C# 2.0 Generic Types and Methods

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- History of generics in programming languages
- Why generic types and methods?
- Using generic classes and interfaces
- Declaring generic classes, interfaces, structs, delegates and methods
- Type parameter constraints
- Differences between Java 5.0 and C# generics
- Standard C#/.Net generic collection classes
- The C5 comprehensive collection class library

History of generics in programming languages

The theory of generic types (parametric polymorphism) is by Hindley (1968) and Milner (1977).

First programming language with parametric polymorphism is ML (1979); then Miranda, Haskell, Clean, . . .

First object-oriented language with generics is Eiffel (1991).

Generics in Java

- PolyJ (Myers, Bank, Liskov; 1997):
  Type parameters can be instantiated by reference types and primitive types; requires an extended JVM.
- Generic Java (Bracha, Odersky, Stoutamire, Wadler 1998):
  Became Java 5.0 generics (plus wildcards, due to researchers at Aarhus University); runs on standard JVM.
- NextGen (Cartwright, Steele; 1998):
  Type parameters can be instantiated by reference types, not primitive types; runs on standard JVM.

Generics in C#

- Generic C# and new Generic Common Language Runtime (Kennedy and Syme, Microsoft Research Cambridge UK, 2001).
- In November 2002, Microsoft announced generics for next version of C#; Redmond had been convinced . . .
- In August 2003, first alpha version of .Net Common Language Infrastructure with generics released.

Why generic types and methods?

Because the old collection classes are dynamically typed: Code may compile OK, then fail at run-time:

```
ArrayList cool = new ArrayList();
cool.Add(new Person("Kristen"));
cool.Add(new Person("Bjarne"));
cool.Add(new Exception("Larry"));      // Wrong, but no compile-time check
cool.Add(new Person("Anders"));
Person p = (Person)cool[2];            // Compiles OK, but fails at run-time
```

With generic types, collections can be statically typed: errors are detected at compile-time:

```
List<Person> cool = new List<Person>();
cool.Add(new Person("Kristen"));
cool.Add(new Person("Bjarne"));
cool.Add(new Exception("Larry"));      // Wrong, detected at compile-time
cool.Add(new Person("Anders"));
Person p = cool[2];                    // No run-time check needed
```

Using a generic class or interface

This works just as in Java 5.0:

```
IMyList<String> cities = new LinkedList<String>("Oslo", "Seattle");
String wa = cities[1];
```

Unlike in Java, type arguments can be value types, not only reference types:

```
Pair<String, int> p = new Pair<String, int>("Carsten", 1964);
int year = p.Snd;
```

No boxing or unboxing is needed for value type arguments; hence better performance and less memory usage.

Example: Enumerators and enumerables

A C# enumerator is similar to a Java iterator, and an enumerable is similar to a Java 5.0 iterable.

An enumerator over type `T` has a current element, can get the next one, and can release resources:

```
interface IEnumerator<T> : IEnumerator {
  T Current { get; };
  bool MoveNext();
  void Dispose();
}
```

An enumerable over type `T` can produce an enumerator over `T`:

```
interface IEnumerable<T> : IEnumerable {
  IEnumerator<T> GetEnumerator();
}
```


Example: Comparables and comparers

An comparable for type `T` can compare itself to another value of type `T` (like a Java comparable):

```
interface IComparable<T> {
  int CompareTo(T that);
  // bool Equals(T that);
}
```

A comparer for type `T` can compare two values of type `T` (like a Java comparator):

```
interface IComparer<T> {
  int Compare(T v1, T v2);
  // bool Equals(T v1, T v2);
  // int GetHashCode(T v);
}
```

(The Microsoft design mistake of including `Equals` and `GetHashCode` has been corrected in beta 2.)

Example: A time of day `(hh, mm)` can be compared to another a time of day:

```
public class Time : IComparable<Time> {
  private readonly int hh, mm;                  // 24-hour clock
  public Time(int hh, int mm) { this.hh = hh; this.mm = mm; }
  public int CompareTo(Time that) {
    return hh != that.hh ? hh - that.hh : mm - that.mm;
  }
  public bool Equals(Time that) { return hh=that.hh && mm==that.mm; }
}
```


Declaring a generic class

An object of class `LinkedList<T>` is a linked list with elements of type `T`:

```
public class LinkedList<T> : IMyList<T> {
  protected Node first, last;
  protected class Node {
    public Node prev, next;                       // Static member class
    public T item;                                // T used in static member
  }
  public LinkedList(params T[] arr) : this() {   // Variable-arity argument
    foreach (T x in arr)                          // Iterate over array arr
      Add(x);
  }
  public int Count { get { return size; } }      // Property
  public T this[int i] { ... }                   // Indexer
  public override bool Equals(Object that) {     // Equality; exact type test
    if (that != null && GetType() == that.GetType() && ...) { ... }
  }
  public IMyList<U> Map<U>(Mapper<T,U> f) { ... }
  ... more ...
}
```

Type parameters can be used also in static members. Each type instance has its own copy of the static fields.

There is a type object at run-time for every type, even for generic type instances (this is used in `GetType`).

Types are overloaded on the number of type parameters, so classes `C` and `C<T>` and `C<T,U>` can co-exist.

Declaring a generic interface — very similar to Java

Interface `IMyList<T>` describes lists with elements of type `T`:

```
public interface IMyList<T> : IEnumerable<T> {
  int Count { get; }                   // Number of elements
  T this[int i] { get; set; }          // Get or set element at index i
  void Add(T item);                    // Add element at end
  void Insert(int i, T item);          // Insert element at index i
  void RemoveAt(int i);                // Remove element at index i
  IMyList<U> Map<U>(Mapper<T,U> f);    // Map f over all elements
}
```

As in Java, generic types are invariant in the type parameters.

So `IMyList<String>` is not a subtype of `IMyList<Object>`,
although `String` is a subclass of `Object`.

Only the declared subtype relations hold: `IMyList<T>` is a subtype of `IEnumerable<T>`, and `LinkedList<T>` is a subtype of `IMyList<T>`.

Declaring a generic struct type — very similar to a generic class

Struct type `Pair<T,U>` is the type of pairs of a `T` and a `U`:

```
public struct Pair<T,U> {
  public readonly T Fst;
  public readonly U Snd;
  public Pair(T fst, U snd) {
    this.Fst = fst;
    this.Snd = snd;
  }
}
```

Using a generic struct type

Declaring `appointments` to be an array of pairs of `Time` and `String`:

```
Pair<Time, String>[] appointments;
```

In contrast to Java, one can use generic type instances just like any other types.

Thus one may create an array whose element type is a generic type instance:

```
appointments = new Pair<Time, String>[100];
```


Declaring a generic delegate type

A delegate of generic delegate type `Mapper<A,R>` takes an argument of type `A` and returns a result of type `R`:

```
public delegate R Mapper<A,R>(A x);
```

The type parameters are given after the delegate type's name, as for classes, interfaces, structs and methods.

Using a generic delegate type

Method `int Sign(double)` from class `Math` can be turned into a delegate:

```
Mapper<double,int> sign = new Mapper<double,int>(Math.Sign);
```


Declaring a generic method

As in Java, a method can take type parameters.

Example: `Map<U>` in `LinkedList<T>` creates a new list by applying `f` to every element of the given list:

```
public class LinkedList<T> : IMyList<T> {
  public IMyList<U> Map<U>(Mapper<T,U> f) {     // Map f over all elements
    LinkedList<U> res = new LinkedList<U>();
    foreach (T x in this)
      res.Add(f(x));
    return res;
  }
  ...
}
```

Calling a generic method

The type parameters of a generic method may be given explicitly, but often they can be inferred automatically:

```
list.Map<int>(...);
list.Map(...);
```

Type parameter constraints

As in Java, the type parameters of a class (or struct type or interface or method) can be constrained.

Example: A printable linked list is a linked list whose elements are printable:

```
class PrintableLinkedList<T> : LinkedList<T>, IPrintable
  where T : IPrintable
{
  public void Print(TextWriter fs) {
    foreach (T x in this)
      x.Print(fs);
  }
}
interface IPrintable { void Print(TextWriter fs); }
```

As in Java, a type parameter constraint may involve the type parameter itself.

Example: An array of T can be sorted if T-values are comparable to T-values:

```
private static void Qsort<T>(T[] arr, int a, int b)
  where T : IComparable<T>
{ ... }
```


Multiple type parameter constraints

Struct type ComparablePair<T,U> is the type of pairs of comparable T and comparable U:

```
struct ComparablePair<T,U> : IComparable<ComparablePair<T,U>>
  where T : IComparable<T>
  where U : IComparable<U>
{
  public readonly T Fst;
  public readonly U Snd;
  public int CompareTo(ComparablePair<T,U> that) {    // Lexicographic ordering
    int firstCmp = this.Fst.CompareTo(that.Fst);
    return firstCmp != 0 ? firstCmp : this.Snd.CompareTo(that.Snd);
  }
  public bool Equals(ComparablePair<T,U> that) {
    return this.Fst.Equals(that.Fst) && this.Snd.Equals(that.Snd);
  }
  ...
}
```


Special kinds of type parameter constraints

C# permits several special constraints on a type parameter T:

Constraint	Meaning
T : t	When t is a type: T must be subclass of (class) t or implement (interface) t
T : class	T must be a reference type
T : struct	T must be a (non-nullable) value type
T : new()	T must have an argumentless constructor; always holds for a value type

Example: A field of type T be null if T is a reference type:

```
class C1<T> where T : class {
  T f = null;                          // Legal: T is a reference type
}
```

Example: One can call new T() only if type T has an argumentless constructor:

```
class C1<T> where T : new() {
  T f = new T();                       // Legal: T() exists
}
```

More generally, default(t) is null for a reference type t, and is new t() for a struct type t.

What can type parameters be used for

In contrast to Java, a type parameter can be used almost as an ordinary type:

```
class C<T> {
  void M(Object o) {
    T[] arr = new T[10];               // Array creation
    if (o is T) {                      // Instance-of test
      T t = (T)o;                      // Type cast
      ...
    }
    T d = default(T):                  // Get default value for T
    Type ty = typeof(T);               // Get type object (reflection)
  }
  void MO(T x) { ... }                 // Overloading on type parameters
  void MO(IMyList<T> x) { ... }        // and type instances
}
```

However:

One cannot call static members of a type parameter T.

One can create an instance of T using new T() only if T has the new() constraint or the struct constraint.

One can use null as a variable of type T only if T has the class constraint.

Comparison of generics in Java 5.0 and C# 2.0

Property	Java	C#
Can use type parameters in static member declarations	No	Yes
Static members are shared between type instances	Yes	No
Wildcard type arguments permitted	Yes	No
All type instances have a common supertype (‘raw type’)	Yes	No
Compiler may emit ‘unchecked’ (= I don’t know) warnings	Yes	No
Type parameters can be instantiated with simple types (int ...)	No	Yes
Can overload a method on different type instances of same generic type	No	Yes
Exact type arguments exist at run-time	No	Yes
Can perform instance-of check against type parameter or type instance	No	Yes
Can cast to type parameter (T)e or type instance (IMyList<int>)e	No	Yes
Can create (new) object whose type is a type parameter or type instance	No	Yes
Can create (new) array whose element type is a type parameter or type instance	No	Yes
Can declare array variable whose element type is a type parameter	Yes	Yes

Why Java cannot create an array whose element type is constructed from a generic type

Java and C# array assignment requires runtime type checks:

```
static void m(Object[] arr, Object x) {
  arr[0] = x;                        // Runtime check needed
}
```

Why? Observe that String is a subclass of Object, then execute:

```
Object[] arr = new String[10];
m(arr, new Object());                // MUST fail at run-time
... otherwise arr[0] now contains an Object, not String, bad ...
```

The exact element type (String) of the array arr is needed to check the assignment in m(...).

Lack of exact runtime types (in Java 5.0) makes runtime type check impossible

This in turn makes it impossible to create an array whose element type is a constructed type:

```
Pair<String,Integer>[] heights = new Pair<String,Integer>[10];
```

This is OK in C# 2.0 because the array element type can be stored in heights.

It is not OK in Java 5.0, because the runtime has no presentation of Pair<String,Integer>.

Java workaround: Use ArrayList<t> instead of t[]. (Question: Why does this work?)

Simulating the wildcard type parameter (<?>) from Java in C#

A wildcard type (<?>) in Java is similar to an unnamed bound type parameter, not used anywhere else.

When used in method parameter declarations it can sometimes be simulated in C# using extra type parameters T:

Context	Java	C#
Unbounded wildcard	tr m(C<?> x)	tr m<T>(C<T> x)
Bounded wildcard	tr m(C<? extends t> x)	tr m<T>(C<T> x) where T : t

Wildcards used in declarations of variables and fields can sometimes be simulated.

This makes some things more complicated in C#, but it seems possible to work around the limitations.

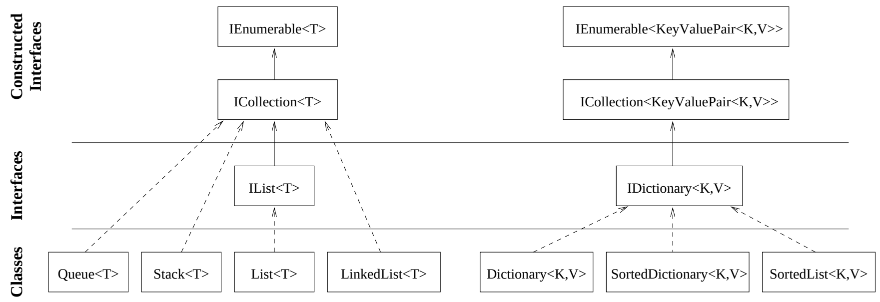
The wildcard <? super t> can sometimes be simulated in C#:
introduce a type parameter T for t and another type parameter U for ?, and then constrain T : U.

An attempt to do this for Java’s Collections.binarySearch crashed Microsoft’s beta 1 compiler:

```
public static int BinarySearch<T,U,S>(List<S> lst, T k)
  where T : U, IComparable<U>
  where S : T
{ ... }
```


The standard generic collection classes (C# Precisely section 24)

Namespace System.Collections.Generic provides some generic collection classes:



Critique of standard generic collection classes

- Only lists and hashtables; no (sorted) tree-based sets or dictionaries.

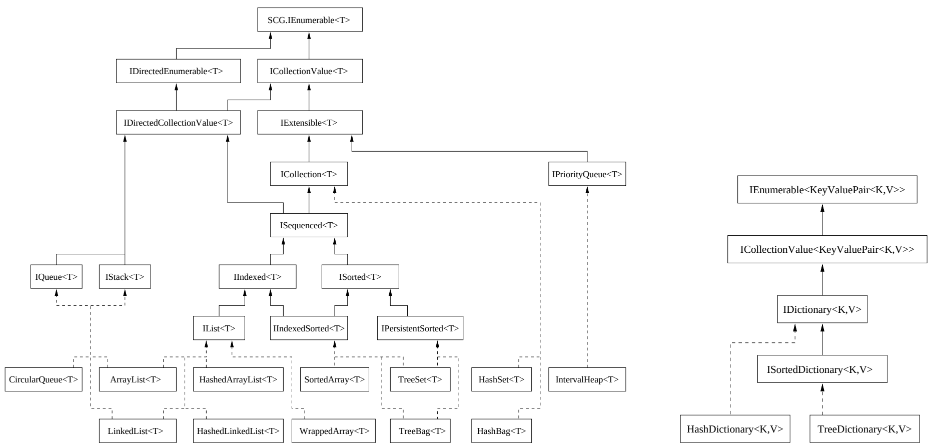
  (But red-black trees will be included later, according to a Microsoft CLI team source.)
- Proliferation of methods and lack of orthogonality: Three versions (entire list, tail of list, segment of list) of each of CopyTo, FindIndex, FindLastIndex, ...; but not so for other methods.
- Strange interfaces: IComparer<T> describes Compare(T,T) but also GetHashCode(T) and Equals(T,T) — invites 'dishonest' implementations.

  Luckily, this has been changed in beta 2: IEqualityComparer<T> and IComparer<T>.
- Array-based lists and linked lists do not have a common interface.
- Low level of abstraction: LinkedList<T> requires working on list nodes; invariants (e.g., every list is acyclic) must be enforced by run-time checks, cannot be checked at compile-time.
- Some methods are virtual while others are non-virtual (for efficiency); risky and confusing.
- Potential performance traps, such as array-based SortedDictionary<K,V>.

  Performing n random insertions would take time $O(n^2)$.

Luckily, much of this was withdrawn from Ecma CLI standardization.

C5: Copenhagen Comprehensive Collection Classes for C#



Some highlights of C5

- Comprehensive interfaces support 'program to an interface, not an implementation'.
- Use best known data structures and algorithms, even if cumbersome to implement.
- Consider asymptotics (scalability) more important than nanosecond efficiency.
- Updatable views (sublists) of lists; ensures orthogonality of operation and range.
- Range queries by index (indexed collections) and by elements (sorted collections).
- Reversible enumeration, also of views.
- Constant-time snapshots of red-black trees (persistent trees); supports geometric algorithms.
- Supports both hash-indexes and views of a linked list.
- Introspective quicksort for arrays; worst-case running-time logarithmic.
- In-place smooth stable mergesort for doubly-linked lists.

Developed by Niels Kokholm and Peter Sestoft with support from Microsoft Research University Relations.

C5 is and will remain freely available from http://www.itu.dk/research/c5/

C5 is included in the Mono project implementation of C#/CLI.

Peter Golde of Wintellect, formerly Microsoft, is developing PowerCollections, another collection class library.