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Hash Tables and Sets

Dictionaries, Hash Tables, Collisions Resolution, Sets

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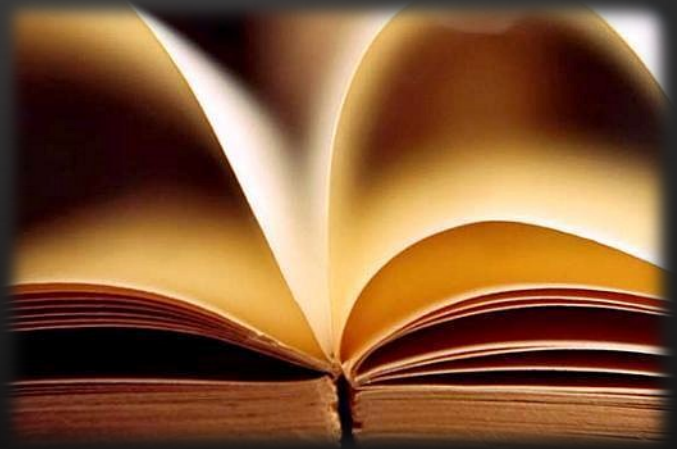

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Dictionaries

Data Structures that Map Keys to Values

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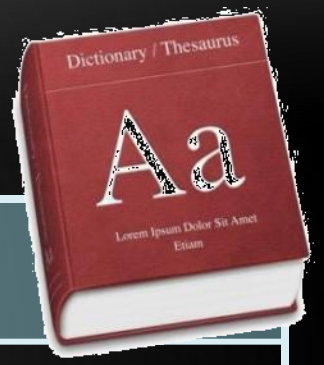
The Dictionary (Map) ADT

- The abstract data type (ADT) "dictionary" maps key to values
  - Also known as "map" or "associative array"
  - Contains a set of (key, value) pairs
- Dictionary ADT operations:
  - `Add(key, value)`
  - `FindByKey(key)` → `value`
  - `Delete(key)`
- Can be implemented in several ways
  - List, array, hash table, balanced tree, …

ADT Dictionary – Example

- Example dictionary:



Key	Value
C#	Modern object-oriented programming language for the Microsoft .NET platform
CLR	Common Language Runtime – execution engine for .NET assemblies, integral part of .NET Framework
compiler	Software that transforms a computer program to executable machine code
…	…

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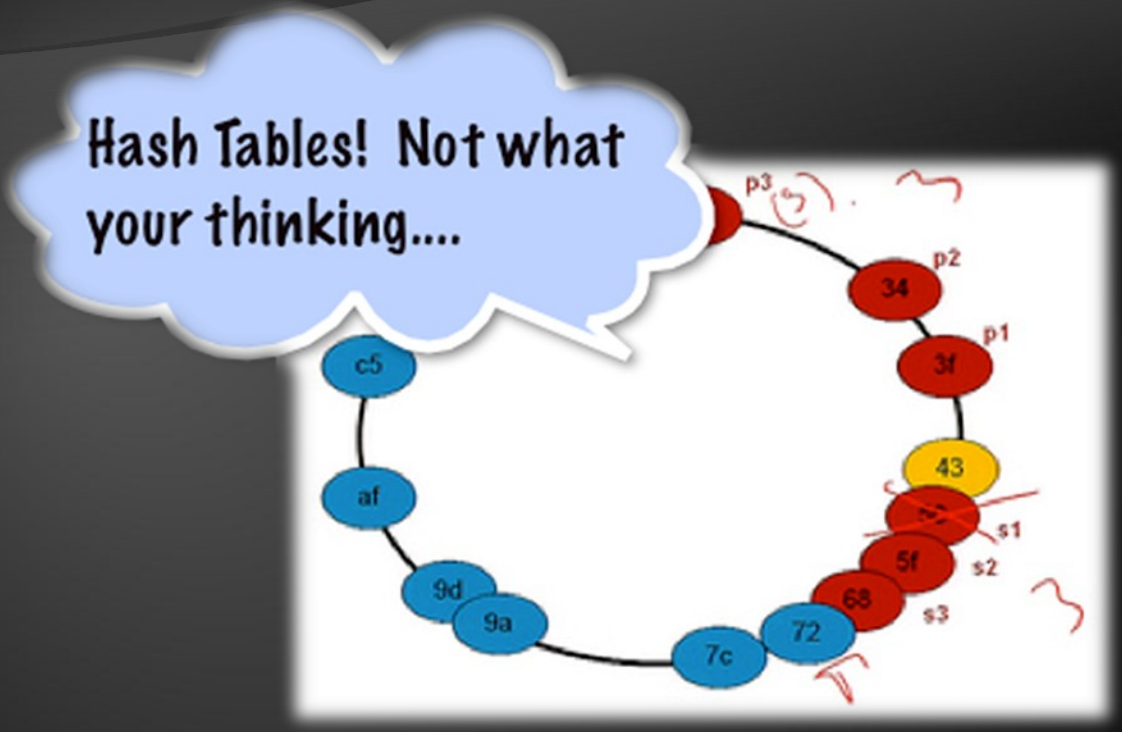

Hash Tables

What is Hash Table? How it Works?

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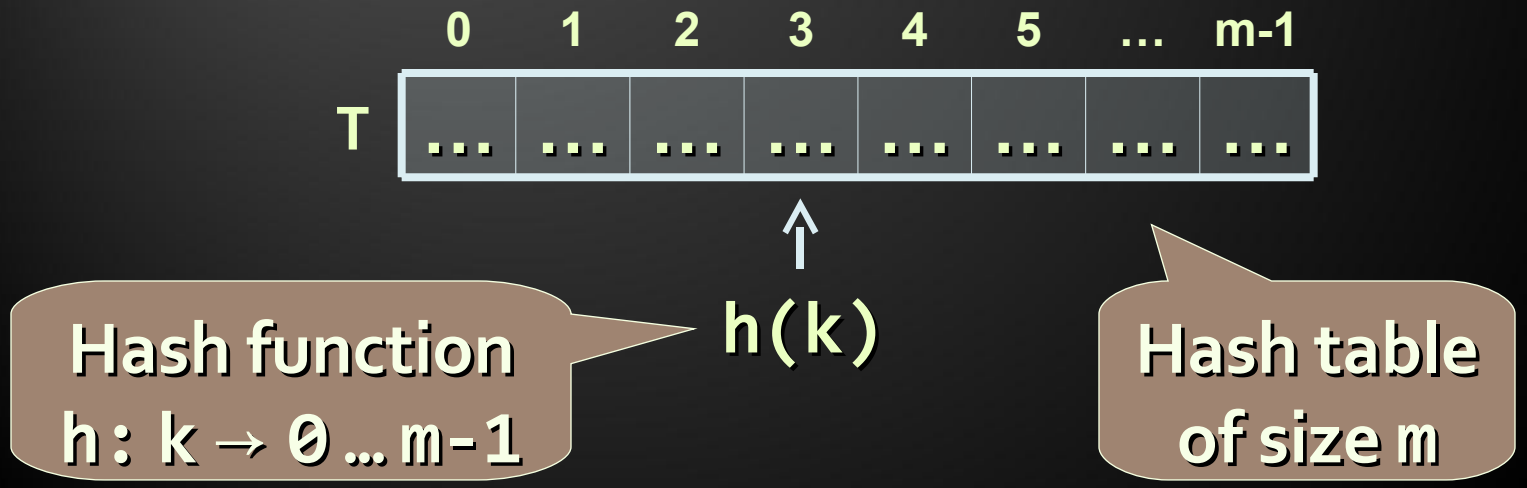
Hash Table

- A hash table is an array that holds a set of (key, value) pairs
- The process of mapping a key to a position in a table is called hashing



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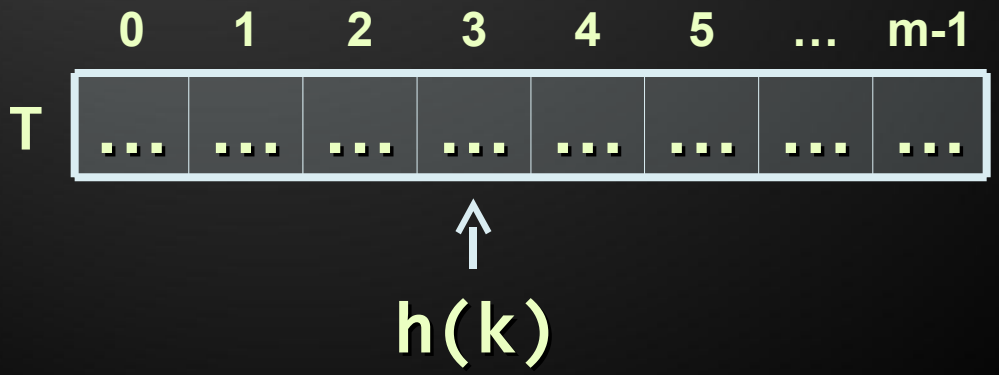
Hash Functions and Hashing

- A hash table has m slots, indexed from 0 to m-1
- A hash function h(k) maps keys to positions:
  - h: k → 0 … m-1
- For any value k in the key range and some hash function h we have h(k) = p and 0 ≤ p < m



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Hashing Functions

- Perfect hashing function (PHF)
  - h(k) : one-to-one mapping of each key k to an integer in the range [0, m-1]
  - The PHF maps each key to a distinct integer within some manageable range
- Finding a perfect hashing function is in most cases impossible
- More realistically
  - Hash function h(k) that maps most of the keys onto unique integers, but not all

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Collisions in a Hash Table

- A collision is the situation when different keys have the same hash value

  $h(k_1) = h(k_2)$ for $k_1 \neq k_2$

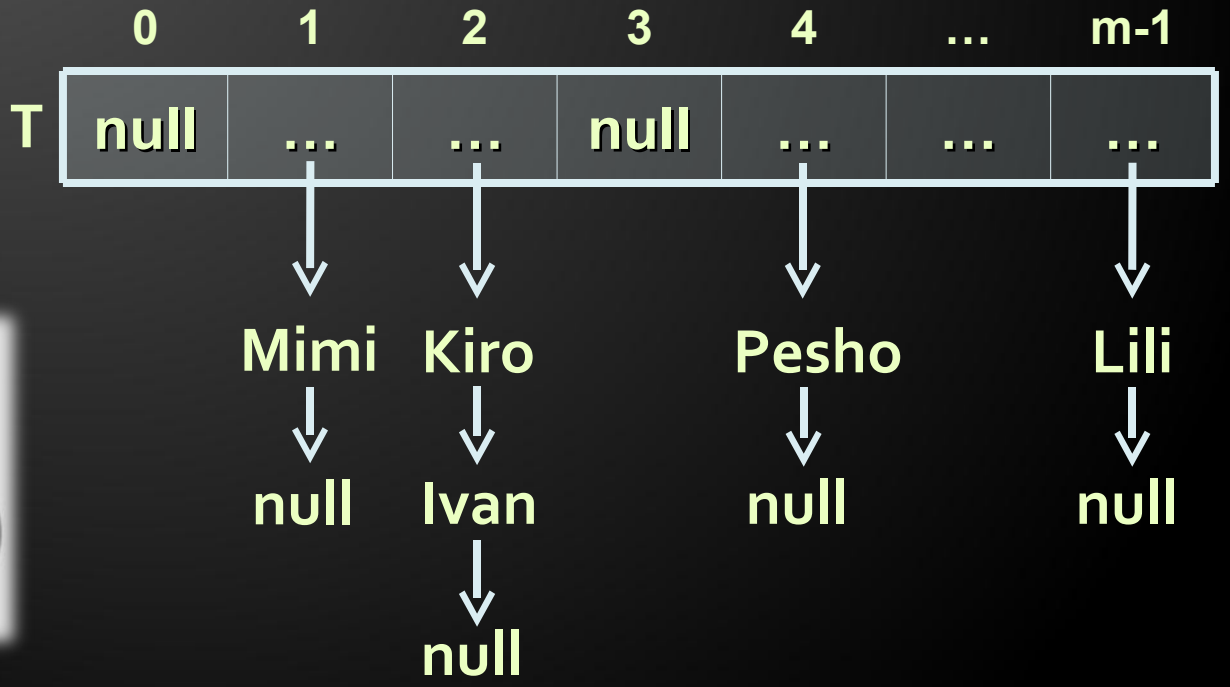
- When the number of collisions is sufficiently small, the hash tables work quite well (fast)
- Several collisions resolution strategies exist
  - Chaining in a list
  - Using the neighboring slots (linear probing)
  - Re-hashing
  - …

Collision Resolution: Chaining

h("Pesho") = 4
h("Kiro") = 2
h("Mimi") = 1
h("Ivan") = 2
h("Lili") = m-1

collision

Chaining elements in case of collision



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Hash Tables and Efficiency

- Hash tables are the most efficient implementation of ADT "dictionary"
- Add / Find / Delete take just few primitive operations
  - Speed does not depend on the size of the hash-table (constant time)
  - Example: finding an element in a hash-table with 1 000 000 elements, takes just few steps
    - Finding an element in array of 1 000 000 elements takes average 500 000 steps

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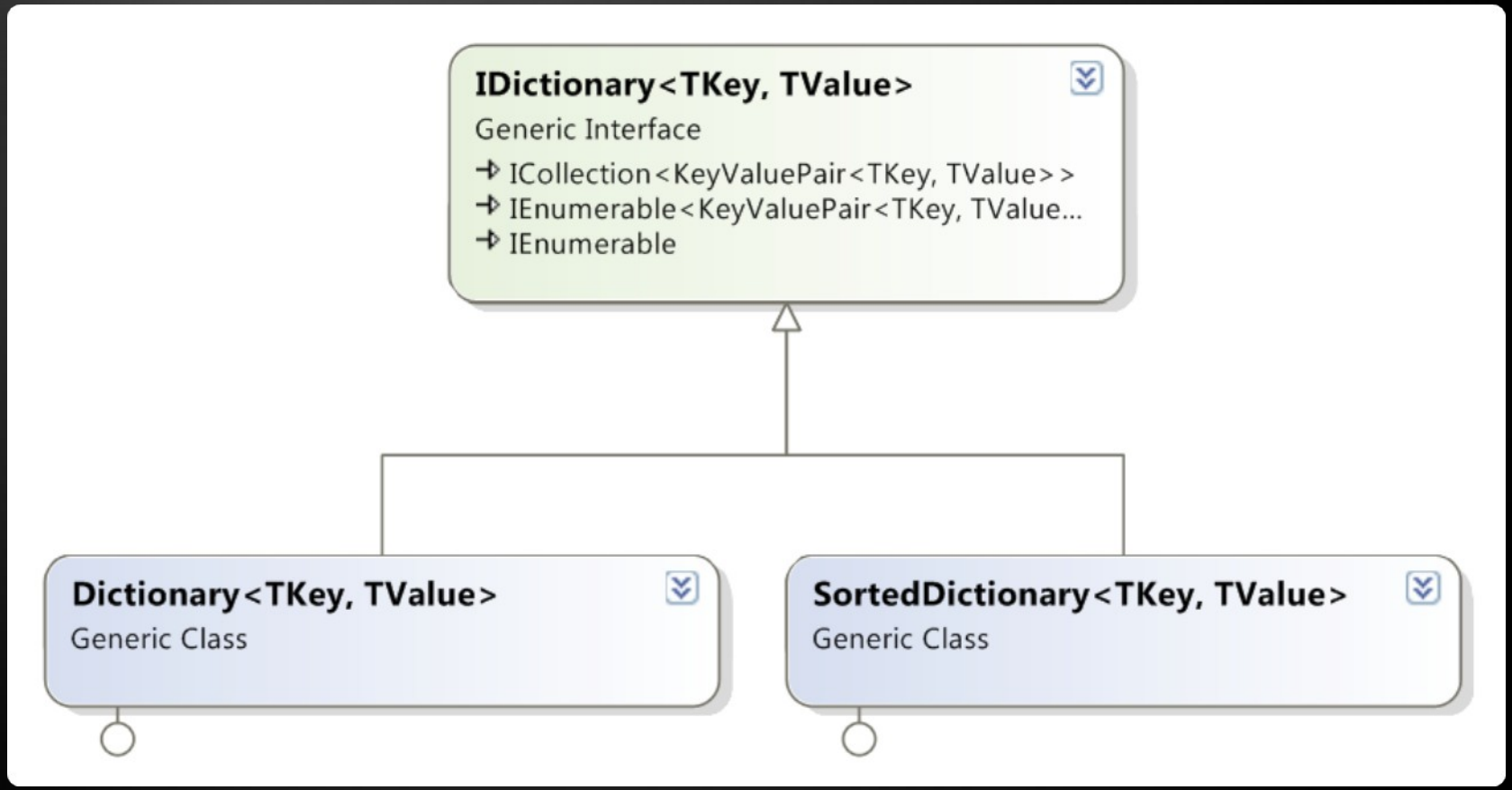
Dictionaries – Interfaces and Implementations



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Hash Tables in C#

The Dictionary<TKey,TValue> Class

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Dictionary<TKey,TValue>

- Implements the ADT dictionary as hash table
  - Size is dynamically increased as needed
  - Contains a collection of key-value pairs
  - Collisions are resolved by chaining
  - Elements have almost random order
    - Ordered by the hash code of the key
- `Dictionary<TKey,TValue>` relies on
  - `Object.Equals()` – for comparing the keys
  - `Object.GetHashCode()` – for calculating the hash codes of the keys

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Dictionary<TKey,TValue> (2)

- Major operations:
  - `Add(TKey,TValue)` – adds an element with the specified key and value
  - `Remove(TKey)` – removes the element by key
  - `this[]` – get/add/replace of element by key
  - `Clear()` – removes all elements
  - `Count` – returns the number of elements
  - `Keys` – returns a collection of the keys
  - `Values` – returns a collection of the values

Dictionary<TKey,TValue> (3)

- Major operations:
  - `ContainsKey(TKey)` – checks whether the dictionary contains given key
  - `ContainsValue(TValue)` – checks whether the dictionary contains given value
    - Warning: slow operation!
  - `TryGetValue(TKey, out TValue)`
    - If the key is found, returns it in the `TValue`
    - Otherwise returns `false`

Dictionary<TKey,TValue> – Example

```
Dictionary<string, int> studentsMarks =
  new Dictionary<string, int>();
studentsMarks.Add("Ivan", 4);
studentsMarks.Add("Peter", 6);
studentsMarks.Add("Maria", 6);
studentsMarks.Add("George", 5);

int peterMark = studentsMarks["Peter"];
Console.WriteLine("Peter's mark: {0}", peterMark);
Console.WriteLine("Is Peter in the hash table: {0}",
  studentsMarks.ContainsKey("Peter"));

Console.WriteLine("Students and grades:");
foreach (var pair in studentsMarks)
{
  Console.WriteLine("{0} --> {1}", pair.Key,
pair.Value);
}
```

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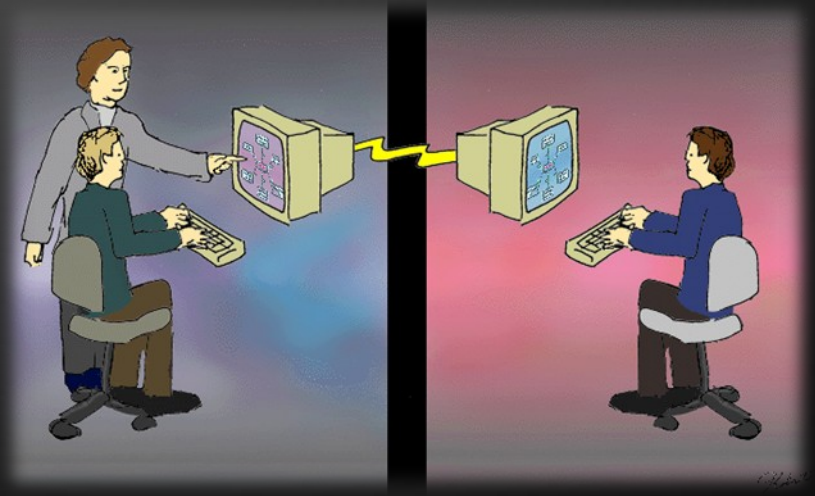
Dictionary<TKey,TValue>

Live Demo



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Counting the Words in a Text

```
string text = "a text, some text, just some text";
IDictionary<string, int> wordsCount =
  new Dictionary<string, int>();

string[] words = text.Split(' ', ',', '.');
foreach (string word in words)
{
  int count = 1;
  if (wordsCount.ContainsKey(word))
    count = wordsCount[word] + 1;
  wordsCount[word] = count;
}

foreach(var pair in wordsCount)
{
  Console.WriteLine("{0} -> {1}", pair.Key, pair.Value);
}
```

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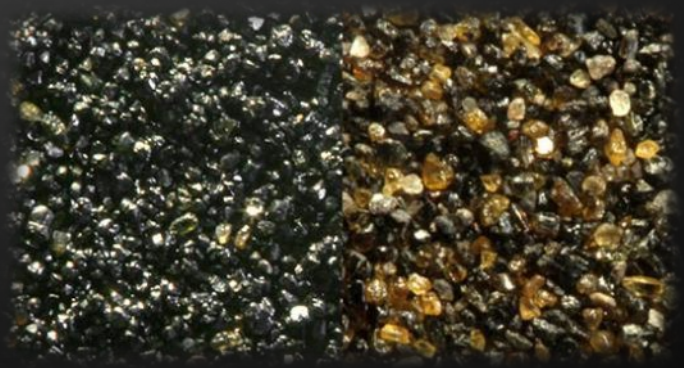
Balanced Tree Dictionaries

The SortedDictionary<TKey,TValue> Class



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SortedDictionary<TKey,TValue>

- SortedDictionary<TKey,TValue> implements the ADT "dictionary" as self-balancing search tree
  - Elements are arranged in the tree ordered by key
  - Traversing the tree returns the elements in increasing order
  - Add / Find / Delete perform $\log_2(n)$ operations
- Use SortedDictionary<TKey,TValue> when you need the elements sorted
  - Otherwise use Dictionary<TKey,TValue> – it has better performance

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Counting Words (Again)

```
string text = "a text, some text, just some text";
IDictionary<string, int> wordsCount =
  new SortedDictionary<string, int>();

string[] words = text.Split(' ', ',', '.');
foreach (string word in words)
{
  int count = 1;
  if (wordsCount.ContainsKey(word))
    count = wordsCount[word] + 1;
  wordsCount[word] = count;
}

foreach(var pair in wordsCount)
{
  Console.WriteLine("{0} -> {1}", pair.Key, pair.Value);
}
```

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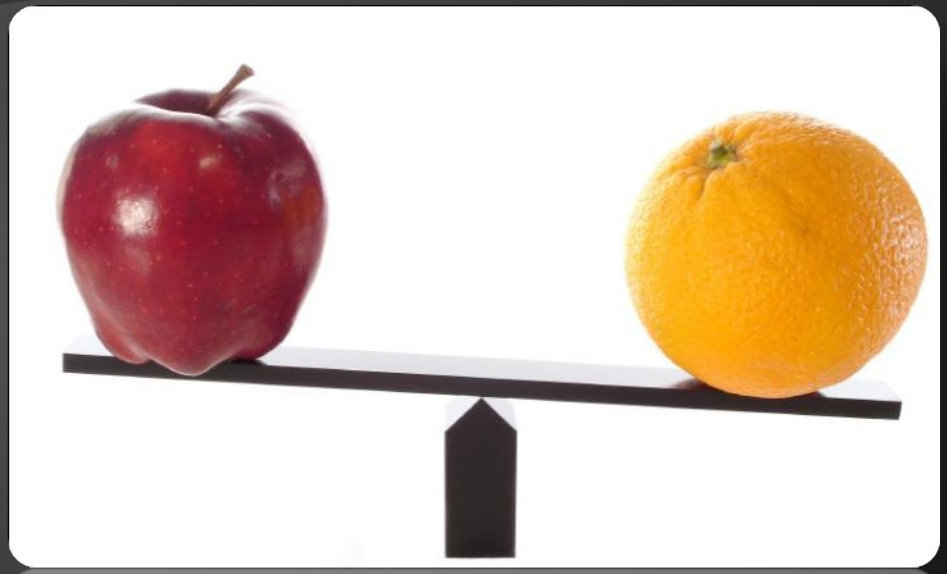

Comparing Dictionary Keys

Using custom key classes in `Dictionary<TKey, TValue>` and `SortedDictionary<TKey,TValue>`

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IComparable<T>

- Dictionary<TKey,TValue> relies on
  - Object.Equals() – for comparing the keys
  - Object.GetHashCode() – for calculating the hash codes of the keys
- SortedDictionary<TKey,TValue> relies on IComparable<T> for ordering the keys
- Built-in types like int, long, float, string and DateTime already implement Equals(), GetHashCode() and IComparable<T>
  - Other types used when used as dictionary keys should provide custom implementations

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Implementing Equals() and GetHashCode()

```
public struct Point
{
  public int X { get; set; }
  public int Y { get; set; }

  public override bool Equals(Object obj)
  {
    if (!(obj is Point) || (obj == null)) return false;
    Point p = (Point)obj;
    return (X == p.X) && (Y == p.Y);
  }

  public override int GetHashCode()
  {
      return (X << 16 | X >> 16) ^ Y;
  }
}
```

Implementing IComparable<T>

```
public struct Point : IComparable<Point>
{
  public int X { get; set; }
  public int Y { get; set; }

  public int CompareTo(Point otherPoint)
  {
    if (X != otherPoint.X)
    {
      return this.X.CompareTo(otherPoint.X);
    }
    else
    {
      return this.Y.CompareTo(otherPoint.Y);
    }
  }
}
```

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Sets

Sets of Elements

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Set and Bag ADTs

- The abstract data type (ADT) "set" keeps a set of elements with no duplicates
- Sets with duplicates are also known as ADT "bag"
- Set operations:
  - `Add(element)`
  - `Contains(element)` → `true / false`
  - `Delete(element)`
  - `Union(set) / Intersect(set)`
- Sets can be implemented in several ways
  - List, array, hash table, balanced tree, …

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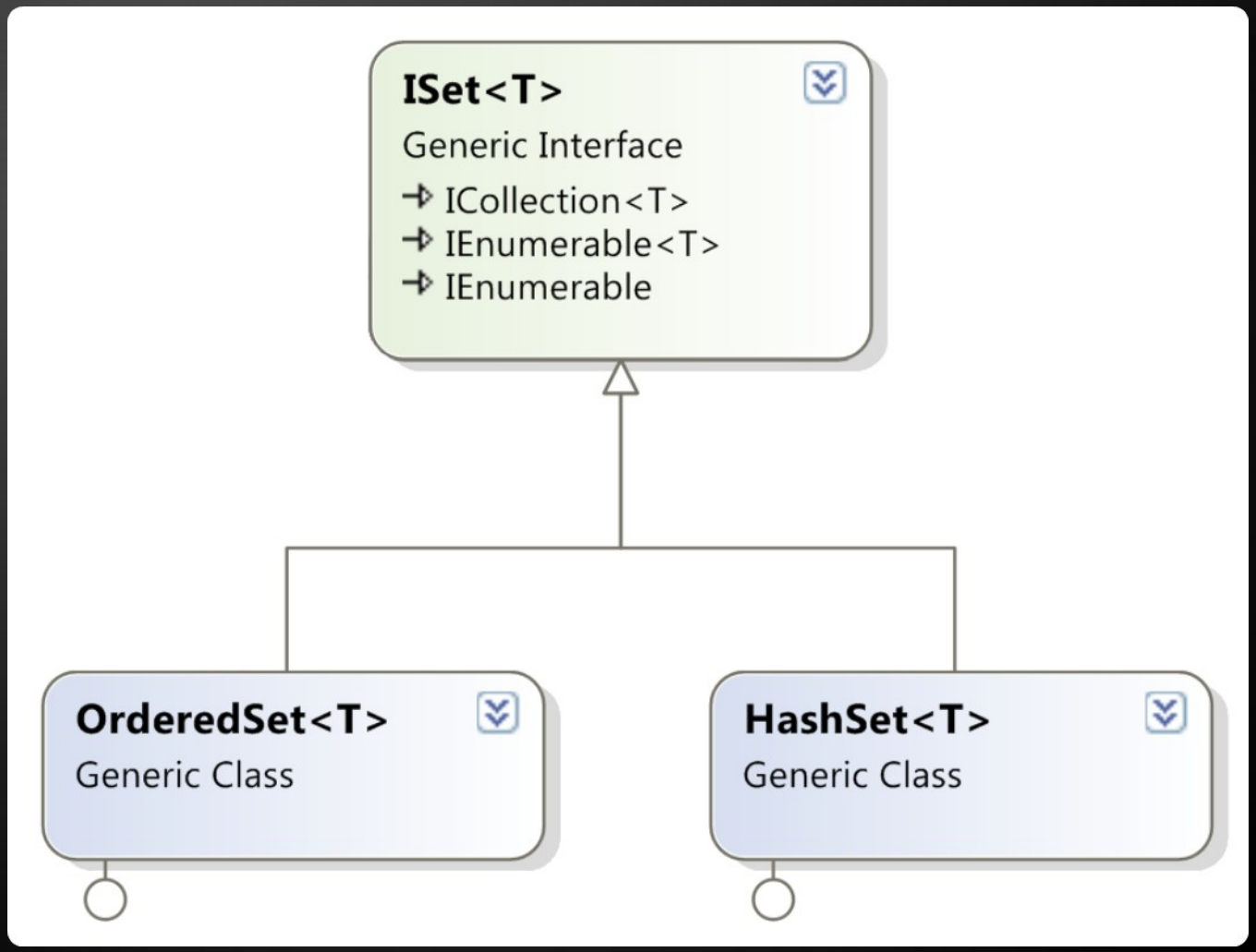
Sets – Interfaces and Implementations



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HashSet<T>

- HashSet<T> implements ADT set by hash table
  - Elements are in no particular order
- All major operations are fast:
  - Add(element) – appends an element to the set
    - Does nothing if the element already exists
  - Remove(element) – removes given element
  - Count – returns the number of elements
  - UnionWith(set) / IntersectWith(set) – performs union / intersection with another set

HashSet<T> – Example

```
ISet<string> firstSet = new HashSet<string>(
    new string[] { "SQL", "Java", "C#", "PHP"  });
ISet<string> secondSet = new HashSet<string>(
    new string[] { "Oracle", "SQL", "MySQL"  });

ISet<string> union = new HashSet<string>(firstSet);
union.UnionWith(secondSet);
PrintSet(union); // SQL Java C# PHP Oracle MySQL

private static void PrintSet<T>(ISet<T> set)
{
    foreach (var element in set)
    {
        Console.Write("{0} ", element);
    }
    Console.WriteLine();
}
```

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SortedSet<T>

- SortedSet<T> implements ADT set by balanced search tree
  - Elements are sorted in increasing order
- Example:

```
ISet<string> firstSet = new SortedSet<string>(
  new string[] { "SQL", "Java", "C#", "PHP" });
ISet<string> secondSet = new SortedSet<string>(
  new string[] { "Oracle", "SQL", "MySQL" });
ISet<string> union = new HashSet<string>(firstSet);
union.UnionWith(secondSet);
PrintSet(union); // C# Java PHP SQL MySQL Oracle
```

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HashSet<T> and SortedSet<T>

Live Demo

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Summary

- Dictionaries map key to value
  - Can be implemented as hash table or balanced search tree
- Hash-tables map keys to values
  - Rely on hash-functions to distribute the keys in the table
  - Collisions needs resolution algorithm (e.g. chaining)
  - Very fast add / find / delete
- Sets hold a group of elements
  - Hash-table or balanced tree implementations

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Hash Tables and Sets

Questions?

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Exercises

1. Write a program that counts in a given array of integers the number of occurrences of each integer. Use `Dictionary<TKey,TValue>`.

   Example: array = {3, 4, 4, 2, 3, 3, 4, 3, 2}

   2 → 2 times

   3 → 4 times

   4 → 3 times

2. Write a program that extracts from a given sequence of strings all elements that present in it odd number of times. Example:

   {C#, SQL, PHP, PHP, SQL, SQL } → {C#, SQL}

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Exercises (2)

1. Write a program that counts how many times each word from given text file `words.txt` appears in it. The character casing differences should be ignored. The result words should be ordered by their number of occurrences in the text. Example:

```
This is the TEXT. Text, text, text – THIS TEXT!
Is this the text?
```

is → 2

the → 2

this → 3

text → 6

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Exercises (3)

1. Implement the data structure "hash table" in a class HashTable<K,T>. Keep the data in array of lists of key-value pairs (LinkedList<KeyValuePair<K,T>>[]) with initial capacity of 16. When the hash table load runs over 75%, perform resizing to 2 times larger capacity. Implement the following methods and properties: `Add(key, value)`, `Find(key)`→`value`, `Remove( key)`, `Count`, `Clear()`, `this[]`, `Keys`. Try to make the hash table to support iterating over its elements with `foreach`.
2. Implement the data structure "set" in a class `HashedSet<T>` using your class HashTable<T,T> to hold the elements. Implement all standard set operations like `Add(T)`, `Find(T)`, `Remove(T)`, `Count`, `Clear()`, union and intersect.