.NET Blog

A first-hand look from the .NET engineering teams

Visual Studio

System.IO.Pipelines: High performance IO in .NET

★★★★☆

July 9, 2018 by David Fowler (MSFT) // 17 Comments

System.IO.Pipelines is a new library that is designed to make it easier to do high performance IO in .NET. It's a library targeting .NET Standard that works on all .NET implementations.

Pipelines was born from the work the .NET Core team did to make Kestrel one of the fastest web servers in the industry. What started as an implementation detail inside of Kestrel progressed into a re-usable API that shipped in 2.1 as a first class BCL API (System.IO.Pipelines) available for all .NET developers.

What problem does it solve?

Correctly parsing data from a stream or socket is dominated by boilerplate code and has many corner cases, leading to complex code that is difficult to maintain.
Achieving high performance and being correct, while also dealing with this complexity is difficult. Pipelines aims to solve this complexity.

What extra complexity exists today?

Let's start with a simple problem. We want to write a TCP server that receives line-delimited messages (delimited by \n) from a client.

TCP Server with NetworkStream

DISCLAIMER: As with all performance sensitive work, each of the scenarios should be measured *within the context of your application. The overhead of the various techniques mentioned may not be necessary depending on the scale your networking applications need to handle.*

The typical code you would write in .NET before pipelines looks something like this:

```
async Task ProcessLinesAsync(NetworkStream stream)
{
    var buffer = new byte[1024];
    await stream.ReadAsync(buffer, 0, buffer.Length);

    // Process a single line from the buffer
    ProcessLine(buffer);
}
```

sample1.cs hosted with ❤ by **GitHub** **view raw**

This code might work when testing locally but it's has several errors:

- The entire message (end of line) may not have been received in a single call to `ReadAsync`.
- It's ignoring the result of `stream.ReadAsync()` which returns how much data was actually filled into the buffer.
- It doesn't handle the case where multiple lines come back in a single `ReadAsync` call.

These are some of the common pitfalls when reading streaming data. To account for this we need to make a few changes:

- We need to buffer the incoming data until we have found a new line.
- We need to parse *all* of the lines returned in the buffer

```
async Task ProcessLinesAsync(NetworkStream stream)
{
    var buffer = new byte[1024];
    var bytesBuffered = 0;
    var bytesConsumed = 0;

    while (true)
    {
        var bytesRead = await stream.ReadAsync(buffer, bytesBuffered, buffer.Leng
        if (bytesRead == 0)
```

```
            {
                // EOF
                break;
            }
            // Keep track of the amount of buffered bytes
            bytesBuffered += bytesRead;

            var linePosition = -1;

            do
            {
                // Look for a EOL in the buffered data
                linePosition = Array.IndexOf(buffer, (byte)'\n', bytesConsumed, bytesI

                if (linePosition >= 0)
                {
                    // Calculate the length of the line based on the offset
                    var lineLength = linePosition - bytesConsumed;

                    // Process the line
                    ProcessLine(buffer, bytesConsumed, lineLength);

                    // Move the bytesConsumed to skip past the line we consumed (inclu
                    bytesConsumed += lineLength + 1;
                }
            }
            while (linePosition >= 0);
        }
    }
```

sample2.cs hosted with ❤ by **GitHub** **view raw**

Once again, this might work in local testing but it's possible that the line is bigger than 1KiB (1024 bytes). We need to resize the input buffer until we have found a new line.

Also, we're allocating buffers on the heap as longer lines are processed. We can improve this by using the `ArrayPool<byte>` to avoid repeated buffer allocations as we parse longer lines from the client.

```
async Task ProcessLinesAsync(NetworkStream stream)
{
    byte[] buffer = ArrayPool<byte>.Shared.Rent(1024);
    var bytesBuffered = 0;
    var bytesConsumed = 0;

    while (true)
    {
        // Calculate the amount of bytes remaining in the buffer
        var bytesRemaining = buffer.Length - bytesBuffered;

        if (bytesRemaining == 0)
        {
            // Double the buffer size and copy the previously buffered data int
            var newBuffer = ArrayPool<byte>.Shared.Rent(buffer.Length * 2);
            Buffer.BlockCopy(buffer, 0, newBuffer, 0, buffer.Length);
            // Return the old buffer to the pool
            ArrayPool<byte>.Shared.Return(buffer);
            buffer = newBuffer;
            bytesRemaining = buffer.Length - bytesBuffered;
        }

        var bytesRead = await stream.ReadAsync(buffer, bytesBuffered, bytesRema
        if (bytesRead == 0)
        {
            // EOF
            break;
        }

        // Keep track of the amount of buffered bytes
        bytesBuffered += bytesRead;

        do
        {
            // Look for a EOL in the buffered data
            linePosition = Array.IndexOf(buffer, (byte)'\n', bytesConsumed, byt

            if (linePosition >= 0)
```

```
            {
                // Calculate the length of the line based on the offset
                var lineLength = linePosition - bytesConsumed;

                // Process the line
                ProcessLine(buffer, bytesConsumed, lineLength);

                // Move the bytesConsumed to skip past the line we consumed (ir
                bytesConsumed += lineLength + 1;
            }
        }
        while (linePosition >= 0);
    }
}
```

sample3.cs hosted with ❤ by GitHub view raw

This code works but now we're re-sizing the buffer which results in more buffer copies. It also uses more memory as the logic doesn't shrink the buffer after lines are processed. To avoid this, we can store a list of buffers instead of resizing each time we cross the 1KiB buffer size.

Also, we don't grow the the 1KiB buffer until it's completely empty. This means we can end up passing smaller and smaller buffers to `ReadAsync` which will result in more calls into the operating system.

To mitigate this, we'll allocate a new buffer when there's less than 512 bytes remaining in the existing buffer:

```
public class BufferSegment
{
    public byte[] Buffer { get; set; }
    public int Count { get; set; }

    public int Remaining => Buffer.Length - Count;
}

async Task ProcessLinesAsync(NetworkStream stream)
{
    const int minimumBufferSize = 512;
```

```
    var segments = new List<BufferSegment>();
    var bytesConsumed = 0;
    var bytesConsumedBufferIndex = 0;
    var segment = new BufferSegment { Buffer = ArrayPool<byte>.Shared.Rent(1024

    segments.Add(segment);

    while (true)
    {
        // Calculate the amount of bytes remaining in the buffer
        if (segment.Remaining < minimumBufferSize)
        {
            // Allocate a new segment
            segment = new BufferSegment { Buffer = ArrayPool<byte>.Shared.Rent(
            segments.Add(segment);
        }

        var bytesRead = await stream.ReadAsync(segment.Buffer, segment.Count, s
        if (bytesRead == 0)
        {
            break;
        }

        // Keep track of the amount of buffered bytes
        segment.Count += bytesRead;

        while (true)
        {
            // Look for a EOL in the list of segments
            var (segmentIndex, segmentOffset) = IndexOf(segments, (byte)'\n', b

            if (segmentIndex >= 0)
            {
                // Process the line
                ProcessLine(segments, segmentIndex, segmentOffset);

                bytesConsumedBufferIndex = segmentOffset;
```

```
                bytesConsumed = segmentOffset + 1;
            }
            else
            {
                break;
            }
        }

        // Drop fully consumed segments from the list so we don't look at them
        for (var i = bytesConsumedBufferIndex; i >= 0; --i)
        {
            var consumedSegment = segments[i];
            // Return all segments unless this is the current segment
            if (consumedSegment != segment)
            {
                ArrayPool<byte>.Shared.Return(consumedSegment.Buffer);
                segments.RemoveAt(i);
            }
        }
    }
}

(int segmentIndex, int segmentOffest) IndexOf(List<BufferSegment> segments, byt
{
    var first = true;
    for (var i = startBufferIndex; i < segments.Count; ++i)
    {
        var segment = segments[i];
        // Start from the correct offset
        var offset = first ? startSegmentOffset : 0;
        var index = Array.IndexOf(segment.Buffer, value, offset, segment.Count

        if (index >= 0)
        {
            // Return the buffer index and the index within that segment where
            return (i, index);
        }

```

```
            first = false;
        }

        return (-1, -1);
    }
```

sample4.cs hosted with ❤ by GitHub　　view raw

This code just got *much* more complicated. We're keeping track of the filled up buffers as we're looking for the delimiter. To do this, we're using a `List<BufferSegment>` here to represent the buffered data while looking for the new line delimiter. As a result, `ProcessLine` and `IndexOf` now accept a `List<BufferSegment>` instead of a `byte[]`, `offset` and `count`. Our parsing logic needs to now handle one or more buffer segments.

Our server now handles partial messages, and it uses pooled memory to reduce overall memory consumption but there are still a couple more changes we need to make:

1. The `byte[]` we're using from the `ArrayPool<byte>` are just regular managed arrays. This means whenever we do a `ReadAsync` or `WriteAsync`, those buffers get pinned for the lifetime of the asynchronous operation (in order to interop with the native IO APIs on the operating system). This has performance implications on the garbage collector since pinned memory cannot be moved which can lead to heap fragmentation. Depending on how long the async operations are pending, the pool implementation may need to change.
2. The throughput can be optimized by decoupling the reading and processing logic. This creates a batching effect that lets the parsing logic consume larger chunks of buffers, instead of reading more data only after parsing a single line. This introduces some additional complexity:
   - We need two loops that run independently of each other. One that reads from the `Socket` and one that parses the buffers.
   - We need a way to signal the parsing logic when data becomes available.
   - We need to decide what happens if the loop reading from the `Socket` is "too fast". We need a way to throttle the reading loop if the parsing logic can't keep up. This is commonly referred to as "flow control" or "back pressure".
   - We need to make sure things are thread safe. We're now sharing a set of buffers between the reading loop and the parsing loop and those run independently on different threads.
   - The memory management logic is now spread across two different pieces of code, the code that rents from the buffer pool is reading from the socket and the code that returns from the buffer pool is the parsing logic.
   - We need to be extremely careful with how we return buffers after the parsing logic is

done with them. If we're not careful, it's possible that we return a buffer that's still being written to by the `Socket` reading logic.

The complexity has gone through the roof (and we haven't even covered all of the cases). High performance networking usually means writing very complex code in order to eke out more performance from the system.

The goal of `System.IO.Pipelines` is to make writing this type of code easier.

TCP server with System.IO.Pipelines

Let's take a look at what this example looks like with `System.IO.Pipelines`:

```
async Task ProcessLinesAsync(Socket socket)
{
    var pipe = new Pipe();
    Task writing = FillPipeAsync(socket, pipe.Writer);
    Task reading = ReadPipeAsync(pipe.Reader);

    return Task.WhenAll(reading, writing);
}

async Task FillPipeAsync(Socket socket, PipeWriter writer)
{
    const int minimumBufferSize = 512;

    while (true)
    {
        // Allocate at least 512 bytes from the PipeWriter
        Memory<byte> memory = writer.GetMemory(minimumBufferSize);
        try
        {
            int bytesRead = await socket.ReceiveAsync(memory, SocketFlags.None)
            if (bytesRead == 0)
            {
                break;
            }
            // Tell the PipeWriter how much was read from the Socket
            writer.Advance(bytesRead);
```

```
        }
        catch (Exception ex)
        {
            LogError(ex);
            break;
        }

        // Make the data available to the PipeReader
        FlushResult result = await writer.FlushAsync();

        if (result.IsCompleted)
        {
            break;
        }
    }

    // Tell the PipeReader that there's no more data coming
    writer.Complete();
}

async Task ReadPipeAsync(PipeReader reader)
{
    while (true)
    {
        ReadResult result = await reader.ReadAsync();

        ReadOnlySequence<byte> buffer = result.Buffer;
        SequencePosition? position = null;

        do
        {
            // Look for a EOL in the buffer
            position = buffer.PositionOf((byte)'\n');

            if (position != null)
            {
                // Process the line
                ProcessLine(buffer.Slice(0, position.Value));
```

```
                // Skip the line + the \n character (basically position)
                buffer = buffer.Slice(buffer.GetPosition(1, position.Value));
            }
        }
        while (position != null);

        // Tell the PipeReader how much of the buffer we have consumed
        reader.AdvanceTo(buffer.Start, buffer.End);

        // Stop reading if there's no more data coming
        if (result.IsCompleted)
        {
            break;
        }
    }

    // Mark the PipeReader as complete
    reader.Complete();
}
```

sample5.cs hosted with ❤ by GitHub view raw

The pipelines version of our line reader has 2 loops:

- `FillPipeAsync` reads from the `Socket` and writes into the `PipeWriter`.
- `ReadPipeAsync` reads from the `PipeReader` and parses incoming lines.

Unlike the original examples, there are no explicit buffers allocated anywhere. This is one of pipelines' core features. All buffer management is delegated to the `PipeReader`/`PipeWriter` implementations.

This makes it easier for consuming code to focus solely on the business logic instead of complex buffer management.

In the first loop, we first call `PipeWriter.GetMemory(int)` to get some memory from the underlying writer; then we call `PipeWriter.Advance(int)` to tell the `PipeWriter` how much data we actually wrote to the buffer. We then call `PipeWriter.FlushAsync()` to make the data available to the `PipeReader`.

In the second loop, we're consuming the buffers written by the `PipeWriter` which ultimately comes from the `Socket`. When the call to `PipeReader.ReadAsync()` returns, we get a `ReadResult` which contains 2 important pieces of information, the data that was read in the form of `ReadOnlySequence<byte>` and a bool `IsCompleted` that lets the reader know if the writer is done writing (EOF). After finding the end of line (EOL) delimiter and parsing the line, we slice the buffer to skip what we've already processed and then we call `PipeReader.AdvanceTo` to tell the `PipeReader` how much data we have consumed.

At the end of each of the loops, we complete both the reader and the writer. This lets the underlying `Pipe` release all of the memory it allocated.

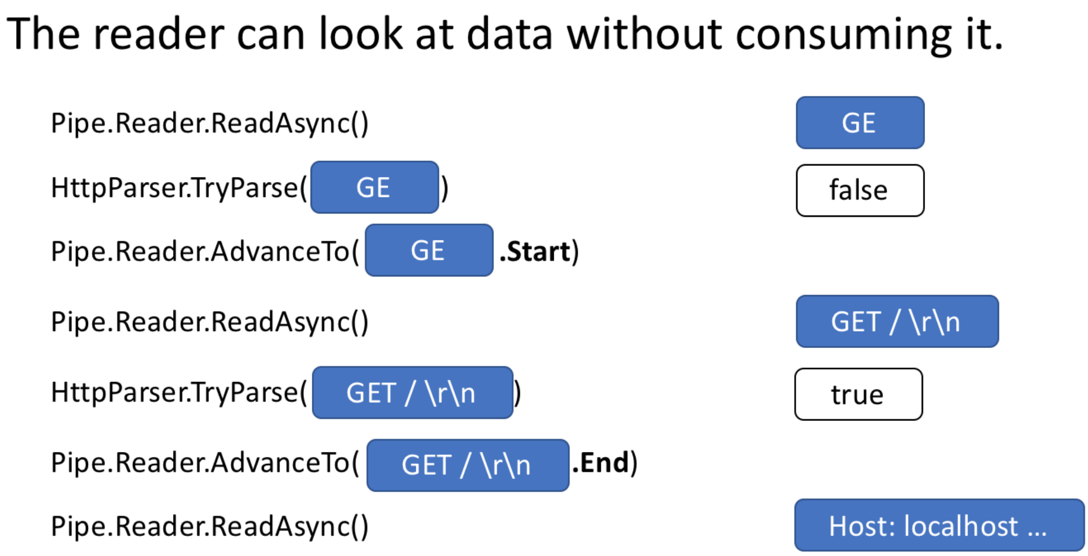
System.IO.Pipelines

Partial Reads

Besides handling the memory management, the other core pipelines feature is the ability to peek at data in the `Pipe` without actually consuming it.

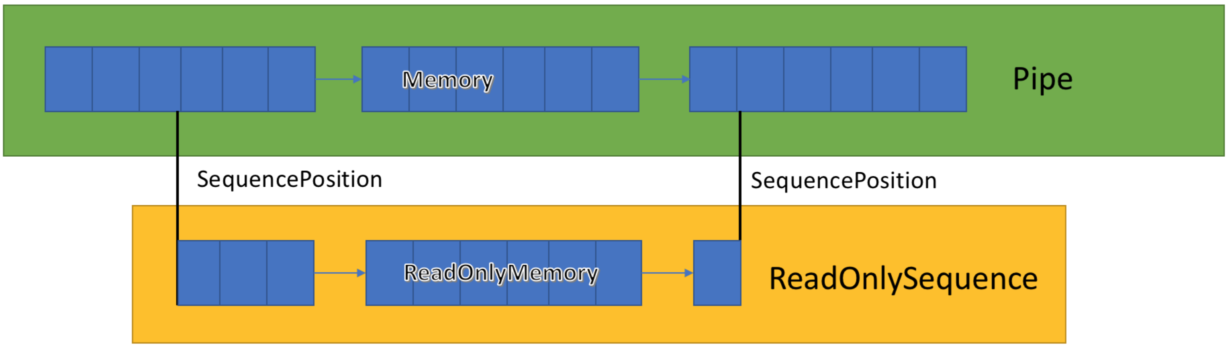
`PipeReader` has two core APIs `ReadAsync` and `AdvanceTo`. `ReadAsync` gets the data in the `Pipe`, `AdvanceTo` tells the `PipeReader` that these buffers are no longer required by the reader so they can be discarded (for example returned to the underlying buffer pool).

Here's an example of an http parser that reads partial data buffers data in the `Pipe` until a valid start line is received.



ReadOnlySequence<T>

The Pipe implementation stores a linked list of buffers that get passed between the PipeWriter and PipeReader. PipeReader.ReadAsync exposes a ReadOnlySequence<T> which is a new BCL type that represents a view over one or more segments of ReadOnlyMemory<T>, similar to Span<T> and Memory<T> which provide a view over arrays and strings.



The Pipe internally maintains pointers to where the reader and writer are in the overall set of allocated data and updates them as data is written or read. The SequencePosition represents a single point in the linked list of buffers and can be used to efficiently slice the ReadOnlySequence<T>.

Since the ReadOnlySequence<T> can support one or more segments, it's typical for high performance processing logic to split fast and slow paths based on single or multiple segments.

For example, here's a routine that converts an ASCII ReadOnlySequence<byte> into a string:

```
string GetAsciiString(ReadOnlySequence<byte> buffer)
{
    if (buffer.IsSingleSegment)
    {
        return Encoding.ASCII.GetString(buffer.First.Span);
    }

    return string.Create((int)buffer.Length, buffer, (span, sequence) =>
    {
        foreach (var segment in sequence)
        {
```

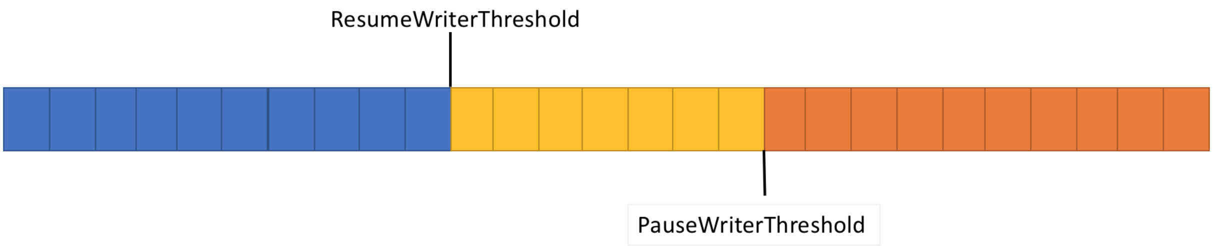
```
            Encoding.ASCII.GetChars(segment.Span, span);

            span = span.Slice(segment.Length);
        }
    });
}
```

sample6.cs hosted with ❤ by GitHub view raw

Back pressure and flow control

In a perfect world, reading & parsing work as a team: the reading thread consumes the data from the network and puts it in buffers while the parsing thread is responsible for constructing the appropriate data structures. Normally, parsing will take more time than just copying blocks of data from the network. As a result, the reading thread can easily overwhelm the parsing thread. The result is that the reading thread will have to either slow down or allocate more memory to store the data for the parsing thread. For optimal performance, there is a balance between frequent pauses and allocating more memory.

To solve this problem, the pipe has two settings to control the flow of data, the `PauseWriterThreshold` and the `ResumeWriterThreshold`. The `PauseWriterThreshold` determines how much data should be buffered before calls to `PipeWriter.FlushAsync` pauses. The `ResumeWriterThreshold` controls how much the reader has to consume before writing can resume.



`PipeWriter.FlushAsync` "blocks" when the amount of data in the `Pipe` crosses `PauseWriterThreshold` and "unblocks" when it becomes lower than `ResumeWriterThreshold`. Two values are used to prevent thrashing around the limit.

Scheduling IO

Usually when using async/await, continuations are called on either on thread pool threads or on the current `SynchronizationContext`.

When doing IO it's very important to have fine-grained control over where that IO is performed so that one can take advantage of CPU caches more effectively, which is critical for high-performance applications like web servers. Pipelines exposes a `PipeScheduler` that determines where asynchronous callbacks run. This gives the caller fine-grained control over exactly what threads are used for IO.

An example of this in practice is in the Kestrel Libuv transport where IO callbacks run on dedicated event loop threads.

Other benefits of the PipeReader pattern:

- Some underlying systems support a "bufferless wait", that is, a buffer never needs to be allocated until there's actually data available in the underlying system. For example on Linux with epoll, it's possible to wait until data is ready before actually supplying a buffer to do the read. This avoids the problem where having a large number of threads waiting for data doesn't immediately require reserving a huge amount of memory.
- The default `Pipe` makes it easy to write unit tests against networking code because the parsing logic is separated from the networking code so unit tests only run the parsing logic against in-memory buffers rather than consuming directly from the network. It also makes it easy to test those hard to test patterns where partial data is sent. ASP.NET Core uses this to test various aspects of the Kestrel's http parser.
- Systems that allow exposing the underlying OS buffers (like the Registered IO APIs on Windows) to user code are a natural fit for pipelines since buffers are always provided by the `PipeReader` implementation.

Other Related types

As part of making System.IO.Pipelines, we also added a number of new primitive BCL types:

- MemoryPool<T>, IMemoryOwner<T>, MemoryManager<T> – .NET Core 1.0 added ArrayPool<T> and in .NET Core 2.1 we now have a more general abstraction for a pool that works over any `Memory<T>`. This provides an extensibility point that lets you plug in more advanced allocation strategies as well as control how buffers are managed (for e.g. provide pre-pinned buffers instead of purely managed arrays).
- IBufferWriter<T> – Represents a sink for writing synchronous buffered data. (`PipeWriter` implements this)
- IValueTaskSource – ValueTask<T> has existed since .NET Core 1.1 but has gained some super powers in .NET Core 2.1 to allow allocation-free awaitable async operations. See

https://github.com/dotnet/corefx/issues/27445 for more details.

How do I use Pipelines?

The APIs exist in the System.IO.Pipelines nuget package.

Here's an example of a .NET Core 2.1 server application that uses pipelines to handle line based messages (our example above) https://github.com/davidfowl/TcpEcho. It should run with `dotnet run` (or by running it in Visual Studio). It listens to a socket on port 8087 and writes out received messages to the console. You can use a client like netcat or putty to make a connection to 8087 and send line based messages to see it working.

Today Pipelines powers Kestrel and SignalR, and we hope to see it at the center of many networking libraries and components from the .NET community.

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Mark Eastwood

2 days ago

Thanks for the great blog David!

I've been writing some TCP code based on SocketAsyncEventArgs (https://docs.microsoft.-com/en-us/dotnet/api/system.net.sockets.socketasynceventargs?view=netcore-2.1). Will I see much of a performance/memory allocation improvement using Pipelines?

David Fowler

1 day ago

It definitely *can*. It'll probably help you write more correct code first off.
It'll also force you into patterns that can improve your memory allocations and throughput (as described in the article). I'd definitely ask you to try the API out and see what you end up with.

Alvaro Rivoir

2 days ago

How should we consume network streams and files using Pipelines?

Vince

2 days ago

Thank you. BTW, "delimeter" should be "delimiter"

David Fowler

1 day ago

Thanks!

PetSerAl

2 days ago

Should it be `bytesConsumedBufferIndex = segmentIndex;` instead of `bytesConsumedBufferIndex = segmentOffset;`?

Łukasz Pyrzyk

1 day ago

Great post!

Derekk

1 day ago

Excellent!

Marcel Veldhuizen

1 day ago

The given code assumes ASCII encoding when searching for the newline. A short note about that might have been good, before people start blindly copying this code 🙂

I understand actually fixing it is outside the scope of the example, unless there is a clever way of dealing with (for example) UTF-8 that I'm not aware of…

Marc Stromko *23 hours ago*

The newline sequence is the same in UTF-8, all 7 bit ASCII characters are the same in the UTF formats. For UTF-8 support beyond ASCII, change the Encoding.ASCII to Encoding.UTF8, and verify that the read buffer is not ending mid-character.

paradyne at work *22 hours ago*

There is a clever way.. Or rather UTF-8 is clever. It never uses values of 0-127 inside multibyte characters so you are safe to just search through to a newline and then convert the bytes up to that point into a string using UTF8.GetString().

See: https://en.wikipedia.org/wiki/UTF-8

Kevin Bryant *24 hours ago*

Thanks for this! Can we please have a post like this for system.threading.channels? The readme from the corefxlabs repo seems to be the only existing documentation, and it appears to be out of date. The comments in the code are great, but aside from the hints in the early readme there doesn't seem to be much describing how it's all intended to fit together. Even a pointer to somewhere it's being used in another project – haven't had much luck finding usage so far.

Juliano Goncalves *21 hours ago*

Really nice article!

I wonder what it would take to abstract this even more maybe using `IObservable` and Rx though. I always found Rx's way of representing this kind of push operation to be incredibly streamlined and simple to comprehend.

Even though the new API is drastically simpler than the old version, I still find it somewhat complex and hard to read. Maybe if another abstraction level is introduced it would be possible to make this a little bit more intuitive.

Yandy Zaldivar

19 hours ago

I've been using a custom TCP binary protocol not delimited by lines or any other character(s), just binary serialized objects with length prefixed. Is this library able to handle this kind of behavior or only line-delimited messages?

Rafael Teixeira

15 hours ago

Definitively yes. You just keep reading until the length you need is completed. You can even get smart with asking buffers from the pipe that match the expected lengths.

Eugeniy

18 hours ago

Don't catch catch(exception) without of rethrowing

Steve S

12 hours ago

Great Post, Fantastic Library