Pooling large arrays with ArrayPool

tl;dr Use `ArrayPool<T>` for large arrays to avoid Full GC.

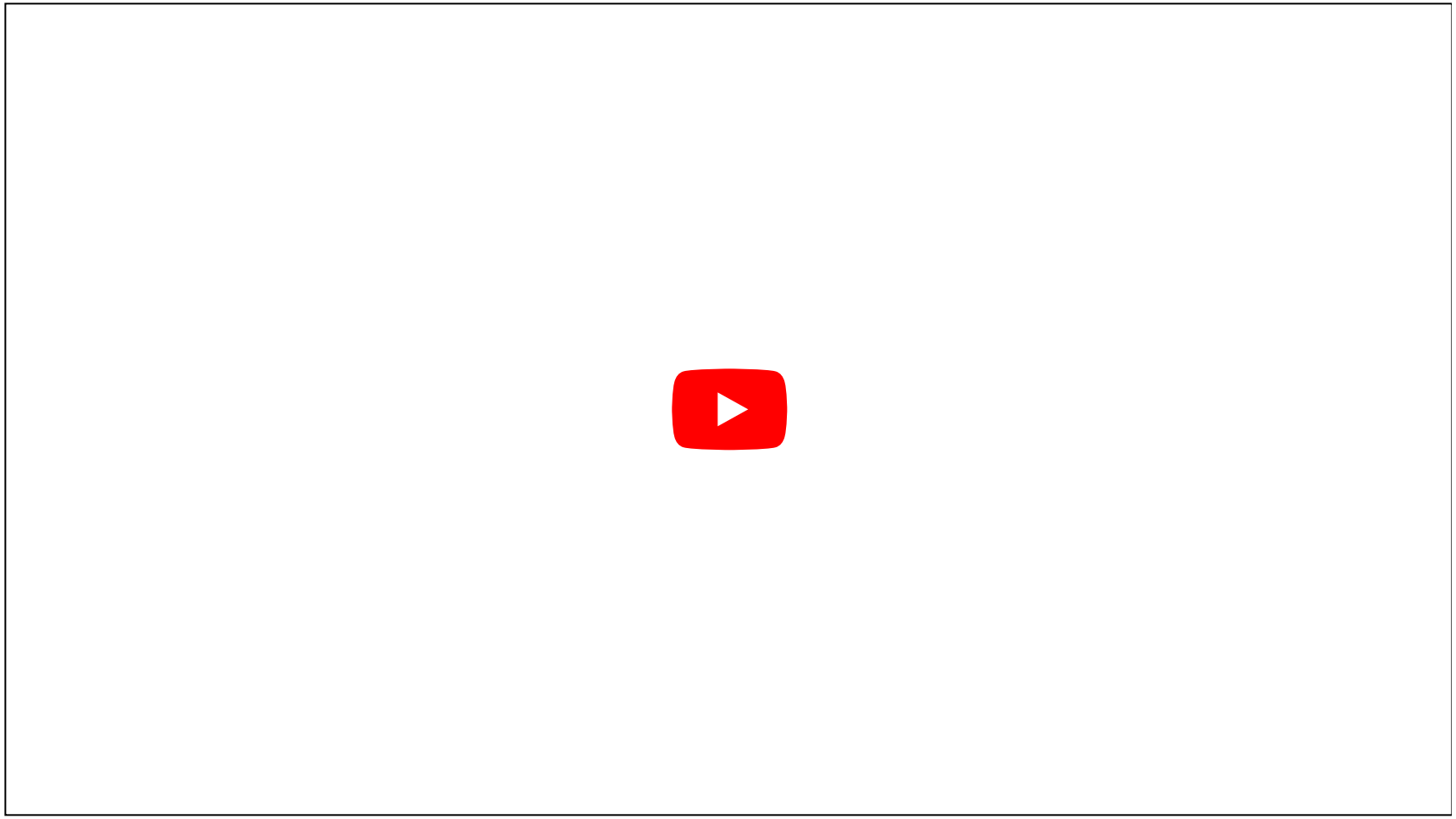
Introduction

.NET's Garbage Collector (GC) implements many performance optimizations. One of them, the generational model assumes that young objects die quickly, whereas old live longer. This is why managed heap is divided into three Generations. We call them Gen 0 (youngest), Gen 1 (short living) and Gen 2 (oldest). New objects are allocated in Gen 0. When GC tries to allocate a new object and Gen 0 is full, it performs the Gen 0 cleanup. So it performs a **partial cleanup** (Gen 0 only)! It is traversing the object's graph, starting from the roots (local variables, static fields & more) and marks all of the referenced objects as living objects.

This is the first phase, called "mark". This phase can be nonblocking, **everything else that GC does is fully blocking**. GC suspends all of the application threads to perform next steps!

Living objects are being promoted (most of the time moved == **copied!**) to Gen 1, and the memory of Gen 0 is being cleaned up. Gen 0 is usually very small, so this is very fast. In a perfect scenario, which could be a web request, none of the objects survive. All allocated objects should die when the request ends. So GC just sets the next object pointer to the beginning of Gen 0. After some Gen 0 collections, we get to the situation, when Gen 1 is also full, so GC can't just promote more objects to it. Then it simply collects Gen 1 memory. Gen 1 is also small, so it's fast. Anyway, the Gen 1 survivors are being promoted to Gen 2. **Gen 2 objects are supposed to**

be long living objects. Gen 2 is very big and it's very time-consuming to collect its memory. So garbage collection of Gen 2 is something that we want to avoid. Why? let's take a look at the following video to find out how the Gen 2 collection can affect user experience:



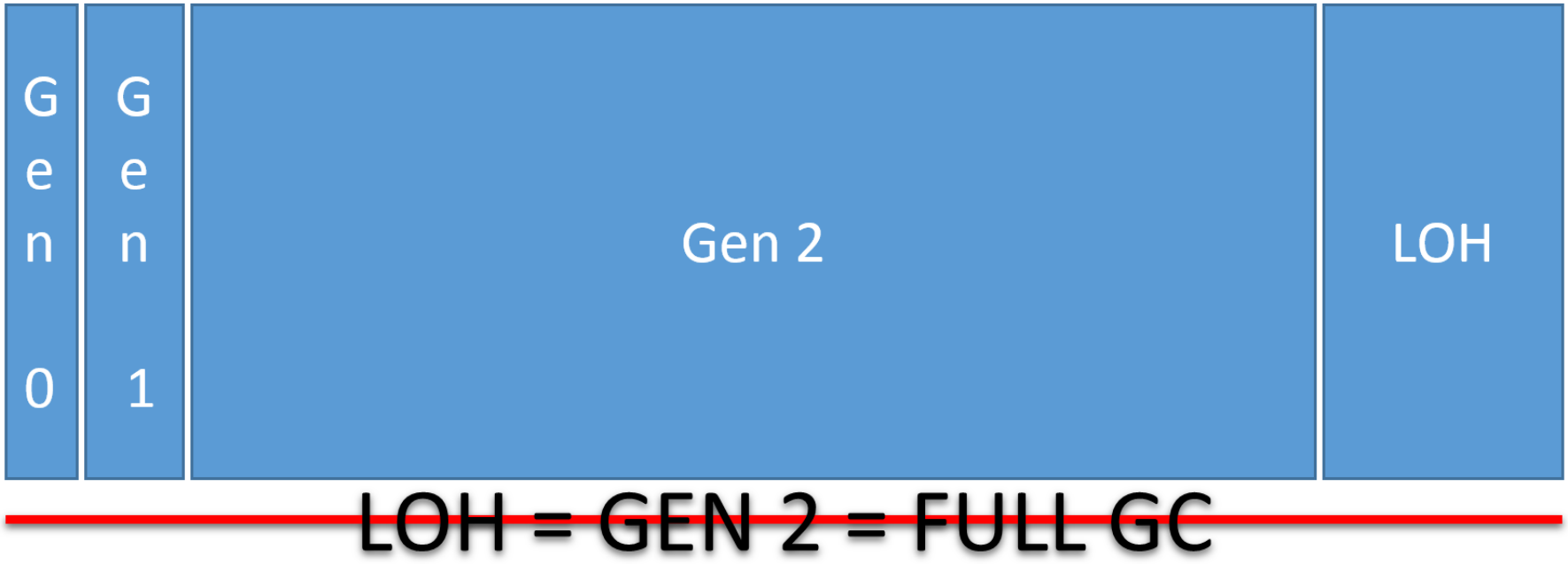
Large Object Heap (LOH)

When GC is promoting objects to next generation it's copying the memory. As you can imagine, it would be very time-consuming for large objects like big arrays or strings. This is why GC has another optimization. Any object that is bigger than `85 000` bytes is considered to be large. Large objects are stored in a separate part of the

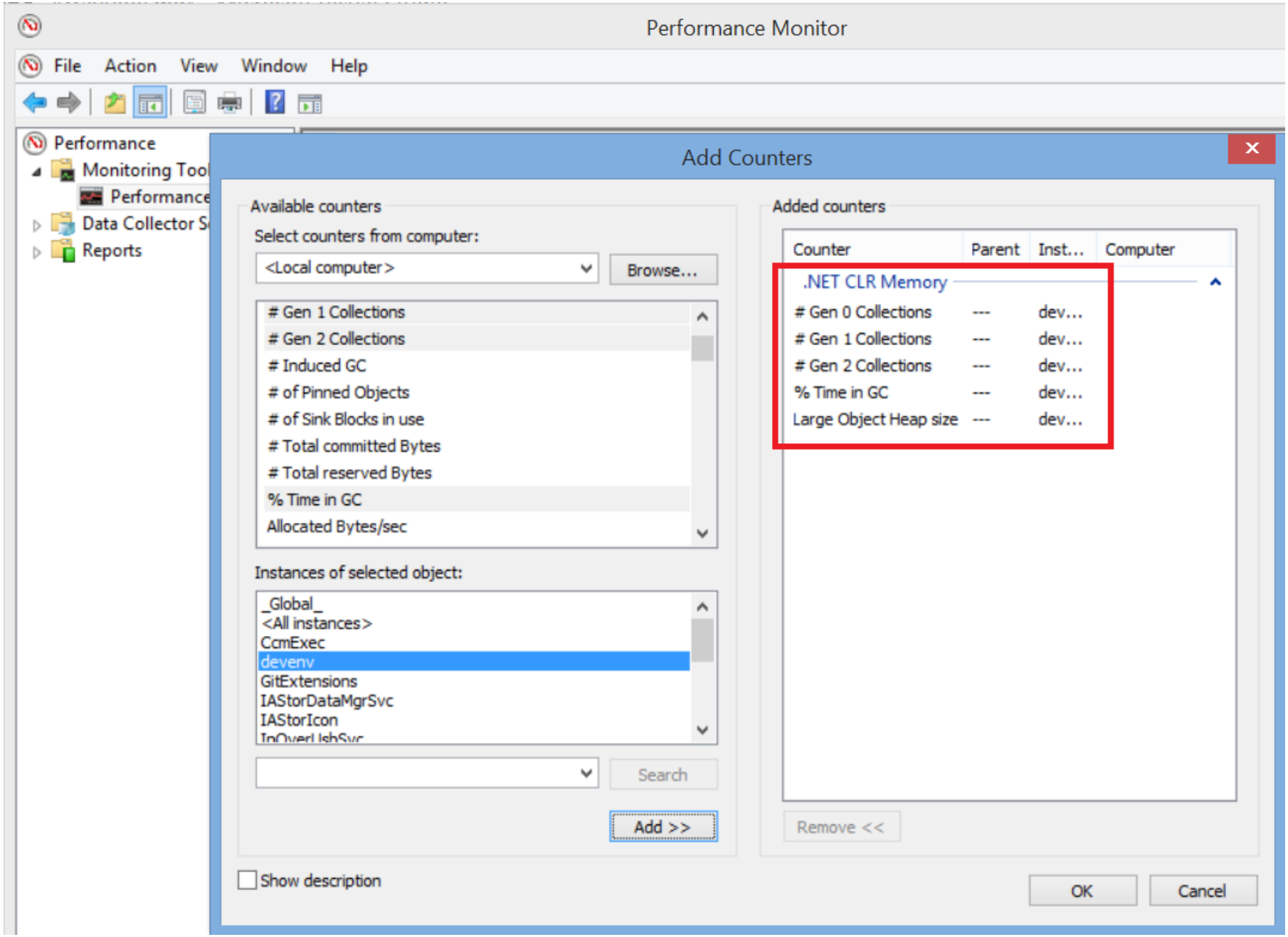
managed heap, called Large Object Heap (LOH). This part is managed with free list algorithm. It means that GC has a list of free segments of memory, and when we want to allocate something big, it's searching through the list to find a feasible segment of memory for it. **So large objects are by default never moved in memory.** However, if you run into LOH fragmentation issues you need to compact LOH. Since .NET 4.5.1 you can do this on demand.

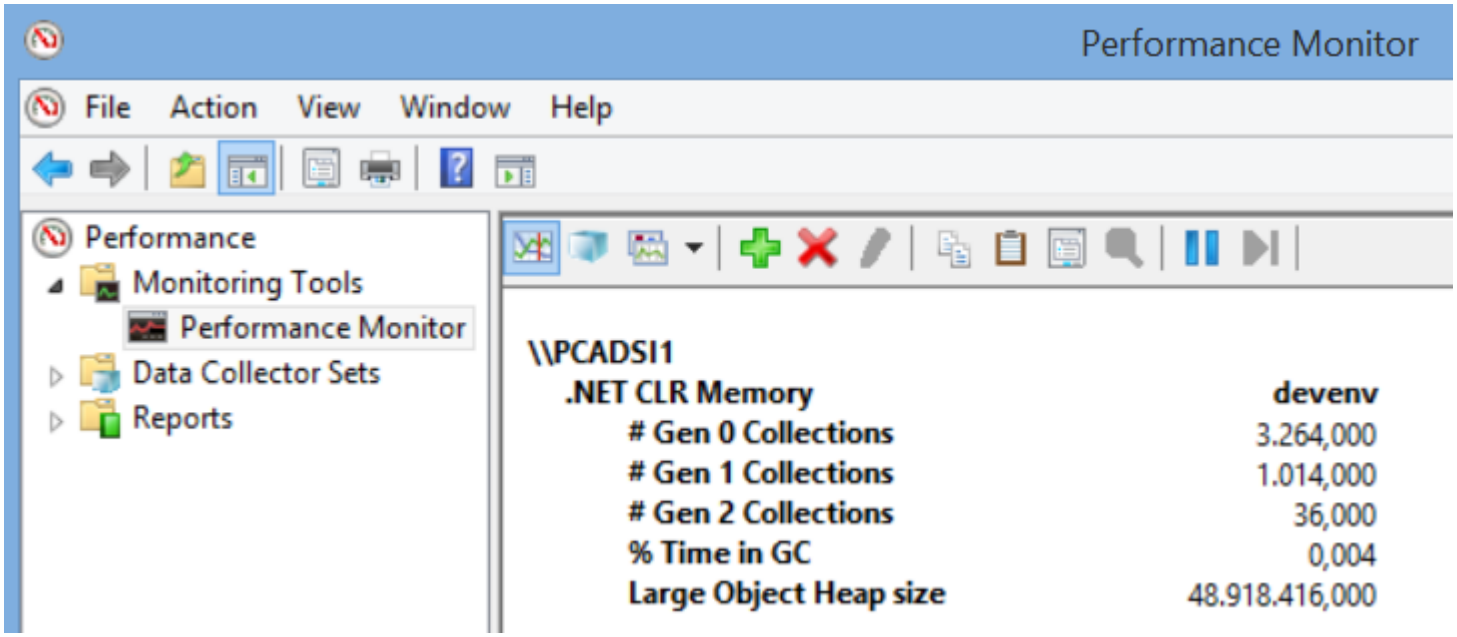
The Problem

When a large object is allocated, it's marked as Gen 2 object. Not Gen 0 as for small objects. The consequences are that **if you run out of memory in LOH, GC cleans up whole managed heap**, not only LOH. So it cleans up Gen 0, Gen 1 and Gen 2 including LOH. This is called full garbage collection and is the most time-consuming garbage collection. For many applications, it can be acceptable. But definitely not for high-performance web servers, where few big memory buffers are needed to handle an average web request (read from a socket, decompress, decode JSON & more).



Is it a problem for your application? You can use the built-in `perfmon.exe` to get an initial overview.





As you can see it's not a problem for my Visual Studio. It was running for few hours and `#Gen 2 Collections` is very low compared to Gen 0/1.

The Solution

The solution is very simple: buffer pooling. Pool is a set of initialized objects that are ready to use. Instead of allocating a new object, we rent it from the pool. Once we are done using it, we return it to the pool. Every large managed object is an array or an array wrapper (string contains a length field and an array of chars). So **we need to pool arrays to avoid this problem**.

`ArrayPool<T>` is a **high performance** pool of managed arrays. You can find it in `System.Buffers` package and it's source code is available on GitHub. It's mature and ready to use in the production. It targets `.NET Stadard 1.1` which means that you can use it not only in your new and fancy `.NET Core` apps, but also in the existing `.NET 4.5.1` apps as well!

Sample

```
var samePool = ArrayPool<byte>.Shared;
byte[] buffer = samePool.Rent(minLength);
try
{
    Use(buffer);
}
finally
{
    samePool.Return(buffer);
    // don't use the reference to the buffer after returning it!
}

void Use(byte[] buffer) // it's an array
```

How to use it?

First of all you need to obtain an instance of the pool. You can do in at least three ways:

- **Recommended: use the `ArrayPool<T>.Shared` property**, which returns a shared pool instance. It's **thread safe** and all you need to remember is that it has a default max array length, equal to `2^20` (`1024*1024 = 1 048 576`).
- Call the static `ArrayPool<T>.Create` method, which creates a **thread safe** pool with custom `maxArrayLength` and `maxArraysPerBucket`. You might need it if the default max array length is not

enough for you. Please be warned, that once you create it, you are responsible for keeping it alive.
- Derive a custom class from abstract `ArrayPool<T>` and handle everything on your own.

Next thing is to call the `Rent` method which requires you to specify minimum length of the buffer. Keep in mind, that what `Rent` returns might be bigger than what you have asked for.

```
byte[] webRequest = request.Bytes;
byte[] buffer = ArrayPool<byte>.Shared.Rent(webRequest.Length);

Array.Copy(
    sourceArray: webRequest,
    destinationArray: buffer,
    length: webRequest.Length); // webRequest.Length != buffer.Length!!
```

Once you are done using it, you just `Return` it to the **SAME** pool. `Return` method has an overload, which allows you to cleanup the buffer so subsequent consumer via `Rent` will not see the previous consumer's content. By default the contents are left unchanged.

Very imporant note from ArrayPool code:

> *Once a buffer has been returned to the pool, the caller gives up all ownership of the buffer and must not use it. The reference returned from a given call to Rent must only be returned via Return once.*

It means, that the developer is responsible for doing things right. If you keep using the reference to the buffer after returning it to the pool, you are risking unexpected behavior. As far as I know, there is no static code analysis tool that can verify the correct usage (as of today). ArrayPool is part of the `corefx` library, it's not a part of the `C#` language.

The Benchmarks!!!

Let's use BenchmarkDotNet and compare the cost of allocating arrays with the `new` operator vs pooling them with `ArrayPool<T>`. To make sure that allocation benchmark is including time spent in GC, I am configuring BenchmarkDotNet explicity to not force GC collections. Pooling is combined cost of `Rent` and `Return`. I am running the benchmarks for .NET Core 2.0, which is important because it has faster version of `ArrayPool<T>`. For .NET Core 2.0 `ArrayPool<T>` is part of the clr, whereas older frameworks use corefx version. Both versions are really fast, comparison of them and analysis of their design could be a separate blog post.

```
class Program
{
    static void Main(string[] args) => BenchmarkRunner.Run<Pooling>();
}

[MemoryDiagnoser]
[Config(typeof(DontForceGcCollectionsConfig))] // we don't want to interfere with
public class Pooling
{
    [Params((int)1E+2, // 100 bytes
        (int)1E+3, // 1 000 bytes = 1 KB
        (int)1E+4, // 10 000 bytes = 10 KB
        (int)1E+5, // 100 000 bytes = 100 KB
```

```
        (int)1E+6, // 1 000 000 bytes = 1 MB
        (int)1E+7)] // 10 000 000 bytes = 10 MB
    public int SizeInBytes { get; set; }

    private ArrayPool<byte> sizeAwarePool;

    [GlobalSetup]
    public void GlobalSetup()
        => sizeAwarePool = ArrayPool<byte>.Create(SizeInBytes + 1, 10); // let's

    [Benchmark]
    public void Allocate()
        => DeadCodeEliminationHelper.KeepAliveWithoutBoxing(new byte[SizeInBytes]

    [Benchmark]
    public void RentAndReturn_Shared()
    {
        var pool = ArrayPool<byte>.Shared;
        byte[] array = pool.Rent(SizeInBytes);
        pool.Return(array);
    }

    [Benchmark]
    public void RentAndReturn_Aware()
    {
        var pool = sizeAwarePool;
        byte[] array = pool.Rent(SizeInBytes);
        pool.Return(array);
```

```
    }
}

public class DontForceGcCollectionsConfig : ManualConfig
{
    public DontForceGcCollectionsConfig()
    {
        Add(Job.Default
            .With(new GcMode()
            {
                Force = false // tell BenchmarkDotNet not to force GC collections
            }));
    }
}
```

The Results

If you are not familiar with the output produced by BenchmarkDotNet with Memory Diagnoser enabled, you can read my dedicated blog post to find out how to read these results.

```
BenchmarkDotNet=v0.10.7, OS=Windows 10 Redstone 1 (10.0.14393)
Processor=Intel Core i7-6600U CPU 2.60GHz (Skylake), ProcessorCount=4
Frequency=2742189 Hz, Resolution=364.6722 ns, Timer=TSC
dotnet cli version=2.0.0-preview1-005977
```

```
  [Host]     : .NET Core 4.6.25302.01, 64bit RyuJIT
  Job-EBWZVT : .NET Core 4.6.25302.01, 64bit RyuJIT
```

Method	SizeInBytes	Mean	Gen 0	Gen 1	Gen 2	Allocated
Allocate	100	**8.078 ns**	0.0610	-	-	128 B
RentAndReturn_Shared	100	**44.219 ns**	-	-	-	0 B

For very small chunks of memory the default allocator can be faster.

Method	SizeInBytes	Mean	Gen 0	Gen 1	Gen 2	Allocated
Allocate	1 000	**41.330 ns**	0.4880	0.0000	-	1024 B
RentAndReturn_Shared	1 000	**43.739 ns**	-	-	-	0 B

For 1 000 bytes they are almost on par.

Method	SizeInBytes	Mean	Gen 0	Gen 1	Gen 2	Allocated
Allocate	10 000	**374.564 ns**	4.7847	0.0000	-	10024 B
RentAndReturn_Shared	10 000	**44.223 ns**	-	-	-	0 B

The bigger it gets, the slower it takes to allocate the memory.

Method	SizeInBytes	Mean	Gen 0	Gen 1	Gen 2	Allocated
Allocate	100 000	3,637.110 ns	31.2497	31.2497	**31.2497**	100024 B
RentAndReturn_Shared	100 000	46.649 ns	-	-	-	0 B

Gen 2 collections! `100 000 > 85 000`, so we get our first Full Garbage Collections!

Method	SizeInBytes	Mean	StdDev	Gen 0/1/2	Allocated
RentAndReturn_Shared	100	**44.219 ns**	**0.0314 ns**	-	0 B
RentAndReturn_Shared	1 000	**43.739 ns**	**0.0337 ns**	-	0 B
RentAndReturn_Shared	10 000	**44.223 ns**	**0.0333 ns**	-	0 B
RentAndReturn_Shared	100 000	**46.649 ns**	**0.0346 ns**	-	0 B
RentAndReturn_Shared	1 000 000	**42.423 ns**	**0.0623 ns**	-	0 B

At this point of time, you should have noticed, that the cost of pooling with `ArrayPool<T>` is constant and size-independent! It's great, because you can predict the behaviour of your code.

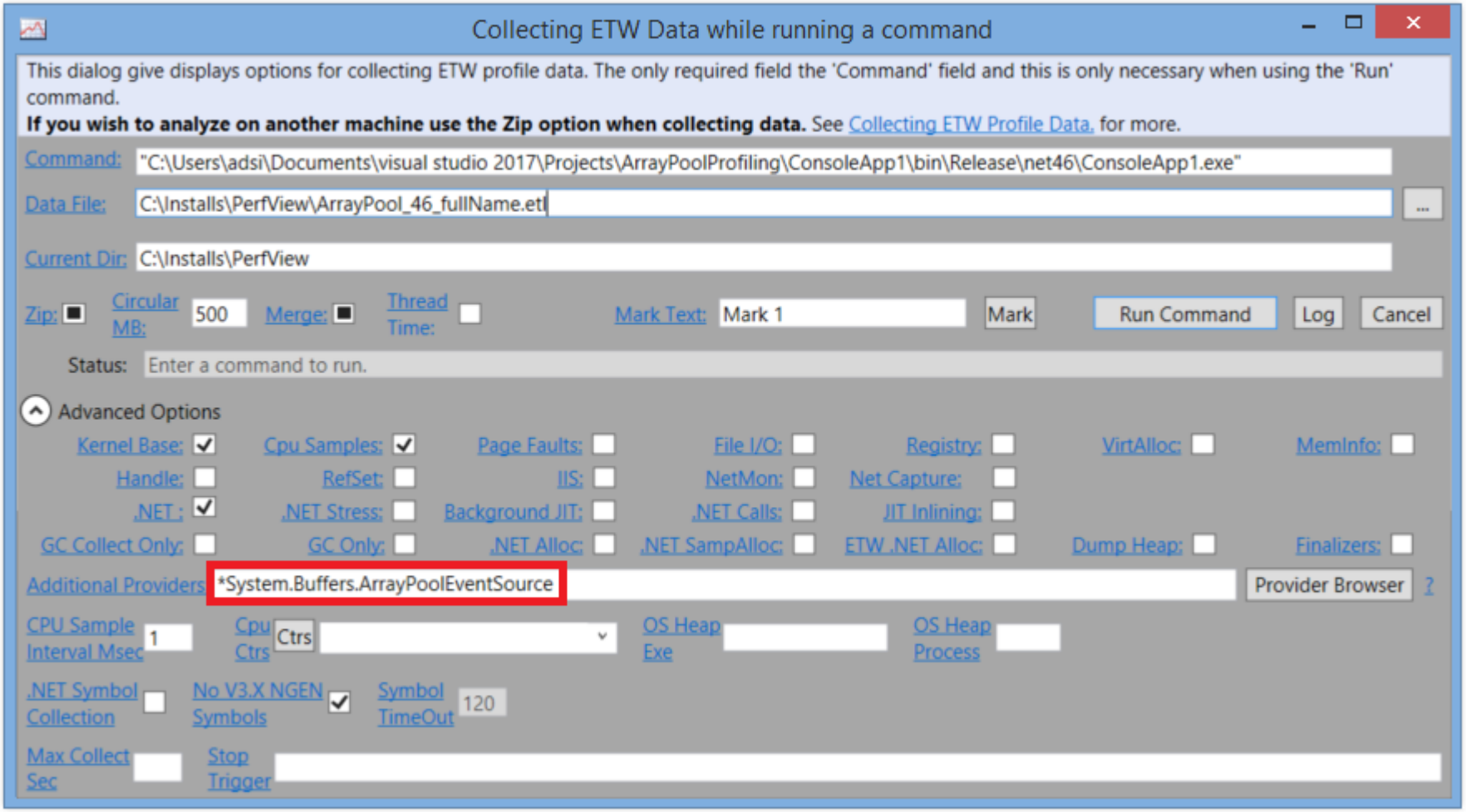
BufferAllocated

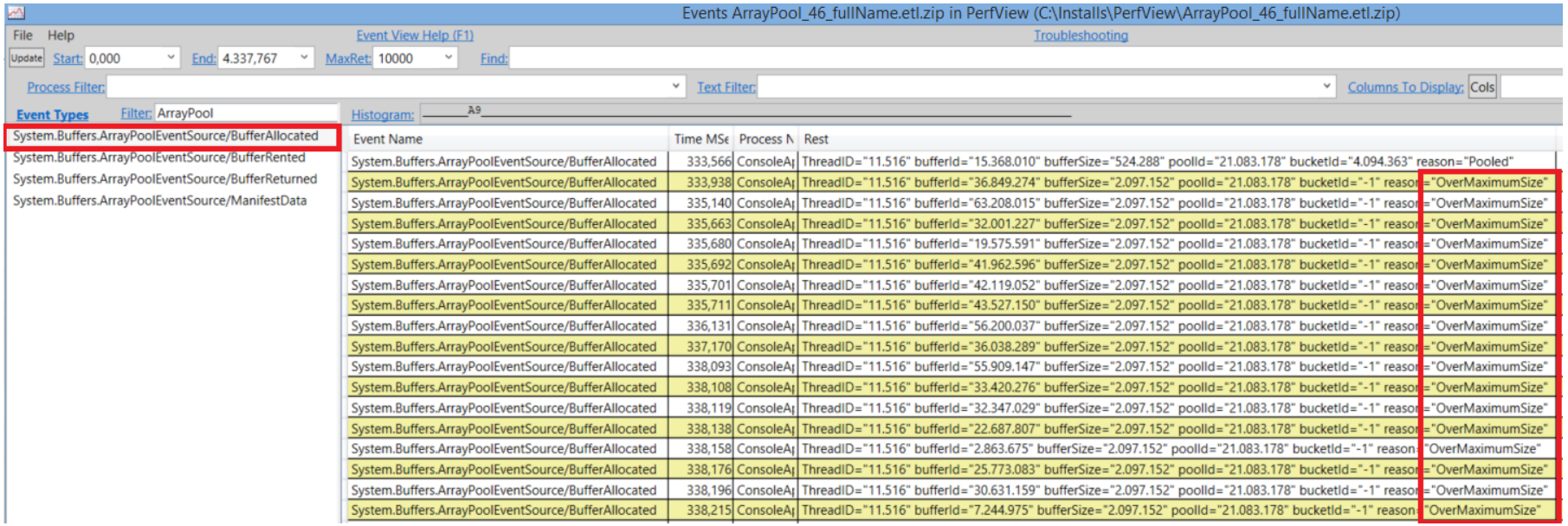
But what happens if you try to rent a buffer, that exceeds the max array length of given pool (2^20 for ArrayPool.Shared)?

Method	SizeInBytes	Mean	Gen 0	Gen 1	Gen 2	Allocated
Allocate	10 000 000	557,963.968 ns	211.5625	211.5625	211.5625	10000024 B
RentAndReturn_Shared	10 000 000	651,147.998 ns	207.1484	207.1484	**207.1484**	10000024 B
RentAndReturn_Aware	10 000 000	47.033 ns	-	-	-	0 B

A new buffer is allocated every time you ask for more than the max array length! And when you return it to the pool, it's just being ignored. Not somehow added to the pool.

Don't worry! `ArrayPool<T>` has it's own ETW Event Provider, so you can use PerfView or any other tool to profile or monitor your application and watch for the BufferAllocated event.





To avoid this problem you can use `ArrayPool<T>.Create` method, which creates a pool with custom `maxArrayLength`. **But don't create too many custom pools!!** The goal of pooling is to keep LOH small. If you create too many pools, you will end up with large LOH, full of big arrays that can not be reclaimed by GC (because they are going to be rooted by your custom pools). This is why all popular libraries like ASP.NET Core or ImageSharp use `ArrayPool<T>.Shared` **only**. If you start using `ArrayPool<T>.Shared` instead of allocating with `new` operator, then in the pessimistic scenario (asking it for array > default max size) you will be slightly slower than before (you will do an extra check and then allocate). But in the optimistic scenario, you will be much faster, because you will just rent it from the pool. So this is why I believe that you can use `ArrayPool<T>.Shared` by default. `ArrayPool<T>.Create` should be used if `BufferAllocated` events are frequent.

Pooling MemoryStream(s)

Sometimes an array might be not enough to avoid LOH allocations. An example can be 3rd party api that accepts `Stream` instance. Thanks to Victor Baybekov I have discovered Microsoft.IO.RecyclableMemoryStream.

This library provides pooling for MemoryStream objects. It was designed by Bing engineers to help with LOH issues. For more details you can go this blog post by Ben Watson.

Summary

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

Sources

- Server GC video by Age of Ascent
- Source code: CoreFx and CoreClr repos
- Pro .NET Performance book by Sasha Goldshtein, Dima Zurbalev, Ido Flatow
- Fundamentals of Garbage Collection article by MSDN
- Large Object Heap Uncovered article by Maoni Stephens
- No More Memory Fragmentation on the .NET Large Object Heap article by Mario Hewardt
- Announcing Microsoft.IO.RecycableMemoryStream article by Ben Watson

Written on June 20, 2017

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Tengan Ichisake • 5 years ago

Very nice blog post! Didn't even know we had such a thing as ArrayPool for us to use

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linkanyway • 4 years ago

the blog is awesome !!

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Adam Sitnik Mod linkanyway • 4 years ago

thank you **@linkanyway**

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devoems • 4 years ago

This blog is great! . Thanks for sharing, I'm a big fan of your knowledge.

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Adam Sitnik Mod devoems • 4 years ago

@devoems Thank you!

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Ehsan Sajjad • 5 years ago

Thanks for writing this all up, very useful information

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Adam Sitnik Mod Ehsan Sajjad • 5 years ago

Thank you **@Ehsan Sajjad** !

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nguyencaoan • 5 years ago

Thank you so much !

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Adam Sitnik Mod nguyencaoan • 5 years ago

Thank you @ng**@nguyencaoan** !

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Carl Scarlett • 5 years ago

Great post Adam! Here I was making my own presized array based pools thinking I would avoid GC when I started to scale. The video example really brings home the message; amazing footage seeing a GC on a simulation of that detail.
Thank goodness there's an alternative collection I can switch with if and when I need to.

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Adam Sitnik Mod Carl Scarlett • 5 years ago

Thank you very much **@Carl Scarlett** ! The credit for the video goes to the Illyriad Games. It's great that they have shared it. If it was a business app it would not be so convincing ;)

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Robert Friberg • 5 years ago

Well written and good timing! Pretty sure this will be useful in our current project, but of course we will measure first :)

Working with large in-memory data structures using OrigoDB, we've had to deal with GC stall issues many times. One thing we've learned is to avoid array based collections and instead use tree-based collections.

Ps. I spotted a typo, you spelled 'Ben' as 'Bet'

1 Reply • Share ›

Adam Sitnik Mod → Robert Friberg • 5 years ago

Thanks, Robert! .NET guys are working really hard on making Kestrel and (ASP).NET Core truly high-performance frameworks. I will try to write more about "new" things (Span, ValueTask, Pipelines, ref returns and locals and C# 7.2) in the next few weeks, so all of us can benefit from their research.

And thanks for letting me know about the typo. It has been fixed.

1 Reply • Share ›

Wojciech Mikołajewicz → Adam Sitnik • 4 years ago

Span<t> and Memory<t> will fit great for this. It can be hidden that buffer is actually bigger than you requested and same memory can be used once as Memory<byte> and another one Memory<int>.

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Alexandr Nikitin • 5 years ago

Adam, thanks for the post! It would be interesting to see multithreaded tests for allocation vs pooling.

1 Reply • Share ›

Adam Sitnik Mod ↗ Alexandr Nikitin • 5 years ago

Thank you Alexandr! I will add some as soon as we support Parallel benchmarks in BenchmarkDotNet. As of today, I don't want to do any manual benchmarking.

^ | v • Reply • Share ›

Tatyana Tarasova ↗ Adam Sitnik • 5 years ago

Thanks, Adam, for the informative post. Any news about multithreaded tests?

^ | v • Reply • Share ›

Adam Sitnik Mod ↗ Tatyana Tarasova • 5 years ago

Hello **@Tatyana Tarasova** . No progress on the multithreaded tests ;/

^ | v • Reply • Share ›

Vicente Gonzalez • 2 years ago

Hi Adam, I hope you are pretty well.
Do you know any tool like this (to see benchmarks) for MacOS?

^ | v • Reply • Share ›

Yawar Murtaza • 3 years ago

Excellent! It started from laying the basis of why we need ArrayPool in the first place by explaining how GC works. Not every author uses this approach.
Enjoyed reading it.

^ | v • Reply • Share ›

Adam Sitnik Mod ↗ Yawar Murtaza • 3 years ago

@Yawar Murtaza thank you!

^ | v • Reply • Share ›

Mustakim • 3 years ago

Since `ArrayPool<char>.Shared.Rent` returns an array with length higher than

requested, I usually need to pass a subset of the returned array (otherwise things break when they see '\0' in the array). So far I could do this 2 ways,

* `Span<char>.Slice` - if span can be used
* new MemoryStream(buffer, index, count); - if span can''t be used but stream can be

however I am in a situation where I *must* pass this array as char[] with the exact length. How can I do that? (I don't want to Create arraypool for that)

The situation is: Npgsql INSERT using Dapper. I am trying to write a record to a `jsonb` db column. I was passing this as string so far - now I want to pass an char[] using ArrayPool. (and these are the only two types I am allowed to pass)

So far I have seen great benefit by rewriting the Read method, by eliminating string allocation using Pooled array. Was looking at the write section today.

 • Reply • Share ›

> **Adam Sitnik** Mod → Mustakim • 3 years ago • edited
>
> Hi **@Mustakim** ! Does Dapper support `IEnumerable` as query argument? If so, you should be able to create ArraySegment for given array of given length and pass it as query argument.
>
> If it does not work I would ask a question on Stack Overflow, I am sure that Marc Gravell knows the answer
>
>  • Reply • Share ›

陈永康 • 3 years ago

> This phase can be nonblocking, everything else that GC does is fully blocking. GC suspends all of the application threads to perform next steps!

There is still room for discussion here.

GC has two sub-modes : concurrent or non-concurrent.The default setting is non-concurrent which means that GC suspends all of the application threads until it is done.

While concurrent garbage collection enables threads to run a concurrently with dedicate thread that performs the garbage collection.Managed threads can continue to run most

of time when garbage collection thread is running,

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Adam Sitnik Mod ➚ 陈永康 • 3 years ago

There are 3 GC phases: Mark, Collect and Compact (optional). Mark can be non-blocking. Collect and Compact are always blocking. This article shows how to use Concurrency Visualizer to get better understanding of it: https://blogs.msdn.microsof...

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Ian Kemp • 4 years ago

"Very imporant note from ArrayPool code" link should now point to https://github.com/dotnet/c...

Reply • Share ›

Adam Sitnik Mod ➚ Ian Kemp • 4 years ago • edited

@Ian Kemp Thank you! I have pushed an update, the change should be visible within the next few minutes.

Reply • Share ›

Alexandre Carvalho • 4 years ago

Nice article. I have a question. where does ArrayPool storage the datas, is it on the LOH?

Reply • Share ›

Adam Sitnik Mod ➚ Alexandre Carvalho • 4 years ago

hi **@Alexandre Carvalho** It depends on the size of the array. Every array bigger than 85 00 bytes is stored on LOH. Smaller ones are not.

Reply • Share ›

Alexandre Carvalho ➚ Adam Sitnik • 4 years ago

I got it that. But in your results ArrayPool always allocate 0B. My questions is where are the data storaged when using ArrayPool? Thank you for answer my previous question.

• Reply • Share ›

Adam Sitnik Mod → Alexandre Carvalho • 4 years ago

The tool that I have used for benchmarking - `BenchmarkDotNet` warms-up the code before running the benchmarks. Here the memory got allocated with the first usage of the pool during the warmup. After the warmup there were no allocations.

• Reply • Share ›

Arash Emadzadeh • 5 years ago

Outstanding post, thanks!

• Reply • Share ›

Adam Sitnik Mod → Arash Emadzadeh • 5 years ago • edited

Thank you **@Arash Emadzadeh** !

• Reply • Share ›

Warren James Buckley • 5 years ago

When creating a new pool via Create(maxBuffSize, maxArrayPerBucket) i'm unsure on what to set the maxArrayPerBucket to. I'm unsure what the benefit would be of having more than 1 array in a bucket. When would I want to have multiple arrays in a single bucket? Is anyone able to clarify this for me?

• Reply • Share ›

Adam Sitnik Mod → Warren James Buckley • 5 years ago

Hi **@Warren James Buckley**

One array in a bucket would be perfect for single threaded, synchronous app.

If you have more threads, it is possible that one of them would rent the buffer and make others starve. The default bucket size for default pool is 50 as of today: https://github.com/dotnet/c...

It depends on the number of parallel threads that can rent buffers in your scenario. 50 is a lot, but it's default. Perhaps you need just few? Or maybe

more? It's up to you

• Reply • Share ›

ssougnez • 5 years ago

Nice, thanks ;-)

• Reply • Share ›

Adam Sitnik Mod ssougnez • 5 years ago

Thank you **@ssougnez** !

• Reply • Share ›

This comment was deleted.

Adam Sitnik Mod Guest • 5 years ago

Thanks @agnicore ! I agree. Most probably every big .NET shop has it's own ArrayPool implementation.

The Pile project looks really impressive. But I guess that very few companies run into the problem that Pile solves.

• Reply • Share ›

Dmitriy Khmaladze Adam Sitnik • 5 years ago

Unfortunately many home-grown buffer pool implementations are plainly done wrong as far as multi-threading and other factors are concerned. I think the whole point of these changes have started with Microsoft's push for speed, as many many people have left ASP stack for Node, Go, Ruby and even PHP (I know a few cases when they did go to PHP from .NET!!!!).

In general; ".NET devs" really rarely cared if ever about such trifles as allocating 1000 byte[] a second instead of using the same instance.

As for Pile, I'd like to add that any system that uses cash - is the candidate for pile. I.e. it is not possible to implement a simple eCommerce catalog without cache. Pile - is the way to make graph dbs,

redis and the like unnecessary and works faster. It was created to keep your data in-process already and CLR has all the necessary tools for