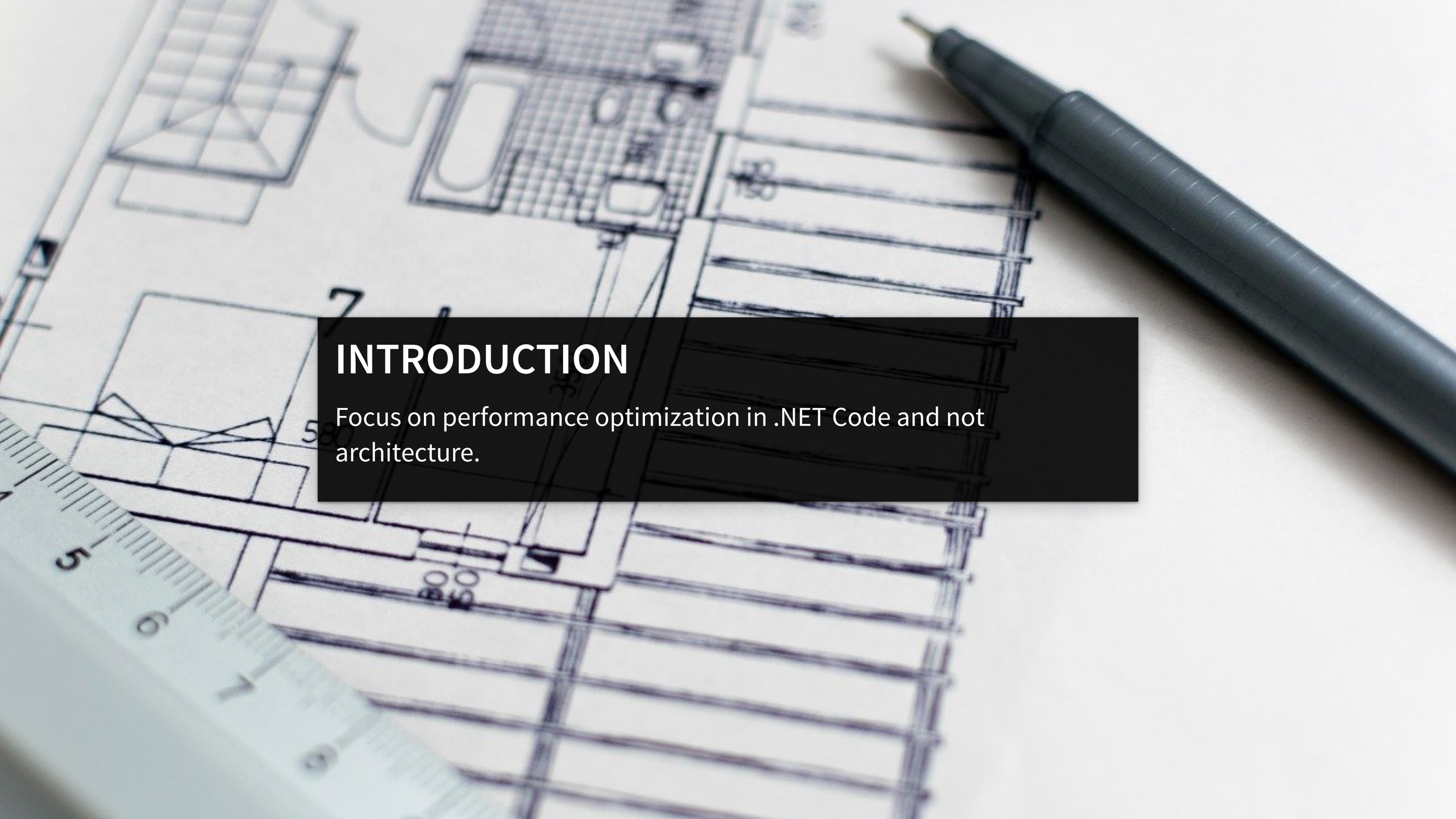
Performance tricks I learned from contributing to the Azure .NET SDK

danielmarbach | daniel.marbach@particular.net

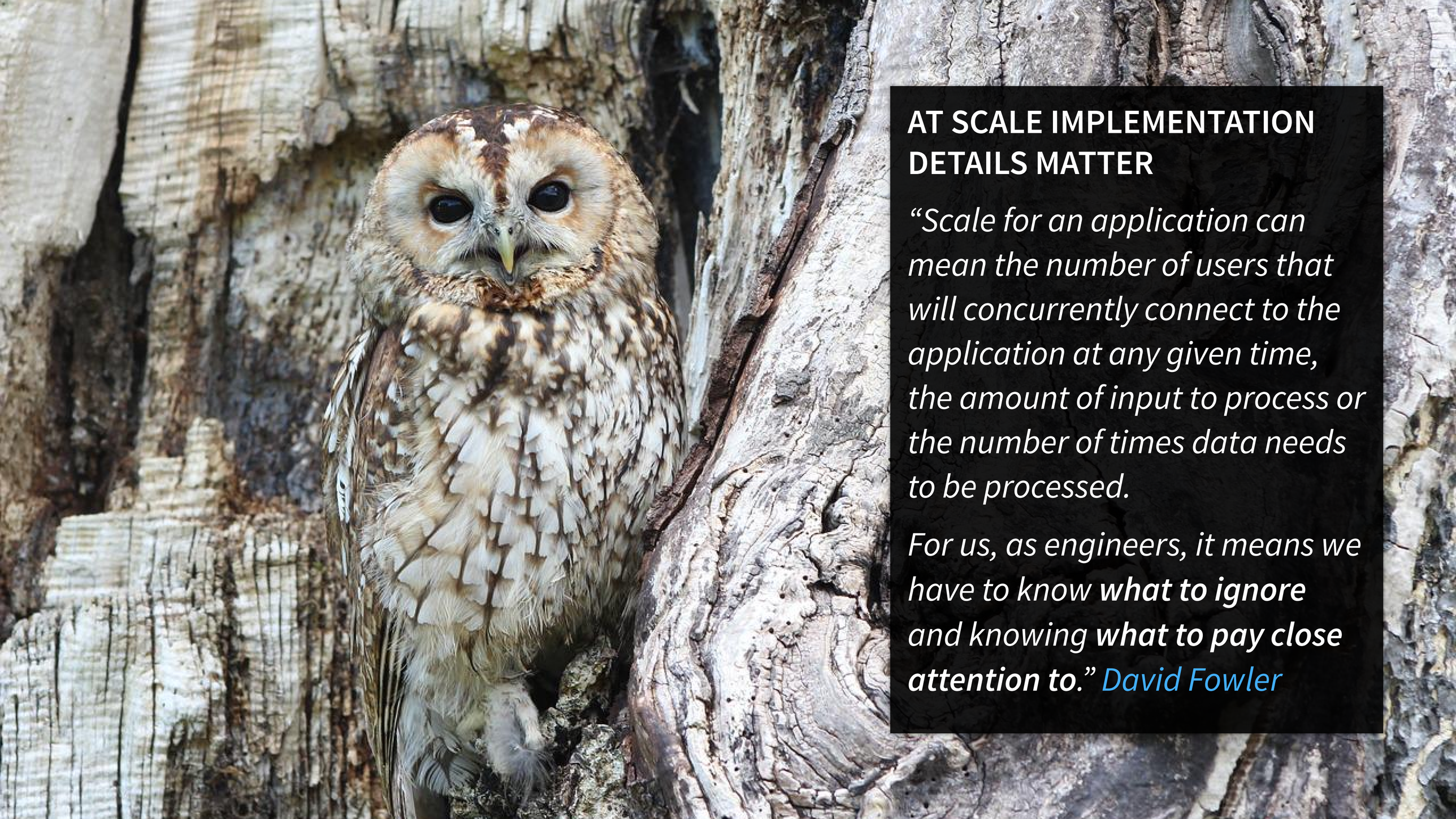


INTRODUCTION

Focus on performance optimization in .NET Code and not architecture.

ESOTERIC

Being called out for premature optimizations.



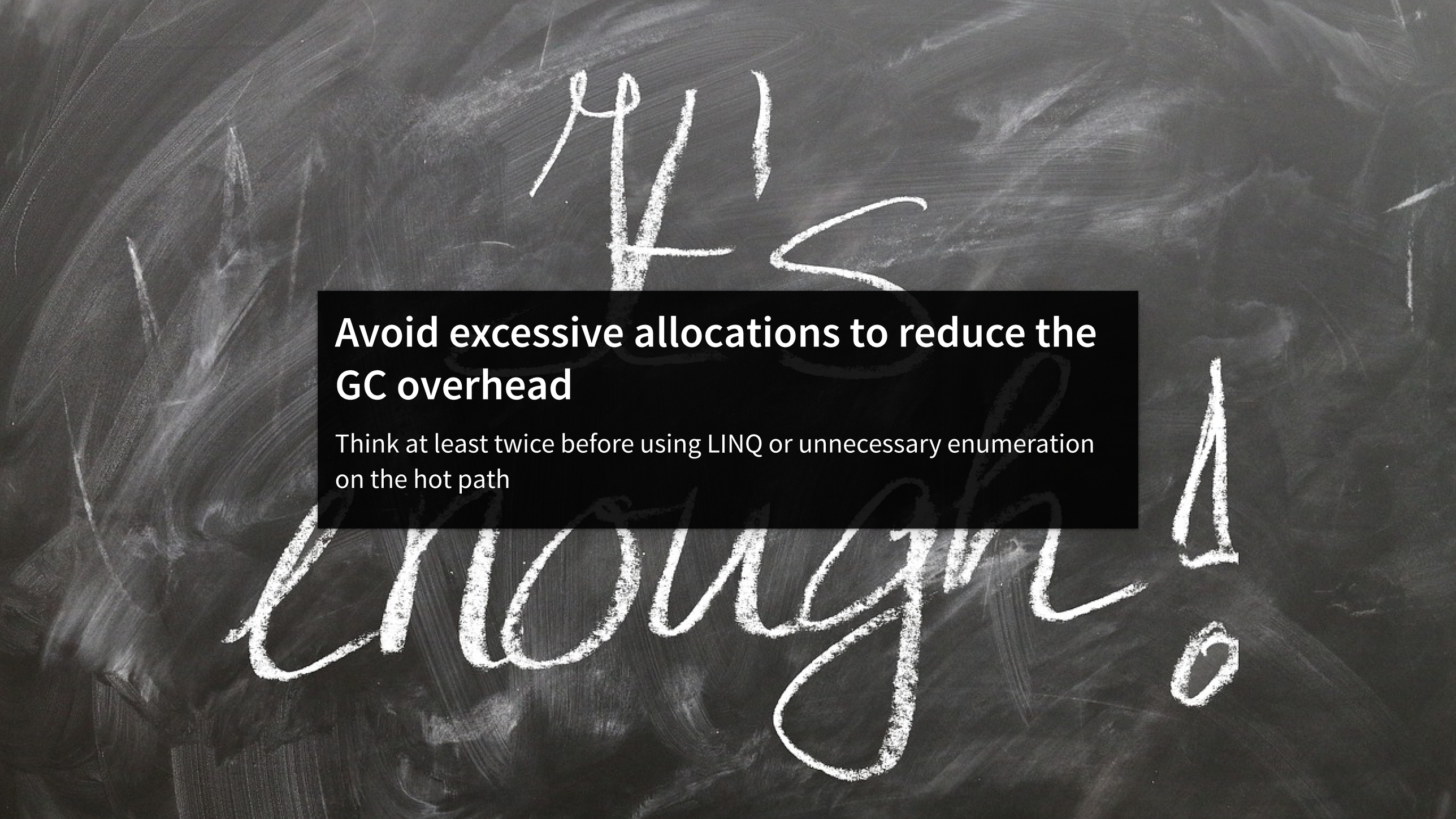
AT SCALE IMPLEMENTATION DETAILS MATTER

“Scale for an application can mean the number of users that will concurrently connect to the application at any given time, the amount of input to process or the number of times data needs to be processed.

For us, as engineers, it means we have to know ***what to ignore*** *and knowing* ***what to pay close attention to****.” David Fowler*


Rules

- Avoid excessive allocations to reduce the GC overhead
- Avoid unnecessary copying of memory



Avoid excessive allocations to reduce the GC overhead

Think at least twice before using LINQ or unnecessary enumeration on the hot path

```
1  public class AmqpReceiver {
2
3    ConcurrentBag<Guid> _lockedMessages = new ();
4
5    public Task CompleteAsync(IEnumerable<string> lockTokens)
6      => CompleteInternalAsync(lockTokens);
7
8    Task CompleteInternalAsync(IEnumerable<string> lockTokens)
9    {
10     Guid[] lockTokenGuids = lockTokens.Select(token => new Guid(token)).ToArray();
11     if (lockTokenGuids.Any(lockToken => _lockedMessages.Contains(lockToken)))
12     {
13       // do special path accessing lockTokenGuids
14       return Task.CompletedTask;
15     }
16     // do normal path accessing lockTokenGuids
17     return Task.CompletedTask;
18   }
19 }
```

Avoid LINQ on the hot path.

```
1  public class AmqpReceiver {
2
3    // ...
4    // Compiler generated chunk we are not really interested in right now
5
6    private Task CompleteInternalAsync(IEnumerable<string> lockTokens)
7    {
8      Enumerable.Any(Enumerable.ToArray(Enumerable.Select(lockTokens, <>c.<>9__2_0 ??
9        (<>c.<>9__2_0 = new Func<string, Guid>(<>c.<>9.<CompleteInternalAsync>b__2_0)))),
10         new Func<Guid, bool>(<CompleteInternalAsync>b__2_1));
11     return Task.CompletedTask;
12   }
13
14   [CompilerGenerated]
15   private bool <CompleteInternalAsync>b__2_1(Guid lockToken)
16   {
17     return Enumerable.Contains(_lockedMessages, lockToken);
18   }
19 }
```

Avoid LINQ on the hot path.

```
1  public Task CompleteAsync(IEnumerable<string> lockTokens)
2    => CompleteInternalAsync(lockTokens);
3
4  Task CompleteInternalAsync(IEnumerable<string> lockTokens)
5  {
6    Guid[] lockTokenGuids = lockTokens.Select(token => new Guid(token)).ToArray();
7    foreach (var tokenGuid in lockTokenGuids)
8    {
9      if (_requestResponseLockedMessages.Contains(tokenGuid))
10     {
11       return Task.CompletedTask;
12     }
13   }
14   return Task.CompletedTask;
15 }
```

Avoid LINQ on the hot path.

```
1  public Task CompleteAsync(IEnumerable<string> lockTokens)
2    => CompleteInternalAsync(lockTokens);
3
4  Task CompleteInternalAsync(IEnumerable<string> lockTokens)
5  {
6    Guid[] array = Enumerable.ToArray(Enumerable.Select(lockTokens,
7      <>c.<>9__2_0 ??
8      (<>c.<>9__2_0 = new Func<string, Guid>(<>c.<>9.<CompleteInternalAsync>b__2_0))));
9
10   int num = 0;
11   while (num < array.Length)
12   {
13     Guid item = array[num];
14     if (_requestResponseLockedMessages.Contains(item))
15     {
16       return Task.CompletedTask;
17     }
18     num++;
19   }
20   return Task.CompletedTask;
21 }
```

Avoid LINQ on the hot path.

Benchmarking Time!

We can only know the before and after when we measure it.

Method	Size	Collection	Mean	Error	StdDev	Ratio	RatioSD	Gen 0	Allocated
Before	0	Array	28.96 ns	18.868 ns	1.034 ns	1.00	0.00	0.0102	64 B
AfterV1	0	Array	17.62 ns	1.285 ns	0.070 ns	0.61	0.02	-	-
Before	0	Enumerable	29.73 ns	3.246 ns	0.178 ns	1.00	0.00	0.0102	64 B
AfterV1	0	Enumerable	23.25 ns	2.844 ns	0.156 ns	0.78	0.00	-	-
Before	0	HashSet	67.52 ns	24.479 ns	1.342 ns	1.00	0.00	0.0267	168 B
AfterV1	0	HashSet	54.60 ns	5.831 ns	0.320 ns	0.81	0.01	0.0166	104 B
Before	0	List	48.46 ns	11.809 ns	0.647 ns	1.00	0.00	0.0229	144 B
AfterV1	0	List	35.27 ns	23.899 ns	1.310 ns	0.73	0.03	0.0127	80 B
Before	1	Array	128.64 ns	7[illegible] ns	[illegible] ns	1.00	0.00	0.0381	240 B
AfterV1	1	Array	93.27 ns	25.817 ns	1.505 ns	0.73	0.02	0.0229	144 B
Before	1	Enumerable	147.40 ns	14[illegible] ns	8.120 ns	1.00	0.00	0.0458	288 B
AfterV1	1	Enumerable	115.77 ns	29.583 ns	1.622 ns	0.79	0.04	0.0305	192 B
Before	1	HashSet	311.50 ns	53.412 ns	2.928 ns	1.00	0.00	0.0596	376 B
AfterV1	1	HashSet	226.89 ns	87.069 ns	4.773 ns	0.73	0.01	0.0443	280 B
Before	1	List	195.72 ns	274.095 ns	15.024 ns	1.00	0.00	0.0420	264 B
AfterV1	1	List	150.91 ns	91.677 ns	5.025 ns	0.77	0.06	0.0267	168 B
Before	4	Array	277.94 ns	41.392 ns	2.269 ns	1.00	0.00	0.0687	432 B
AfterV1	4	Array	235.52 ns	28.813 ns	1.579 ns	0.85	0.01	0.0534	336 B
Before	4	Enumerable	353.15 ns	152.507 ns	8.359 ns	1.00	0.00	0.0763	480 B
AfterV1	4	Enumerable	287.29 ns	86.240 ns	4.727 ns	0.81	0.03	0.0610	384 B

~20-40%

~20-40%

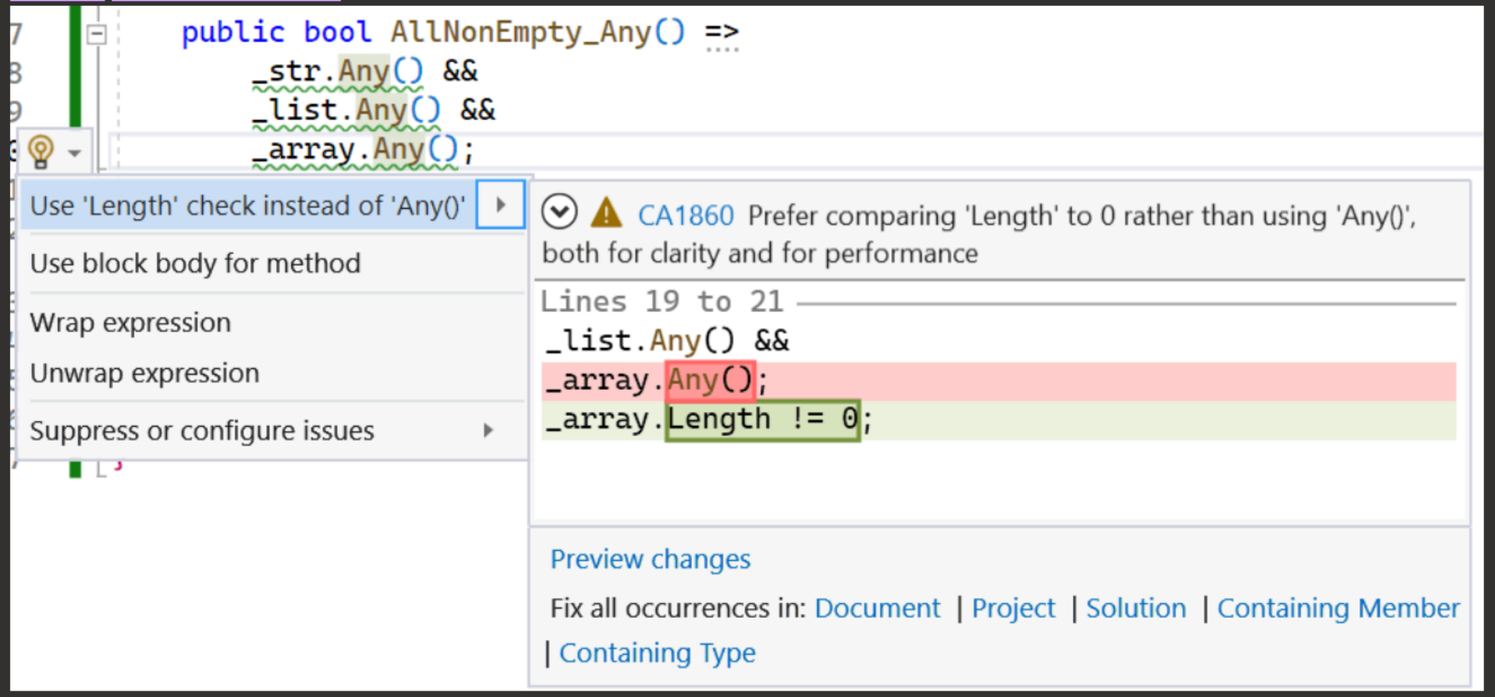

Rules

LINQ TO COLLECTION-BASED OPERATIONS

- Use `Array.Empty<T>` to represent empty arrays
- Use `Enumerable.Empty<T>` to represent empty enumerables
- Use CSharp12 collection expressions
- Prevent collections from growing
- Use concrete collection types
- Leverage pattern matching or `Enumerable.TryGetNonEnumeratedCount`
- Wait with instantiating collections until really needed
- There be dragons
  - Align access or use unsafe to avoid bound checks
  - Use CollectionMarshal/MemoryMarshal/Unsafe to access the underlying data directly
- Keep yourself up to date with latest .NET performance improvements

OrderByToArray	.NET 8.0	67.54 ms	0.36

Of course, sometimes the most efficient use of LINQ is simply not using it. It's an amazing productivity tool, and it goes to great lengths to be efficient, but sometimes there are better answers that are just as simple. CA1860, added in dotnet/roslyn-analyzers#6236 from @CollinAlpert, flags one such case. It looks for use of `Enumerable.Any` on collections that directly expose a `Count`, `Length`, or `IsEmpty` property that could be used instead. While `Any` does use `Enumerable.TryGetNonEnumeratedCount` in an attempt to check the collection's number of items without allocating or using an enumerator, even if it's successful in doing so it incurs the overhead of the interface check and dispatch. It's faster to just use the properties directly. dotnet/runtime#81583 fixed several cases of this.



```
1  public Task CompleteAsync(IEnumerable<string> lockTokens)
2    => CompleteInternalAsync(lockTokens);
3
4  Task CompleteInternalAsync(IEnumerable<string> lockTokens)
5  {
6    Guid[] lockTokenGuids = lockTokens.Select(token => new Guid(token)).ToArray();
7    foreach (var tokenGuid in lockTokenGuids)
8    {
9      if (_requestResponseLockedMessages.Contains(tokenGuid))
10     {
11       return Task.CompletedTask;
12     }
13   }
14   return Task.CompletedTask;
15 }
```

Avoid LINQ on the hot path.

```
1  public Task CompleteAsync(IEnumerable<string> lockTokens) {
2    IReadOnlyCollection<string> readOnlyCollection = lockTokens switch
3    {
4      IReadOnlyCollection<string> asReadOnlyCollection => asReadOnlyCollection,
5      _ => lockTokens.ToArray(),
6    };
7    return CompleteInternalAsync(readOnlyCollection);
8  }
9
10 Task CompleteInternalAsync(IReadOnlyCollection<string> lockTokens)
11 {
12   int count = lockTokens.Count;
13   Guid[] lockTokenGuids = count == 0 ? Array.Empty<Guid>() : new Guid[count];
14   int index = 0;
15   foreach (var token in lockTokens)
16   {
17     var tokenGuid = new Guid(token);
18     lockTokenGuids[index++] = tokenGuid;
19     if (_requestResponseLockedMessages.Contains(tokenGuid))
20     {
21       return Task.CompletedTask;
22     }
23   }
24   return Task.CompletedTask;
25 }
```

Avoid LINQ on the hot path.

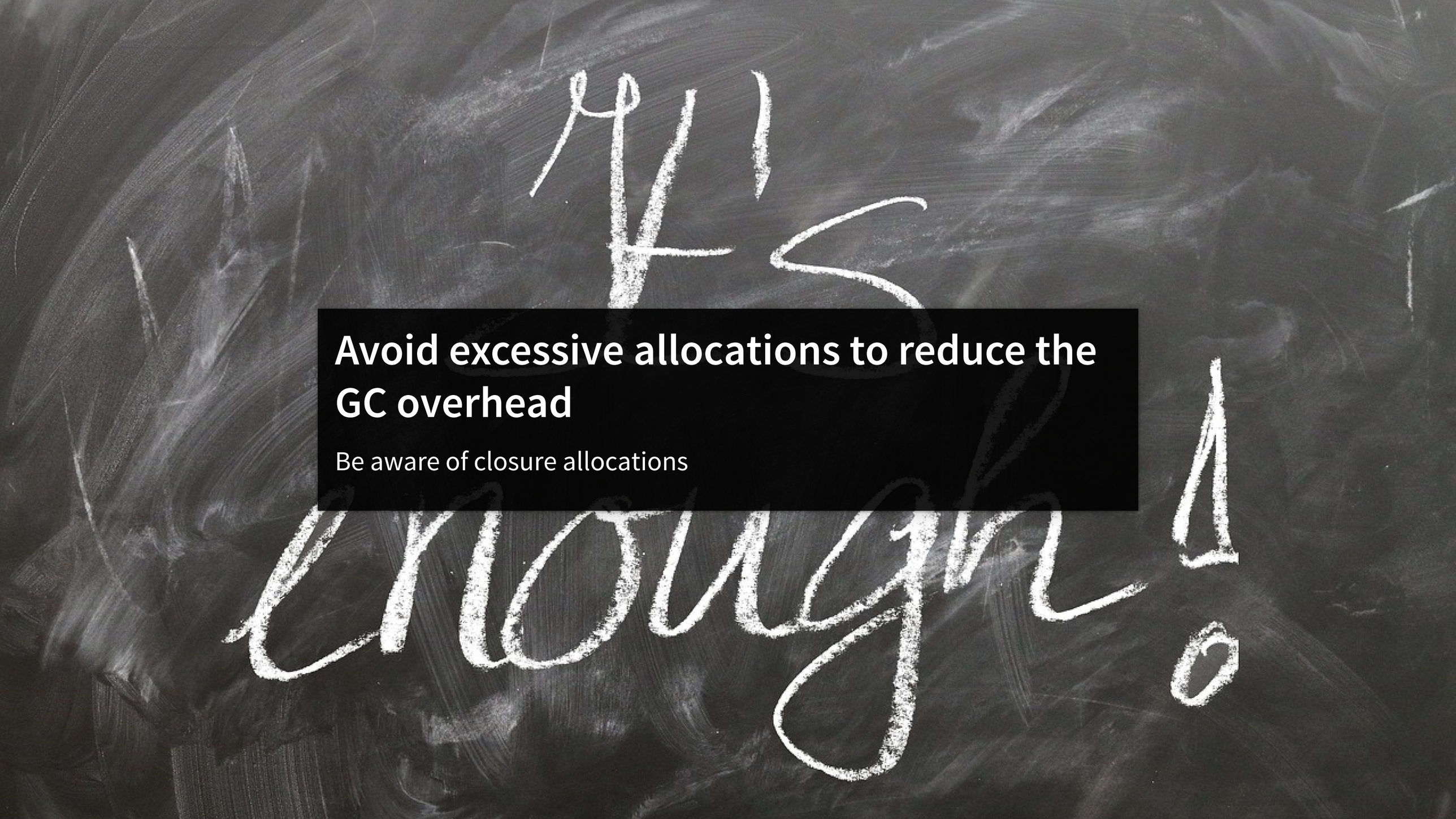
Benchmarking Time!

We can only know the before and after when we measure it.

Method	Size	Collection	Mean	Error	StdDev	Ratio	RatioSD	Gen 0	Allocated
AfterV1	0	Array	19.81 ns	29.413 ns	1.612 ns	1.00	0.00	-	-
AfterV2	0	Array	16.35 ns	0.722 ns	0.040 ns	0.83	0.07	-	-
AfterV1	0	Enumerable	20.25 ns	34.142 ns	1.871 ns	1.00	0.00	-	-
AfterV2	0	Enumerable	31.26 ns	76.364 ns	4.186 ns	1.56	0.29	-	-
AfterV1	0	HashSet	53.28 ns	78.903 ns	4.325 ns	1.00	0.00	0.0166	104 B
AfterV2	0	HashSet	29.80 ns	4.916 ns	0.269 ns	0.56	0.04	0.0063	40 B
AfterV1	0	List	37.30 ns	17.950 ns	0.984 ns	1.00	0.00	0.0127	80 B
AfterV2	0	List	26.72 ns	3.334 ns	0.183 ns	0.72	0.02	0.0063	40 B
AfterV1	1	Array	91.51 ns	76.518 ns	4.194 ns	1.00	0.00	0.0229	144 B
AfterV2	1	Array	76.42 ns	18.677 ns	1.024 ns	0.84	0.04	0.0191	120 B
AfterV1	1	Enumerable	112.50 ns	8.[illegible] ns	[illegible] ns	1.00	0.00	0.0305	192 B
AfterV2	1	Enumerable	117.57 ns	18.823 ns	1.032 ns	1.05	0.01	0.0241	152 B
AfterV1	1	HashSet	147.98 ns	25.249 ns	1.384 ns	1.00	0.00	0.0446	280 B
AfterV2	1	HashSet	80.78 ns	9.157 ns	0.502 ns	0.55	0.01	0.0204	128 B
AfterV1	1	List	97.80 ns	41.142 ns	2.255 ns	1.00	0.00	0.0267	168 B
AfterV2	1	List	92.70 ns	31.934 ns	1.750 ns	0.95	0.00	0.0204	128 B
AfterV1	4	Array	244.28 ns	92.399 ns	5.065 ns	1.00	0.00	0.0534	336 B
AfterV2	4	Array	350.87 ns	180.579 ns	9.898 ns	1.44	0.01	0.0496	312 B
AfterV1	4	Enumerable	426.69 ns	283.441 ns	15.536 ns	1.00	0.00	0.0610	384 B
AfterV2	4	Enumerable	441.16 ns	108.507 ns	5.948 ns	1.03	0.03	0.0587	368 B
AfterV1	4	HashSet	225.05 ns	12.186 ns	0.668 ns	1.00	0.00	0.0443	280 B
AfterV2	4	HashSet	80.35 ns	28.545 ns	1.565 ns	0.36	0.01	0.0204	128 B
AfterV1	4	List	249.84 ns	89.131 ns	4.886 ns	1.00	0.00	0.0572	360 B
AfterV2	4	List	229.86 ns	98.608 ns	5.405 ns	0.92	0.01	0.0508	320 B

+56%

~23-61%



Avoid excessive allocations to reduce the GC overhead

Be aware of closure allocations

```
1  async Task RunOperation(
2    Func<TimeSpan, Task> operation,
3    TransportConnectionScope scope, CancellationToken cancellationToken)
4  {
5    TimeSpan tryTimeout = CalculateTryTimeout(0);
6    // omitted
7    while (!cancellationToken.IsCancellationRequested) {
8      if (IsServerBusy) {
9        await Task.Delay(ServerBusyBaseSleepTime, cancellationToken);
10     }
11
12     try {
13       await operation(tryTimeout);
14       return;
15     }
16     catch {
17       // omitted
18     }
19   }
20 }
```

Remove closure allocations.

```
TransportMessageBatch messageBatch = null;
Task createBatchTask = _retryPolicy.RunOperation(async (timeout) =>
{
  messageBatch =
    await CreateMessageBatchInternalAsync(options, timeout);
},
_connectionScope,
cancellationToken);
await createBatchTask;
return messageBatch;
```

Remove closure allocations.

```
1  if (num1 != 0)  {
2    this.\u003C\u003E8__1 = new AmqpSender.\u003C\u003Ec__DisplayClass16_0();
3    this.\u003C\u003E8__1.\u003C\u003E4__this = this.\u003C\u003E4__this;
4    this.\u003C\u003E8__1.options = this.options;
5    this.\u003C\u003E8__1.messageBatch = (TransportMessageBatch) null;
6
7    configuredTaskAwaiter = amqpSender._retryPolicy.RunOperation(
8      new Func<TimeSpan, Task>((object) this.\u003C\u003E8__1,
9          __methodptr(\u003CCreateMessageBatchAsync\u003Eb__0)),
10         (TransportConnectionScope) amqpSender._connectionScope,
11         this.cancellationToken).ConfigureAwait(false).GetAwaiter();
12
```

Remove closure allocations.

```
internal async ValueTask<TResult> RunOperation<T1, TResult>(
  Func<T1, TimeSpan, CancellationToken, ValueTask<TResult>> operation,
  T1 t1,
  TransportConnectionScope scope,
  CancellationToken cancellationToken) {
  TimeSpan tryTimeout = CalculateTryTimeout(0);
  // omitted
  while (!cancellationToken.IsCancellationRequested) {
    if (IsServerBusy) {
      await Task.Delay(ServerBusyBaseSleepTime, cancellationToken);
    }

    try {
      return await operation(t1, tryTimeout, cancellationToken);
    }
    catch {
      // omitted
    }
  }
}
```

Remove closure allocations.

```
internal async ValueTask RunOperation<T1>(
  Func<T1, TimeSpan, CancellationToken, ValueTask> operation,
  T1 t1,
  TransportConnectionScope scope,
  CancellationToken cancellationToken) =>
    await RunOperation(static async (value, timeout, token) =>
    {
      var (t1, operation) = value;
      await operation(t1, timeout, token);
      return default(object);
    },
  (t1, operation),
  scope, cancellationToken);
```

Remove closure allocations.

```
if (num1 != 0) {
  configuredTaskAwaiter = t1._retryPolicy
    .RunOperation<AmqpSender, CreateMessageBatchOptions, TransportMessageBatch>(
    AmqpSender.\u003C\u003Ec.\u003C\u003E9__16_0 ?? (AmqpSender.\u003C\u003Ec.\u003C\u003E9__16_0 =
      new Func<AmqpSender, CreateMessageBatchOptions, TimeSpan, CancellationToken, Task<TransportMessageBatch>>
        (object) AmqpSender.\u003C\u003Ec.\u003C\u003E9,
        __methodptr(\u003CCreateMessageBatchAsync\u003Eb__16_0))),
        t1,
        this.options,
        (TransportConnectionScope) t1._connectionScope,
        this.cancellationToken).ConfigureAwait(false).GetAwaiter();
  // rest omitted
}
```

Remove closure allocations.

HOW TO DETECT THOSE ALLOCATIONS?

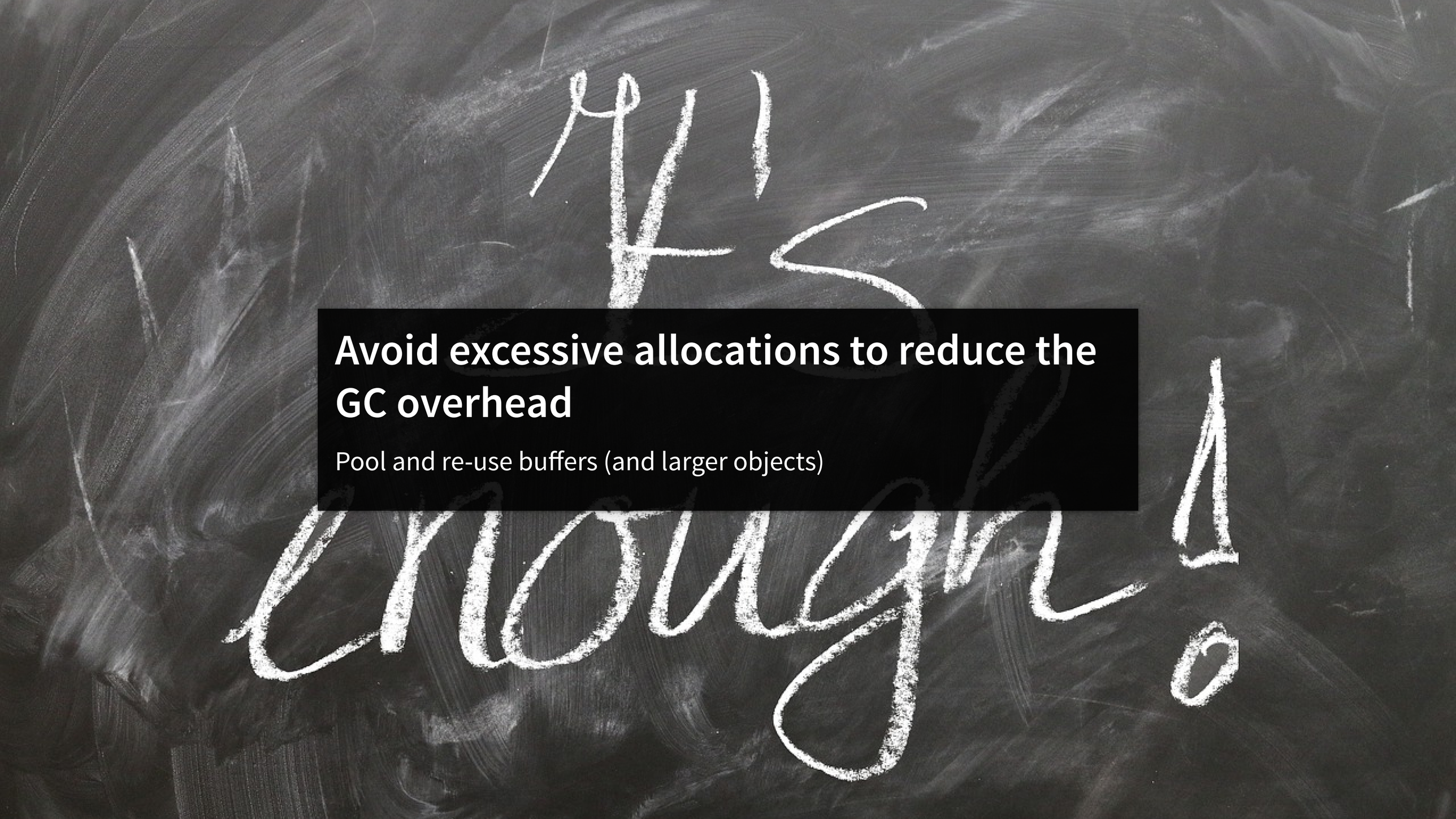
- Use memory profilers and watch out for excessive allocations of `*__DisplayClass*` or various variants of `Action*` and `Func*`
- Use tools like Heap Allocation Viewer (Rider) or Heap Allocation Analyzer (Visual Studio)
- Many built-in .NET types that use delegates have nowadays generic overloads that allow to pass state into the delegate.

Method	Calls	PipelineDepth	Mean	Error	StdDev	Ratio	RatioSD	Gen 0	Allocated
V8_PipelineBeforeOptimizations	**20000**	**10**	**7.083 ms**	**3.1550 ms**	**0.1729 ms**	**1.00**	**0.00**	**3054.6875**	**19,200,023 B**
V8_PipelineAfterOptimizations	20000	10	1.588 ms	1.1607 ms	0.0636 ms	0.22	0.01	-	1 B
V8_PipelineBeforeOptimizations	**20000**	**20**	**10.989 ms**	**9.0910 ms**	**0.4983 ms**	**1.00**	**0.00**	**6109.3750**	**38,400,049 B**
V8_PipelineAfterOptimizations	20000	20	2.830 ms	2.4414 ms	0.1338 ms	0.26	0.00	-	2 B
V8_PipelineBeforeOptimizations	**20000**	**40**	**23.054 ms**	**11.1449 ms**	**0.6109 ms**	**1.00**	**0.00**	**12218.7500**	**76,800,012 B**
V8_PipelineAfterOptimizations	20000	40	5.192 ms	4.4372 ms	0.2432 ms	0.23	0.02	-	3 B

~74-78%

~Gone!

go.particular.net/ndc-porto-2023-pipeline



Avoid excessive allocations to reduce the GC overhead

Pool and re-use buffers (and larger objects)

```
1 var data = new ArraySegment<byte>(Guid.NewGuid().ToByteArray());
2
3 var guidBuffer = new byte[16];
4 Buffer.BlockCopy(data.Array, data.Offset, guidBuffer, 0, 16);
5 var lockTokenGuid = new Guid(guidBuffer);
```

Pool and re-use buffers.

```
1 byte[] guidBuffer =  ArrayPool<byte>.Shared.Rent(16);
2 Buffer.BlockCopy(data.Array, data.Offset, guidBuffer, 0, 16);
3 var lockTokenGuid = new Guid(guidBuffer);
4 ArrayPool<byte>.Shared.Return(guidBuffer);
```

Pool and re-use buffers.

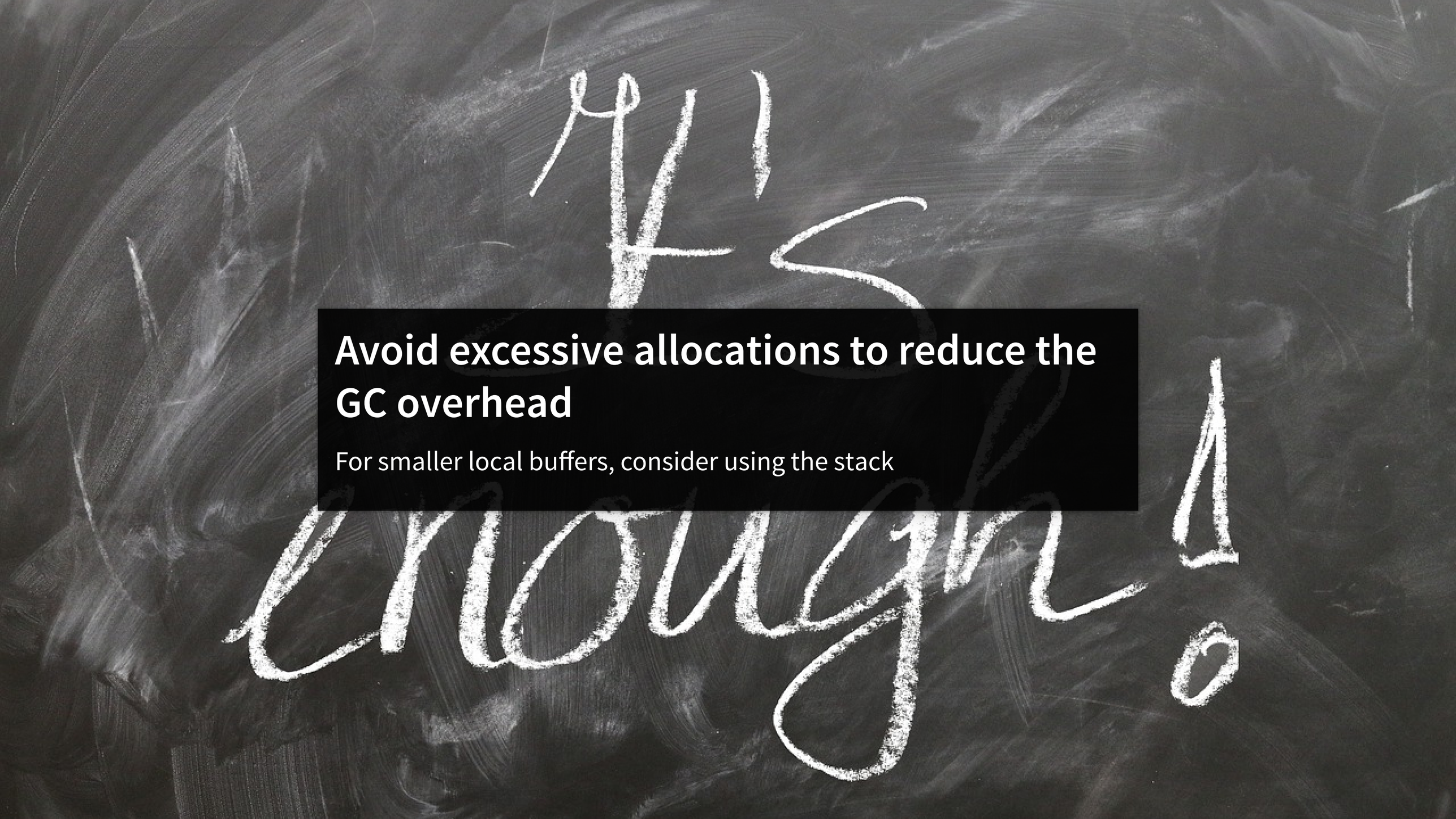
Benchmarking Time!

We can only know the before and after when we measure it.

Method	Mean	StdDev	Ratio	RatioSD	Gen 0	Allocated
BufferAndBlockCopy	10.975 ns	0.1740 ns	1.00	0.00	0.0064	40 B
BufferPool	24.718 ns	0.2555 ns	2.26	0.03	-	-

+226%

~Gone!



Avoid excessive allocations to reduce the GC overhead

For smaller local buffers, consider using the stack

```
1 Span<byte> guidBytes = stackalloc byte[16];
2 data.AsSpan().CopyTo(guidBytes);
3 var lockTokenGuid = new Guid(guidBytes);
```

Small local buffers on stack.

Benchmarking Time!

We can only know the before and after when we measure it.

Method	Mean	Error	StdDev	Ratio	RatioSD	Gen 0	Allocated
BufferAndBlockCopy	10.975 ns	0.1860 ns	0.1740 ns	1.00	0.00	0.0064	40 B
BufferPool	24.718 ns	0.2490 ns	0.2555 ns	2.26	0.03	-	-
StackallocWithGuid	6.078 ns	0.0362 ns	0.0321 ns	0.55	0.01	-	-

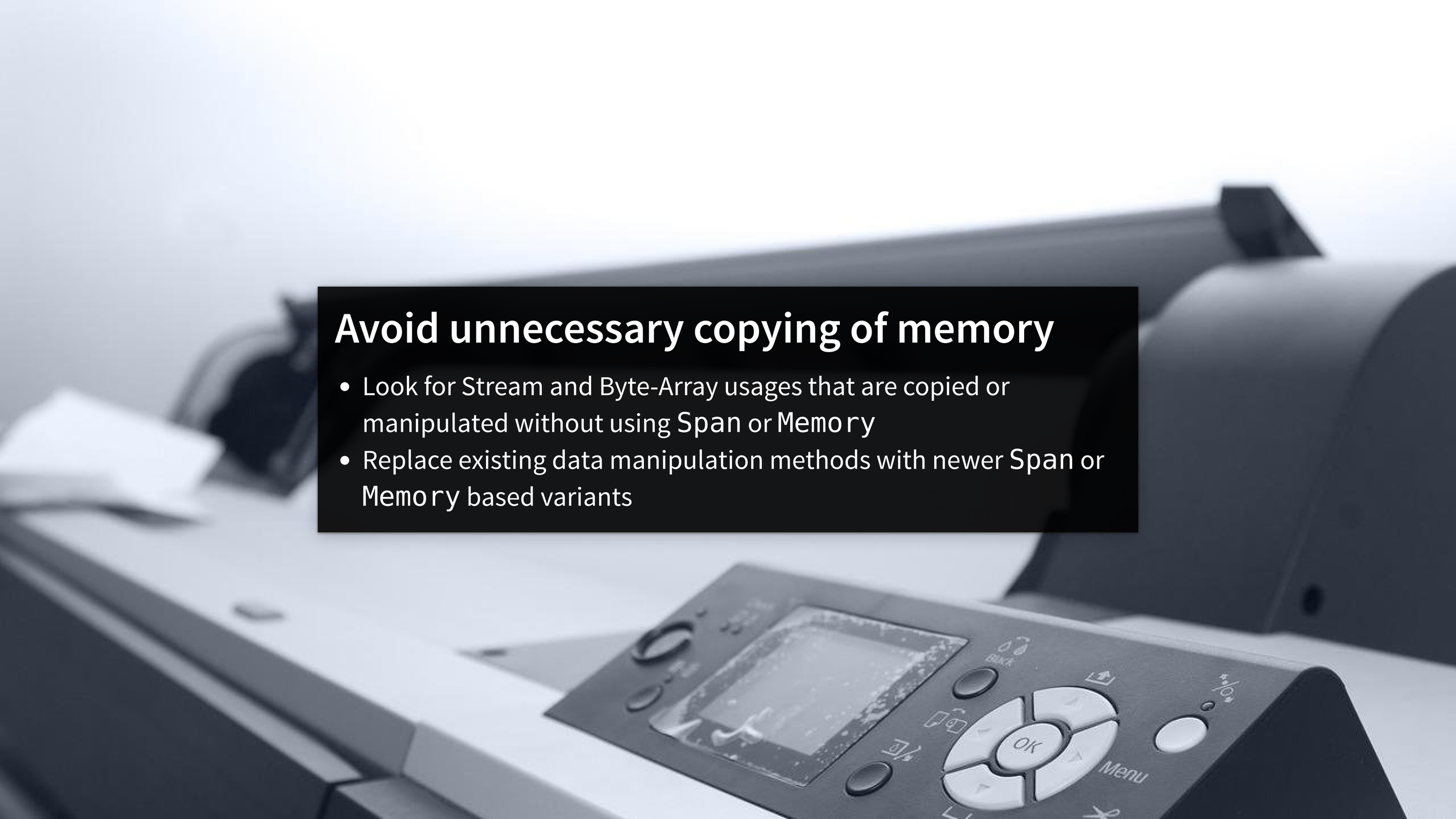
~45%

~Gone!


Rules

- Avoid excessive allocations to reduce the GC overhead
  - Think at least twice before using LINQ or unnecessary enumeration on the hot path
  - Be aware of closure allocations
  - Pool and re-use buffers
  - For smaller local buffers, consider using the stack
  - Be aware of parameter overloads
  - Where possible and feasible use value types but pay attention to unnecessary boxing
  - Move allocations away from the hot-path where possible


Avoid unnecessary copying of memory
B&W
OK
Menu



Avoid unnecessary copying of memory

- Look for Stream and Byte-Array usages that are copied or manipulated without using `Span` or `Memory`
- Replace existing data manipulation methods with newer `Span` or `Memory` based variants

```
1  private static short GenerateHashCode(string partitionKey) {
2    if (partitionKey == null) {
3      return 0;
4    }
5
6    var encoding = Encoding.UTF8;
7    ComputeHash(encoding.GetBytes(partitionKey), 0, 0, out uint hash1, out uint hash2);
8    return (short)(hash1 ^ hash2);
9  }
10
11 private static void ComputeHash(byte[] data, uint seed1, uint seed2,
12   out uint hash1, out uint hash2) {
13
14   uint a, b, c;
15
16   a = b = c = (uint)(0xdeadbeef + data.Length + seed1);
17   c += seed2;
18
19   int index = 0, size = data.Length;
20   while (size > 12) {
21     a += BitConverter.ToUInt32(data, index);
22     b += BitConverter.ToUInt32(data, index + 4);
23     c += BitConverter.ToUInt32(data, index + 8);
24
25   // rest omitted
26 }
```

Avoid unnecessary copying of memory.

```
1  [SkipLocalsInit]
2  private static short GenerateHashCode(string partitionKey) {
3    if (partitionKey == null) {
4      return 0;
5    }
6
7    const int MaxStackLimit = 256;
8
9    byte[] sharedBuffer = null;
10   var partitionKeySpan = partitionKey.AsSpan();
11   var encoding = Encoding.UTF8;
12
13   var partitionKeyByteLength = encoding.GetMaxByteCount(partitionKey.Length);
14   var hashBuffer = partitionKeyByteLength <= MaxStackLimit ?
15     stackalloc byte[MaxStackLimit] :
16     sharedBuffer = ArrayPool<byte>.Shared.Rent(partitionKeyByteLength);
17
18   var written = encoding.GetBytes(partitionKeySpan, hashBuffer);
19   var slicedBuffer = hashBuffer.Slice(0, written);
20
21   ComputeHash(slicedBuffer, 0, 0, out uint hash1, out uint hash2);
22
23   if (sharedBuffer != null) {
24     ArrayPool<byte>.Shared.Return(sharedBuffer);
25   }
26   return (short)(hash1 ^ hash2);
27 }
28
29 private static void ComputeHash(ReadonlySpan<byte> data, uint seed1, uint seed2,
30   out uint hash1, out uint hash2) {
31   // rest omitted
32 }
```

Avoid unnecessary copying of memory.

Benchmarking Time!

We can only know the before and after when we measure it.

Method	Size	Mean	Error	StdDev	Ratio	RatioSD	Gen 0	Allocated
Before	8	30.46 ns	10.493 ns	0.575 ns	1.00	0.00	0.0010	32 B
After	8	18.47 ns	2.863 ns	0.157 ns	0.61	0.02	-	-
Before	12	31.88 ns	5.089 ns	0.279 ns	1.00	0.00	0.0012	40 B
After	12	18.71 ns	2.281 ns	0.125 ns	0.59	0.01	-	-
Before	24	38.95 ns	3.828 ns	0.210 ns	1.00	0.00	0.0014	48 B
After	24	24.19 ns	0.476 ns	0.026 ns	0.62	0.00	-	-
Before	32	45.05 ns	6.978 ns	0.383 ns	1.00	0.00	0.0017	56 B
After	32	27.53 ns	1.200 ns	0.066 ns	0.61	0.00	-	-
Before	64	74.93 ns	7.068 ns	0.387 ns	1.00	0.00	0.0026	88 B
After	64	39.59 ns	1.935 ns	0.106 ns	0.53	0.00	-	-
Before	128	123.84 ns	12.736 ns	0.698 ns	1.00	0.00	0.0045	152 B
After	128	78.06 ns	2.420 ns	0.133 ns	0.63	0.00	-	-
Before	255	199.68 ns	11.492 ns	0.630 ns	1.00	0.00	0.0083	280 B
After	255	126.24 ns	1.639 ns	0.090 ns	0.63	0.00	-	-
Before	257	206.22 ns	8.201 ns	0.450 ns	1.00	0.00	0.0086	288 B
After	257	128.98 ns	2.596 ns	0.142 ns	0.63	0.00	-	-
Before	512	380.75 ns	74.100 ns	4.062 ns	1.00	0.00	0.0157	536 B
After	512	212.34 ns	14.202 ns	0.778 ns	0.56	0.01	-	-

~38-47%

~Gone!


Rules

- Look for Stream and Byte-Array usages that are copied or manipulated without using `Span` or `Memory`
- Replace existing data manipulation methods with newer `Span` or `Memory` based variants
- Watch out for immutable/readonly data that is copied

- Avoid excessive allocations to reduce the GC overhead
  - Be aware of closure allocations
  - Think at least twice before using LINQ
    or unnecessary enumeration on the hot path
    - Use `Array.Empty<T>` to represent empty arrays
    - Use `Enumerable.Empty<T>` to represent empty enumerables
    - Use CSharp12 collection expressions
    - Prevent collections from growing
    - Use concrete collection types
    - Leverage pattern matching or `Enumerable.TryGetNonEnumeratedCount`
    - Wait with instantiating collections until really needed
    - There be dragons
      - Align access or use unsafe to avoid bound checks
      - Use CollectionMarshal/MemoryMarshal/Unsafe to access the underlying data directly
    - Keep yourself up to date with latest .NET performance improvements
  - Pool and re-use buffers
  - For smaller local buffers, consider using the stack
  - Be aware of parameter overloads
  - Where possible and feasible use value types but pay attention to unnecessary boxing
  - Move allocations away from the hot-path where possible

- Avoid unnecessary copying of memory
  - Watch out for immutable/readonly data that is copied
  - Look for Stream and Byte-Array usages that are copied or manipulated without using `Span` or `Memory`
  - Replace existing data manipulation methods with newer `Span` or `Memory` based variants

In case you are up for a challenge

The original `ComputeHash` method had a 🐞.
Did you spot it?

```
static void ComputeHash(byte[] data, uint seed1, uint seed2,
        out uint hash1, out uint hash2) {

    uint a, b, c;

    a = b = c = (uint)(0xdeadbeef + data.Length + seed1);
    c += seed2;

    int index = 0, size = data.Length;
    while (size > 12) {
       a += BitConverter.ToUInt32(data, index);
       b += BitConverter.ToUInt32(data, index + 4);
       c += BitConverter.ToUInt32(data, index + 8);

       // rest omitted
    }
```

AT SCALE IMPLEMENTATION DETAILS MATTER

Tweak expensive I/O operations first.
Pay close attention to the context of the code.
Apply the principles where they matter.
Everywhere else, favor readability.

github.com/danielmarbach/PerformanceTricksAzureSDK

Happy coding!

danielmarbach daniel.marbach@particular.net