method empty:

```
private void GrowIfNeeded()
{
    // TODO: implement this later!
}
```

Next, **find the slot** that should hold the element to be added. The slot number is calculated by the **hash value** of the key. Typically, the **`GetHashCode()`** method from **`System.Object`** class in .NET framework provides hash codes calculation for the built-in types as well as for the custom types. It returns arbitrary 32-bit number. We need a number in the range [0 … size-1] so we take the modulus of the hash code:

```
private int FindSlotNumber(TKey key)
{
    var slotNumber = Math.Abs(key.GetHashCode()) % this.slots.Length;
    return slotNumber;
}
```

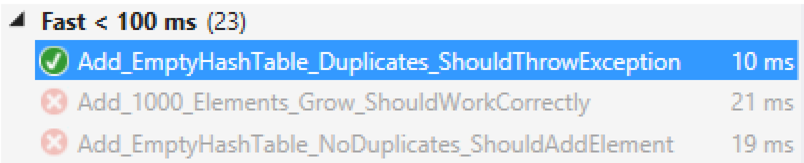
We take the absolute value because **`GetHashCode()`** sometimes return negative numbers.

Once we have the slot number, it is either empty (**`null`**) or holds a **linked list** of elements with the same hash code like the new element. In both cases, we should have in the target slot a **linked list** holding the elements with the same hash value like the **key**.

We **check for duplicated key** and throw an exception if the same key already exists. Then we **append the new element** at the end of the linked list in the target slot of the hash table and increase **`this.Count`**.

Problem 7. Run the Unit Tests

It is too early, but let's run the unit tests. We will have one test passed:



To have more tests passed, we need to implement the enumerator that return all hash table elements.

Problem 8. Implement the Enumerator (IEnumerable<T>)

Now let's implement the enumerator: a method that passed through all elements in the hash table exactly once. In C# and .NET Framework this is achieved by implementing the **`IEnumerable<T>`** interface. The hash table holds key-value pairs (**`KeyValue<TKey, TValue>`**) elements, so we need to implement the interface **`IEnumerable<KeyValue<TKey, TValue>>`**. It holds two methods:

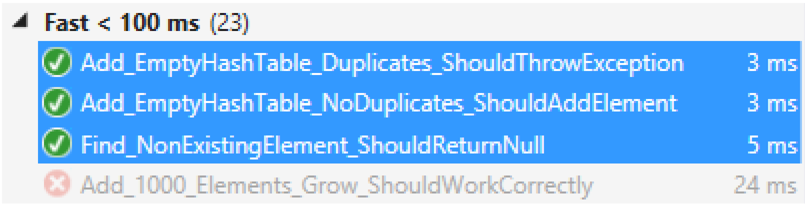
```
IEnumerator IEnumerable.GetEnumerator()
{
    return this.GetEnumerator();
}
```

```csharp
public IEnumerator<KeyValue<TKey, TValue>> GetEnumerator()
{
    foreach (var elements in this.slots)
    {
        if (elements != null)
        {
            foreach (var element in elements)
            {
                yield return element;
            }
        }
    }
}
```

The first method calls the second. The second does the job: it **passes through all slots** and **through all elements** in the linked list in each slot and returns the elements in a sequence (as a stream). It uses the **`yield return`** construct in C# (generator function) to return the elements "on demand" upon request. Learn more about **generator functions** and **`yield return`** from Wikipedia: https://en.wikipedia.org/wiki/Generator_(computer_programming).

Problem 9. Run the Unit Tests Again

Now let's run the unit tests again. We will have passed the tests for the **`Add(key, value)`** operation:



To have more tests passed, we need to implement the other hash table operations.

Problem 10. Implement Find(key)

Let's implement the second most important operation after adding a key-value pair – **finding an element by key**. The **`Find(key)`** method should either **return the element** by its key or **return `null`** if the key does not exist:

```csharp
public KeyValue<TKey, TValue> Find(TKey key)
{
    int slotNumber = this.FindSlotNumber(key);
    var elements = this.slots[slotNumber];
    if (elements != null)
    {
        foreach (var element in elements)
        {
            if (element.Key.Equals(key))
            {
                // TODO: key found --> return the element
            }
        }
    }
    // TODO: Key not found --> return null
}
```

The above code works as follows:

1. **Finds the slot** holding the specified key (by calculating the hash code modulus the hash table size).

2. **Passes through all elements in the target slot** (in its linked list) and compare their key with the target key.

Note: the code is intentionally unfinished. **Fix the TODOs** yourself.

Problem 11. Run the Unit Tests Again

Run the unit tests again to check whether **`Find(key)`** works as expected. Two more tests should pass:

Fast < 100 ms (23)	
Add_EmptyHashTable_Duplicates_ShouldThrowException	10 ms
Add_EmptyHashTable_NoDuplicates_ShouldAddElement	6 ms
Find_ExistingElement_ShouldReturnTheElement	2 ms
Find_NonExistingElement_ShouldReturnNull	10 ms
Add_1000_Elements_Grow_ShouldWorkCorrectly	24 ms
AddOrReplace_WithDuplicates_ShouldWorkCorrectly	3 ms

Problem 12. Implement Get(key), TryGetValue(key, out value) and ContainsKey(key) Methods

Once we have the **`Find(key)`** method, it is easy to implement the methods that directly depend on it:

- **`Get(key)`** – returns the element by given key or throws and exception when the key does not exist
- **`TryGetValue(key, out value)`** – conditional find by key
  - Returns **true** + the **value** if the ey exists in the hash table
  - Returns false if the key does not exist in the hash table
- **`ContainsK(key)`** – returns whether the key exists in the hash table

Let's start with the **`Get(key)`** method:

```
public TValue Get(TKey key)
{
    var element = this.Find(key);
    if (element == null)
    {
        // TODO: throw KeyNotFoundException
    }
    return element.Value;
}
```

Implement the **`TryGetValue(key, out value)`** method in similar way:

```
public bool TryGetValue(TKey key, out TValue value)
{
    [illegible]
}
```

Notes:

- The code above is **intentionally blurred**. Implement it yourself!
- The method should always return a value in the **`value`** parameter. It is **output parameter**. The C# compiler will not allow you to leave it untouched. Use the expression **`default(TValue)`** when you need to return a **neutral value** of type **`TValue`** (**`null`** for classes or **`0`** for numbers).

The **`ContainsKey(key)`** method is trivial. Implement it yourself:

```
public bool ContainsKey(TKey key)
{

}
```

Problem 13. Run the Unit Tests Again

Run the unit tests again to check whether the new methods work as expected. Several more tests should pass:

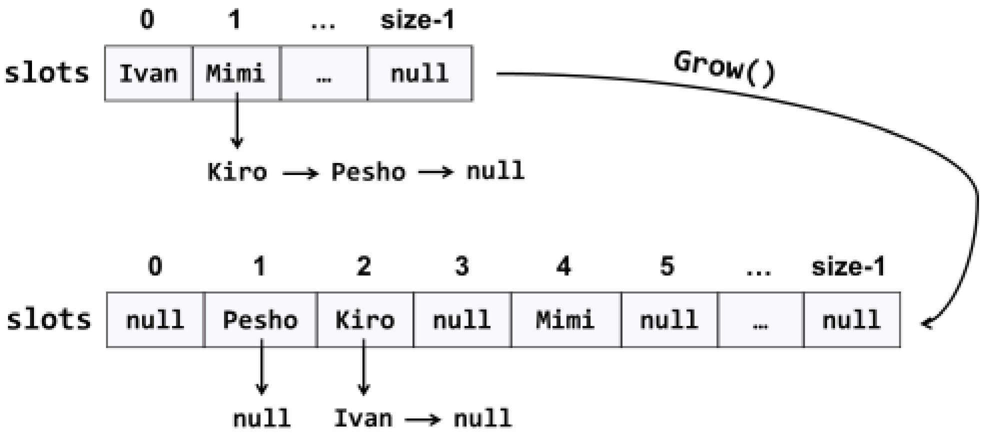
Fast < 100 ms (23)	
Add_EmptyHashTable_Duplicates_ShouldThrowException	5 ms
Add_EmptyHashTable_NoDuplicates_ShouldAddElement	6 ms
ContainsKey_ExistingElement_ShouldReturnTrue	3 ms
ContainsKey_NonExistingElement_ShouldReturnFalse	< 1 ms
Find_ExistingElement_ShouldReturnTheElement	2 ms
Find_NonExistingElement_ShouldReturnNull	1 ms
Get_ExistingElement_ShouldReturnTheValue	12 ms
Get_NonExistingElement_ShouldThrowException	< 1 ms
TryGetValue_ExistingElement_ShouldReturnTheValue	< 1 ms
TryGetValue_NonExistingElement_ShouldReturnFalse	< 1 ms
Add_1000_Elements_Grow_ShouldWorkCorrectly	26 ms

Problem 14. Implement the GrowIfNeeded() and Grow() Methods

The **`GrowIfNeeded()`** method check whether the hash table should grow. The hash table should grow when it has filled its capacity to **more than 75%** (load factor > 75%) and we are trying to add a new element. In this case, it first calls **`Grow()`**, otherwise does nothing:

```
public const float LoadFactor = 0.75f;

1 reference
private void GrowIfNeeded()
{
    if ((float)(this.Count + 1) / this.Capacity > LoadFactor)
    {
        // Hash table loaded too much --> resize
        this.Grow();
    }
}
```

The **`Grow()`** method allocates a **new hash table** with **double capacity** and adds the old elements in the new hash table, then replaces the old hash table with the new one:

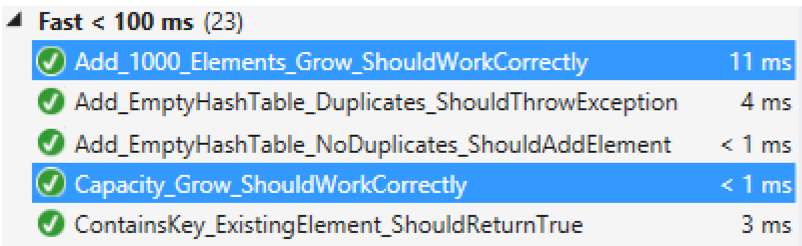


The code might look like this:

```
private void Grow()
{
    var newHashTable = new HashTable<TKey, TValue>(2 * this.Capacity);
    foreach (var element in this)
    {
        newHashTable.Add(element.Key, element.Value);
    }
    this.slots = newHashTable.slots;
    this.Count = newHashTable.Count;
}
```

Problem 15. Run the Unit Tests Again

Run the unit tests again to check whether the methods testing the "grow" functionality work as expected:



Problem 16. Implement AddOrReplace(key, value)

The method **`AddOrReplace(key, value)`** is very similar to the **`Add(key, value)`** method. The only difference is the **`Add(key, value)`** throws and exception when the key is found to already exist in the hash table, while in the same situation **`AddOrReplace(key, value)`** replaces the **value** in the element holding the **key**, with the **new value** passed as argument.

Hint: copy / paste the code from **`Add(key, value)`** and slightly modify its logic.

Implement **`AddOrReplace(key, value)`** yourself. The code below is intentionally blurred:

```
public bool AddOrReplace(TKey key, TValue value)
{
    GrowIfNeeded();
    int slotNumber = this.FindSlotNumber(key);
    if (this.slots[slotNumber] == null)
    {
        this.slots[slotNumber] = new LinkedList<KeyValue<TKey, TValue>>();
    }
    foreach (var element in this.slots[slotNumber])
    {
        if (element.Key.Equals(key))
        {
            // Replace an existing value with the new value
            element.Value = value;
            return false;
        }
    }
    var newElement = new KeyValue<TKey, TValue>(key, value);
    this.slots[slotNumber].AddLast(newElement);
    this.Count++;
    return true;
}
```

Problem 17. Run the Unit Tests Again

Run the unit tests again to check whether the "add or replace" functionality work as expected:

✔ Add_EmptyHashTable_NoDuplicates_ShouldAddElement	11 ms
✔ AddOrReplace_WithDuplicates_ShouldWorkCorrectly	< 1 ms
✔ Capacity_Grow_ShouldWorkCorrectly	< 1 ms

Problem 18. Indexer this[key]

Now we are ready to implement the indexer **this[key]**. It is a special method that accesses the hash table indexed by key. It does two things:

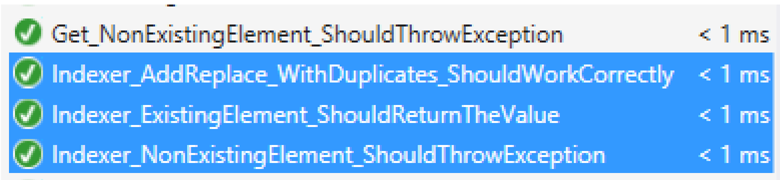
- **get** by **key** – returns the **value** by given **key** or exception when the key is not found.
- **set** a **value** by **key** – adds or replace the **value** by given **key**.

We already have methods **Get(key)** and **AddOrReplace(key, value)**, so the indexer becomes is trivial:

```
public TValue this[TKey key]
{
    get
    {
        // TODO: return the value by key
    }
    set
    {
        // TODO: add or replace the value by key
    }
}
```

Problem 19. Run the Unit Tests Again

Run the unit tests again to check whether the "indexer" functionality work as expected:



Problem 20. Implement Remove(key)

The next important functionality waiting to be implemented is **removing an element by its key**. The method **`Remove(key)`** should either:

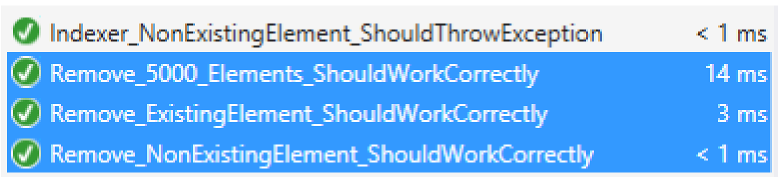
- Successfully **remove the element** (when the key exists) from the hash table and return **`true`**.
- Return **`false`** when the key does not exist in the hash table.

The **`Remove(key)`** method is not trivial. It should first **find the slot** that is expected to hold the key, then **traverse the linked list** from its first to its last element and **remove the element** is case the key is found and return **`true`**. Otherwise, it should return **`false`**:

```
public bool Remove(TKey key)
{
    int slotNumber = this.FindSlotNumber(key);
    var elements = this.slots[slotNumber];
    if (elements != null)
    {
        var currentElement = elements.First;
        while (currentElement != null)
        {
            if (currentElement.Value.Key.Equals(key))
            {
                elements.Remove(currentElement);
                this.Count--;
                return true;
            }
            currentElement = currentElement.Next;
        }
    }

    return false;
}
```

Problem 21. Run the Unit Tests Again

Now **run the unit tests** again to check whether the "remove" functionality works as expected:



Problem 22. Implement Clear()

The **`Clear()`** method is trivial. It should reinitialize **`this.slots`** and **`this.Count`**, like it was initially done in the hash table constructor. Implement it yourself:

```
public void Clear()
{
    // TODO: initialize this.slots and this.Count
}
```

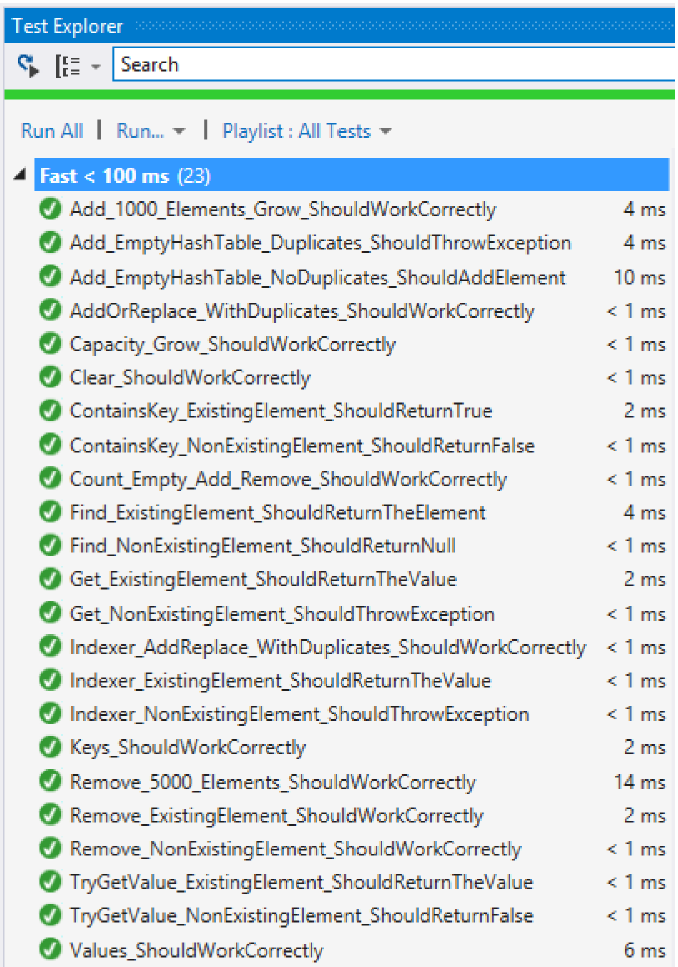
Problem 23. Implement Keys and Values

Now implement the last piece of missing functionality: **enumerating all keys and values**. You can use LINQ extension method to select the keys / values from all hash table elements. We already have enumerator that returns all elements from the hash table. We just need to filter (select) the keys / values:

```
public IEnumerable<TKey> Keys
{
    get { return this.Select(element => element.Key); }
}

3 references | 0/1 passing
public IEnumerable<TValue> Values
{
    // TODO: similar to Keys --> just select the Key from all hast table elements
}
```

Problem 24. Run the Unit Tests (Finally)

Now **run the unit tests** again (for the last time). You should have all the tests passed (green):



Congratulations! You have implemented your hash table with chaining.