

THE PERFORMANCE LOOP

A PRACTICAL GUIDE TO PROFILING AND BENCHMARKING

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```
[SimpleJob]
[MemoryDiagnoser]
public class StringJoinBenchmarks {

    [Benchmark]
    public string StringJoin() {
        return string.Join(", ", Enumerable.Range(0, 10).Select(i => i.ToString()));
    }

    [Benchmark]
    public string StringBuilder() {
        var sb = new StringBuilder();
        for (int i = 0; i < 10; i++) {
            sb.Append(i);
            sb.Append(", ");
        }

        return sb.ToString(0, sb.Length - 2);
    }

    [Benchmark]
    public string ValueStringBuilder() {
        var separator = new ReadOnlySpan<char>(new char[] { ',', ',' });
        using var sb = new ValueStringBuilder(stackalloc char[30]);
        for (int i = 0; i < 10; i++)
        {
            sb.Append(i);
            sb.Append(separator);
        }

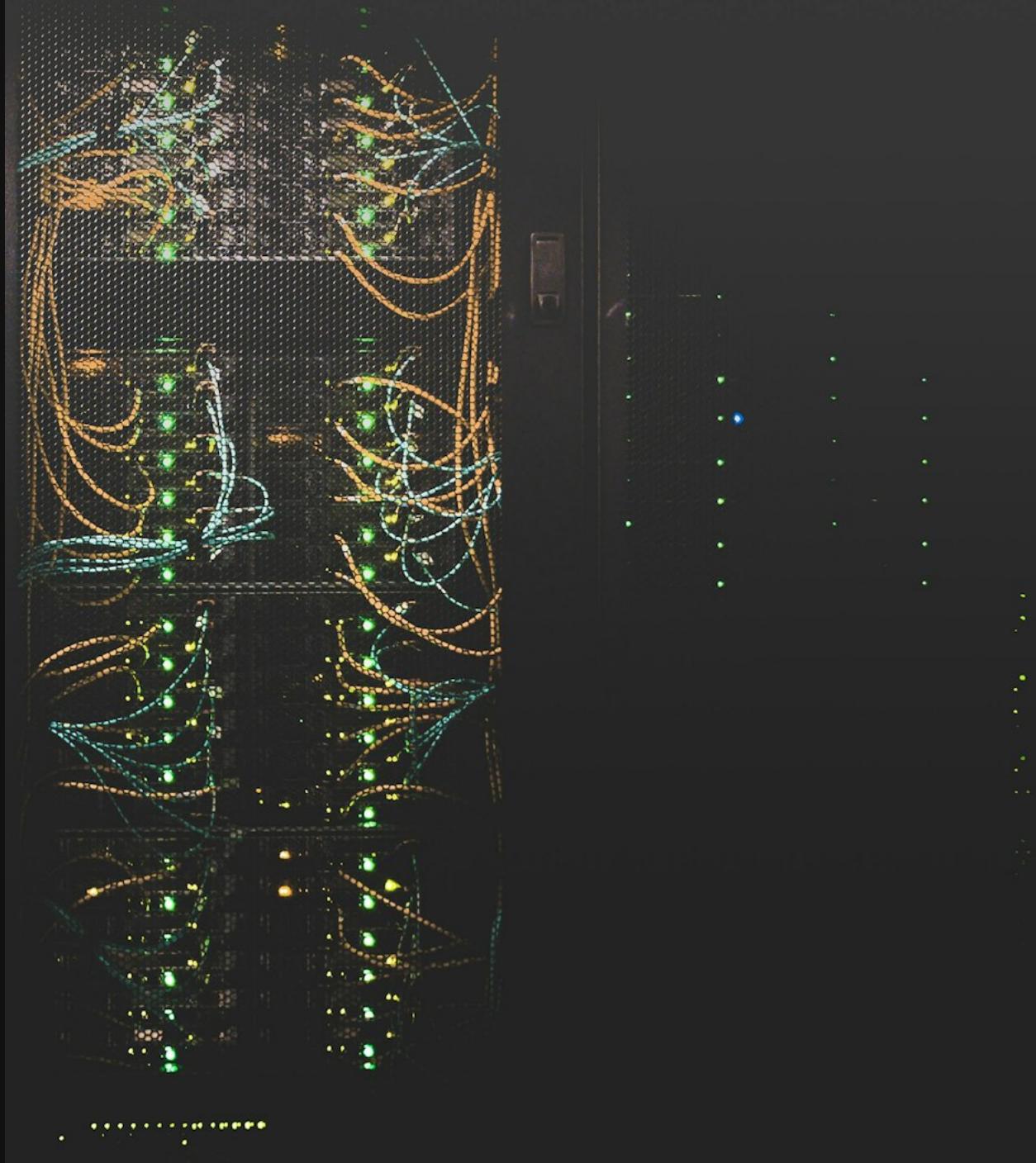
        return sb.AsSpan(0, sb.Length - 2).ToString();
    }
}
```

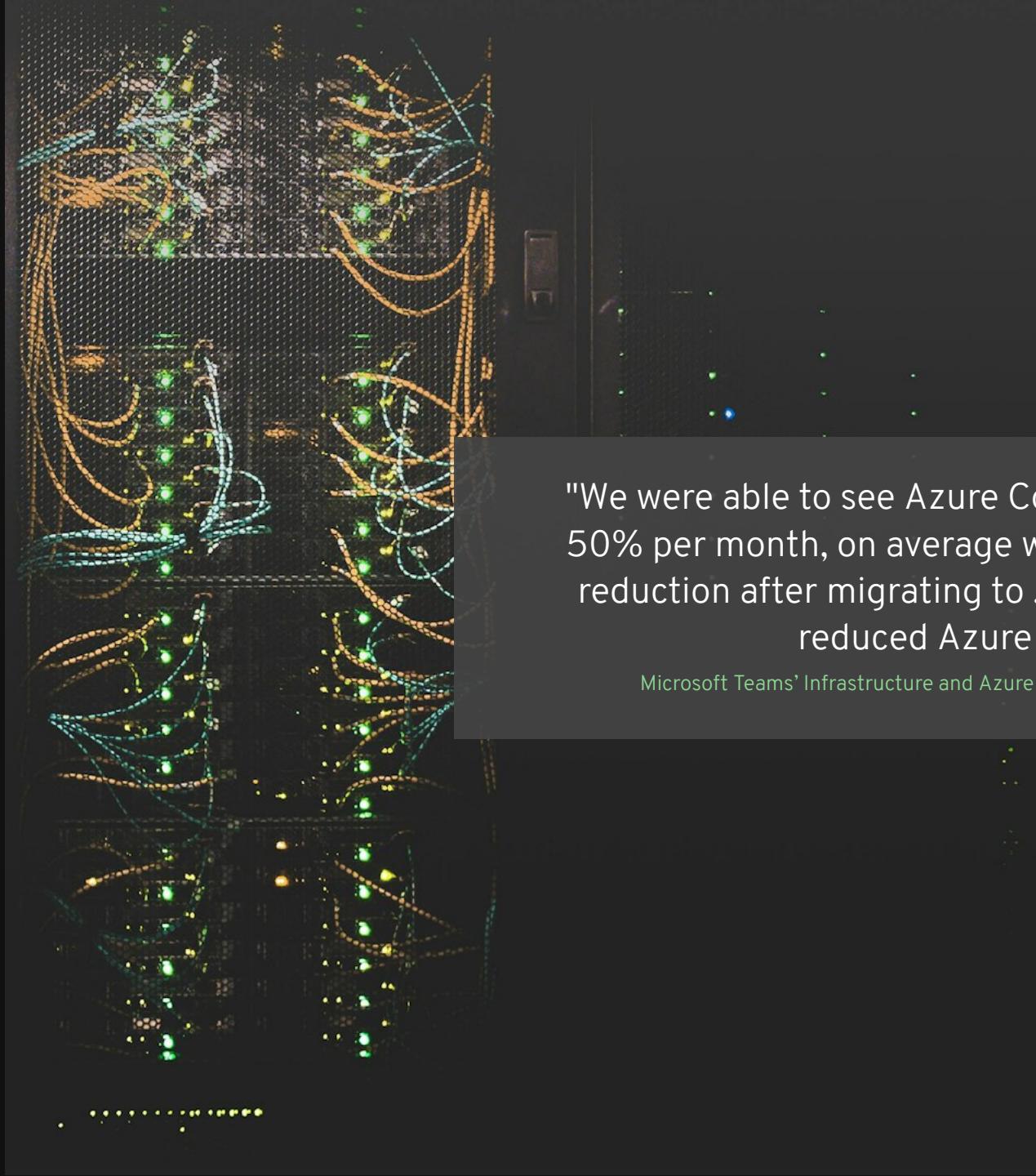
"SIMPLE"



Wrong!

$$2 + 2 = 5$$





"We were able to see Azure Compute cost reduction of up to 50% per month, on average we observed 24% monthly cost reduction after migrating to .NET 6. The reduction in cores reduced Azure spend by 24%."

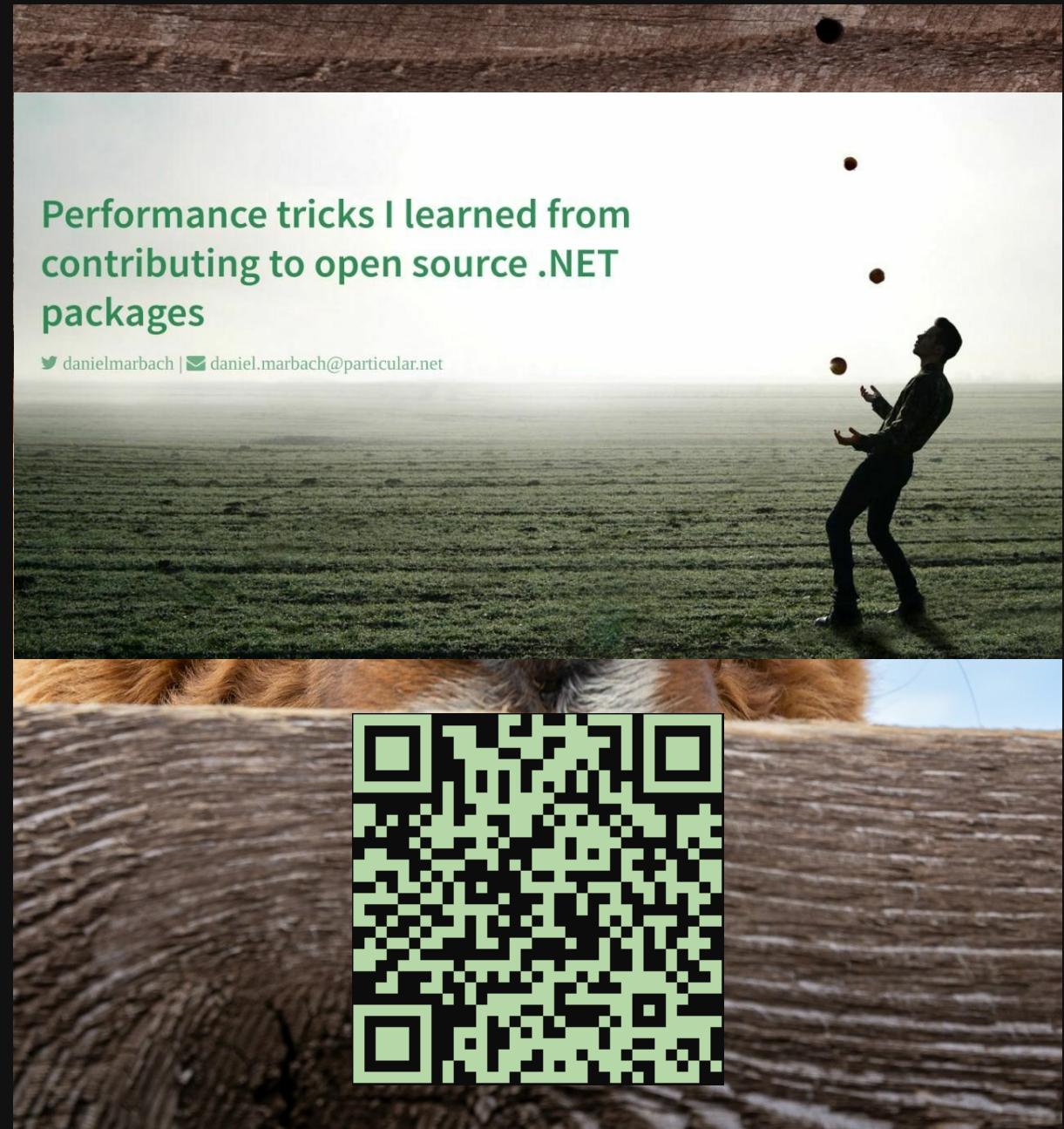
Microsoft Teams' Infrastructure and Azure Communication Services' Journey to .NET 6



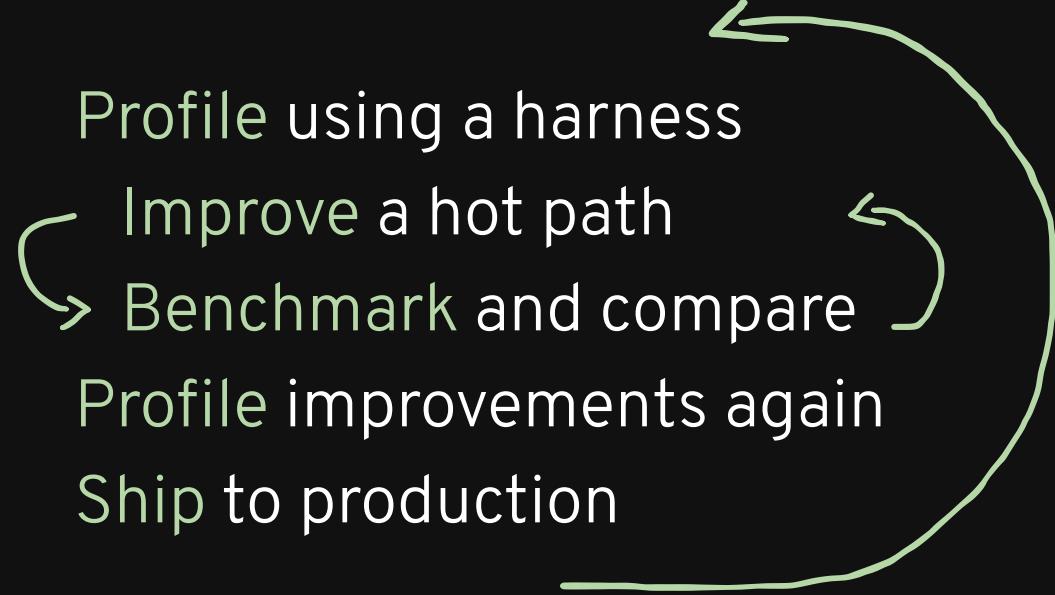


BE CURIOUS.... UNDERSTAND THE CONTEXT

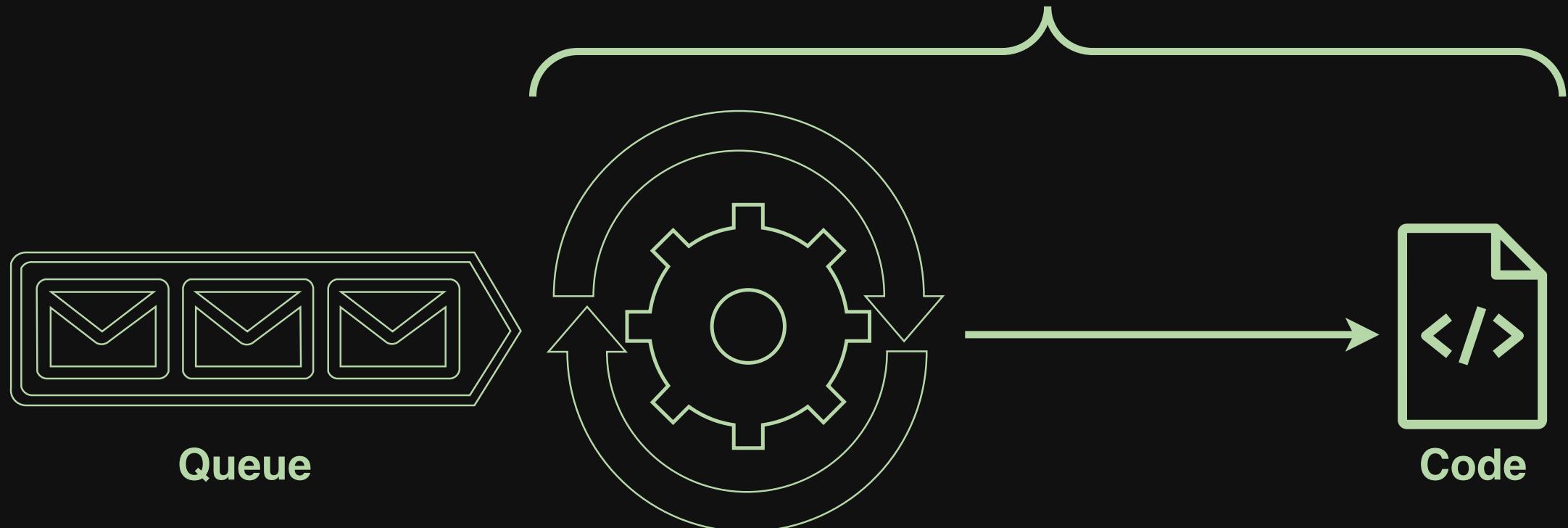
- How is this code going to be executed at scale, and what would the memory characteristics be (gut feeling)
- Are there simple low-hanging fruits I can apply to accelerate this code?
- Are there things I can move away from the hot path by simply restructuring a bit my code?
- What part is under my control and what isn't really?
- What optimizations can I apply, and when should I stop?



THE PERFORMANCE LOOP

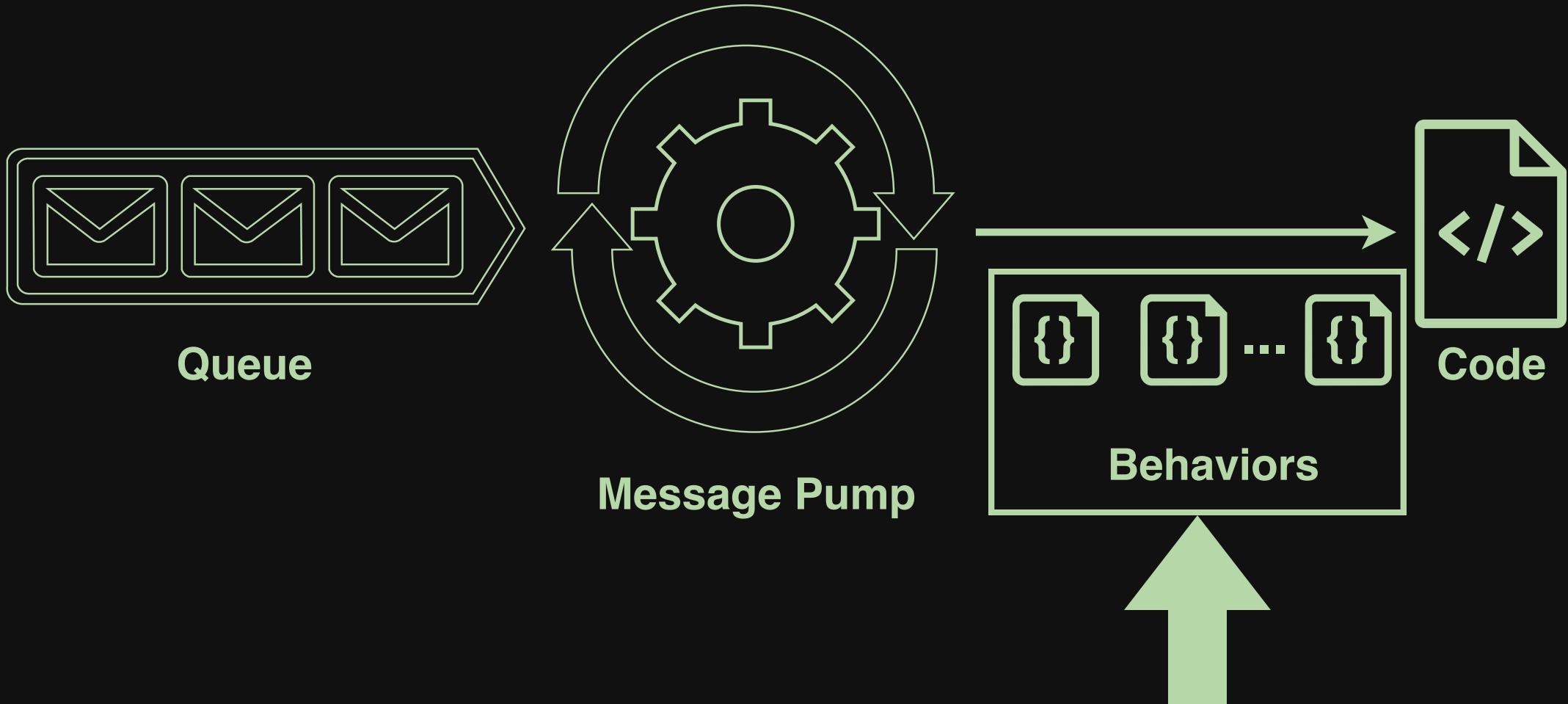


NSERVICEBUS



go.particular.net/ndc-london-2025-quickstart

NSERVICEBUS PIPELINE



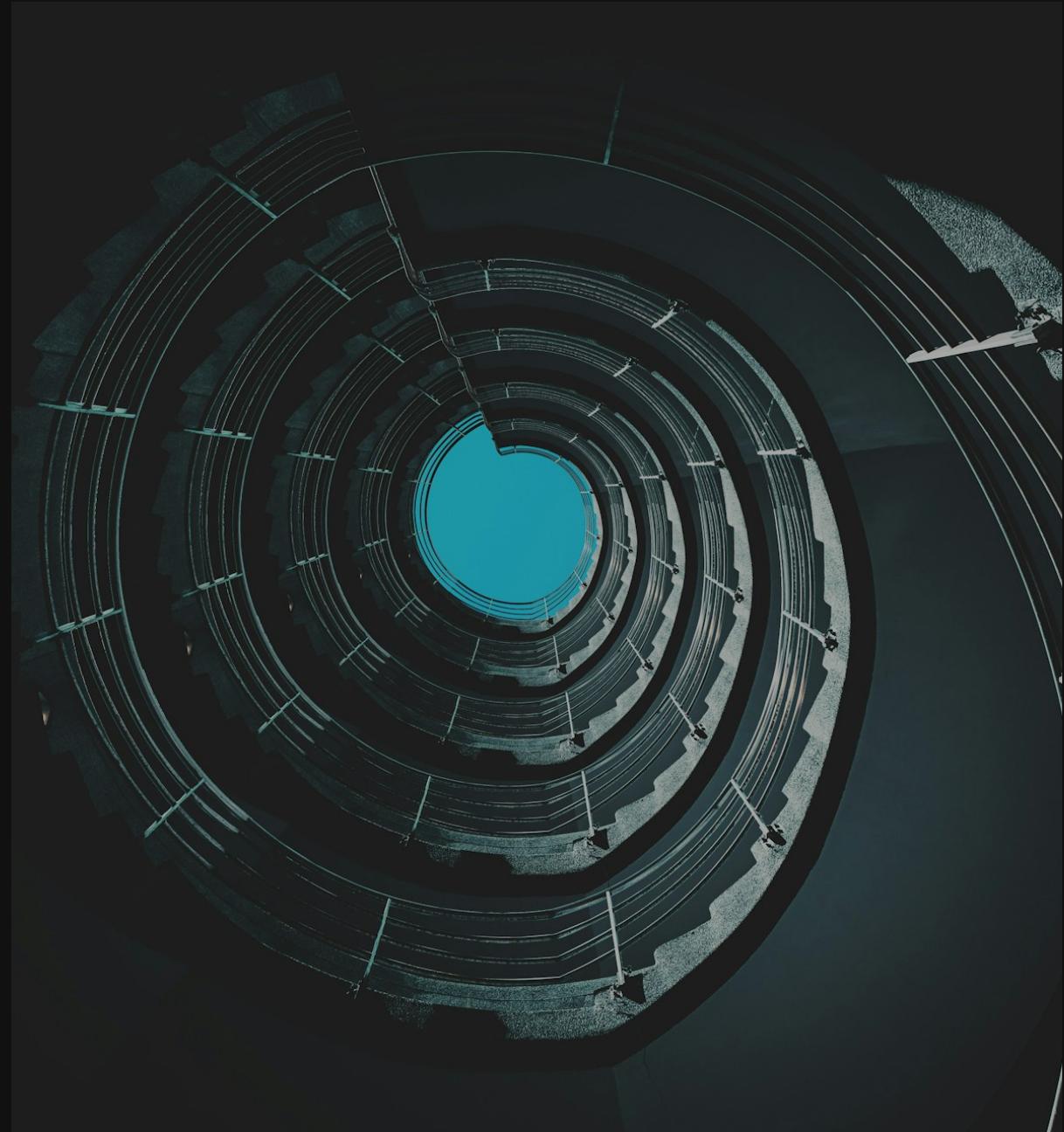
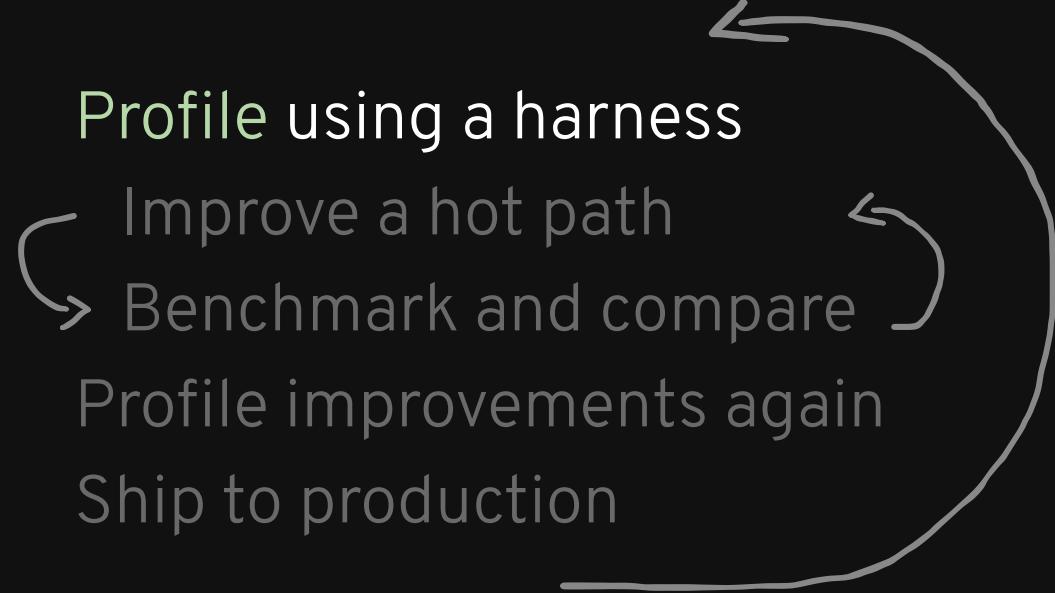
ASP.NET CORE MIDDLEWARE

```
  ● ● ●  
1 public class RequestCultureMiddleware {  
2     private readonly RequestDelegate _next;  
3  
4     public RequestCultureMiddleware(RequestDelegate next) {  
5         _next = next;  
6     }  
7  
8     public async Task InvokeAsync(HttpContext context) {  
9         // Do work that does something before  
10        await _next(context);  
11        // Do work that does something after  
12    }  
13 }
```

BEHAVIORS

```
  ● ● ●  
1 public class Behavior : Behavior<IIncomingLogicalMessageContext> {  
2     public override Task  
3         Invoke(IIncomingLogicalMessageContext context, Func<Task> next) {  
4             // Do work that does something before  
5             await next();  
6             // Do work that does something after  
7         }  
8     }
```

THE PERFORMANCE LOOP



PROFILING THE PIPELINE



THE HARNESS

•••

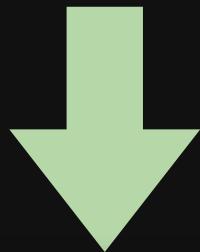
```
1 var endpointConfiguration = new EndpointConfiguration("Harness");
2 endpointConfiguration.UseSerialization<JsonSerializer>();
3 var transport = endpointConfiguration.UseTransport<MsmqTransport>();
4 endpointConfiguration.UsePersistence<InMemoryPersistence>();
5
6 var endpointInstance = await Endpoint.Start(endpointConfiguration);
7
8 Console.WriteLine("Attach the profiler and hit <enter>.");
9 Console.ReadLine();
10
11 var tasks = new List<Task>(1000);
12 for (int i = 0; i < 1000; i++)
13 {
14     tasks.Add(endpointInstance.Publish(new MyEvent()));
15 }
16 await Task.WhenAll(tasks);
17
18 Console.WriteLine("Publish 1000 done. Get a snapshot");
19 Console.ReadLine();
```

Publish Pipeline



Profiling the pipeline > Improving > Benchmarking > Profiling

THE HARNESS



Receive Pipeline

```
...  
  
public class MyEventHandler : IHandleMessages<MyEvent> {  
    public Task Handle(MyEvent message, IMessageHandlerContext context)  
    {  
        return Task.CompletedTask;  
    }  
}
```



Profiling the pipeline > Improving > Benchmarking > Profiling

THE HARNESS

- Compiled and executed in Release mode
- Runs a few seconds and keeps overhead minimal
- Disabled Tiered JIT
`<TieredCompilation>false</TieredCompilation>`
- Emits full symbols
`<DebugType>pdbonly</DebugType>`
`<DebugSymbols>true</DebugSymbols>`



```
var endpointConfiguration = new EndpointConfiguration("Harness");
endpointConfiguration.UseSerialization<JsonSerializer>();
var transport = endpointConfiguration.UseTransport<MsmqTransport>();
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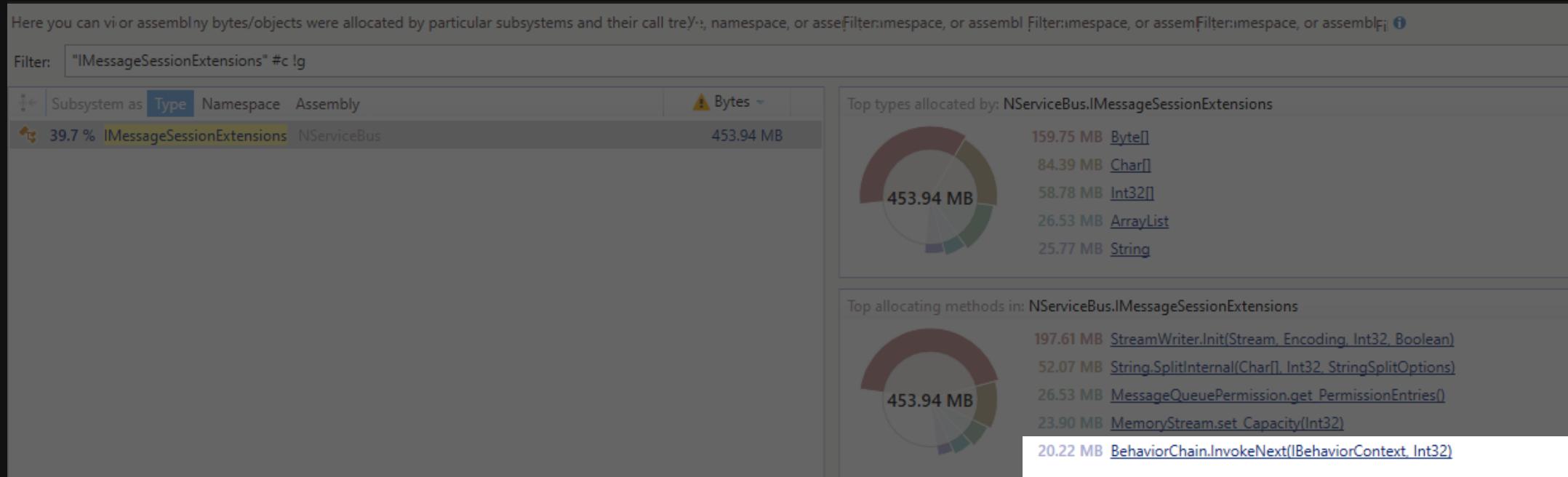
Console.WriteLine("Publish 1000 done. Get a snapshot");
Console.ReadLine();
```



```
public class MyEventHandler : IHandleMessages<MyEvent> {
    public Task Handle(MyEvent message, IMessageHandlerContext context)
    {
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    }
}
```



MEMORY CHARACTERISTICS

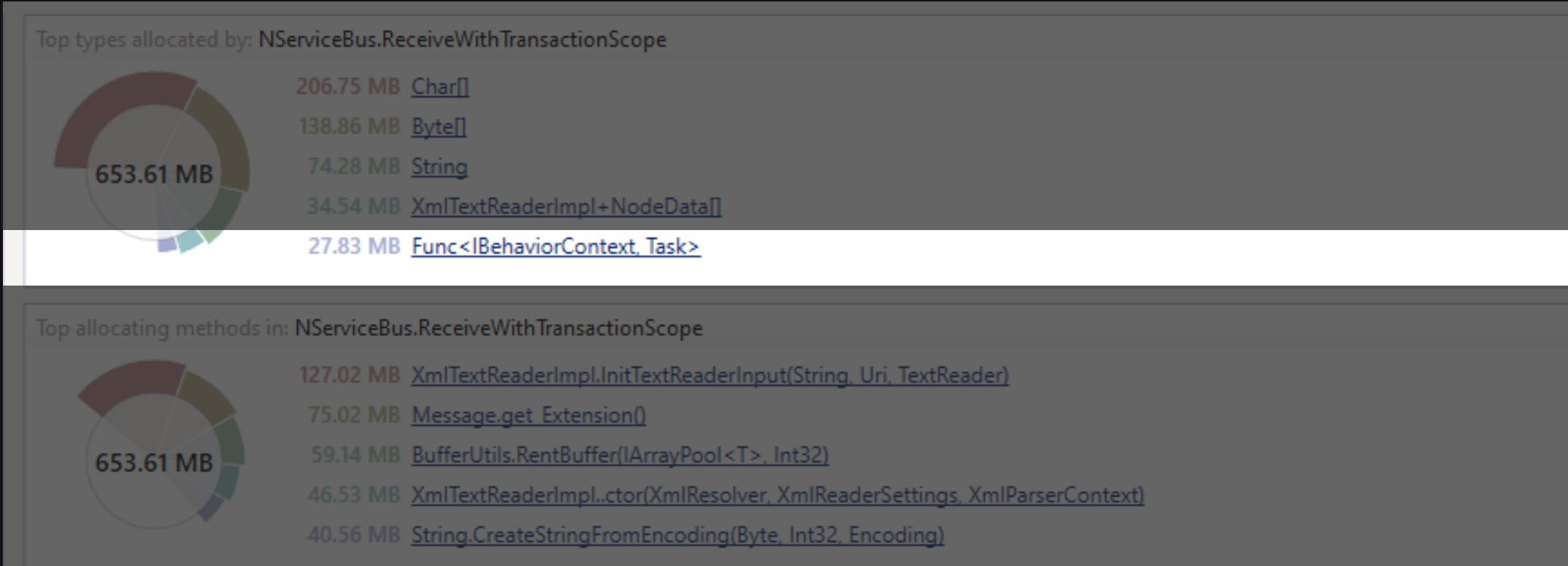


PUBLISH



Profiling the pipeline > Improving > Benchmarking > Profiling

MEMORY CHARACTERISTICS



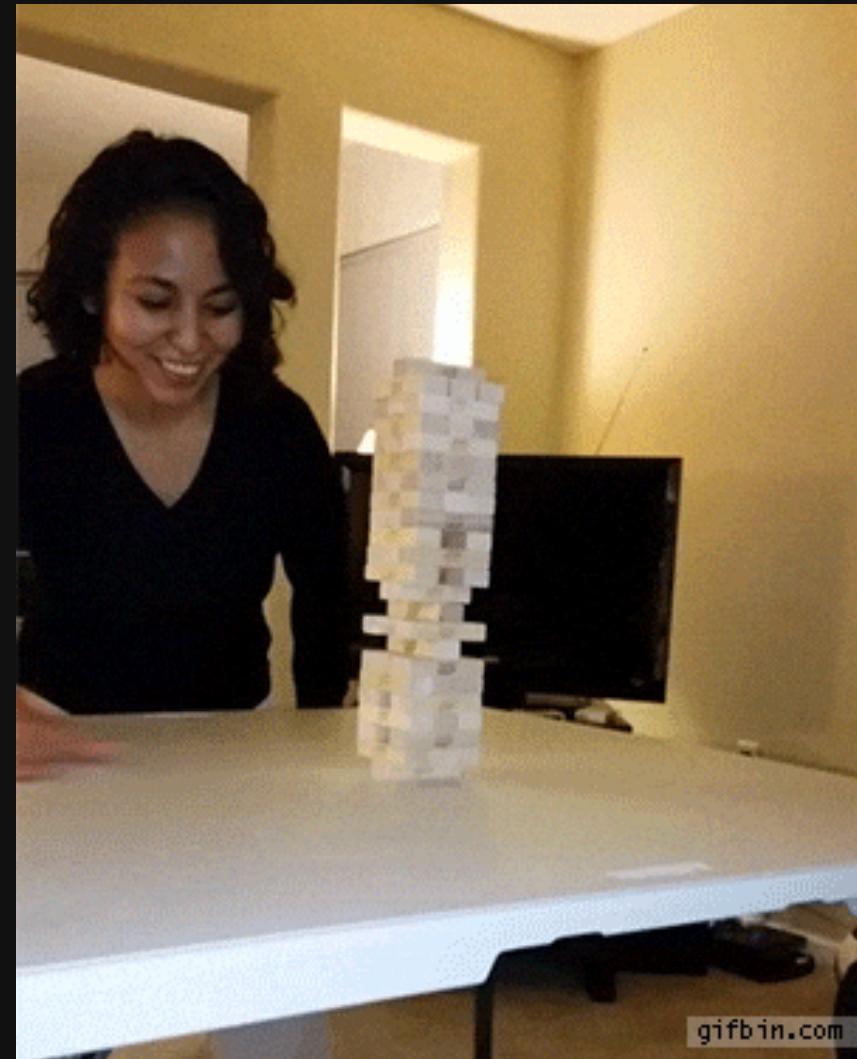
RECEIVE



MEMORY CHARACTERISTICS

- MSMQ has a diminishing user-base
- Ramping up knowledge may not be feasible
- Iterative gains on the hot path will lead to overall improvements
- Pipeline optimizations benefits all users

CONTEXT MATTERS
YOU ARE THE EXPERT



MEMORY CHARACTERISTICS

Top types allocated by: Behavior<TContext>.Invoke(...)



15.15 MB [Func<Task>](#)

225.3 KB [Behavior+ <>c DisplayClass0 0<|OutgoingLogicalMessageContext>](#)

110.3 KB [Behavior+ <>c DisplayClass0 0<|OutgoingPublishContext>](#)

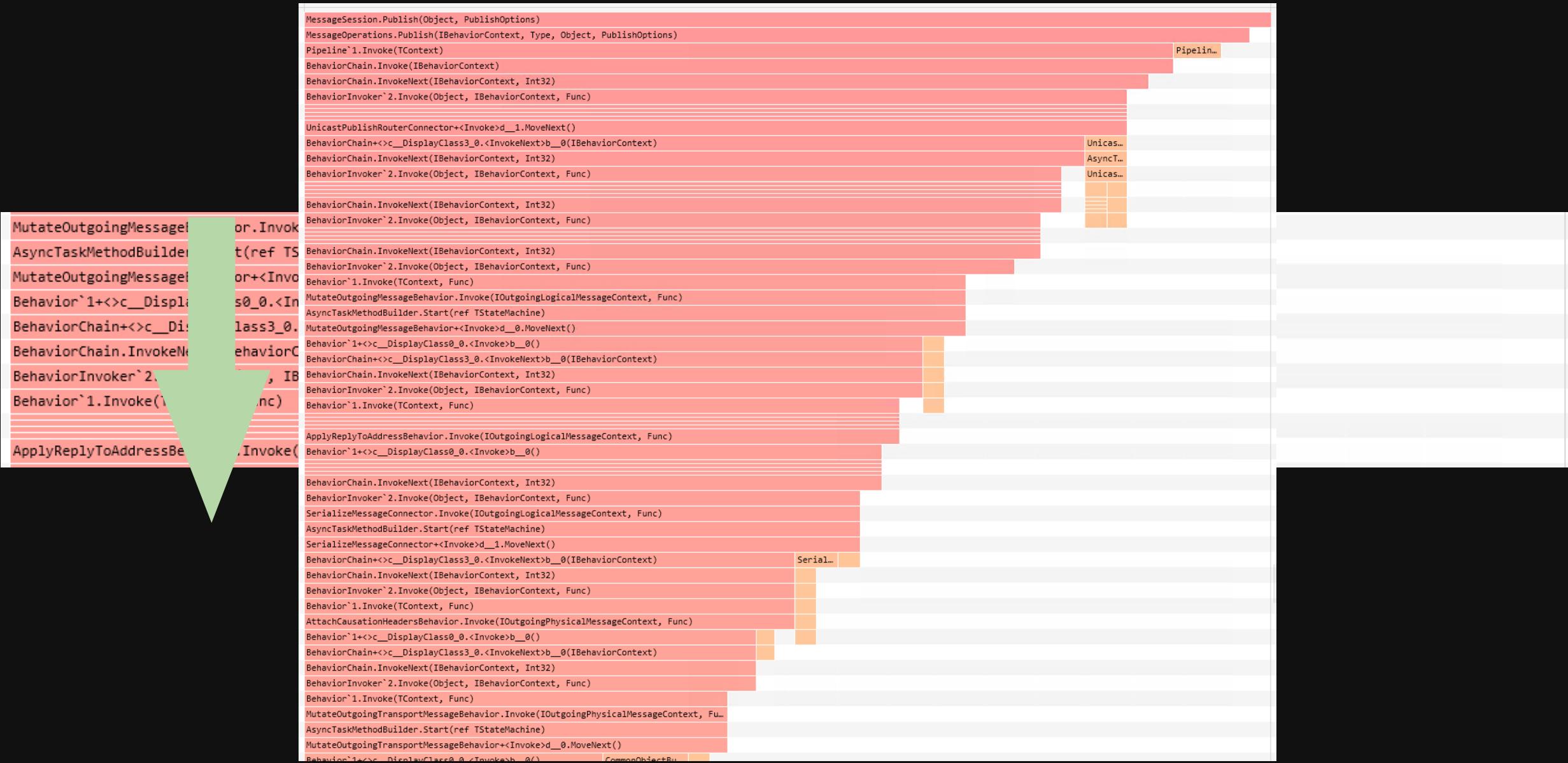


MEMORY CHARACTERISTICS

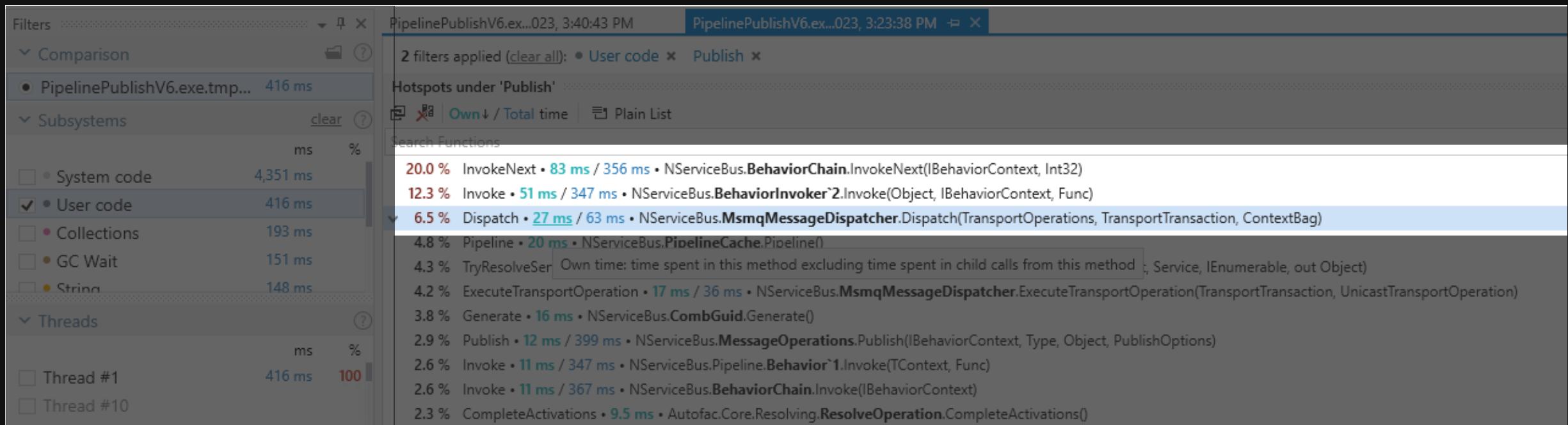
Type	Bytes
StageForkConnector+<>c_DisplayClass0_0<ITransportReceiveContext, IIncomingPhysicalMessageContext>	15.74 MB
Behavior+<>c_DisplayClass0_0<IOutgoingLogicalMessageContext>	NServiceBus.Pipeline
Behavior+<>c_DisplayClass0_0<IRoutingContext>	NServiceBus.Pipeline
Behavior+<>c_DisplayClass0_0<IOutgoingPhysicalMessageContext>	NServiceBus.Pipeline

CPU CHARACTERISTICS

CPU CHARACTERISTICS



CPU CHARACTERISTICS

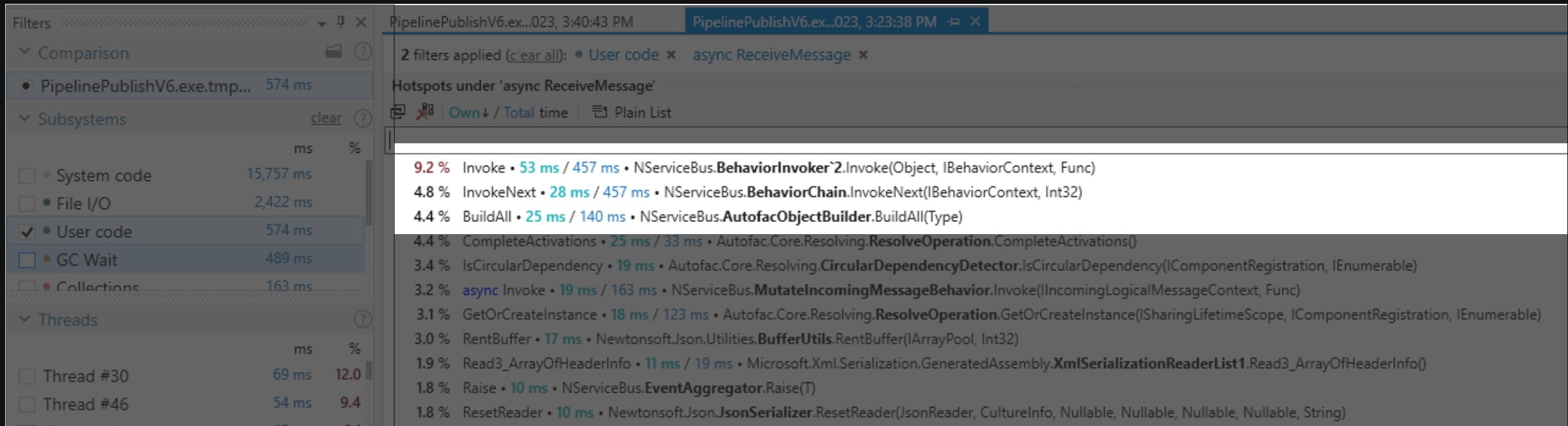


PUBLISH



Profiling the pipeline > Improving > Benchmarking > Profiling

CPU CHARACTERISTICS

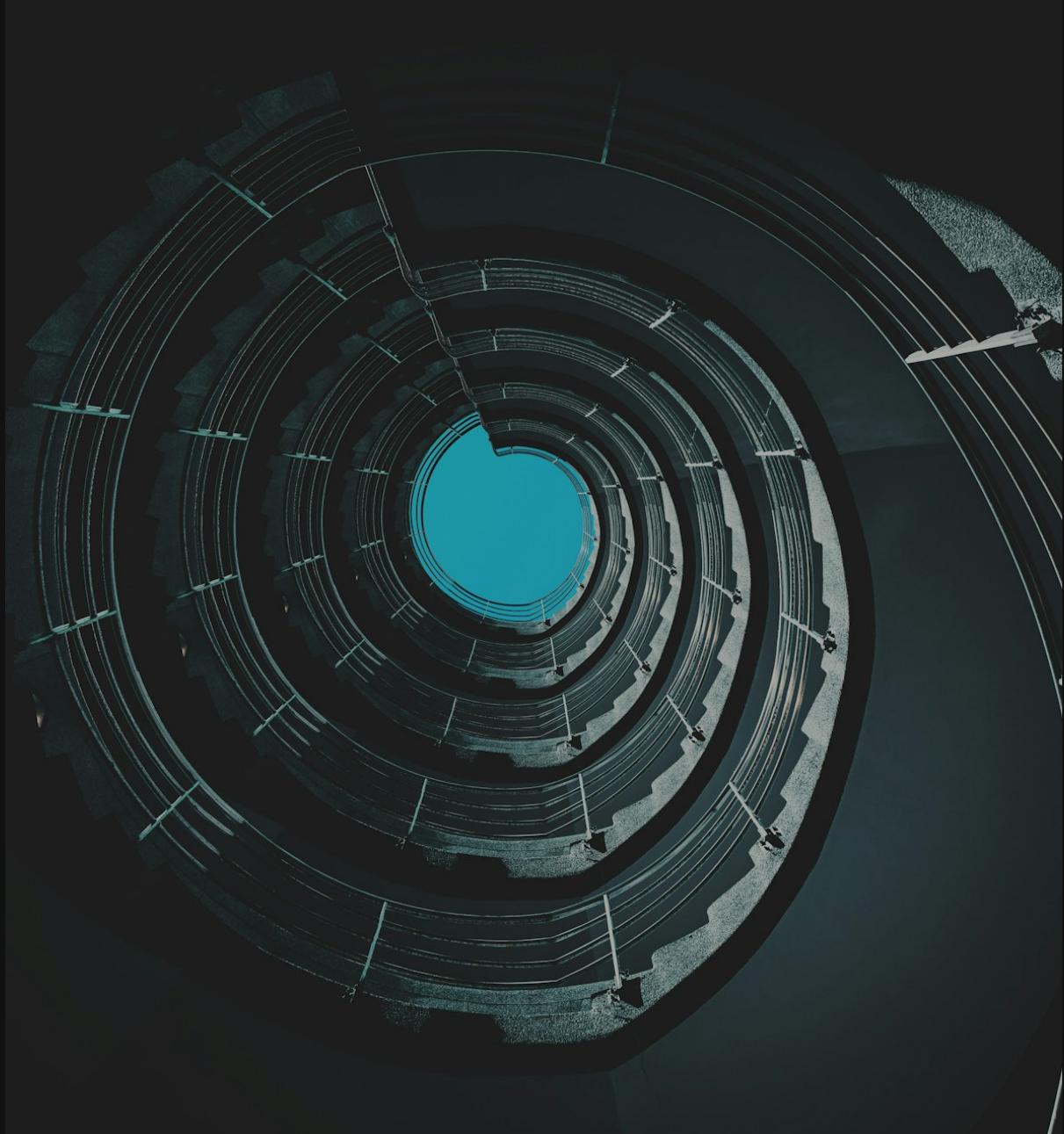
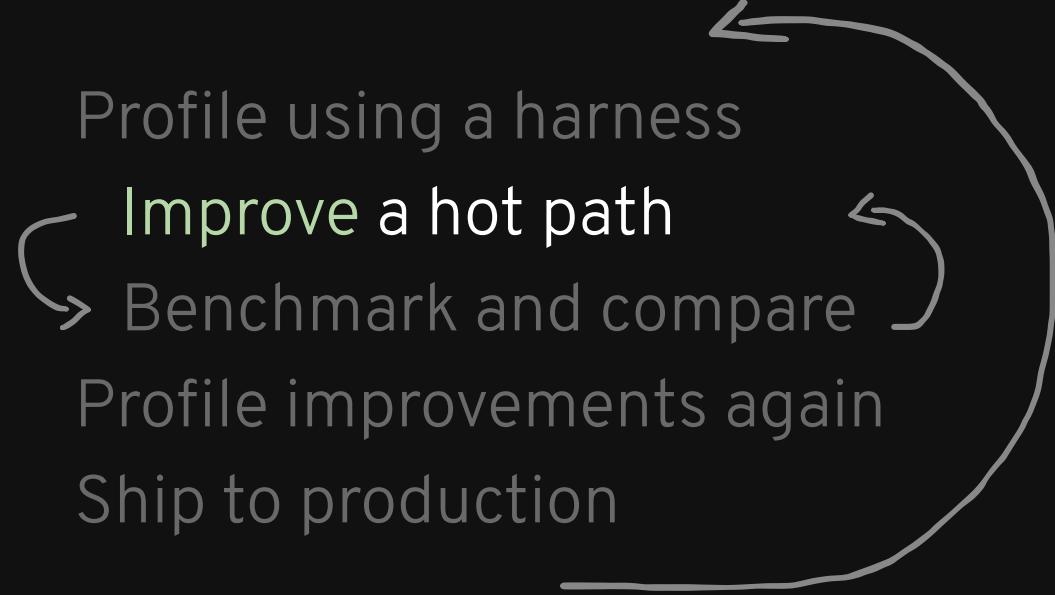


RECEIVE



Profiling the pipeline > Improving > Benchmarking > Profiling

THE PERFORMANCE LOOP



IMPROVING

```
✓ NServiceBus.Core.Tests (3 tests) Success
  > ? RedirectHelper (net472) (1 test)
  ✓ RedirectHelper (net7.0) (2 tests) Success
    ✓ () NServiceBus.Core.Tests (2 tests) Success
      ✓ GlobalTestSetup (2 tests) Success
      ✓ () Pipeline (2 tests) Success
        ✓ PipelineTests (2 tests) Success
          ✓ ShouldExecutePipeline Success
          ✓ ShouldNotCacheContext Success
```

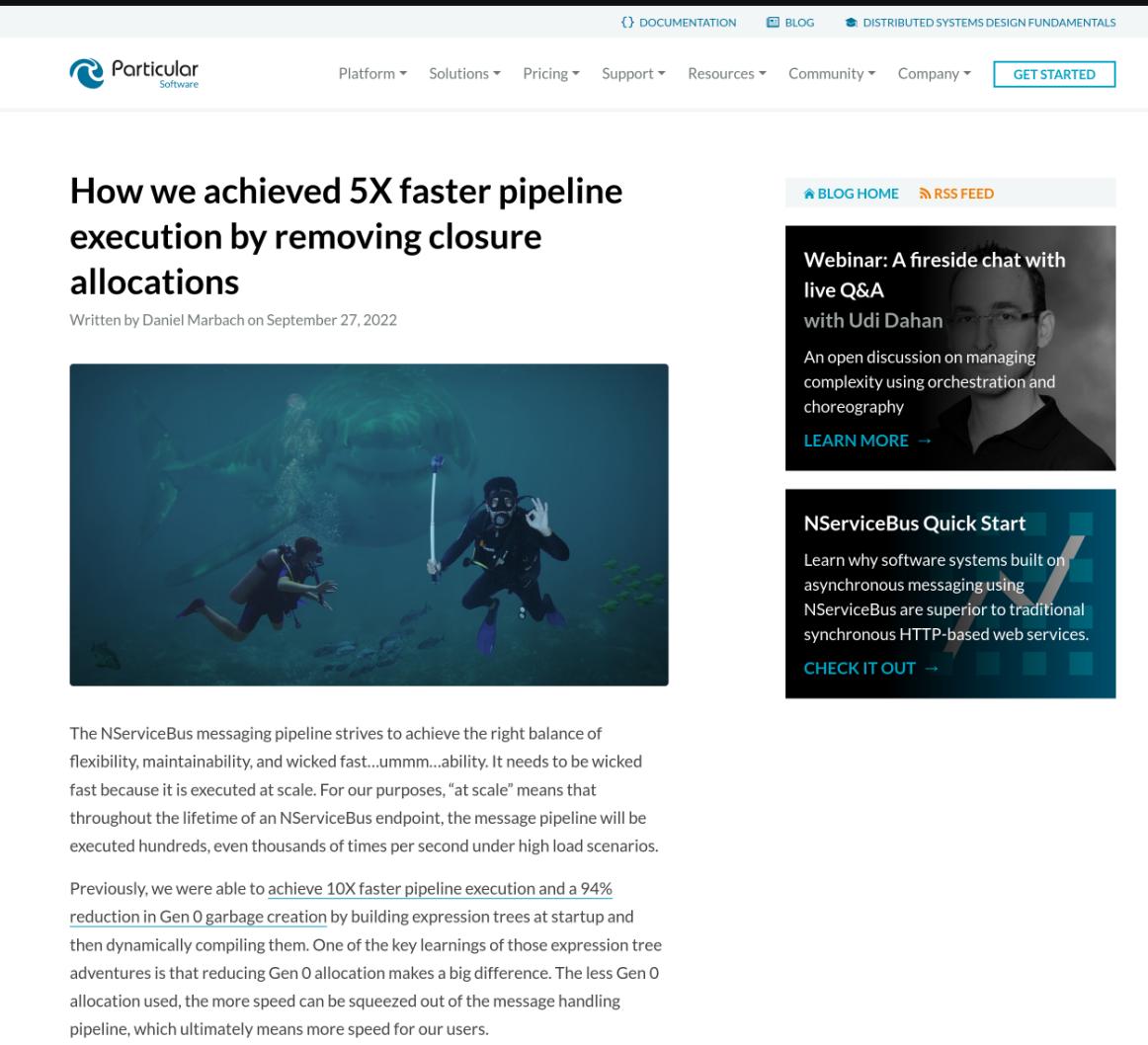
IMPROVING

💡 10X faster execution with compiled expression trees

💡 How we achieved 5X faster pipeline execution by removing closure allocations

go.particular.net/ndc-london-2025-pipeline

Profiling >  Improving > Benchmarking > Profiling



The screenshot shows the Particular Software website. At the top right, there are links for Documentation, Blog, and Distributed Systems Design Fundamentals. Below that is a navigation bar with links for Platform, Solutions, Pricing, Support, Resources, Community, and Company, along with a "GET STARTED" button. The main content area features a blog post titled "How we achieved 5X faster pipeline execution by removing closure allocations" by Daniel Marbach on September 27, 2022. The post includes a subheadings "10X faster execution with compiled expression trees" and "How we achieved 5X faster pipeline execution by removing closure allocations". It features a large image of two scuba divers swimming with sharks. Below the image, the text discusses the NServiceBus messaging pipeline's balance of flexibility, maintainability, and performance. It mentions achieving 10X faster pipeline execution and a 94% reduction in Gen 0 garbage creation by using compiled expression trees. To the right of the main content are two sidebar boxes: one for a webinar with Udi Dahan and another for a quick start guide to NServiceBus.

Particular Software

Platform ▾ Solutions ▾ Pricing ▾ Support ▾ Resources ▾ Community ▾ Company ▾ GET STARTED

DOCUMENTATION BLOG DISTRIBUTED SYSTEMS DESIGN FUNDAMENTALS

How we achieved 5X faster pipeline execution by removing closure allocations

Written by Daniel Marbach on September 27, 2022

10X faster execution with compiled expression trees

How we achieved 5X faster pipeline execution by removing closure allocations



The NServiceBus messaging pipeline strives to achieve the right balance of flexibility, maintainability, and wicked fast...ummm...ability. It needs to be wicked fast because it is executed at scale. For our purposes, “at scale” means that throughout the lifetime of an NServiceBus endpoint, the message pipeline will be executed hundreds, even thousands of times per second under high load scenarios.

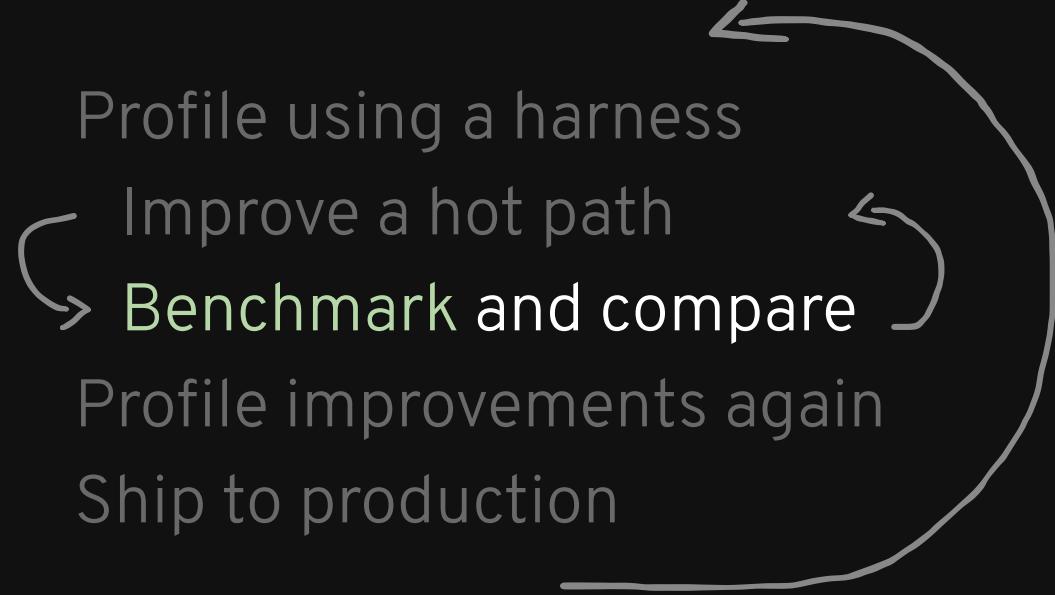
Previously, we were able to achieve 10X faster pipeline execution and a 94% reduction in Gen 0 garbage creation by building expression trees at startup and then dynamically compiling them. One of the key learnings of those expression tree adventures is that reducing Gen 0 allocation makes a big difference. The less Gen 0 allocation used, the more speed can be squeezed out of the message handling pipeline, which ultimately means more speed for our users.

BLOG HOME RSS FEED

Webinar: A fireside chat with live Q&A with Udi Dahan An open discussion on managing complexity using orchestration and choreography LEARN MORE →

NServiceBus Quick Start Learn why software systems built on asynchronous messaging using NServiceBus are superior to traditional synchronous HTTP-based web services. CHECK IT OUT →

THE PERFORMANCE LOOP



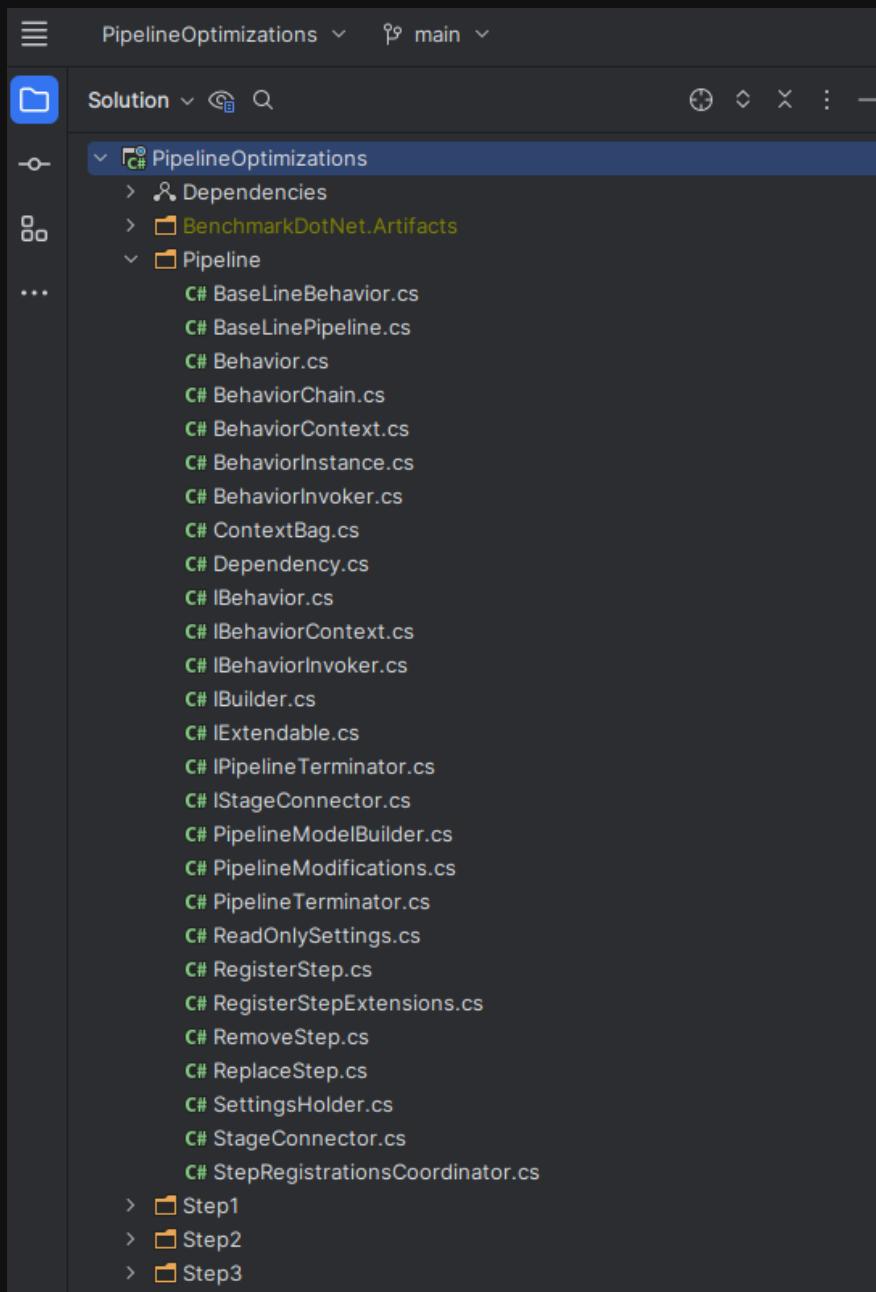
BENCHMARKING THE PIPELINE



A disgusting, festering mess.

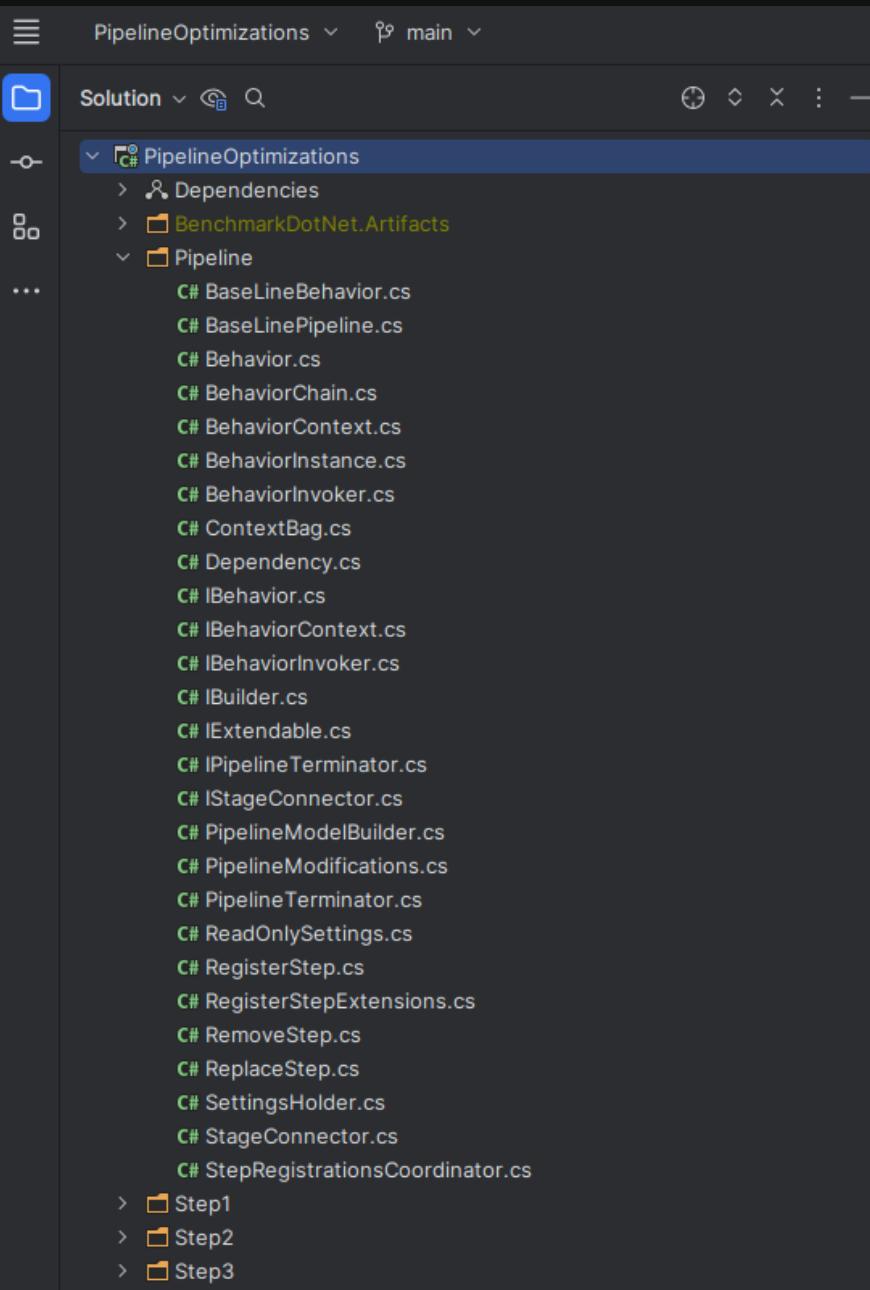
EXTRACT CODE

- Copy and paste relevant code
- Adjust it to the bare essentials to create a controllable environment



EXTRACT CODE

- Trim down to relevant behaviors
- Replaced dependency injection container with creating relevant classes
- Replaced IO-operations with completed tasks



PERFORMANCE CULTURE

- Get started with small steps
- Culture change takes time
- Make changes gradually



UNLIKE A UNIT TEST

- Measures a distribution of values

● ● ●

Method	Mean	Error	StdDev	Ratio	Param
Before	51.57 us	0.311 us	0.291 us	1.00	Value
After	21.91 us	0.138 us	0.129 us	0.42	Value

- Executed until results are stable potentially hundreds or thousands of times
- Takes minutes or hours
- Focuses on most common cases of frequently used code (hot path) with the required amount of permutations
- Cases should be derived from production usage

● ● ●

```
1 // Special nobs and dials
2 [Job]
3 [XYZDiagnoser]
4 public class Benchmark {
5
6     // Permutations that influence your scenario
7
8     [Params(...)]
9     public int Parameter1 { get; set; }
10
11    [Params(...)]
12    public int Parameter2 { get; set; }
13
14
15    [GlobalSetup]
16    public void SetUp() {
17        // Stuff that you don't want to measure
18    }
19
20    [Benchmark(Baseline = true)]
21    public void Before() {
22        // Your code before the changes
23    }
24
25    [Benchmark]
26    public void After() {
27        // Your code after the changes
28    }
29 }
```

```
● ● ●
1 [ShortRunJob]
2 [MemoryDiagnoser]
3 public class PipelineExecution {
4
5     [Params(10, 20, 40)]
6     public int PipelineDepth { get; set; }
7
8
9     [GlobalSetup]
10    public void SetUp() {
11        behaviorContext = new BehaviorContext();
12
13        pipelineModificationsBeforeOptimizations = new PipelineModifications();
14        for (int i = 0; i < PipelineDepth; i++)
15        {
16            pipelineModificationsBeforeOptimizations.Additions.Add(RegisterStep.Create(i.ToString(),
17                typeof(BaseLineBehavior), i.ToString(), b => new BaseLineBehavior()));
18        }
19
20        pipelineModificationsAfterOptimizations = new PipelineModifications();
21        for (int i = 0; i < PipelineDepth; i++)
22        {
23            pipelineModificationsAfterOptimizations.Additions.Add(RegisterStep.Create(i.ToString(),
24                typeof(BehaviorOptimization), i.ToString(), b => new BehaviorOptimization()));
25        }
26
27        pipelineBeforeOptimizations = new BaseLinePipeline<IBehaviorContext>(null, new SettingsHolder(),
28            pipelineModificationsBeforeOptimizations);
29        pipelineAfterOptimizations = new PipelineOptimization<IBehaviorContext>(null, new SettingsHolder(),
30            pipelineModificationsAfterOptimizations);
31    }
32
33     [Benchmark(Baseline = true)]
34     public async Task Before() {
35         await pipelineBeforeOptimizations.Invoke(behaviorContext);
36     }
37
38     [Benchmark]
39     public async Task After() {
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41     }
42 }
```

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41    }
42 }
```

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

PRACTICES

- Single Responsibility Principle
- No side effects
- Prevents dead code elimination
- Delegates heavy lifting to the framework
- Is explicit
 - No implicit casting
 - Explicit types were necessary
- Avoid running any other resource-heavy processes while benchmarking





BenchmarkDotNet

Powerful .NET library for benchmarking

Benchmarking is really hard

BenchmarkDotNet will protect you from the common pitfalls
because it does all the dirty work for you

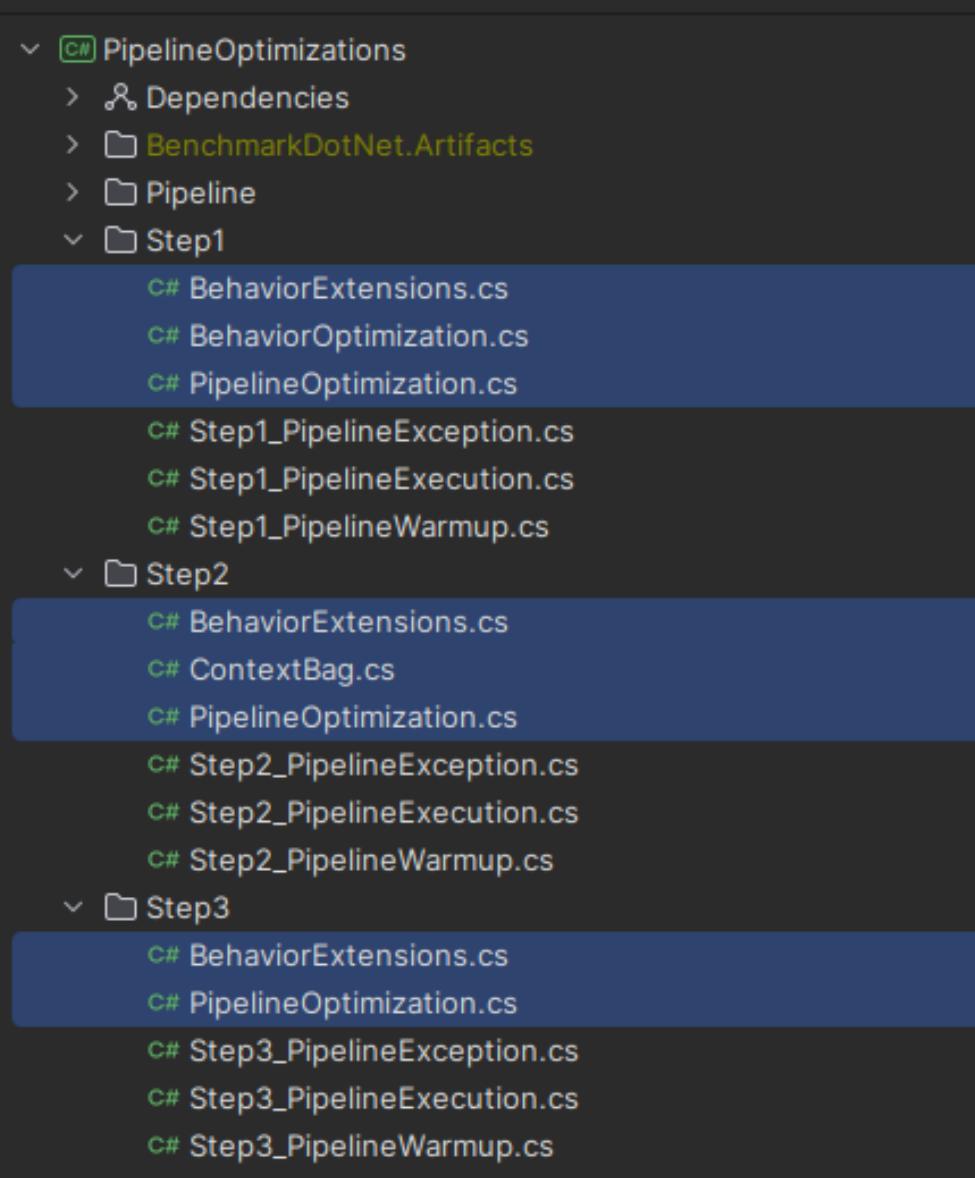
```
● ● ●
```

```
1 [ShortRunJob]
2 [MemoryDiagnoser]
3 public class Step2_PipelineException {
4     [GlobalSetup]
5     public void SetUp() {
6         ...
7         var stepId = PipelineDepth + 1;
8         pipelineModificationsBeforeOptimizations.Additions.Add(RegisterStep.Create(stepId.ToString(), typeof(Throwing), "1", b
=> new Throwing()));
9
10        ...
11        pipelineModificationsAfterOptimizations.Additions.Add(RegisterStep.Create(stepId.ToString(), typeof(Throwing), "1", b
=> new Throwing()));
12
13        pipelineBeforeOptimizations = new Step1.PipelineOptimization<IBehaviorContext>(null, new SettingsHolder(),
14            pipelineModificationsBeforeOptimizations);
15        pipelineAfterOptimizations = new PipelineOptimization<IBehaviorContext>(null, new SettingsHolder(),
16            pipelineModificationsAfterOptimizations);
17    }
18
19    [Benchmark(Baseline = true)]
20    public async Task Before() {
21        try
22        {
23            await pipelineBeforeOptimizations.Invoke(context).ConfigureAwait(false);
24        }
25        catch (InvalidOperationException)
26        {
27        }
28    }
29
30    [Benchmark]
31    public async Task After() {
32        try
33        {
34            await pipelineAfterOptimizations.Invoke(context).ConfigureAwait(false);
35        }
36        catch (InvalidOperationException)
37        {
38        }
39    }
40
41    class Throwing : Behavior<IBehaviorContext> {
42        public override Task Invoke(IBehaviorContext context, Func<Task> next)
43        {
44            throw new InvalidOperationException();
45        }
46    }
47 }
```

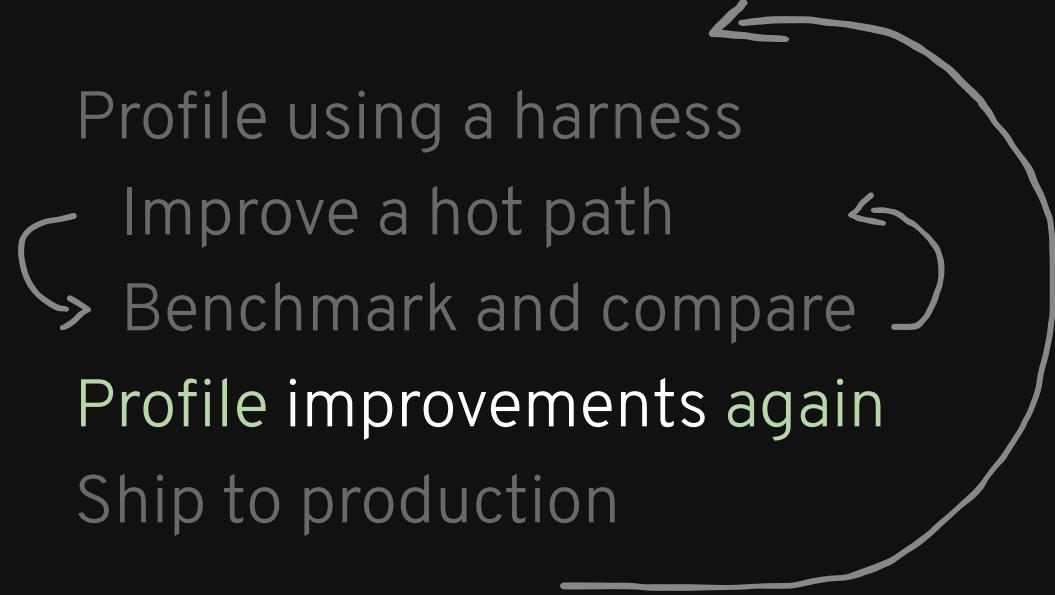
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9         pipelineModificationsBeforeOptimizations.Additions.Add(RegisterStep.Create(stepId.ToString(), typeof(Throwing), "1", b => new Throwing()));
10
11         ...
12
13         pipelineBeforeOptimizations = new
14             Step1.PipelineOptimization<IBehaviorContext>(null, new SettingsHolder(),
15                 pipelineModificationsBeforeOptimizations);
16         pipelineAfterOptimizations = new PipelineOptimization<IBehaviorContext>
17             (null, new SettingsHolder(),
18                 pipelineModificationsAfterOptimizations);
19     }
20 }
```



```
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THE PERFORMANCE LOOP

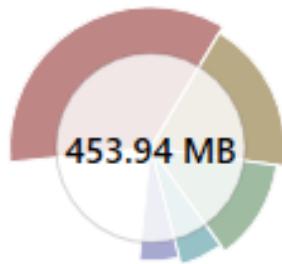


PROFILING THE PIPELINE (AGAIN)



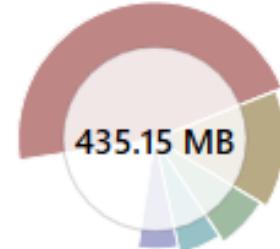
MEMORY CHARACTERISTICS

Top types allocated by: NServiceBus.IMessageSessionExtensions



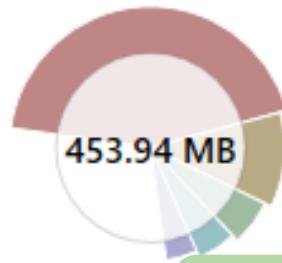
159.75 MB [Byte\[\]](#)
84.39 MB [Char\[\]](#)
58.78 MB [Int32\[\]](#)
26.53 MB [ArrayList](#)
25.77 MB [String](#)

Top types allocated by: NServiceBus.IMessageSessionExtensions



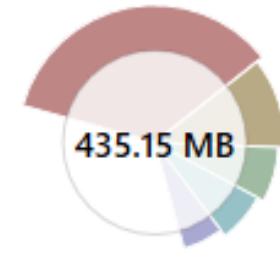
201.96 MB [Byte\[\]](#)
63.77 MB [Char\[\]](#)
30.59 MB [Int32\[\]](#)
25.92 MB [Lookup+Grouping<String, Subscriber>\[\]](#)
25.48 MB [String](#)

Top allocating methods in: NServiceBus.IMessageSessionExtensions



197.61 MB [StreamWriter.Init\(Stream, Encoding, Int32, Boolean\)](#)
52.07 MB [String.SplitInternal\(Char\[\], Int32, StringSplitOptions\)](#)
26.53 MB [MessageQueuePermission.get_PermissionEntries\(\)](#)
23.90 MB [MemoryStream.set_Capacity\(Int32\)](#)
20.22 MB [BehaviorChain.InvokeNext\(IHandlerContext, Int32\)](#)

Top allocating methods in: NServiceBus.IMessageSessionExtensions



152.55 MB [StreamWriter.Init\(Stream, Encoding, Int32, Boolean\)](#)
49.01 MB [MemoryStream.set_Capacity\(Int32\)](#)
31.30 MB [MemoryStream.ToArray\(\)](#)
30.02 MB [Message.IdFromByteArray\(Byte\[\]\)](#)
25.92 MB [Lookup< TKey, TElement >.ctor\(IEqualityComparer< T >\)](#)



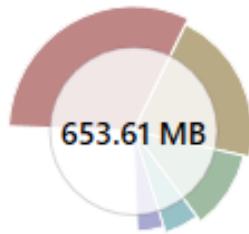
BEFORE

PUBLISH

AFTER

MEMORY CHARACTERISTICS

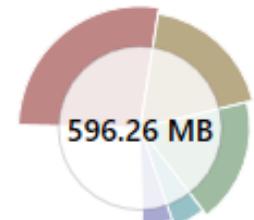
Top types allocated by: NServiceBus.ReceiveWithTransactionScope



206.75 MB [Char\[\]](#)
138.86 MB [Byte\[\]](#)
74.28 MB [String](#)
34.54 MB [XmlTextReaderImpl+NodeData](#)
27.83 MB [Func<IBehaviorContext, Task>](#)

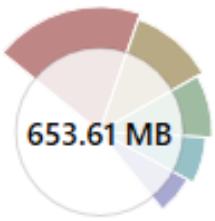


Top types allocated by: NServiceBus.ReceiveWithTransactionScope



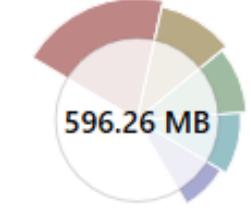
161.42 MB [Char\[\]](#)
111.67 MB [String](#)
109.93 MB [Byte\[\]](#)
29.97 MB [Int32\[\]](#)
29.33 MB [Dictionary+Entry<String, Object>\[\]](#)

Top allocating methods in: NServiceBus.ReceiveWithTransactionScope



127.02 MB [XmlTextReaderImpl.InitTextReaderInput\(String, Uri, TextReader\)](#)
75.02 MB [Message.get Extension\(\)](#)
59.14 MB [BufferUtils.RentBuffer\(IArrayPool<T>, Int32\)](#)
46.53 MB [XmlTextReaderImpl..ctor\(XmlResolver, XmlReaderSettings, XmlParserCor](#)
40.56 MB [String.CreateStringFromEncoding\(Byte, Int32, Encoding\)](#)

Top allocating methods in: NServiceBus.ReceiveWithTransactionScope



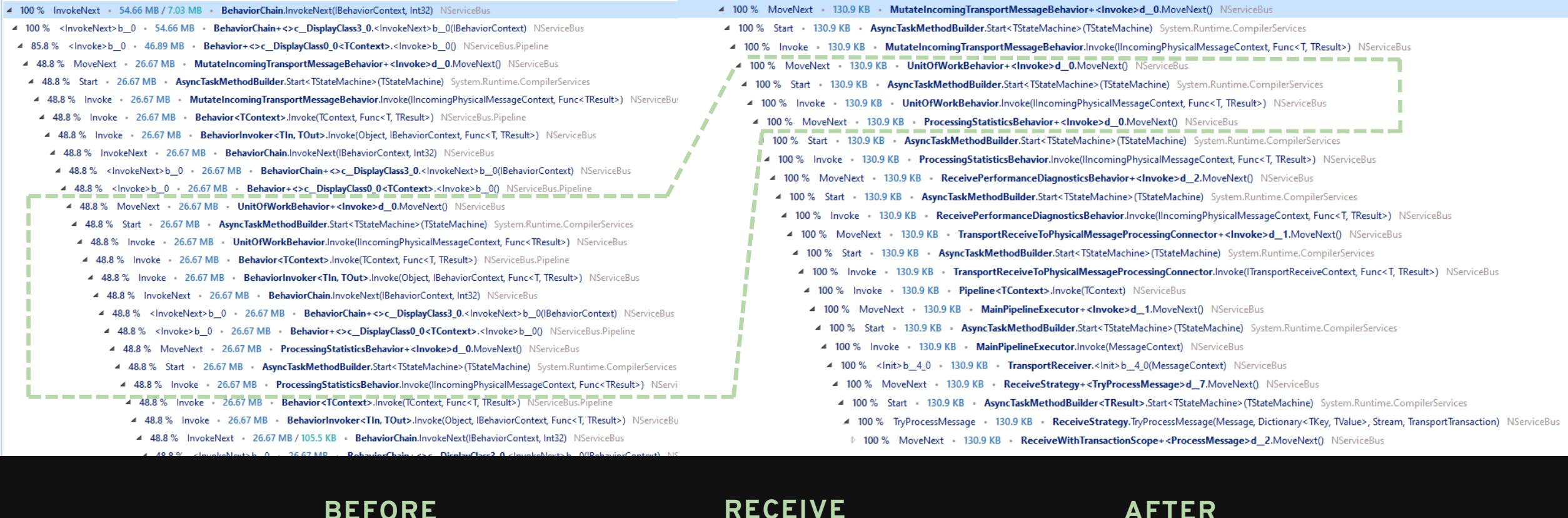
63.52 MB [XmlTextReaderImpl.InitTextReaderInput\(String, Uri, TextReader\)](#)
58.75 MB [String.CreateStringFromEncoding\(Byte, Int32, Encoding\)](#)
57.62 MB [Dictionary< TKey, TValue >.Initialize\(Int32\)](#)
47.10 MB [Message.get Extension\(\)](#)
47.10 MB [String.CtorCharArrayStartLength\(Char\[\], Int32, Int32\)](#)

BEFORE

RECEIVE

AFTER

MEMORY CHARACTERISTICS



BEFORE

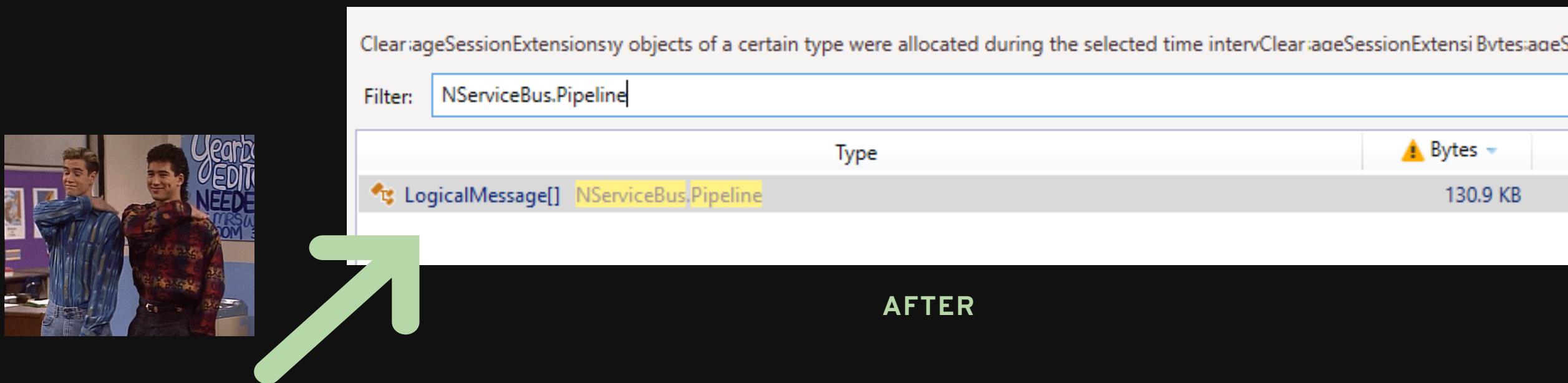
RECEIVE

AFTER

MEMORY CHARACTERISTICS

Type	Bytes
StageForkConnector+<>c_DisplayClass0_0<ITransportReceiveContext, IIIncomingPhysicalMessageContext>	15.74 MB
Behavior+<>c_DisplayClass0_0<IOutgoingLogicalMessageContext>	NServiceBus.Pipeline
Behavior+<>c_DisplayClass0_0<IRoutingContext>	NServiceBus.Pipeline
Behavior+<>c_DisplayClass0_0<IOutgoingPhysicalMessageContext>	NServiceBus.Pipeline

BEFORE

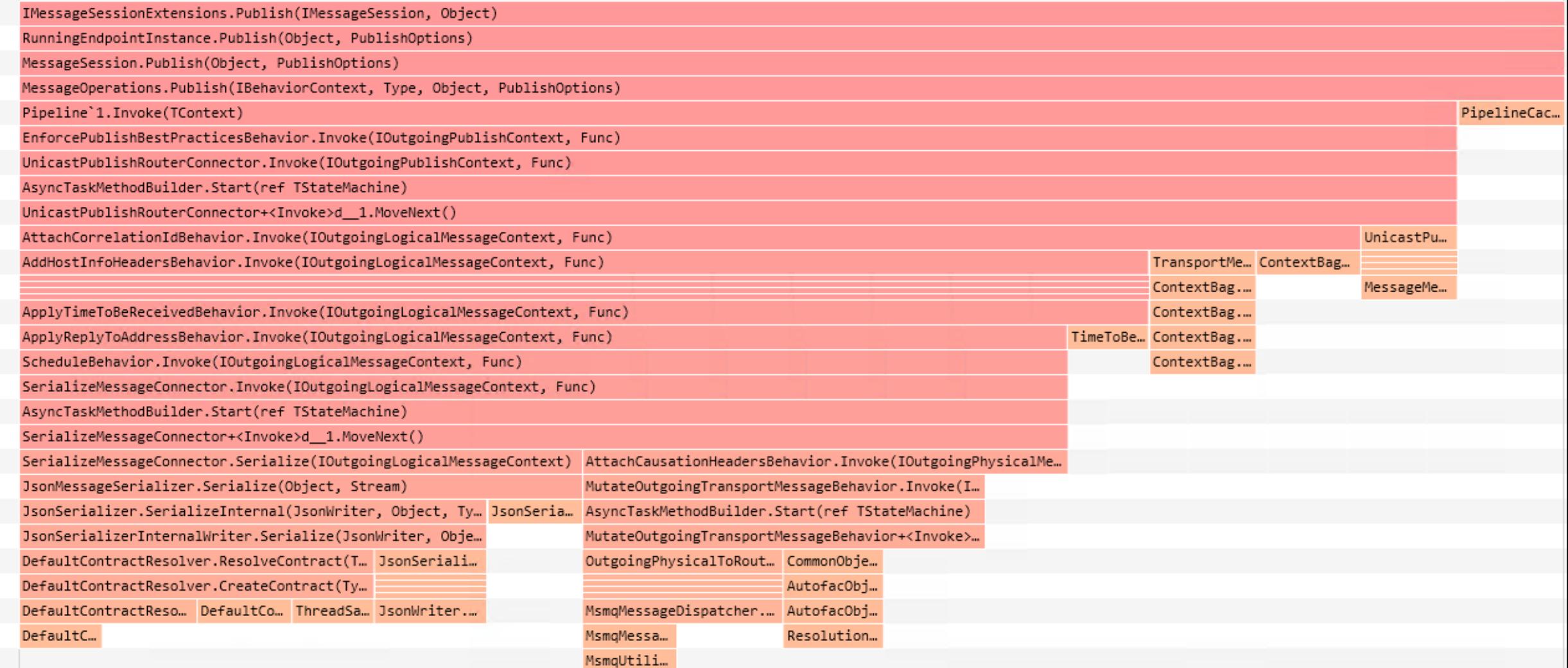


oh look, there is nothing 😊

Profiling > Improving > Benchmarking > Profiling the pipeline (again)

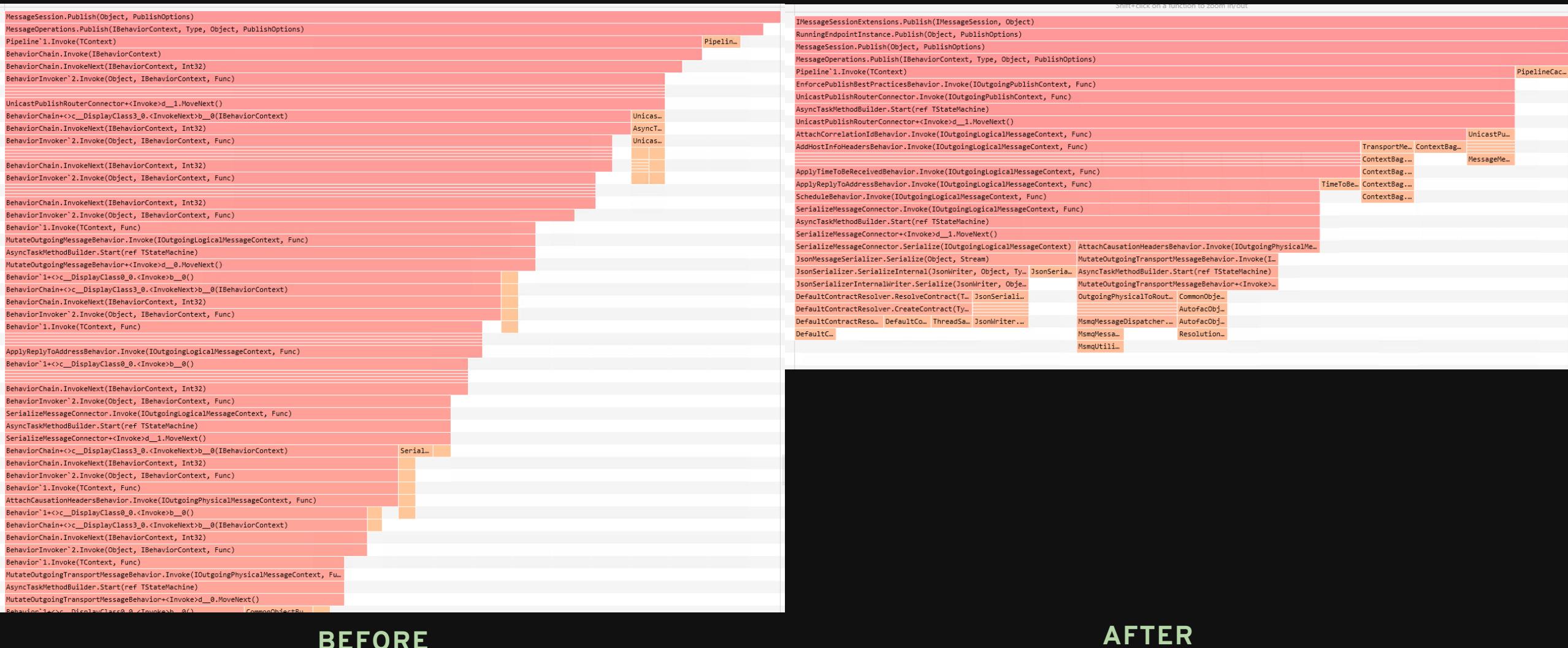
CPU CHARACTERISTICS

Shift+click on a function to zoom in/out



AsyncTaskMethodBuilder.Start(ref TStateMachine)
 MutateOutgoingTransportMessageBehavior+<Invoke>d__0.MoveNext()
 Behavior`1+<>c__DisplayClass0_0.<Invoke>b__0() CommonObjectBu...

CPU CHARACTERISTICS



BEFORE

AFTER

PUBLISH

Profiling > Improving > Benchmarking > Profiling the pipeline (again)

PREVENTING REGRESSIONS

- Guidance Preventing Regressions
- ResultComparer Tool

● ● ●

```
1 C:\Projects\performance\src\benchmarks\micro>
dotnet run -c Release -f net8.0 \
2      --artifacts "C:\results\before"
```

● ● ●

```
1 C:\Projects\performance\src\benchmarks\micro>
dotnet run -c Release -f net8.0 \
2      --artifacts "C:\results\after"
```

● ● ●

```
1 C:\Projects\performance\src\tools\ResultsComparer>
dotnet run --base "C:\results\before"
2 --diff "C:\results\after" --threshold 2%
```

"CPU-bound benchmarks are much more stable than Memory/Disk-bound benchmarks, but the *average* performance levels still can be up to **three times** different across builds."

Andrey Akinshin - Performance stability of GitHub Actions

THE PERFORMANCE LOOP

A PRACTICAL GUIDE TO PROFILING AND BENCHMARKING

🦋 @daniel.openplace.net | 📧 daniel.marbach@particular.net | 💬 Daniel Marbach

- Use the performance loop to improve your code where it matters
- Combine it with profiling to observe how the small changes add up
- Optimize until you hit a diminishing point of return
- You'll learn a ton about potential improvements for a new design



github.com/danielmarbach/BeyondSimpleBenchmarks

