The .NET Developer's Guide
Memory and Performance Profiling

Rough Cut

Telerik Q3 2012

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The .NET Developer's Guide to Memory and Performance Profiling

by Christopher Brian Eargle

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ABOUT THE AUTHOR

Christopher Brian Eargle is a Telerik Technical Evangelist with over a decade of experience designing and developing enterprise applications, and he runs the local .NET User Group: the Columbia Enterprise Developers Guild. He is a frequent guest of conferences and community events promoting best practices and new technologies.

Chris is a native Carolinian; his family settled the Dutch Form region of South Carolina in 1752. He currently resides in Columbia with his wife, Binyue, his dog, Laika, and his three cats: Meeko, Tigger, and Sookie. Amazingly, they all get along… except for Meeko, who is by no means meek.

Chris is a Microsoft C# MVP currently serves on the INETA Board of Directors. He is in charge of the Community Speakers Program, having come from the program himself before he began working at Telerik. If you are passionate about software development, you are encouraged to join INETA to be connected to hundreds of groups. It is free to join, and INETA helps cover your travel expenses for speaking.

Chris' blog, kodefuguru.com, features content to guide you in becoming a .NET Ninja!

ABOUT THIS EDITION

Telerik released its first .NET memory and performance profiler, JustTrace, in 2011. Since then, we have published a lot of good material on the product, and we felt like we should move beyond that by providing general resources to our users.

Books take time to write, and this is especially true for technical books, which may require intense research. Since this is to be published on the web, we decided to start releasing material with cycles. You are currently reading the very first rough cut coincides with the Telerik Q3 2012 product release. If significant time has passed, be sure to check the site for an update.

This edition is released free of charge. If you paid for it, you paid too much.

TABLE OF CONTENTS

GETTING STARTED

WHAT IS PROFILING?

Profiling is a form of program analysis to collect metrics on properties of software such as memory usage and execution time. Memory and performance profiling is used to detect memory and performance issues to optimize an application.

WHAT IS OPTIMIZATION?

Optimizing involves making small changes to code to improve performance or memory management without changing the external behavior. These goals can sometimes conflicts. For example, improving performance may require loading a large amount of data in memory. An optimization that does this is memoization, a form of caching that stores results of a function call so subsequent calls receive it faster. Both optimizations and refactorings have names and involve making small changes. The example given is called MEMOIZE FUNCTION.

The primary difference is that refactorings address readability and maintainability. Optimizations often negatively affect the goals of refactoring.

OPTIMIZING VERSUS TUNING

Optimization can be considered part of performance tuning, which addresses the system as a whole. I find it most useful to use tuning in reference to environmental issues such as bottlenecks and solutions such as load balancing.

WHEN TO OPTIMIZE

Life is rarely black and white, and choosing to optimize requires the ability to see in shades of gray as well. Acceptable limits should be established in the assessment phase, and the further it is outside of limits, the more severe the issue is. There are other considerations for severity; I would address a heavily used function that is moderately outside the limit sooner than I would a function that is rarely called but even less performant. It is also important to know if the necessary optimization will negatively affect other non-functional requirements. In software, compromises are necessary.

FOUR STEPS

Profiling and optimizing your application can be broken down into four steps:

1. Assess
2. Acquire
3. Analyze

4. Act

The remainder of this book is divided into these steps. To summarize, you must first assess your situation; determine what kind of problem you are trying to solve and to ensure you are spending your time wisely. The second step is to acquire memory and performance data for your application. The third step is to analyze this data to determine what actions should be taken to improve the application's performance. The final step is to act upon your analysis if necessary.

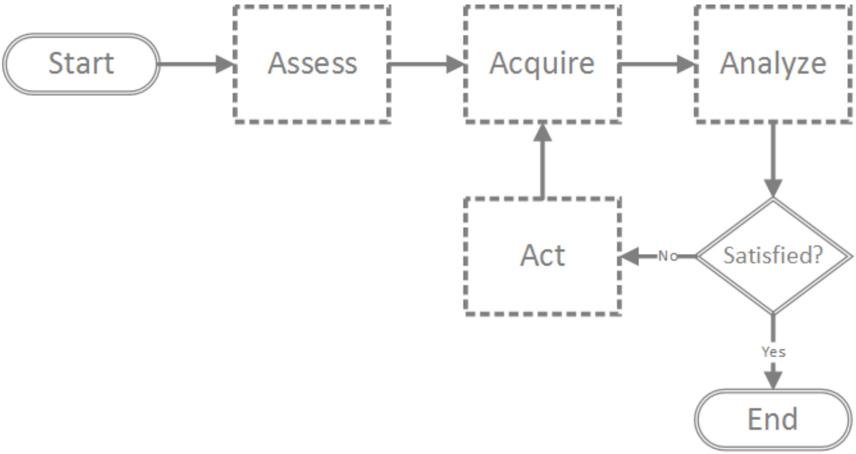


FIGURE 1: PROFILING FLOWCHART

ASSESS

COMPARATIVE ASSESSMENT

Comparative assessment is most commonly used when a developer is attempting to determine a particular strategy in designing a piece of a system. For example, many different search algorithms are more or less efficient depending on the data structures used and the data these structures contain. You may want to know which would be best for data received from an external service. You can obtain a few data sets and profile the application to determine which algorithm performs best. It is essential to have test data that appropriately represents data commonly retrieved by the system. However, testing unproven data sets is better than making an arbitrary decision based on personal preference.

This form of assessment can also aid an architect in deciding on whether to use a particular component or service. Here is another example: You are working for a corporation that is deciding on whether a move to Oracle would be wise. They currently have data stored in SQL Server. You can set up identical VMs for both servers and create packages to copy the data into Oracle. The application uses Entity Framework, so you first run integration tests to determine if there are compatibility issues then profile the applications to determine which is better from a performance perspective. In this situation, there may be other factors at play, so the results are primarily to provide feedback on potential issues or benefits gained by switching systems.

REACTIVE ASSESSMENT

Reactive assessments involve attention given to performance and memory management when an issue surfaced.

Here is a scenario with which you may be familiar:

> Multiple bug reports were received that the application was unstable and caused the workstation to slow down. This was never noticed by development or quality assurance. After interviewing the users reporting the bugs, it was found that these particular users very rarely closed their applications or rebooted their workstations. Further investigation on their stations revealed that the application was consuming several gigs of RAM. When the application was first opened, it only consumed a hundred MB of RAM. The application had a memory leak.

Profiling the application was predicated upon an identified issue.

PROACTIVE ASSESSMENT

In contrast to reactive assessment, proactive assessment includes profiling as part of the development process. There are many non-functional requirements that are part of the system, and use cases must be established for acceptable performance, or responsiveness, and reliability, or probability of failure. To connect the last part to JustTrace, consider the reactive scenario that was presented. The software worked fine at first, but it caused issues over time. In other words, its reliability was dependent on the length and frequency of its usage.

Due to the growing complexity of maintaining software, it is often best to write maintainable code first, then optimize as needed. Having performance and reliability requirements documented enables this. A danger some fall into is the desire to squeeze the most performance out of a system. Oftentimes, this is a waste of time and may even cause issues, as the application becomes a Byzantine mess of extremely performant code.

We recommend that you establish your non-functional requirements up-front and regularly profile your solution. When the metrics go beyond the acceptable range, you should concern yourself with optimizing a particular piece of the system.

ACQUIRE

This section will contain information on acquiring data that can be analyzed to determine memory and performance issues. This is a rough cut of the book and is not ready.

This book is meant to provide general information about memory and performance profiling. Since this portion is not quite ready, we are including product specific information from the author's introductory article on Telerik JustTrace. At the very least, it will be useful for Telerik users seeking guidance.

OBTAIN A TOOL

To acquire performance and memory usage data, you will need a tool. You can try Telerik JustTrace for 30 days by going to http://www.telerik.com/justtrace. Best of all, it contains what you need to determine both performance and reliability by including performance and memory profilers. JustTrace is available as a standalone tool, but it is also packaged with Visual Studio Integration components. Which one you choose to run it depends on your workflow and preference.

Run JustTrace to begin a new profiling session.

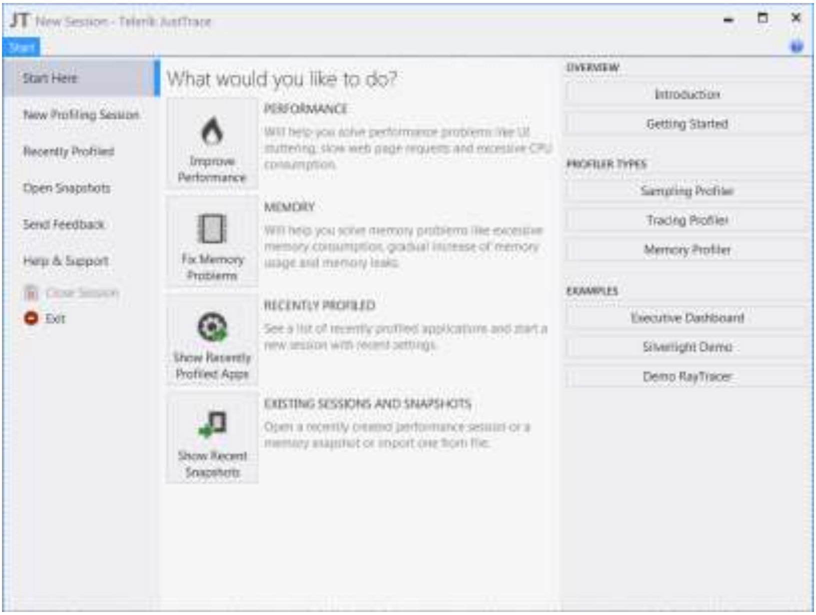


FIGURE 2: JUSTTRACE START SCREEN

OBTAIN DATA

Acquiring data is as simple as choosing your application type and profiler. Using JustTrace from within Visual Studio will eliminate the first option. The stand-alone version allows you to attach the profiler to a local executable, a running application, Silverlight applications, Windows Services, Windows Store Apps, and ASP.NET applications hosted in IIS, IIS Express, or Windows Development Server.

JustTrace is packaged with two types of profilers: memory and performance. The memory profiler collects information on the application's memory usage. The performance profiler collects information on the amount of time spent in method calls. There are two different flavors for the performance profiler. The performance (sampling) profiler dumps the call stack at regular intervals, which has a minimal impact on the application's performance. The performance (tracing) profiler reads all CLR events when entering and leaving methods. This is extremely accurate, but the profiler will have an increased impact on the real performance of the application.

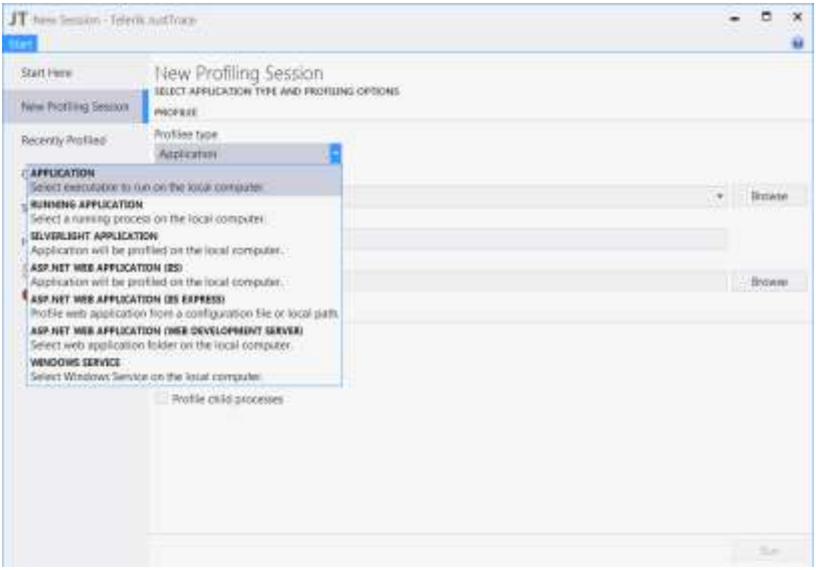


FIGURE 3: APPLICATION TYPES

Run the profiler and use your application to obtain snapshots of the application.

ANALYZE

This section will explain how to analyze profiling data to determine potential memory and performance issues. This is a rough cut of the book and is not ready.

This book is meant to provide general information about memory and performance profiling. Since this portion is not quite ready, we are including product specific information from the author's introductory article on Telerik JustTrace. At the very least, it will be useful for Telerik users seeking guidance.

With the profile of your application on hand, the next step is to analyze the data acquired to track down issues.

PERFORMANCE SNAPSHOTS

A performance snapshot contains a timeline, which allows you to view the calls made in an application in a specific range of time. You can also compare two different ranges. This profile allows you to see metric overviews, the call tree, the method list, and hot spots.

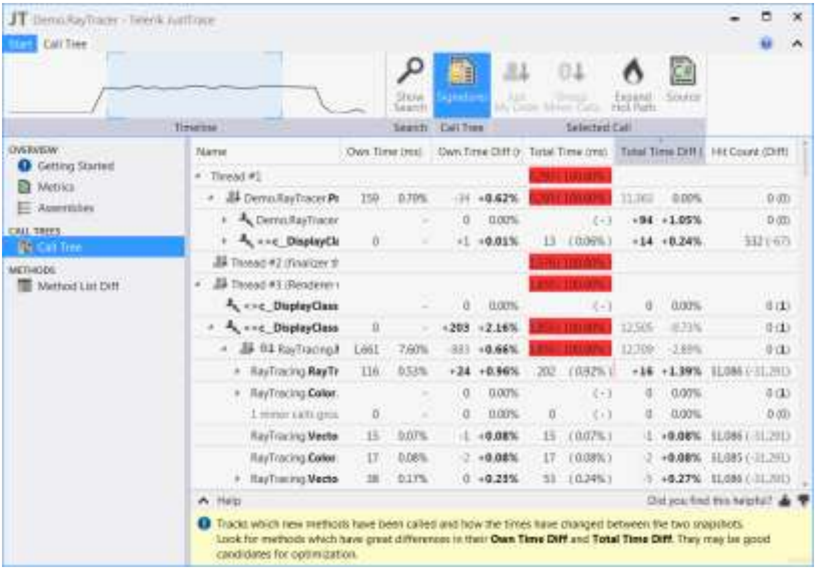


FIGURE 4: CALL TREE

MEMORY SNAPSHOTS

Memory snapshots show the application's state when the snapshot was taken. You can view a list of all types with their memory consumption, incoming type references, types that are retaining the largest amount of memory, and view an instance's path to the garbage collection root.

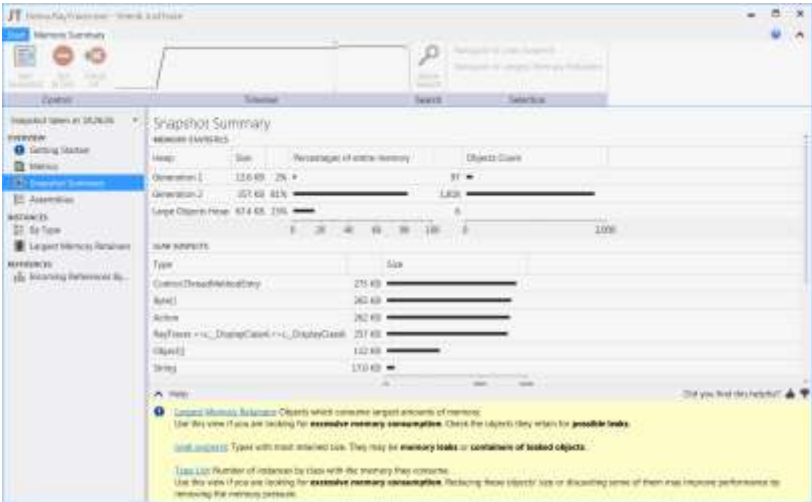


FIGURE 5: MEMORY SNAPSHOT SUMMARY

ACT

This section consists of issues you may an encounter and potential solutions. This is a rough cut and will contain more information in future releases.

STRING CONCATENATION

A primary task when working with strings is adding them together. The string class has an operator overload for + that converts the call to a String.Concat. The C# compiler optimizes the code by concatenating string literals.

Here is an example with string literals.

```
string panda = "bear" + "cat";
```

This line is converted to the following by the compiler.

```
string panda = "bearcat";
```

Here is an example using string variables.

```
string panda = "bear";
panda += "cat";
```

The compiler converts concatenation with variables and non-string literals into a call to String.Concat.

```
string panda = "bear";
panda = String.Concat(panda, "cat");
```

Developers will often explicitly call the ToString method on an object when concatenating its string representation with another string. This is unnecessary as String.Concat has an overload for object and will call ToString() for you, but calling ToString() on a value type is useful as it prevents boxing. In any case, when implementing a class or struct it is a good practice to override the ToString method and provide an appropriate representation of the object in a string format.

```
public void LogAccess(Employee employee)
{
    Console.WriteLine(employee + " accessed the system at "
+ .Now.TimeOfDay);
}
```

The expected behavior would be a name or another identifier for the employee would be written to the screen. Unless ToString is overridden, the fully qualified class name is written instead:

> "DevelopersGuide.Employee accessed the system at 17:41:05.4530627."

Perhaps the most pervasive problem with string concatenation involves building a large string composed of many known elements. Approaching this problem with simple concatenation techniques leads to the creation of many small objects that must be garbage collected.

```
public static string
SerializeGeometry(IEnumerable<GeographicPoint> points)
{
    Contract.Requires(points != null, "Points parameter must
not be null.");
    string result = "<Coordinates>";

    foreach (var point in points)
    {
        result += "\t<Coordinate>" + point +
"</Coordinate>";
    }

    result += "<Coordinate>";
    return result;
}
```

The SerializeGeometry method is creating an xml string based on an IEnumerable of GeographicPoint. There are an unknown number of elements in the sequence, so it is iterated appending as many strings as needed to the result variable. Since string is immutable, this causes a new string to be allocated every pass through the loop. This problem can be prevented by using the StringBuilder class.

```
public static string
SerializeGeometry(IEnumerable<GeographicPoint> points)
{
    Contract.Requires(points != null, "Points parameter must
not be null.");
    StringBuilder result = new StringBuilder();
    result.AppendLine("<Coordinates>");

    foreach (var point in points)
    {
        result.AppendLine("\t<Coordinate>" + point +
"</Coordinate>");
    }
```

```
    result.AppendLine("<Coordinate>");
    return result.ToString();
}
```

NUMERIC OVERFLOW

It is tempting to use unsigned integers such as System.UInt32 when requirements clearly call for a positive number. Although it may seem like a good decision at first, it carries consequences that affect language compatibility, performance, and memory usage.

```
public class TreeNode
{
    private List<TreeNode> children = new List<TreeNode>();

    public ICollection<TreeNode> Children
    {
        get
        {
            return children;
        }
    }

    public string Text { get; set; }

    public uint Count()
    {
        uint count = 1;

        foreach(var node in children)
        {
            count += node.Count();
        }

        return count;
    }
}
```

The Count method of this simple TreeNode class will never return a negative number, but it is not CLS-compliant. Attempting to mark this class as such will generate the following warning: “Return type of 'DevelopersGuide.TreeNode.Count()' is not CLS-compliant.” Attempting to test this class causes further problems.

```
TreeNode tree = new TreeNode { Text = "Root" };
tree.Children.Add(new TreeNode { Text = "Child" });

Assert.AreEqual(2, tree.Count());
```

When Assert.AreEqual is called, an exception is thrown: “Assert.AreEqual failed. Expected:<2 (System.Int32)>. Actual:<2 (System.UInt32)>.” The value 2 is interpreted by the CLR as an integer since the AreEqual method takes it as a parameter. Literal conversions are done in the following order: int, uint, long, ulong. In the above example, the value 2 can be forced to be interpreted as a uint by using the U suffix.

Implicit conversions exist for int from sbyte, byte, short, ushort, and char. These conversions also exist for integral types to float types. However, explicit conversions must be used for float to integral conversion.

COLLECTION TYPES

Arrays and other collection types are reference types that act as container objects. Arrays have not changed much in the past few years, but the release of .NET 2.0 saw the rise in the popularity of the generically typed List<T>.

Before the introduction of List<T>, ArrayList was prevalent, and can found in codebases even today. The problem with ArrayList is that it is not type-safe, and it therefore requires casting and causes boxing.

```
var list = new ArrayList
{
  0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89
};

foreach (object fib in list)
{
  Console.WriteLine(fib);
}
```

List<T> is type-safe and more performant and it should replace ArrayList in most circumstances.

```
var list = new List<int>
{
  0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89
};

foreach (int fib in list)
{
    Console.WriteLine(fib);
}
```

There are common interfaces using and manipulating collections.

- IEnumerable & IEnumerable<T> - Iterating the sequence.
- ICollection & ICollection<T> - Adding and removing items.
- IList & IList<T> - Indexed access.

The interfaces implement each other, from the last to the top.

Suppose we would like to create a method that adds a number to the sequence.

```
public void AddFibonacci(ICollection<int> collection)
{
    switch (collection.Count)
    {
        case (0):
            collection.Add(0);
            break;
        case (1):
            collection.Add(1);
            break;
        default:
            collection.Add(collection.Skip(collection.Count
- 2).Take(2).Sum());
            break;
    }
}
```

We can test this by calling it with our previous list method.

```
var list = new List<int>
{
  0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89
};
```

```
AddFibonacci(list);
Assert.AreEqual(144, list.Last());
```

That works great. There is only one problem.

```
var array = new[]
{
  0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89
};

AddFibonacci(array);
Assert.AreEqual(144, array.Last());
```

Arrays implement ICollection<T>, but they are of a fixed-size. This throws a NotSupportedException. This is a common mistake when accepting one of the collection or list interfaces as a method parameter. Arrays are common constructs and could easily be passed in if this were implemented in a public API. There are other collections that can't be written to either. To defend against this issue, the ReadOnly property of ICollection must be checked. This is rather a misnomer for arrays, as their memory is indeed writeable; only their size can't be modified. You can, however, write it as an extension method and return an IEnumerable<int>.

```
public static IEnumerable<int> AddFibonacci(this
IEnumerable<int> source)
{
    int a = 0;
    int b = 0;

    foreach (int n in source)
    {
```

```
        a = b;
        b = n;
        yield return n;
    }

    yield return a + b;
}
```

If it is necessary to return the sequence to an array, using LINQ is the most elegant solution.

```
array = array.AddFibonacci().ToArray();
```

Generic lists increase their size for you automatically, and many people are content to let this happen. But is this really the best way?

When you add an item to a generic list, the size must be checked to ensure that there is room. If there isn't, the capacity is doubled by instantiating a new array of its type and copying its contents into it. Here's the code from Telerik JustDecompile.

```
public void Add(T item)
{
    if (this._size == this._items.Length)
    {
        this.EnsureCapacity(this._size + 1);
    }
    this._items[this._size++] = item;
    this._version++;
}

private void EnsureCapacity(int min)
{
    if (this._items.Length < min)
```

```
    {
        int num = (this._items.Length == 0) ? 4 :
(this._items.Length * 2);
        if (num < min)
        {
            num = min;
        }
        this.Capacity = num;
    }
}

// Inside Capacity setter

T[] destinationArray = new T[value];
if (this._size > 0)
{
    Array.Copy(this._items, 0, destinationArray, 0,
this._size);
}
this._items = destinationArray;
```

DELAYED EVALUATION WITH YIELD

In C#, the yield keyword is used to generate an implementation of the Iterator pattern, which in .NET is an implementation of IEnumerator. It is a useful, and perhaps under-utilized, feature of the C# language that can greatly reduce the complexity of iterating lazy or dynamic collections of objects. Methods using the yield keyword must return IEnumerable, IEnumerable<T>, IEnumerator, or IEnumerator<T>. For type-safety and semantics, it is often preferred to return IEnumerable<T>.

```
public void ReturnTypes()
{
    foreach (var t in Enumerable())
```

```
        Console.WriteLine(t);

    foreach (var t in EnumerableT())
        Console.WriteLine(t);

    IEnumerator enumerator = Enumerator();

    while(enumerator.MoveNext())
        Console.WriteLine(enumerator.Current);

    IEnumerator<string> enumeratorT = EnumeratorT();

    while (enumeratorT.MoveNext())
        Console.WriteLine(enumeratorT.Current);
}

public IEnumerable Enumerable()
{
    yield return "a";
}

public IEnumerable<string> EnumerableT()
{
    yield return "b";
}

public IEnumerator Enumerator()
{
    yield return "c";
}

public IEnumerator<string> EnumeratorT()
{
    yield return "d";
}
```

The yield keyword is combined with one of two other keywords to provide its semantics: return and break. As can be ascertained from the example above, yield return causes the IEnumerator.Current property to change. The example did not show yield break, but it causes control to end. Here is an example with both.

```
public void WriteTilNull()
{
    foreach (var line in ArgsTilNull("Almost", "Midnight",
null, "end"))
    {
        Console.WriteLine(line);
    }

}


public IEnumerable<T> ArgsTilNull<T>(params T[] args)
{
    foreach (var t in args)
    {
        if (t == null)
        {
            yield break;
        }

        yield return t;
    }
}
```

The ArgsTilNull method will return values until null is reached, then control is broken. The WriteTilNull method writes only the first two strings to the screen. Recall the previous example and how the IEnumerator versions called MoveNext and Current. The foreach statement is essentially doing the same thing, lazily stepping through the code. If you were to take this example and step through it, you will find the debugger stepping into the ArgsTilNull method in each pass of WriteTilNull's foreach statement to retrieve the next value.

The largest impact the use of the Iterator pattern will have on memory and performance is making the decision on whether it is more valuable to lazily retrieve values or retain those values in memory. Lazy retrieval ensures the data is current, keeps the heap clear, but could potentially impact garbage collection with the creation of many small objects. Maintaining the data in memory is better if it is unlikely to change, is used more often, but it could move the larger object to a higher generation.

My recommendation is to convert iterators to collection types at application, framework, and layer boundaries.

DELEGATES

Executable code typically exists as a method belonging to a static or instance of a struct or class. A delegate is another reference type that represents a method, similar to a function pointer in other languages. However, delegates are type-safe and secure, providing object-oriented functions.

Although the CLR supports a simple delegate type, delegates in C# and VB.NET inherit from System.MulticastDelegate (which inherits from System.Delegate and in turn from System.Object). This type provides a linked list of delegates, which are invoked synchronously in order.

```
public delegate void Function();

public void WriteInformation()
{
    Debug.WriteLine("Got Here");
}

public void CallFunction()
{
    Function function = new Function(WriteInformation);
    function();
}
```

Parameters can be added to a delegate, which are then necessary for the method the delegate is instantiated with and the delegate's invocation.

```
public delegate void Function(string info);

public void WriteInformation(string info)
{
    Debug.WriteLine(info);
}

public void CallFunction()
{
    Function function = new Function(WriteInformation);
    function("function called");
}
```

Delegates can be combined by called the Delegate.Combine method. The semantics of the delegate are then lost and it must be invoked through the DynamicInvoke method.

```
public delegate void Function(string info);
```

```
public void WriteInformation(string info)
{
    Debug.WriteLine(info);
}

public void WriteToConsole(string info)
{
    Console.WriteLine(info);
}

public void CallFunction()
{
    Function function = new Function(WriteInformation);
    Function another = new Function(WriteToConsole);
    var del = Delegate.Combine(function, another);
    del.DynamicInvoke("multicast");
}
```

This is useful for writing reusable delegates, but oftentimes delegates are scoped within a method. The concept of anonymous methods was introduced as an alternative to named methods.

```
public delegate void Function(string info);

public void CallFunction()
{
    Function function = delegate(string info) {
Debug.WriteLine(info); };
    function("This method is anonymous");
}
```

More innovations in the .NET languages took place, and anonymous functions were introduced. Lambda expressions further reduced the amount of typing necessary to create a delegate. In addition, standardized, generic delegate types were introduced to the .NET framework allowing the creation of delegates without a user definition.

Delegates without return types are known as Actions, and those with return types are known as Funcs. The last generic parameter of a Func type is the return type.

```
Action<string> function = info => Debug.WriteLine(info);
function("Created from a lambda");
```

Despite the progression of delegate usage in the language, behind the scenes the story remains largely the same. The compiler creates a static delegate definition and a named method. It places the code contained within the lambda expression inside of the named method. It then creates the delegate, if it does not already exist, and calls it. Anonymous methods and functions are syntactic sugar.

A common use of delegates is for event handlers, which allows you to loosely couple functionality through an eventing model. The classic example of this is performing an action when a button is clicked.

```
public MainWindow()
{
    InitializeComponent();
    button.Click += (sender, e) =>
MessageBox.Show("Developer’s Guide");
}
```

Notice the operator that adds the lambda expression to the Click event. Events are added to an event list to be invoked. It is important to release the delegates in the event list or set the event to null when disposing of the object. Classes that implement events should implement IDisposable. It is not so bad when only one object has a reference to the delegate. However, if more than one object has a reference to the same delegate, they will all be kept alive until all the objects with a reference to the same delegate are released.

Variables that are created outside of the anonymous method but used within it are captured in a closure. This allows the delegate to have access to the value even when the variable goes out of scope.

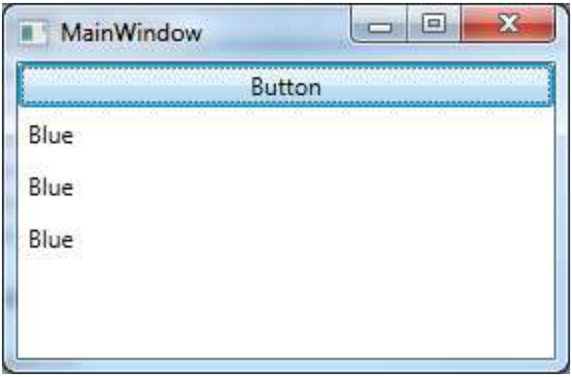
```
string str = "Original";
Action writeLine = () => Console.WriteLine(str);
writeLine();

str = "Changed";
writeLine();
```

From reading the code, it is expected that it will first write 'Original' to the screen then 'Changed'. That is exactly how it works, which seems odd in light of the fact that string is immutable and it has already been passed into the delegate.

The compiler does the heavy lifting for you by creating a class and assigning the values to it. This will affect you anytime you use an outside variable inside of an anonymous method or function. Be aware that in this particular context, even if a variable appears to be a value type, you are actually assigning a property of a reference type.

```
foreach (string color in new[] { "Red", "Green", "Blue" })
{
    button.Click += (sender, e) =>
        stackPanel.Children.Add(new Label { Content = color
});
}
```



Although the color variable is changed during each iteration of the loop, the variable is being assigned to the capture class before it is being used in the lambda expression. To fix this problem, assign the variable to a temporary variable.

```
foreach (string color in new[] { "Red", "Green", "Blue" })
{
   string c = color;
    button.Click += (sender, e) =>
        stackPanel.Children.Add(new Label { Content = c });
}
```

FRAGMENTATION

Heap fragmentation occurs when allocating new objects to the space formerly occupied by objects collected from the large object heap.

Memory containing pinned objected is not compacted, leaving behind gaps. In long running applications with large objects, this can result in out of memory exceptions despite the availability of memory. There just is not a large enough block of memory for an object to fit in. This is typically a generation 2 problem, and you can detect it by comparing free blocks of memory versus the total size of memory.

Some fragmentation will occur in the life of an application. Avoid pinning to avoid this problem. Pinning occurs when using fixed variables or fixed size buffers to create a guaranteed location and size for a variable. You can then pass these variables to an external, unmanaged DLL.

EXCESSIVE WRITES

Writing to a memory address by modifying an old object flags a range of memory as modified. The garbage collector then treats these objects as roots to analyze when determining if any objects need to be collected. This is efficient in many programs, as older objects are less likely to be modified. However, writing to longer-lived, complex object models can cause the garbage collector to analyze the entire object graph, affecting performance.

EXCESSIVE REFERENCES

The garbage collector must analyze the entire graph to discover which objects can be collected. Complex models tax the collector, affecting performance. The solution is to use architectural designs that load information as needed and release it when it is no longer necessary to maintain the reference.

LONG LIVED OBJECTS

Only a full garbage collection will take care of an object that has made it to Gen 2, and these objects can possibly consume memory long after they are dead. Therefore, it is best to make sure that these object sizes are kept to a minimum.

Inefficient code can make objects live longer than they should, reaching Gen 2 and wasting memory unnecessarily. Avoid this by only allocating objects you need and letting go of references when they are no longer necessary: references on the stack cause rooted objects for the garbage collector. I sometimes review code that has been rewritten several times without attention to cleanup.

Keep your methods small, create objects as close as possible to when you're going to use them, and always remember to call Dispose() on your disposable objects.

APPENDIX

TABLE OF FIGURES

INDEX