

.NET Core: Performance Revolution

Adam Sitnik

About myself

Open Source:

- BenchmarkDotNet
- Awesome .NET Performance
- Core CLR (Span<T>)
- CoreFx Lab (Span<T>)
- & more

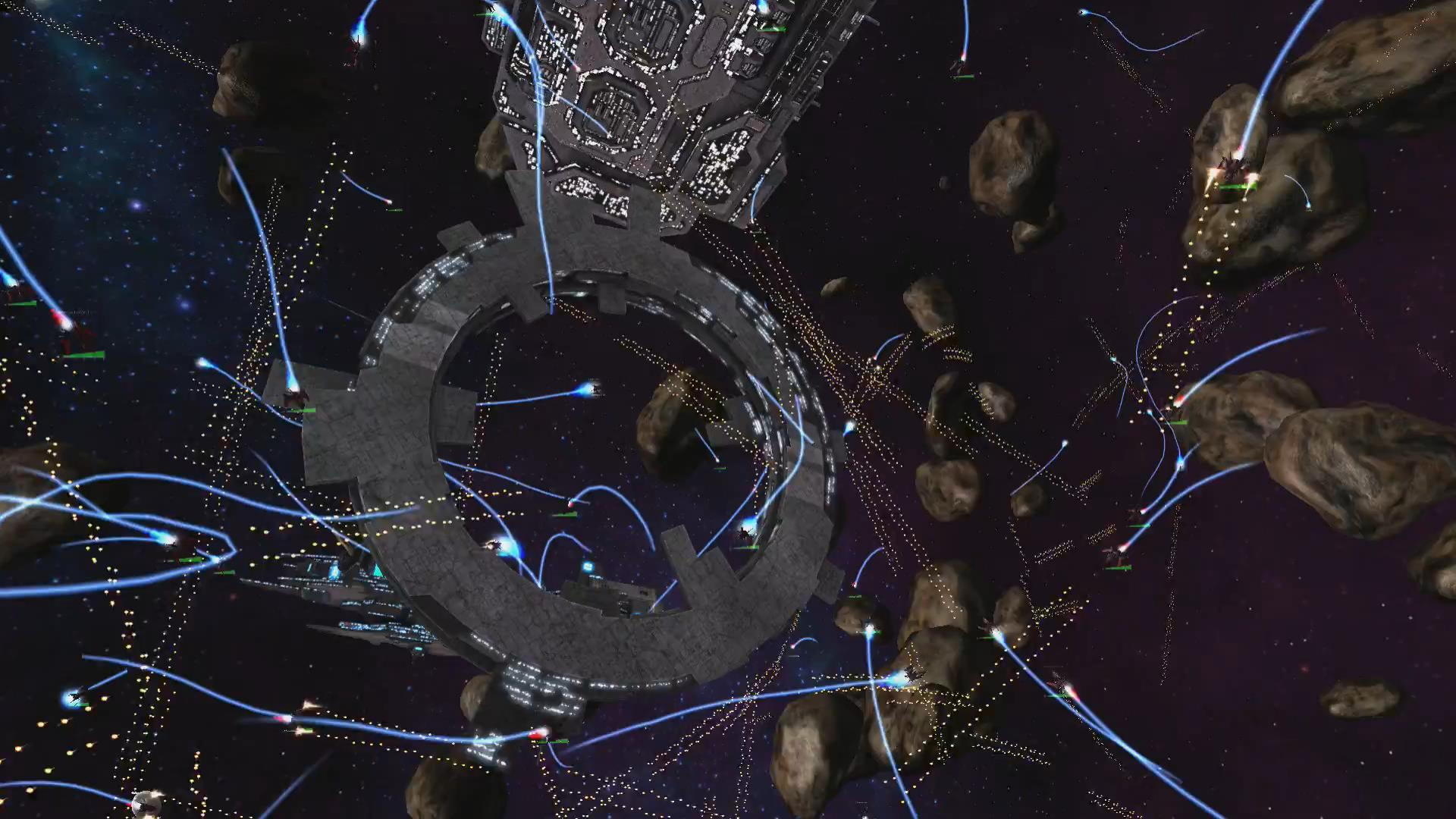
Work:



- Energy Trading
(.NET Core running in
production since July 2016)

ASP.NET Core road to high-performance

- [Performance Improvements in .NET Core](#)
- [Performance Improvements in RyuJIT](#)
- .NET Native & CoreRT (later today)
- New tools:
 - Span<T>
 - ArrayPool<T>
 - ValueTask<T>
 - Unsafe



How to avoid GC?

- Reduce allocations
- Eliminate all managed allocations:
 - Pool the memory
 - Use unmanaged memory

Async on hotpath

```
Task<T> SmallMethodExecutedVeryVeryOften()  
{  
    if(CanRunSynchronously()) // true most of the time  
    {  
        return Task.FromResult(ExecuteSynchronous());  
    }  
    return ExecuteAsync();  
}
```

Sample ValueTask usage

```
[MethodImpl(MethodImplOptions.AggressiveInlining)]
ValueTask<int> SampleUsage()
    => IsFastSynchronousExecutionPossible()
        ? new ValueTask<int>(
            result: ExecuteSynchronous()) // INLINEABLE!!!
        : new ValueTask<int>(
            task: ExecuteAsync());

int ExecuteSynchronous() { }
Task<int> ExecuteAsync() { }
```

How **not** to consume ValueTask

```
async ValueTask<int> ConsumeWrong(int repeats)
{
    int total = 0;
    while (repeats-- > 0)
        total += await SampleUsage();

    return total;
}
```


Async Task Method Builder

```
[AsyncStateMachine(typeof(DemoInt.<ConsumeWrong>d__4))]  
private Task ConsumeWrong(int repeats)  
{  
    DemoInt.<ConsumeWrong>d__4 <ConsumeWrong>d__;  
    <ConsumeWrong>d__.<>4__this = this;  
    <ConsumeWrong>d__.repeats = repeats;  
    <ConsumeWrong>d__.<>t__builder = AsyncTaskMethodBuilder.Create();  
    <ConsumeWrong>d__.<>1__state = -1;  
    AsyncTaskMethodBuilder <>t__builder = <ConsumeWrong>d__.<>t__builder;  
    <>t__builder.Start<DemoInt.<ConsumeWrong>d__4>(ref <ConsumeWrong>d__);  
    return <ConsumeWrong>d__.<>t__builder.Task;  
}
```

How to consume ValueTask

```
async ValueTask<int> ConsumeProperly(int repeats)
{
    int total = 0;
    while (repeats-- > 0)
    {
        ValueTask<int> valueTask = SampleUsage(); // INLINEABLE

        total += valueTask.IsCompleted
            ? valueTask.Result // hot path
            : await valueTask.AsTask();
    }

    return total;
}
```

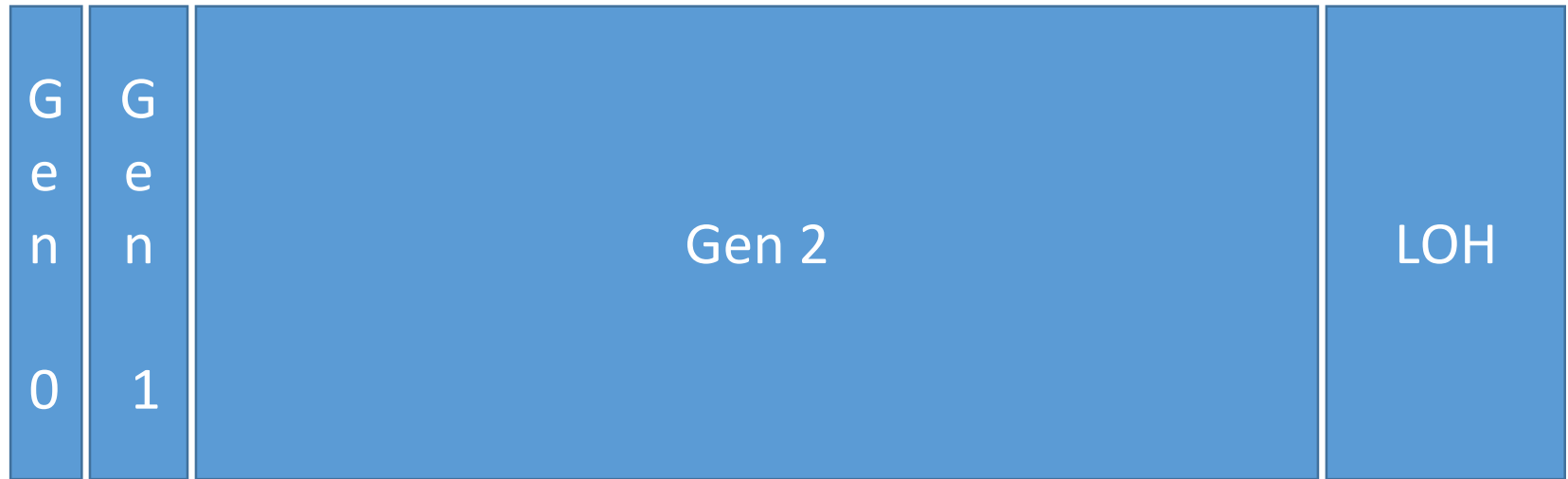
ValueTask vs Task: Overhead Only

Method	Repeats	Mean	Scaled	Gen 0	Gen 1	Allocated
Task	100	720.9 ns	1.49	3.4674	0.0001	7272 B
ValueTask_Wrong	100	1,097.4 ns	2.27	-	-	0 B
ValueTask_Properly	100	482.9 ns	1.00	-	-	0 B

Value Task: Summary

- It's not about replacing Task
- It has a **single purpose**: reduce heap allocations in async hot path where common synchronous execution is possible
- You can benefit from inlining, but not for free
- Use the `.IsCompleted` and `.Result` for getting best performance

.NET Managed Heap*



~~LOH = GEN 2 = FULL GC~~

* - simplified, Workstation mode or view per logical processor in Server mode

ArrayPool

- **Pool of reusable managed arrays**
- The default maximum length of each array in the pool is 2^{20} (1024*1024 = 1 048 576)
- System.Buffers package

ArrayPool: Sample

```
var samePool = ArrayPool<byte>.Shared;  
byte[] buffer = samePool.Rent(minLength);  
try  
{  
    Use(buffer);  
}  
finally  
{  
    samePool.Return(buffer);  
}
```

Allocate? Pool?

Method	Size	Mean	StdDev	Gen 0	Gen 1	Gen 2	Allocated
Allocate	100	8.149 ns	0.0169 ns	0.0610	-	-	128 B
RentAndReturn_Shared	100	43.446 ns	0.0908 ns	-	-	-	0 B

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Allocate	100	8.149 ns	0.0169 ns	0.0610	-	-	128 B
RentAndReturn_Shared	100	43.446 ns	0.0908 ns	-	-	-	0 B
Allocate	1 000	41.122 ns	0.0812 ns	0.4880	0.0000	-	1024 B
RentAndReturn_Shared	1 000	42.535 ns	0.0621 ns	-	-	-	0 B

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Allocate	1 000	41.122 ns	0.0812 ns	0.4880	0.0000	-	1024 B
RentAndReturn_Shared	1 000	42.535 ns	0.0621 ns	-	-	-	0 B
Allocate	10 000	371.113 ns	3.2994 ns	4.7847	0.0000	-	10024 B
RentAndReturn_Shared	10 000	42.565 ns	0.0450 ns	-	-	-	0 B

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Allocate	10 000	371.113 ns	3.2994 ns	4.7847	0.0000	-	10024 B
RentAndReturn_Shared	10 000	42.565 ns	0.0450 ns	-	-	-	0 B
Allocate	100 000	3,625.029 ns	17.2533 ns	31.2497	31.2497	31.2497	100024 B
RentAndReturn_Shared	100 000	42.426 ns	0.0555 ns	-	-	-	0 B

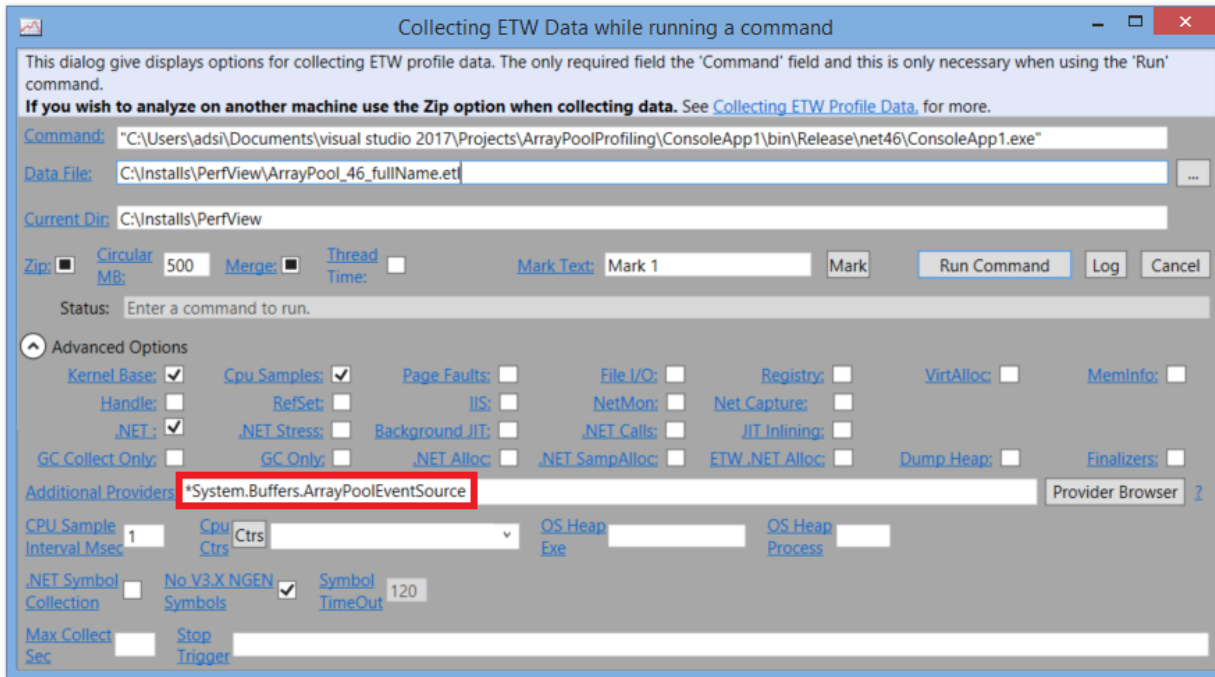
Allocate? Pool?

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Allocate	100 000	3,625.029 ns	17.2533 ns	31.2497	31.2497	31.2497	100024 B
RentAndReturn_Shared	100 000	42.426 ns	0.0555 ns	-	-	-	0 B
Allocate	1 000 000	18,769.792 ns	60.4307 ns	249.9980	249.9980	249.9980	1000024 B
RentAndReturn_Shared	1 000 000	41.979 ns	0.0555 ns	-	-	-	0 B

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Allocate	100	8.149 ns	0.0169 ns	0.0610	-	-	128 B
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RentAndReturn_Shared	1 000 000	41.979 ns	0.0555 ns	-	-	-	0 B
Allocate	10 000 000	521,016.536 ns	55,326.9203 ns	211.2695	211.2695	211.2695	10000024 B
RentAndReturn_Shared	10 000 000	639,916.968 ns	116,288.7309 ns	206.3623	206.3623	206.3623	10000024 B
RentAndReturn_Aware	10 000 000	47.200 ns	0.0407 ns	-	-	-	0 B

System.Buffers.ArrayPoolEventSource



BufferAllocated event

Events ArrayPool_46_fullName.etl.zip in PerfView (C:\Installs\PerfView\ArrayPool_46_fullName.etl.zip)

File Help Event View Help (F1) Troubleshooting

Update Start: 0,000 End: 4,337,767 MaxRet: 10000 Find:

Process Filter: Text Filter: Columns To Display: Cols

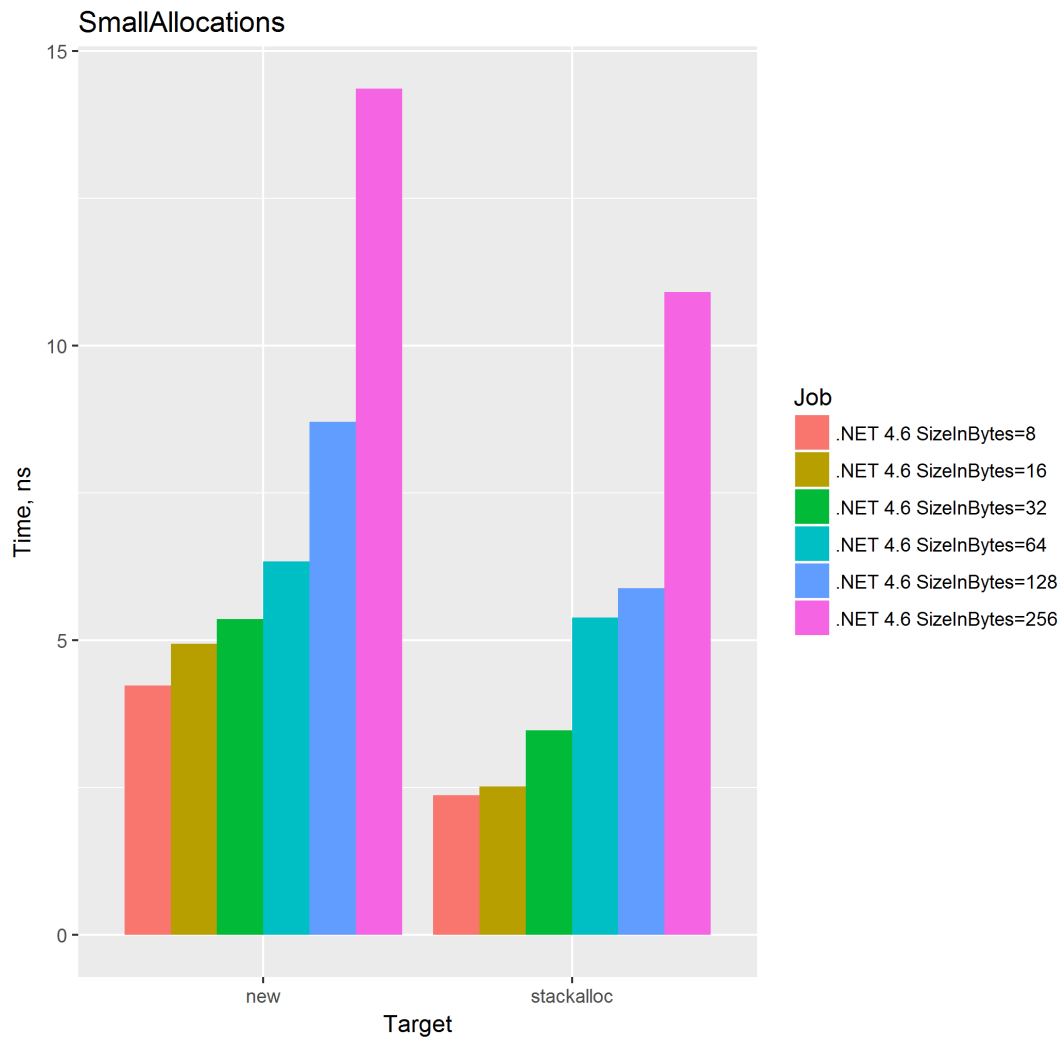
Event Types Filter: ArrayPool Histogram: A9

Event Name	Time MS	Process N	Rest
System.Buffers.ArrayPoolEventSource/BufferAllocated	333,566	ConsoleA	ThreadId="11.516" bufferId="15.368.010" bufferSize="524.288" poolId="21.083.178" bucketId="4.094.363" reason="Pooled"
System.Buffers.ArrayPoolEventSource/BufferAllocated	333,938	ConsoleA	ThreadId="11.516" bufferId="36.849.274" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	335,140	ConsoleA	ThreadId="11.516" bufferId="63.208.015" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	335,663	ConsoleA	ThreadId="11.516" bufferId="32.001.227" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	335,680	ConsoleA	ThreadId="11.516" bufferId="19.575.591" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	335,692	ConsoleA	ThreadId="11.516" bufferId="41.962.596" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	335,701	ConsoleA	ThreadId="11.516" bufferId="42.119.052" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	335,711	ConsoleA	ThreadId="11.516" bufferId="43.527.150" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	336,131	ConsoleA	ThreadId="11.516" bufferId="56.200.037" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	337,170	ConsoleA	ThreadId="11.516" bufferId="36.038.289" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	338,093	ConsoleA	ThreadId="11.516" bufferId="55.909.147" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	338,108	ConsoleA	ThreadId="11.516" bufferId="33.420.276" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	338,119	ConsoleA	ThreadId="11.516" bufferId="32.347.029" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	338,138	ConsoleA	ThreadId="11.516" bufferId="22.687.807" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	338,158	ConsoleA	ThreadId="11.516" bufferId="2.863.675" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	338,176	ConsoleA	ThreadId="11.516" bufferId="25.773.083" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	338,196	ConsoleA	ThreadId="11.516" bufferId="30.631.159" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"
System.Buffers.ArrayPoolEventSource/BufferAllocated	338,215	ConsoleA	ThreadId="11.516" bufferId="7.244.975" bufferSize="2.097.152" poolId="21.083.178" bucketId="-1" reason="OverMaximumSize"

ArrayPool: Summary

- **LOH = Gen 2 = Full GC**
- ArrayPool was designed for best possible performance
- Pool the memory if you can control the lifetime
- Use **Pool.Shared** by default
- Pool allocates the memory for buffers > maxSize
- **The fewer pools, the smaller LOH, the better!**

Stackalloc is
the fastest
way to
allocate
small chunks
of memory
in .NET



	Allocation	Deallocation	Usage
Managed < 85 KB	Very fast	<ul style="list-style-type: none"> • Non-deterministic • Blocking • Very slow 	<ul style="list-style-type: none"> • Very easy • Common • Safe
Managed: LOH	Fast		
Stackalloc	Super fast	<ul style="list-style-type: none"> • Deterministic • Super fast 	<ul style="list-style-type: none"> • Unsafe • Not common • Limited
Marshal	Fast	<ul style="list-style-type: none"> • Deterministic • Fast 	

APIs before Span: parsing integer

```
int Parse(string input);
```

```
int Parse(string input, int startIndex, int length);
```

```
int Parse(string input, long startIndex, int length);
```

```
unsafe int Parse(char* input, int length);
```

```
unsafe int Parse(char* input, long startIndex, int length);
```

Span<T>

It provides a uniform API for working with:

- Unmanaged memory buffers
- Arrays and subarrays
- Strings and substrings

It's fully **type-safe** and **memory-safe**.

Almost no overhead.

It's a stack only Value Type.

Supports **any** memory

```
byte* pointerToStack = stackalloc byte[256];  
Span<byte> stackMemory = new Span<byte>(pointerToStack, 256);  
  
IntPtr unmanagedHandle = Marshal.AllocHGlobal(256);  
Span<byte> unmanaged = new Span<byte>(unmanagedHandle.ToPointer(), 256);  
  
char[] array = new char[] { 'i', 'm', 'p', 'l', 'i', 'c', 'i', 't' };  
Span<char> fromArray = array; // implicit cast  
  
ReadOnlySpan<char> fromString = "State of the .NET Performance".AsSpan();
```

Simple API*

```
public int Length { get; }  
public T this[int index] { get; set; }
```

```
public Span<T> Slice(int start);  
public Span<T> Slice(int start, int length);
```

```
public void Clear();  
public void Fill(T value);
```

```
public void CopyTo(Span<T> destination);  
public bool TryCopyTo(Span<T> destination);
```

```
public ref T DangerousGetPinnableReference();
```

* It's not the full list

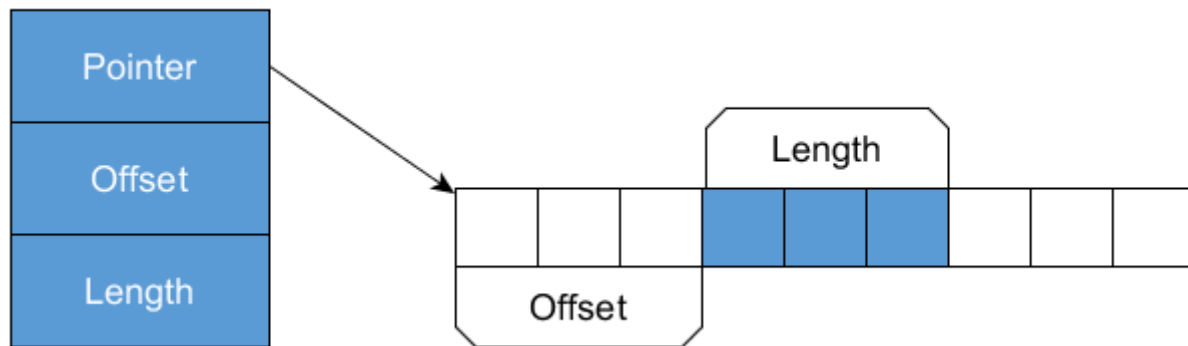
API Simplicity!

```
int Parse(Span<char> input)
```

```
void Copy<T>(Span<T> source, Span<T> destination)
```

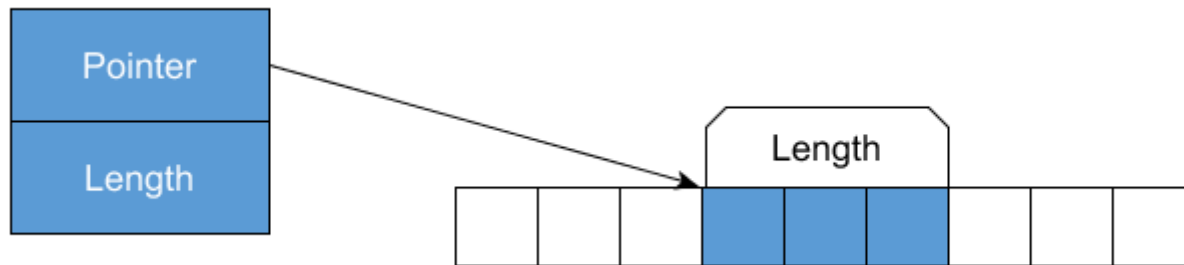
Span for existing runtimes

.NET Standard 1.0 (.NET 4.5+)



Span for new runtimes

.NET Core 2.0 and any other runtime supporting by-ref fields



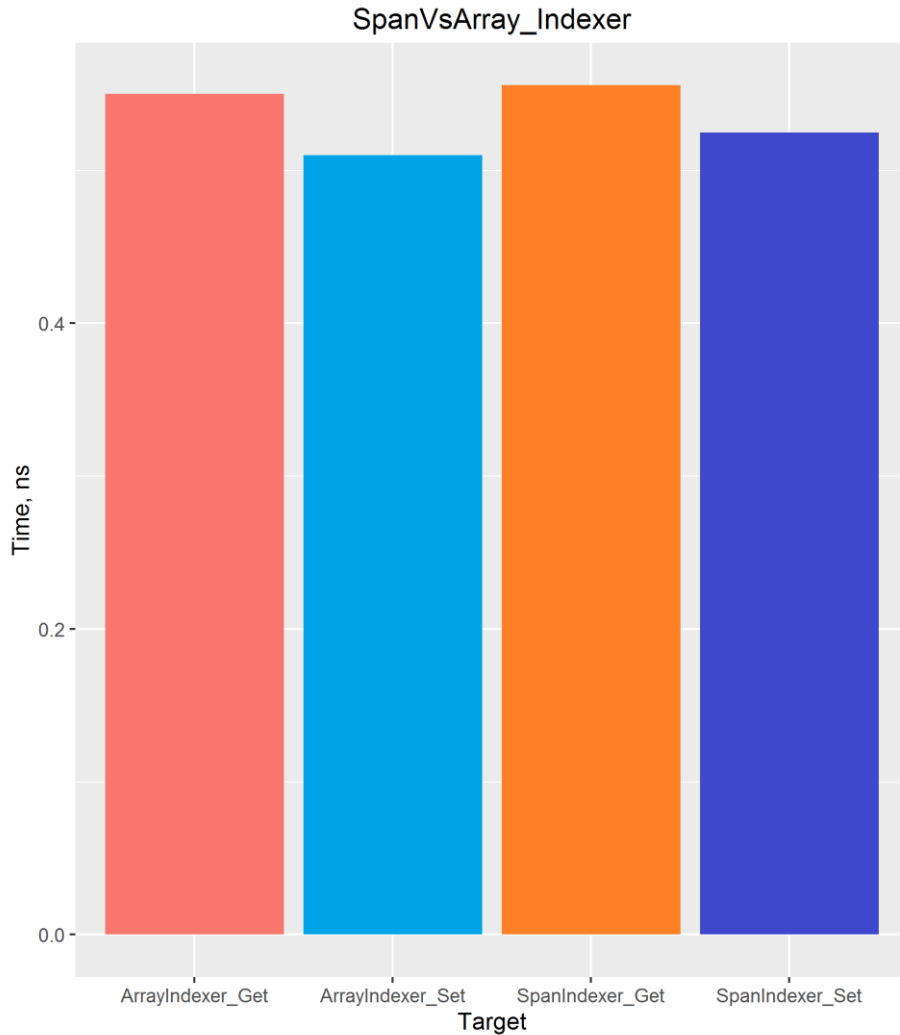
“Fast” vs “Slow” Span

Method	Job	Mean	Scaled
SpanIndexer_Get	.NET 4.6	0.6119 ns	1.14
SpanIndexer_Get	.NET Core 1.1	0.6092 ns	1.13
SpanIndexer_Get	.NET Core 2.0	0.5368 ns	1.00
SpanIndexer_Set	.NET 4.6	0.6117 ns	1.13
SpanIndexer_Set	.NET Core 1.1	0.6082 ns	1.12
SpanIndexer_Set	.NET Core 2.0	0.5417 ns	1.00

There is some place for further improvement!

Span
is on
par
with
Array*!

*.NET Core 2.0



Creating substrings **before Span** (pseudocode)

```
string Substring(string text, int startIndex, int length)
{
    string result = new string(length); // ALLOCATION!

    Memory.Copy(text, result, startIndex, length); // COPYING

    return result;
}
```

Creating substrings **without allocation!** (pseudocode)

```
ReadOnlySpan<char> Slice(string text, int startIndex, int length)
=> new ReadOnlySpan<char>(
    ref text[0] + (startIndex * sizeof(char)),
    length);
```

Substring vs Slice

Method	Chars	Mean	StdDev	Scaled	Gen 0	Allocated
Substring	10	8.277 ns	0.1938 ns	4.54	0.0191	40 B
Slice	10	1.822 ns	0.0383 ns	1.00	-	0 B
Substring	1000	85.518 ns	1.3474 ns	47.22	0.4919	1032 B
Slice	1000	1.811 ns	0.0205 ns	1.00	-	0 B

Possible usages

- Parsing without allocations
- Formatting
- Base64/Unicode encoding
- HTTP Parsing/Writing
- Compression/Decompression
- XML/JSON parsing/writing
- Binary reading/writing
- & more!!

Stack Only

- Instances can reside only on the stack
- Which is accessed by one thread at the same time

Advantages:

- Few pointers for GC to track
- Safe Concurrency (no Struct Tearing)
- Safe lifetime. Method ends = memory can be returned to the pool or released

The Limitations <http://adamsitnik.com/Span/#the-limitations>

Span: Summary

- Allows to work with **any** type of memory.
- It makes working with native memory much easier.
- Simple abstraction over Pointer Arithmetic.
- **Avoid allocation and copying of memory with Slicing.**
- Supports .NET Standard 1.0+
- It's performance is on par with Array for new runtimes.
- It's limited due to stack only requirements.

System.Runtime.CompilerServices.Unsafe

Overcoming C# limitations:

- Managed Pointer Arithmetic
- Casting w/o constraints
- Copy/Init Block
- Read/Write w/o constraints
- SizeOf(T)

```
ref T AddByteOffset<T>(ref T source, IntPtr byteOffset)
ref T Add<T>(ref T source, int elementOffset)
ref T Add<T>(ref T source, IntPtr elementOffset)
bool AreSame<T>(ref T left, ref T right)
void* AsPointer<T>(ref T value)
ref T AsRef<T>(void* source)
T As<T>(object o) where T : class
ref TTo As<TFrom, TTo>(ref TFrom source)
IntPtr ByteOffset<T>(ref T origin, ref T target)
void CopyBlock(ref byte destination, ref byte source, uint byteCount)
void CopyBlock(void* destination, void* source, uint byteCount)
void CopyBlockUnaligned(ref byte destination, ref byte source, uint byteCount)
void CopyBlockUnaligned(void* destination, void* source, uint byteCount)
void Copy<T>(void* destination, ref T source)
void Copy<T>(ref T destination, void* source)
void InitBlock(ref byte startAddress, byte value, uint byteCount)
void InitBlock(void* startAddress, byte value, uint byteCount)
void InitBlockUnaligned(ref byte startAddress, byte value, uint byteCount)
void InitBlockUnaligned(void* startAddress, byte value, uint byteCount)
T Read<T>(void* source)
T ReadUnaligned<T>(void* source)
T ReadUnaligned<T>(ref byte source)
int SizeOf<T>()
ref T SubtractByteOffset<T>(ref T source, IntPtr byteOffset)
ref T Subtract<T>(ref T source, int elementOffset)
ref T Subtract<T>(ref T source, IntPtr elementOffset)
void Write<T>(void* destination, T value)
void WriteUnaligned<T>(void* destination, T value)
void WriteUnaligned<T>(ref byte destination, T value)
```

.NET Standard

Package name	.NET Standard	.NET Framework
System.Memory	1.0	4.5
System Buffers	1.1	4.5.1
System.Threading.Tasks.Extensions	1.0	4.5
System.Runtime.CompilerServices.Unsafe	1.0	4.5

Summary

- Use ValueTask only if it can help you!
- Pool the memory with ArrayPool
- Use Span and slicing to avoid allocations
- Use Span to take advantage of the native memory
- Use the “Unsafe” api to use C# only

Sources

- [Span<T> design document](#)
- [Compile time enforcement of safety for ref-like types](#)
- [ValueTask doesn't inline well- GitHub issue](#)

Děkuji!

Slides: <http://adamsitnik.com/files/Prague.pdf>

Code: <https://github.com/adamsitnik/StateOfTheDotNetPerformance>

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