Deficiencies of .NET CLR JIT compilers

Another reason to use a GPU

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Who are We

Software and solution provider for high performance and GPU computing, subsidiary of InCube

Technology driven financial services company

Managed Code Efficiency

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- Can managed code be as efficient as native code?
- In some cases optimized JIT code is as fast as native!
- For many cases optimized JIT code is significantly slower
  - 40% to 400% performance degradation

- JIT optimization tradeoff
  - Balance increased JIT compilation time against improved execution efficiency
  - Additional safety guards also in release mode
    - Range checks for array access
  - SSE vector instructions

Side Note

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- Inspecting generated MSIL code is not enough
- Need to look **at assembly code** generated by JIT compiler in **release mode**

- How to:
  - In project settings set **Generate debug info** to **pdb-only**
  - Go to **Tools → Options → Debugging → General**
    - Uncheck **Suppress JIT optimization on module load**
    - Uncheck **Enable Just My Code**
  - Compile in release mode and set breakpoint code
  - Run with debugger
  - Once debugger stopped right click and select **Go To Disassembly**

Example 1 – Simple Loop

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- Write to array in a loop

```
for (var i = 0; i < a.Length; ++i)
{
    a[i] = i;
}
```

Example 1 – Simple Loop

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```
for (var i = 0; i < a.Length; ++i)
00007FFF309244F0  xor          eax,eax
00007FFF309244F2  mov          edx,dword ptr [rcx+8]
00007FFF309244F5  test         edx,edx
00007FFF309244F7  jle          00007FFF30924507
{
    a[i] = i;
00007FFF309244F9  movsxd       r8,eax
00007FFF309244FC  mov          dword ptr [rcx+r8*4+10h],eax
for (var i = 0; i < a.Length; ++i)
00007FFF30924501  inc          eax
00007FFF30924503  cmp          edx,eax
00007FFF30924505  jg           00007FFF309244F9
00007FFF30924507  ret
```

Optimized

Example 2 – Nested Loops

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- Read from array and write to array in nested loops

```
for (var i = 0; i < lda; ++i)
{
    for (var j = 0; j < lda; ++j)
    {
        a[i*lda + j] = b[j*lda + i];
    }
}
```

Example 2 – Nested Loops

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```
. . .
for (var j = 0; j < lda; ++j)
00007FFF30944521  test        r8d,r8d
00007FFF30944524  jle         00007FFF30944560
00007FFF30944526  mov         r10d,dword ptr [rdx+8]
00007FFF3094452A  mov         r11d,eax
00007FFF3094452D  imul        r11d,r8d
00007FFF30944531  mov         esi,dword ptr [rcx+8]
                  {
                      a[i*lda + j] = b[j*lda + i];
00007FFF30944534  mov         edi,r9d
00007FFF30944537  imul        edi,r8d
00007FFF3094453B  add         edi,eax
00007FFF3094453D  cmp         edi,r10d
00007FFF30944540  jae         00007FFF3094456F

. . .
```

Range check not optimized

Example 3 – Floyd Warshall

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- Solving all shortest path problem – with 2d arrays

```
public static void FloydWarshall(int[,] d, int[,] p)
{
    var n = d.GetLength(0);
    for (var u = 0; u < n; u++) {
        for (var v1 = 0; v1 < n; v1++) {
            for (var v2 = 0; v2 < n; v2++) {
                var newPath = d[v1, u] + d[u, v2];
                var oldPath = d[v1, v2];
                if (oldPath > newPath) {
                    d[v1, v2] = newPath;
                    p[v1, v2] = p[u, v2];
                }
            }
        }
    }
}
```

Example 3 – Floyd Warshall

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- Solving all shortest path problem – flatten to improve performance

```
public static void FloydWarshall(int n, int[] d, int[] p)
{
    for (var u = 0; u < n; u++) {
        for (var v1 = 0; v1 < n; v1++) {
            for (var v2 = 0; v2 < n; v2++) {
                var newPath = d[v1 * n + u] + d[u * n + v2];
                var oldPath = d[v1 * n + v2];
                if (oldPath > newPath) {
                    d[v1 * n + v2] = newPath;
                    p[v1 * n + v2] = p[u * n + v2];
                }
            }
        }
    }
}
```

Floyd Warshall Performance

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- Comparing against C++ native
- Small size problem 1000 nodes 150000 edges
- I7-4770K @ 3.5Gz
  - C# 2.3 s
  - Microsoft C++ 1.7
  - C# roughly 35% slower

Moving to GPU

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- Often CRL JIT compilers cannot properly optimize numerical codes
  - Linear algebra
  - Search algorithms
  - Numerical optimization
- Moving to unmanaged C++ and using PInvoke leads to unwanted maintenance effort and language diversity

- Many numerical algorithms show some degree of parallelism
- Move to GPU to get hyper speedup!

GPU is a Coprocessor

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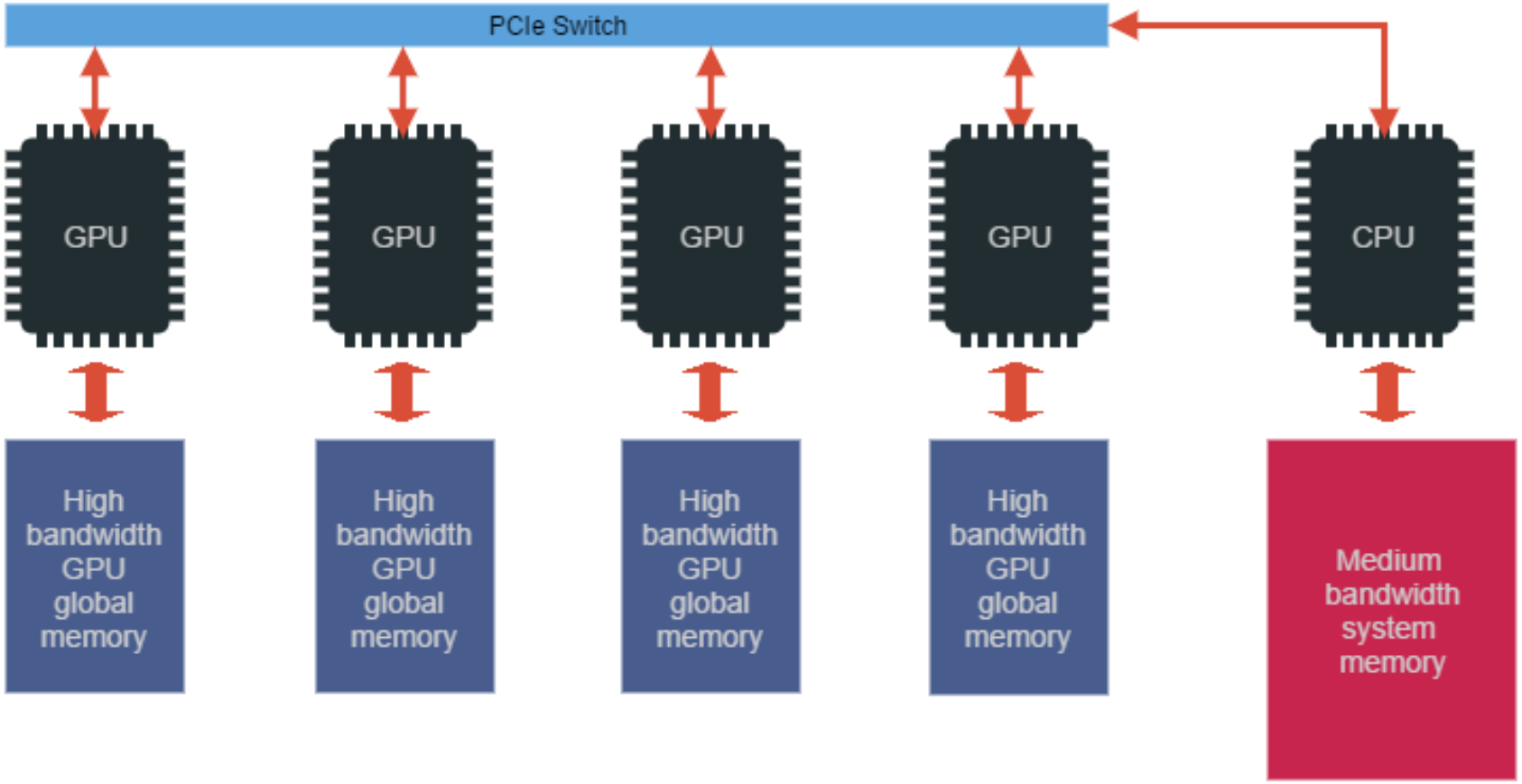

Basic CUDA Concepts

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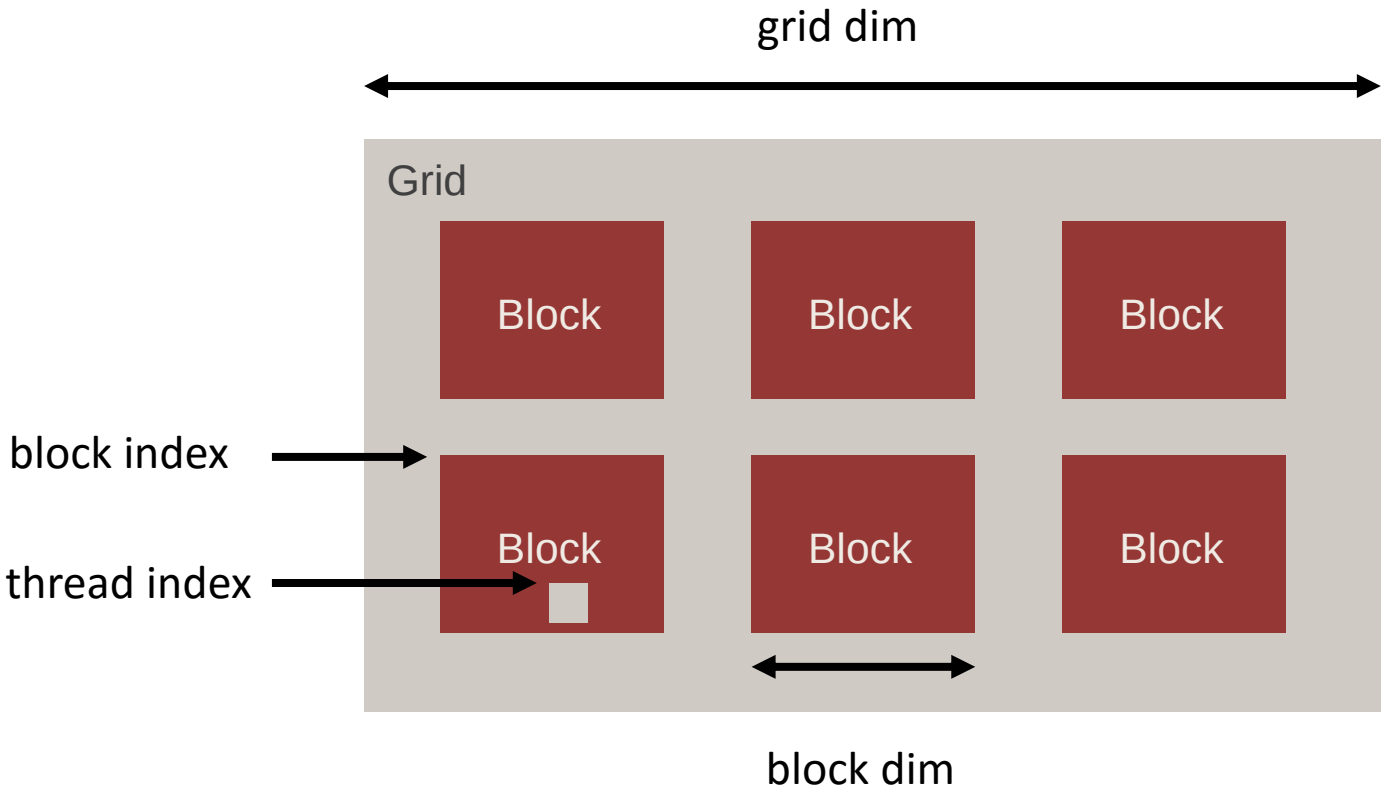
- Kernel
- Grid and thread block



FW GPU – Simple Implementation

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- GPU kernel with .NET types

```
public static void KernelSingleStage(int u, int[,] d, int[,] p)
{
    var n = d.GetLength(0);
    var v1 = blockDim.y * blockIdx.y + threadIdx.y;
    var v2 = blockDim.x * blockIdx.x + threadIdx.x;

    if (v1 < n && v2 < n)  {
        var newPath = d[v1, u] + d[u, v2];
        var oldPath = d[v1, v2];
        if (oldPath > newPath) {
            d[v1, v2] = newPath;
            p[v1, v2] = p[u, v2];
        }
    }
}
```

FW GPU – Simple Implementation

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- GPU kernel launching

```
[GpuManaged]
public static void Run(Gpu gpu, int[,] d, int[,] p)
{
    var n = d.GetLength(0);
    var gridDim =
        new dim3((n - 1)/BlockWidth + 1, (n - 1)/BlockWidth + 1, 1);
    var blockDim = new dim3(BlockWidth, BlockWidth, 1);
    var lp = new LaunchParam(gridDim, blockDim);
    for (var u = 0; u < n; u++) {
        gpu.Launch(KernelSingleStage, lp, u, d, p);
    }
}
```

FW GPU – Simple Implementation

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- Comparing against CUDA C++ native
- Small size problem 1000 nodes 150000 edges
- Tesla 40c with I7-4770K @ 3.5Gz
  - C# 2.3 s
  - GPU C# 6.2 s
  - **GPU C# 2.7 times slower than C# CPU**
  - **GPU C# 85 times slower than native CUDA C++**

- Issues
  - Memory must be well aligned, i.e. using pitched memory and device pointers
  - Only copy minimal amount of data, i.e. explicit memory management

FW GPU – Optimization I

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- GPU kernel with GPU optimized types

```
public static void KernelSingleStage(int u, int n, int pitch,
    deviceptr<int> d, deviceptr<int> p)
{
    var v1 = blockDim.y * blockIdx.y + threadIdx.y;
    var v2 = blockDim.x * blockIdx.x + threadIdx.x;

    if (v1 < n && v2 < n) {
        var newPath = d[v1*pitch + u] + d[u*pitch + v2];
        var oldPath = d[v1*pitch + v2];
        if (oldPath > newPath) {
            d[v1*pitch + v2] = newPath;
            p[v1*pitch + v2] = p[u*pitch + v2];
        }
    }
}
```

FW GPU – Optimization I

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- GPU kernel launching with explicit pitched memory management

```
public static Tuple<int[,], int[,]> Run(Gpu gpu, int[,] dh, int[,] ph)
{
    using (var d = gpu.AllocateDevice(dh))
    using (var p = gpu.AllocateDevice(ph)) {
        var n = dh.GetLength(0);
        var gridDim =
            new dim3((n - 1)/BlockWidth + 1, (n - 1)/BlockWidth + 1, 1);
        var blockDim = new dim3(BlockWidth, BlockWidth, 1);
        var lp = new LaunchParam(gridDim, blockDim);
        var pitch = (int)d.PitchInElements;
        for (var u = 0; u < n; u++) {
            gpu.Launch(KernelSingleStage, lp, u, n, pitch, d.Ptr, p.Ptr);
        }

        var dRes = Gpu.Copy2DToHost(d);
        var pRes = Gpu.Copy2DToHost(p);
        return new Tuple<int[,], int[,]>(dRes, pRes);
}}
```

FW GPU – Optimization I

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- Comparing against CUDA C++ native
- Small size problem 1000 nodes 150000 edges
- Tesla 40c with I7-4770K @ 3.5Gz
  - GPU C# with pitched memory explicitly managed 0.075 s
  - **GPU C# 30 times faster**
  - CUDA C++ 0.073 s

- Issues
  - Overall 2.7% performance degradation against CUDA C++
  - Inspecting with profiler: kernel execution times are identical
  - Launching GPU kernels from .NET has a marshalling overhead
  - Arrays must be pinned before sending to GPU

FW GPU – Optimization II

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- Change to blocked Floyd-Warshall algorithm
- Improve cache efficiency by using shared memory
- Minimize shared memory utilization
- Reduce instruction count
- Use less expensive instructions
- Price
  - More code
  - More complex algorithm
  - Requires detailed understanding of GPUs and parallel algorithms
- Benefit
  - Factor 2 to 5 speedup

FW GPU – Optimization II

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- Tesla 40c with I7-4770K @ 3.5Gz
- Small size problem 1000 nodes 150000 edges
  - GPU C# with pitched memory explicitly managed 0.037 s
  - CUDA C++ 0.034 s
  - GPU C# version **60 times faster** than initial C# version
- Larger problem 10000 nodes 2000000 edges
  - C# **2082 s approx 0.5 h**
  - GPU C# and CUDA C++ 46.4 s (Opt I) **16.5 s** (Opt II)
  - GPU C# version **125 times faster** than initial C# version
  - Overhead as compared to native CUDA C++ implementation immaterial

Wait a sec, I am lost!

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Does it need to be so complicated?

Fortunately not!

Use parallel for and parallel aggregate

Parallel-For

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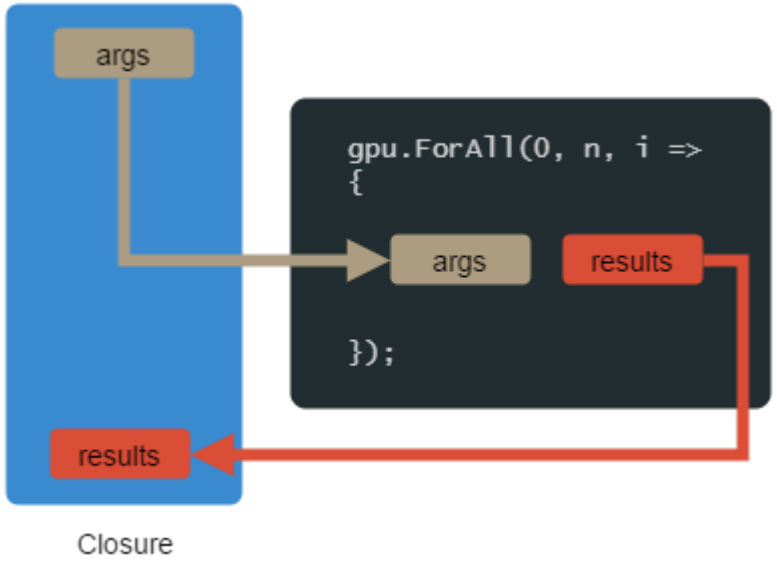
- Independent operation for each
  - element of a collection
  - index of an ordered range

```
void Gpu.For(int start, int end, Action<int> op);
```

- Arguments and the result are captured in a closure and passed to the parallel-for body



Parallel Aggregate

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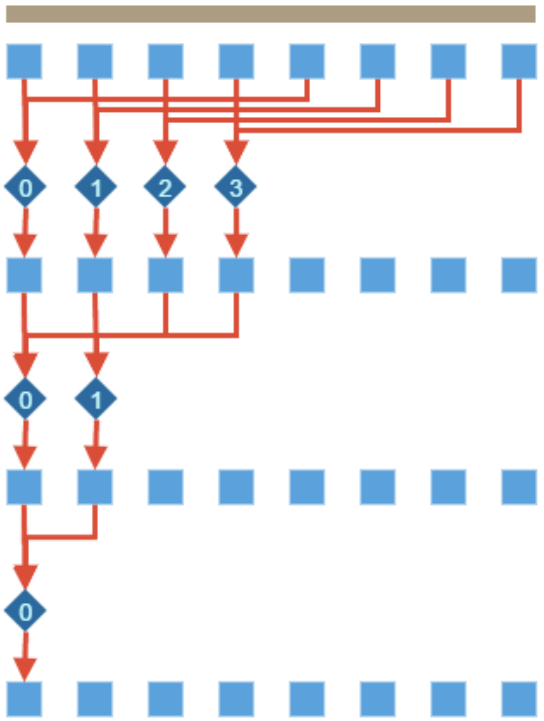
- Reduce collection of elements with an associative binary operator to a single value.

```
T Gpu.Aggregate<T>(T[] elements, Func<T, T, T> op);
```

- Convenience overloads for
  - Sum
  - Average
- Highly efficient implementation
  - Comparable to NVIDIA CUB



GPU Computing Made Simple

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```
int n = 1000;
var rng = new System.Random();
var x = Enumerable.Range(0, n).Select(_ =>
    rng.NextDouble()).ToArray();
var y = Enumerable.Range(0, n).Select(_ =>
    rng.NextDouble()).ToArray();
var res = new double[n];

Parallel.For(0, n, i => res[i] = x[i] + y[i]);

var expected = x.Zip(y, (xi, yi) => xi + yi);

Assert.That(res, Is.EqualTo(expected));

var sum = x.AsParallel().Aggregate((xi, yi) => xi + yi);

Assert.That(sum, Is.EqualTo(x.Sum()).Within(1e-12));
```

GPU Computing Made Simple

QuantAlea

```
int n = 1000;
var rng = new System.Random();
var x = Enumerable.Range(0, n).Select(_ =>
    rng.NextDouble()).ToArray();
var y = Enumerable.Range(0, n).Select(_ =>
    rng.NextDouble()).ToArray();
var res = new double[n];

Gpu.Default.For(0, n, i => res[i] = x[i] + y[i]);

var expected = x.Zip(y, (xi, yi) => xi + yi);

Assert.That(res, Is.EqualTo(expected));

var sum = Gpu.Default.Aggregate(x, (xi, yi) => xi + yi);

Assert.That(sum, Is.EqualTo(x.Sum()).Within(1e-12));
```

Same delegate

Pointers

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- Alea GPU V3
  - http://www.aleagpu.com/release
  - Samples in sample gallery http://www.aleagpu.com/release/3_0_0-beta10/doc/gallery.html
  - Alea GPU 2.x community license also works for Alea GPU V3
- Alea GPU V3 beta NuGet packages
  - http://beta.aleagpu.com/nuget
- Alea TK
  - New open source deep learning stack based on Alea GPU
  - To be released around September 2016

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