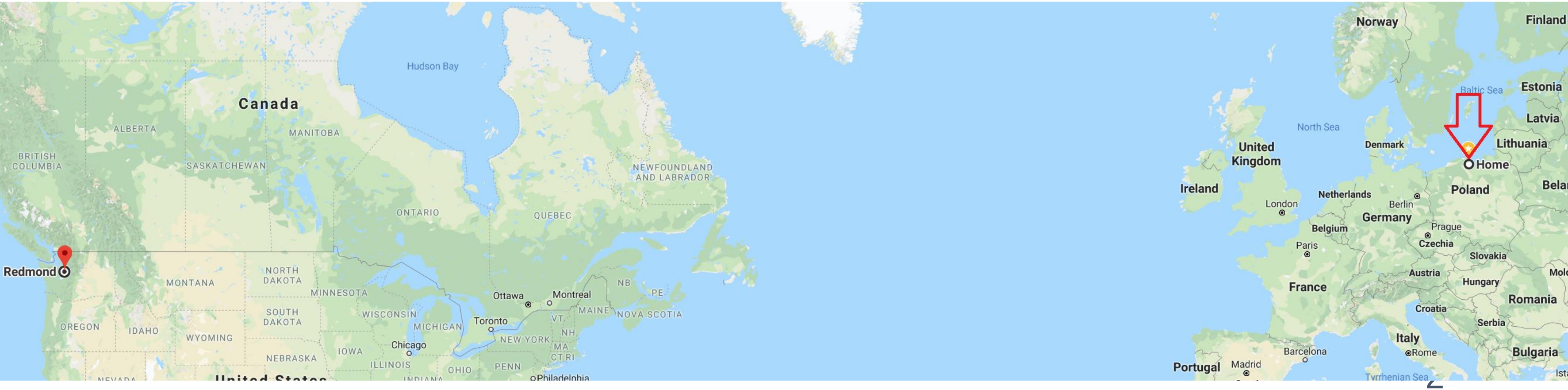
POWERFUL BENCHMARKING IN .NET

Adam Sitnik

About Myself

- Open Source Contributor
- BenchmarkDotNet maintainer
- Performance Champion on the .NET Team at Microsoft



Why performance is important?

- Responsiveness – customer experience $
- Scalability – scale and earn more $
- Capacity – optimize and save more $
- Power – CPU uses power, which costs $
- Heat – CPU generates heat, contributes to global warming!

Without data you’re just another person with an opinion

— W. Edwards Deming, a data scientist

The worst optimizations are the ones based on invalid measurements.

Benchmark? Profiler?

„In computing, a benchmark is the act of running a computer program, a set of programs, or other operations, in order to assess the relative performance of an object, normally by running a number of standard tests and trials against it”

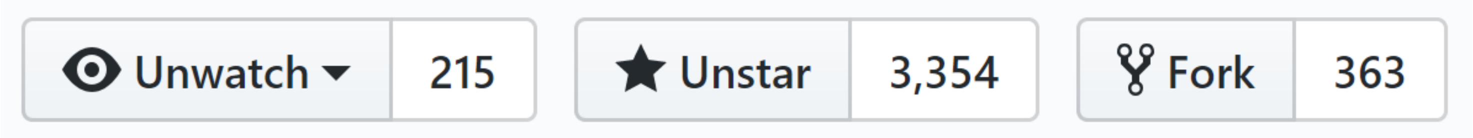
Wikipedia

„In software engineering, profiling ("program profiling", "software profiling") is a form of dynamic program analysis that measures, for example, the space (memory) or time complexity of a program, the usage of particular instructions, or the frequency and duration of function calls. Most commonly, profiling information serves to aid program optimization.”

Wikipedia

What is BenchmarkDotNet?

*„**BenchmarkDotNet** is a powerful .NET library for benchmarking.”*



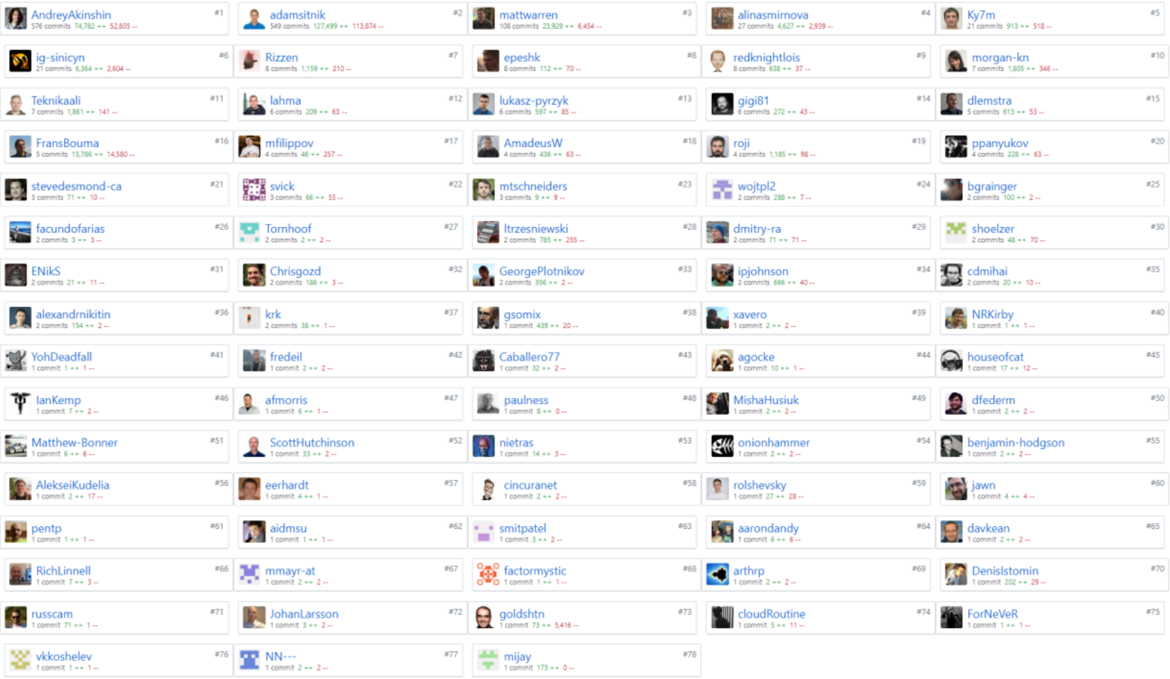
Kestrel SignalR Entity Framework F# Orleans

Elasticsearch Dapper ImageSharp RavenDB NodaTime

MIT

.NET foundation

The Contributors

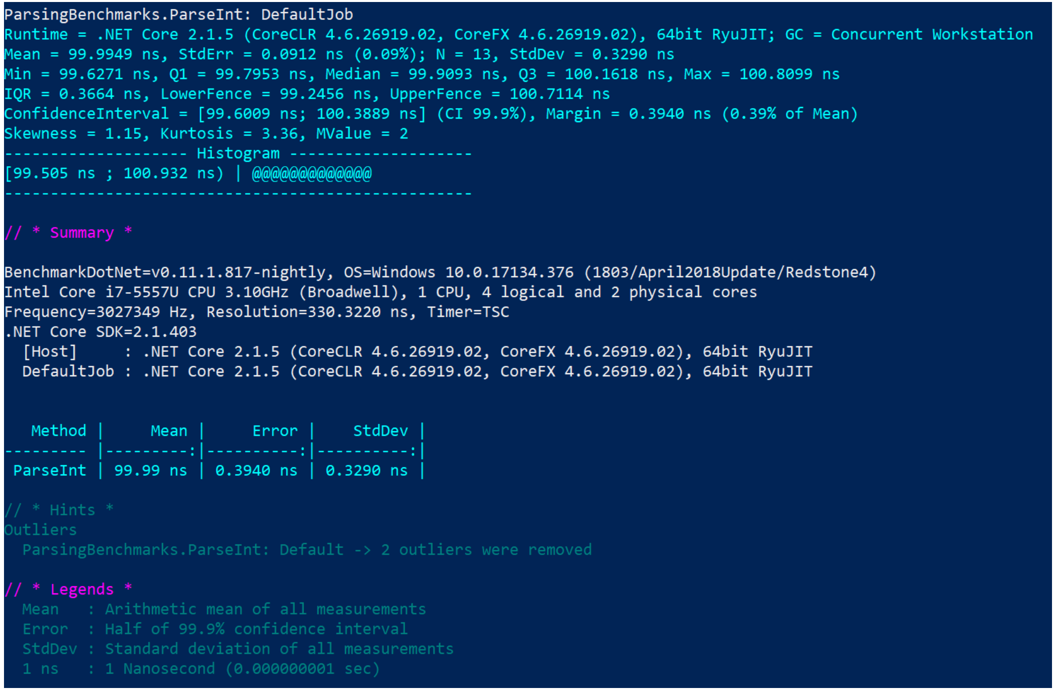


AndreyAkinshin	576 commits	74,782 ++	52,805 --	#1
adamsitnik	549 commits	127,499 ++	113,874 --	#2
mattwarren	108 commits	23,929 ++	6,454 --	#3
alinasmirnova	27 commits	4,627 ++	2,939 --	#4
Ky7m	21 commits	913 ++	518 --	#5
ig-sinicyn	21 commits	6,364 ++	2,604 --	#6
Rizzen	8 commits	1,159 ++	210 --	#7
epeshk	8 commits	112 ++	70 --	#8
redknightlois	8 commits	638 ++	37 --	#9
morgan-kn	7 commits	1,805 ++	346 --	#10
Teknikaali	7 commits	1,861 ++	141 --	#11
lahma	6 commits	209 ++	63 --	#12
lukasz-pyrzyk	6 commits	597 ++	85 --	#13
gigi81	6 commits	272 ++	43 --	#14
dlemstra	5 commits	613 ++	53 --	#15
FransBouma	5 commits	15,786 ++	14,580 --	#16
mfilippov	4 commits	46 ++	257 --	#17
AmadeusW	4 commits	436 ++	63 --	#18
roji	4 commits	1,185 ++	98 --	#19
ppanyukov	4 commits	228 ++	63 --	#20
stevedesmond-ca	3 commits	71 ++	10 --	#21
svick	3 commits	66 ++	55 --	#22
mtschneiders	3 commits	9 ++	9 --	#23
wojtpl2	2 commits	288 ++	7 --	#24
bgrainger	2 commits	100 ++	2 --	#25
facundofarias	2 commits	3 ++	3 --	#26
Tornhoof	2 commits	2 ++	2 --	#27
ltrzesniewski	2 commits	785 ++	255 --	#28
dmitry-ra	2 commits	71 ++	71 --	#29
shoelzer	2 commits	48 ++	70 --	#30
ENikS	2 commits	21 ++	11 --	#31
Chrisgozd	2 commits	186 ++	3 --	#32
GeorgePlotnikov	2 commits	356 ++	2 --	#33
ipjohnson	2 commits	666 ++	40 --	#34
cdmihai	2 commits	20 ++	10 --	#35
alexandrnikitin	2 commits	154 ++	2 --	#36
krk	2 commits	38 ++	1 --	#37
gsomix	1 commit	439 ++	20 --	#38
xavero	1 commit	2 ++	2 --	#39
NRKirby	1 commit	1 ++	1 --	#40
YohDeadfall	1 commit	1 ++	1 --	#41
fredeil	1 commit	2 ++	2 --	#42
Caballero77	1 commit	32 ++	2 --	#43
agocke	1 commit	10 ++	1 --	#44
houseofcat	1 commit	17 ++	12 --	#45
IanKemp	1 commit	7 ++	2 --	#46
afmorris	1 commit	6 ++	1 --	#47
paulness	1 commit	8 ++	0 --	#48
MishaHusiuk	1 commit	2 ++	2 --	#49
dfederm	1 commit	2 ++	2 --	#50
Matthew-Bonner	1 commit	6 ++	6 --	#51
ScottHutchinson	1 commit	33 ++	2 --	#52
nietras	1 commit	14 ++	3 --	#53
onionhammer	1 commit	2 ++	2 --	#54
benjamin-hodgson	1 commit	2 ++	2 --	#55
AlekseiKudelia	1 commit	2 ++	17 --	#56
eerhardt	1 commit	4 ++	1 --	#57
cincuranet	1 commit	2 ++	2 --	#58
rolshevsky	1 commit	27 ++	28 --	#59
jawn	1 commit	4 ++	4 --	#60
pentp	1 commit	1 ++	1 --	#61
aidmsu	1 commit	1 ++	1 --	#62
smitpatel	1 commit	3 ++	2 --	#63
aarondandy	1 commit	6 ++	6 --	#64
davkean	1 commit	2 ++	2 --	#65
RichLinnell	1 commit	7 ++	3 --	#66
mmayr-at	1 commit	2 ++	2 --	#67
factormystic	1 commit	1 ++	1 --	#68
arthrp	1 commit	2 ++	2 --	#69
DenisIstomin	1 commit	202 ++	29 --	#70
russcam	1 commit	71 ++	1 --	#71
JohanLarsson	1 commit	3 ++	2 --	#72
goldshtn	1 commit	73 ++	5,416 --	#73
cloudRoutine	1 commit	5 ++	11 --	#74
ForNeVeR	1 commit	1 ++	1 --	#75
vkkoshelev	1 commit	1 ++	1 --	#76
NN---	1 commit	2 ++	2 --	#77
mijay	1 commit	173 ++	0 --	#78

Sample

```
public class ParsingBenchmarks
{
    [Benchmark]
    public int ParseInt() => int.Parse("123456789");
}

void Main(string[] args)
    => BenchmarkRunner.Run<ParsingBenchmarks>();
```

Sample Results



```
ParsingBenchmarks.ParseInt: DefaultJob
Runtime = .NET Core 2.1.5 (CoreCLR 4.6.26919.02, CoreFX 4.6.26919.02), 64bit RyuJIT; GC = Concurrent Workstation
Mean = 99.9949 ns, StdErr = 0.0912 ns (0.09%); N = 13, StdDev = 0.3290 ns
Min = 99.6271 ns, Q1 = 99.7953 ns, Median = 99.9093 ns, Q3 = 100.1618 ns, Max = 100.8099 ns
IQR = 0.3664 ns, LowerFence = 99.2456 ns, UpperFence = 100.7114 ns
ConfidenceInterval = [99.6009 ns; 100.3889 ns] (CI 99.9%), Margin = 0.3940 ns (0.39% of Mean)
Skewness = 1.15, Kurtosis = 3.36, MValue = 2
-------------------- Histogram --------------------
[99.505 ns ; 100.932 ns) | @@@@@@@@@@@@@
---------------------------------------------------

// * Summary *

BenchmarkDotNet=v0.11.1.817-nightly, OS=Windows 10.0.17134.376 (1803/April2018Update/Redstone4)
Intel Core i7-5557U CPU 3.10GHz (Broadwell), 1 CPU, 4 logical and 2 physical cores
Frequency=3027349 Hz, Resolution=330.3220 ns, Timer=TSC
.NET Core SDK=2.1.403
  [Host]     : .NET Core 2.1.5 (CoreCLR 4.6.26919.02, CoreFX 4.6.26919.02), 64bit RyuJIT
  DefaultJob : .NET Core 2.1.5 (CoreCLR 4.6.26919.02, CoreFX 4.6.26919.02), 64bit RyuJIT


   Method |     Mean |     Error |    StdDev |
--------- |---------:|----------:|----------:|
 ParseInt | 99.99 ns | 0.3940 ns | 0.3290 ns |

// * Hints *
Outliers
  ParsingBenchmarks.ParseInt: Default -> 2 outliers were removed

// * Legends *
  Mean   : Arithmetic mean of all measurements
  Error  : Half of 99.9% confidence interval
  StdDev : Standard deviation of all measurements
  1 ns   : 1 Nanosecond (0.000000001 sec)
```

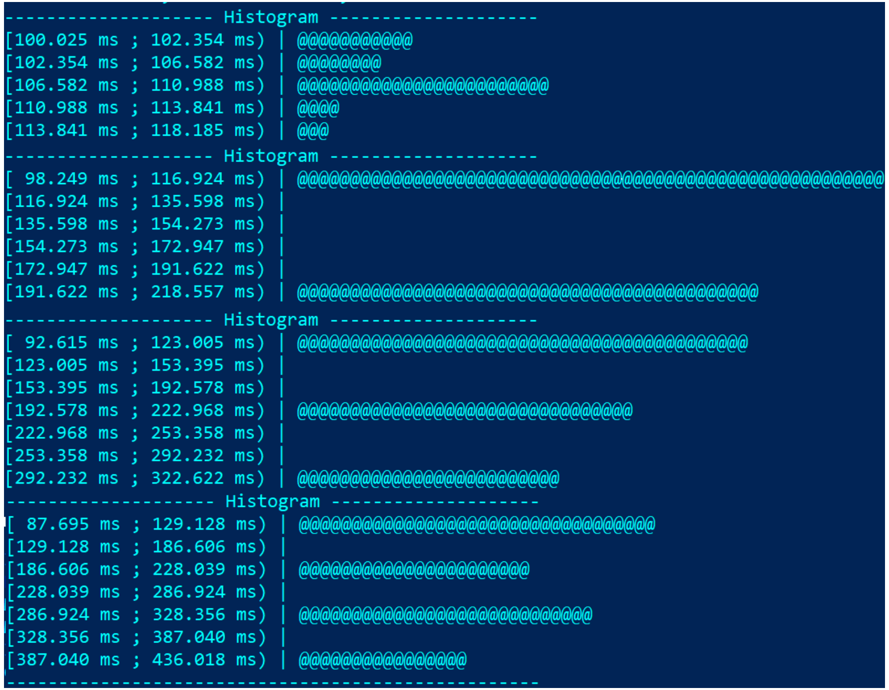
Statistics

- Min, Lower Fence, Q1, Median, Mean, Q3, Upper Fence, Max, Interquartile Range, Outliers
- Standard Error, Variance, Standard Deviation
- Skewness, Kurtosis
- Confidence Interval (Mean, Error, Level, Margin, Lower, Upper)
- Percentiles (P0, P25, P50, P67, P80, P85, P90, P95, P100)

Multimodal distribution

```
[MValueColumn]
[SimpleJob(RunStrategy.Throughput, 1, 0, -1, 1, "MainJob")]
public class IntroMultimodal
{
    private readonly Random rnd = new Random(42);

    private void Multimodal(int n) => Thread.Sleep((rnd.Next(n) + 1) * 100);

    [Benchmark]
    public void Unimodal() => Multimodal(1);

    [Benchmark]
    public void Bimodal() => Multimodal(2);

    [Benchmark]
    public void Trimodal() => Multimodal(3);

    [Benchmark]
    public void Quadrimodal() => Multimodal(4);
}
```

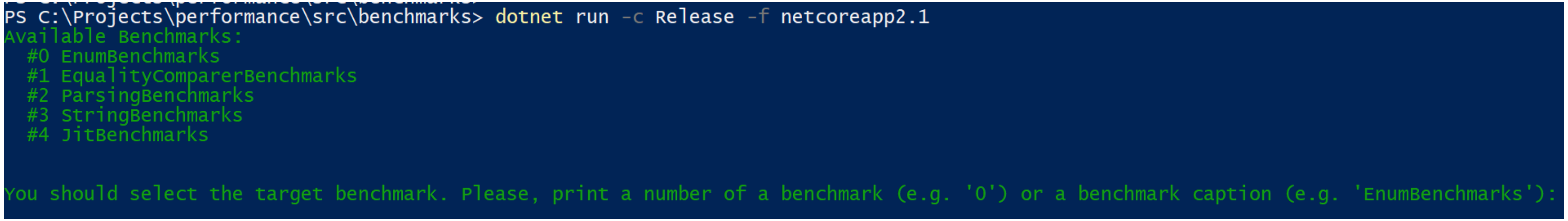
Histogram



```
-------------------- Histogram --------------------
[100.025 ms ; 102.354 ms) | @@@@@@@@@@@
[102.354 ms ; 106.582 ms) | @@@@@@@@
[106.582 ms ; 110.988 ms) | @@@@@@@@@@@@@@@@@@@@@@@@
[110.988 ms ; 113.841 ms) | @@@@
[113.841 ms ; 118.185 ms) | @@@
-------------------- Histogram --------------------
[ 98.249 ms ; 116.924 ms) | @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
[116.924 ms ; 135.598 ms) |
[135.598 ms ; 154.273 ms) |
[154.273 ms ; 172.947 ms) |
[172.947 ms ; 191.622 ms) |
[191.622 ms ; 218.557 ms) | @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
-------------------- Histogram --------------------
[ 92.615 ms ; 123.005 ms) | @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
[123.005 ms ; 153.395 ms) |
[153.395 ms ; 192.578 ms) |
[192.578 ms ; 222.968 ms) | @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
[222.968 ms ; 253.358 ms) |
[253.358 ms ; 292.232 ms) |
[292.232 ms ; 322.622 ms) | @@@@@@@@@@@@@@@@@@@@@@@@@
-------------------- Histogram --------------------
[ 87.695 ms ; 129.128 ms) | @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
[129.128 ms ; 186.606 ms) |
[186.606 ms ; 228.039 ms) | @@@@@@@@@@@@@@@@@@@@@@
[228.039 ms ; 286.924 ms) |
[286.924 ms ; 328.356 ms) | @@@@@@@@@@@@@@@@@@@@@@@@@@@@
[328.356 ms ; 387.040 ms) |
[387.040 ms ; 436.018 ms) | @@@@@@@@@@@@@@@@
---------------------------------------------------
```

BenchmarkSwitcher

```
void Main(string[] args)
    => BenchmarkSwitcher
        .FromAssembly(typeof(Program).Assembly)
        .Run(args);
```

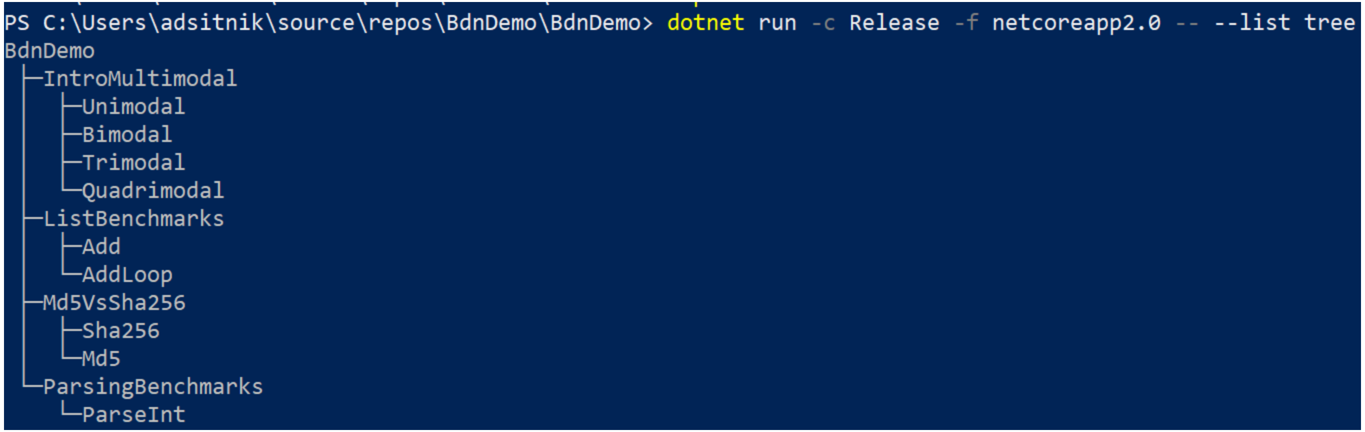


```
PS C:\Projects\performance\src\benchmarks>
PS C:\Projects\performance\src\benchmarks> dotnet run -c Release -f netcoreapp2.1
Available Benchmarks:
  #0 EnumBenchmarks
  #1 EqualityComparerBenchmarks
  #2 ParsingBenchmarks
  #3 StringBenchmarks
  #4 JitBenchmarks


You should select the target benchmark. Please, print a number of a benchmark (e.g. '0') or a benchmark caption (e.g. 'EnumBenchmarks'):
```

Use `--filter` and `--list`!

--list

- --list flat | tree

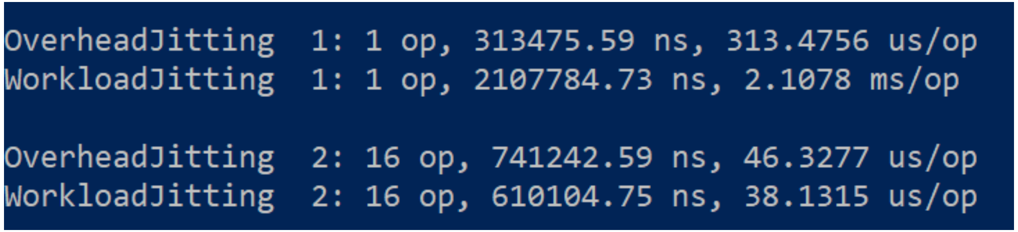


```
PS C:\Users\adsitnik\source\repos\BdnDemo\BdnDemo> dotnet run -c Release -f netcoreapp2.0 -- --list tree
BdnDemo
 ├─IntroMultimodal
 │  ├─Unimodal
 │  ├─Bimodal
 │  ├─Trimodal
 │  └─Quadrimodal
 ├─ListBenchmarks
 │  ├─Add
 │  └─AddLoop
 ├─Md5VsSha256
 │  ├─Sha256
 │  └─Md5
 └─ParsingBenchmarks
    └─ParseInt
```

How does it work?

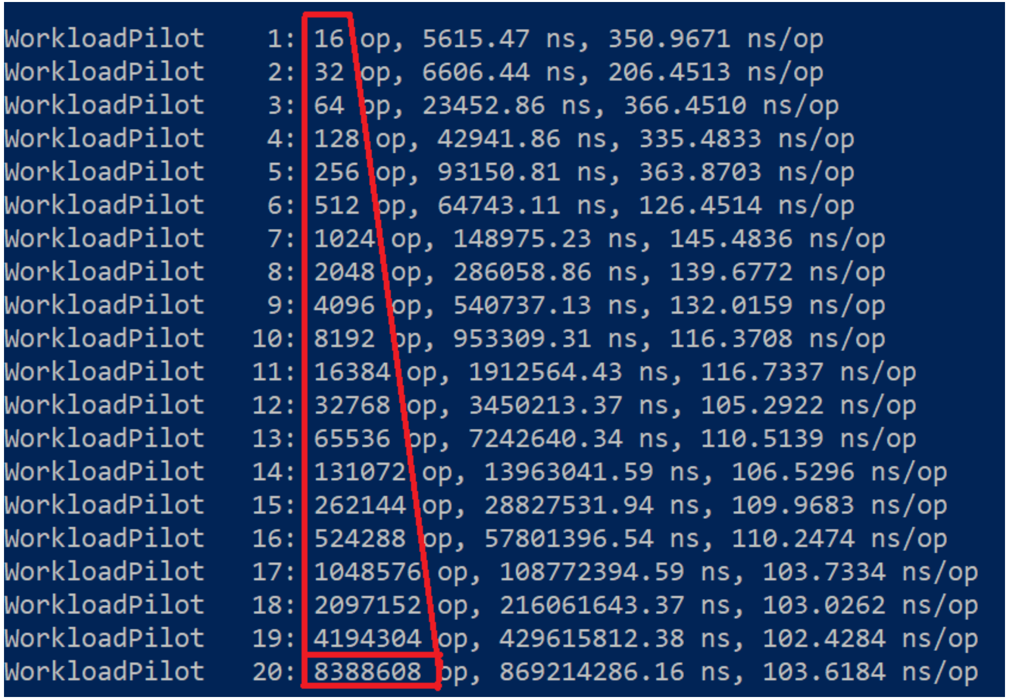
- Auto mode (default):
  - Jitting
  - Pilot
  - Overhead Warmup
  - Overhead Actual
  - Workload Warmup
  - Workload Actual
- Specific (configured):
  - Overhead Warmup
  - Overhead Actual
  - Workload Warmup
  - Workload Actual

Jitting



```
OverheadJitting  1: 1 op, 313475.59 ns, 313.4756 us/op
WorkloadJitting  1: 1 op, 2107784.73 ns, 2.1078 ms/op

OverheadJitting  2: 16 op, 741242.59 ns, 46.3277 us/op
WorkloadJitting  2: 16 op, 610104.75 ns, 38.1315 us/op
```

Pilot stage – perfect invocation count

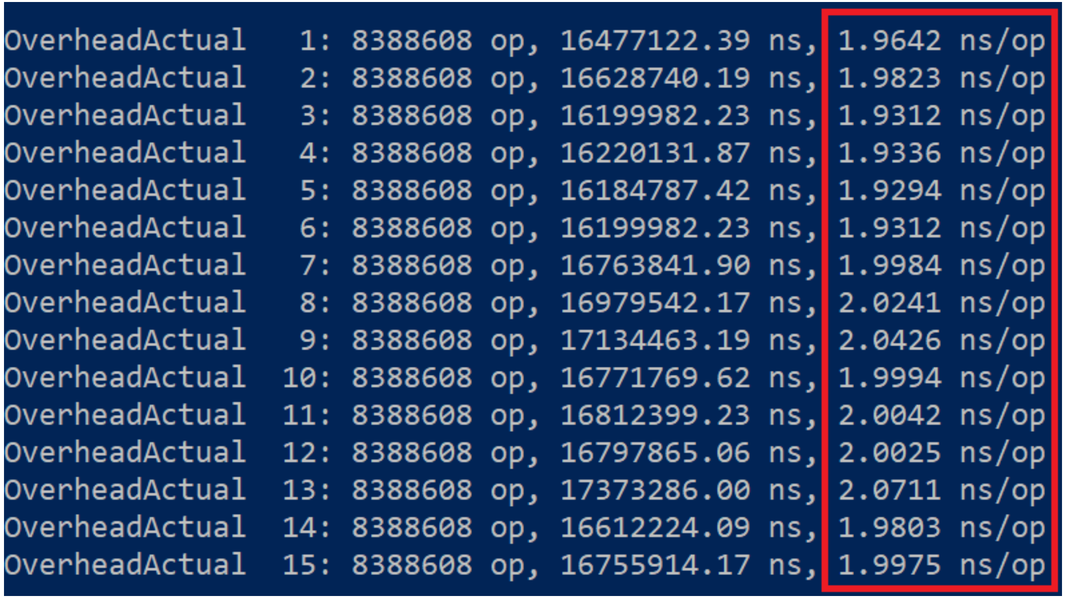


```
WorkloadPilot    1: 16 op, 5615.47 ns, 350.9671 ns/op
WorkloadPilot    2: 32 op, 6606.44 ns, 206.4513 ns/op
WorkloadPilot    3: 64 op, 23452.86 ns, 366.4510 ns/op
WorkloadPilot    4: 128 op, 42941.86 ns, 335.4833 ns/op
WorkloadPilot    5: 256 op, 93150.81 ns, 363.8703 ns/op
WorkloadPilot    6: 512 op, 64743.11 ns, 126.4514 ns/op
WorkloadPilot    7: 1024 op, 148975.23 ns, 145.4836 ns/op
WorkloadPilot    8: 2048 op, 286058.86 ns, 139.6772 ns/op
WorkloadPilot    9: 4096 op, 540737.13 ns, 132.0159 ns/op
WorkloadPilot   10: 8192 op, 953309.31 ns, 116.3708 ns/op
WorkloadPilot   11: 16384 op, 1912564.43 ns, 116.7337 ns/op
WorkloadPilot   12: 32768 op, 3450213.37 ns, 105.2922 ns/op
WorkloadPilot   13: 65536 op, 7242640.34 ns, 110.5139 ns/op
WorkloadPilot   14: 131072 op, 13963041.59 ns, 106.5296 ns/op
WorkloadPilot   15: 262144 op, 28827531.94 ns, 109.9683 ns/op
WorkloadPilot   16: 524288 op, 57801396.54 ns, 110.2474 ns/op
WorkloadPilot   17: 1048576 op, 108772394.59 ns, 103.7334 ns/op
WorkloadPilot   18: 2097152 op, 216061643.37 ns, 103.0262 ns/op
WorkloadPilot   19: 4194304 op, 429615812.38 ns, 102.4284 ns/op
WorkloadPilot   20: 8388608 op, 869214286.16 ns, 103.6184 ns/op
```

Heuristic

```
job.WithInvocationCount(count) or --invocationCount
```

Result = (Result + Overhead) - Overhead

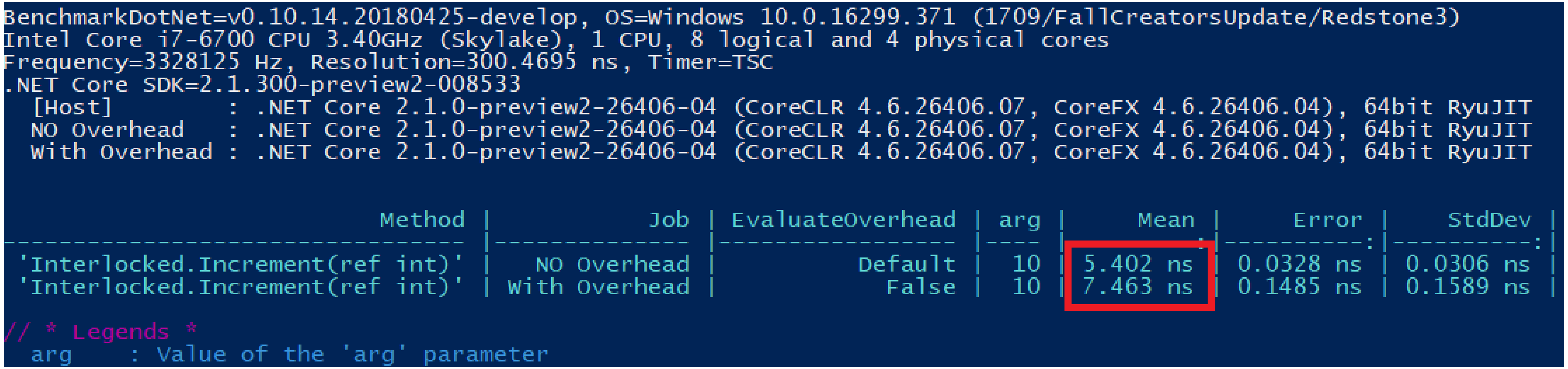


```
OverheadActual   1: 8388608 op, 16477122.39 ns, 1.9642 ns/op
OverheadActual   2: 8388608 op, 16628740.19 ns, 1.9823 ns/op
OverheadActual   3: 8388608 op, 16199982.23 ns, 1.9312 ns/op
OverheadActual   4: 8388608 op, 16220131.87 ns, 1.9336 ns/op
OverheadActual   5: 8388608 op, 16184787.42 ns, 1.9294 ns/op
OverheadActual   6: 8388608 op, 16199982.23 ns, 1.9312 ns/op
OverheadActual   7: 8388608 op, 16763841.90 ns, 1.9984 ns/op
OverheadActual   8: 8388608 op, 16979542.17 ns, 2.0241 ns/op
OverheadActual   9: 8388608 op, 17134463.19 ns, 2.0426 ns/op
OverheadActual  10: 8388608 op, 16771769.62 ns, 1.9994 ns/op
OverheadActual  11: 8388608 op, 16812399.23 ns, 2.0042 ns/op
OverheadActual  12: 8388608 op, 16797865.06 ns, 2.0025 ns/op
OverheadActual  13: 8388608 op, 17373286.00 ns, 2.0711 ns/op
OverheadActual  14: 8388608 op, 16612224.09 ns, 1.9803 ns/op
OverheadActual  15: 8388608 op, 16755914.17 ns, 1.9975 ns/op
```

The Overhead

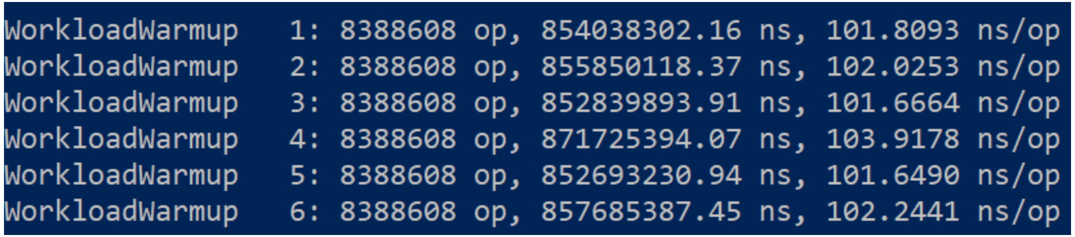
```
[Benchmark(Description = "Interlocked.Increment(ref int)")]
[Arguments(10)]
public int Increment(ref int arg) => Interlocked.Increment(ref arg);

[Benchmark]
[Arguments(10)]
public int Overhead(ref int arg) => 0;

DefaultConfig.Instance
    .With(Job.Default.WithId("NO Overhead"))
    .With(Job.Default.WithEvaluateOverhead(false).WithId("With Overhead"))
```

The difference



```
BenchmarkDotNet=v0.10.14.20180425-develop, OS=Windows 10.0.16299.371 (1709/FallCreatorsUpdate/Redstone3)
Intel Core i7-6700 CPU 3.40GHz (Skylake), 1 CPU, 8 logical and 4 physical cores
Frequency=3328125 Hz, Resolution=300.4695 ns, Timer=TSC
.NET Core SDK=2.1.300-preview2-008533
  [Host]        : .NET Core 2.1.0-preview2-26406-04 (CoreCLR 4.6.26406.07, CoreFX 4.6.26406.04), 64bit RyuJIT
  NO Overhead   : .NET Core 2.1.0-preview2-26406-04 (CoreCLR 4.6.26406.07, CoreFX 4.6.26406.04), 64bit RyuJIT
  With Overhead : .NET Core 2.1.0-preview2-26406-04 (CoreCLR 4.6.26406.07, CoreFX 4.6.26406.04), 64bit RyuJIT


                           Method |           Job | EvaluateOverhead | arg |     Mean |     Error |    StdDev |
--------------------------------- |-------------- |----------------- |---- |---------:|----------:|----------:|
 'Interlocked.Increment(ref int)' |   NO Overhead |          Default |  10 | 5.402 ns | 0.0328 ns | 0.0306 ns |
 'Interlocked.Increment(ref int)' | With Overhead |            False |  10 | 7.463 ns | 0.1485 ns | 0.1589 ns |

// * Legends *
  arg    : Value of the 'arg' parameter
```

Warmup stage

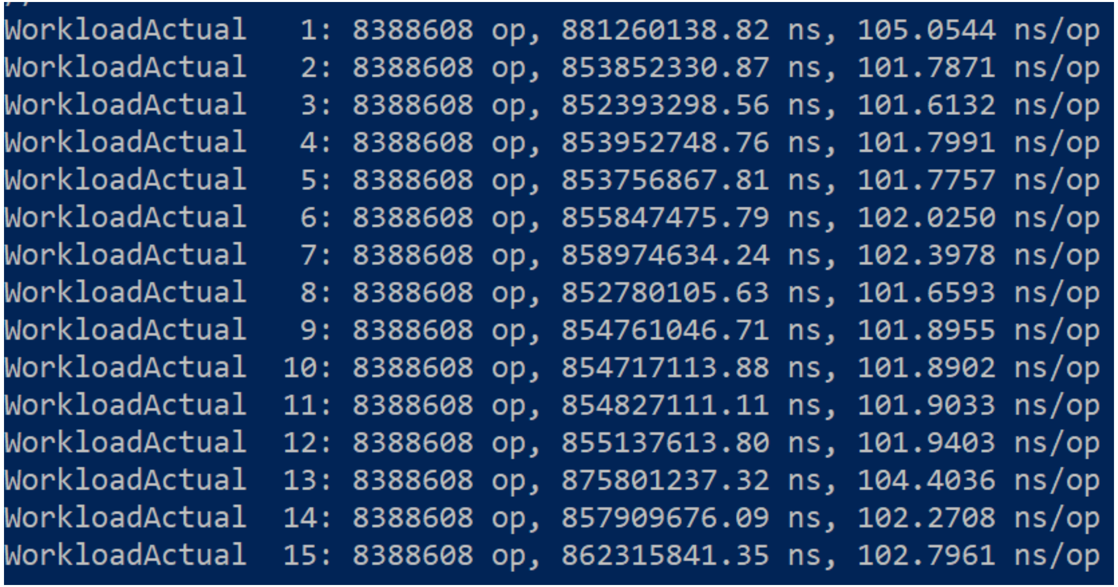


```
WorkloadWarmup   1: 8388608 op, 854038302.16 ns, 101.8093 ns/op
WorkloadWarmup   2: 8388608 op, 855850118.37 ns, 102.0253 ns/op
WorkloadWarmup   3: 8388608 op, 852839893.91 ns, 101.6664 ns/op
WorkloadWarmup   4: 8388608 op, 871725394.07 ns, 103.9178 ns/op
WorkloadWarmup   5: 8388608 op, 852693230.94 ns, 101.6490 ns/op
WorkloadWarmup   6: 8388608 op, 857685387.45 ns, 102.2441 ns/op
```

```
job.WithWarmupCount(count)
or
--warmupCount
--minWarmupCount
--maxWarmupCount
```

Heuristic

Actual Workload

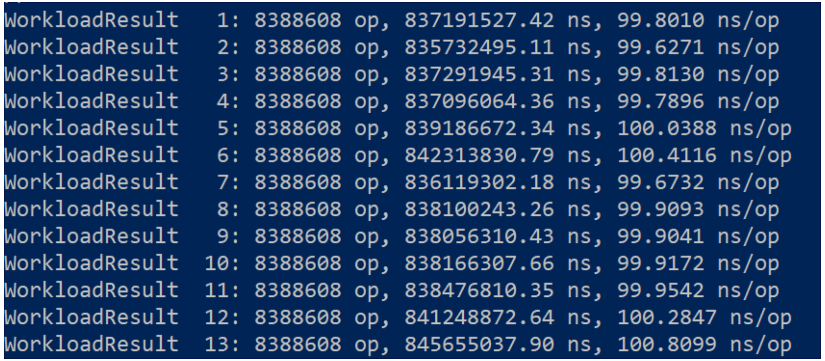


```
WorkloadActual   1: 8388608 op, 881260138.82 ns, 105.0544 ns/op
WorkloadActual   2: 8388608 op, 853852330.87 ns, 101.7871 ns/op
WorkloadActual   3: 8388608 op, 852393298.56 ns, 101.6132 ns/op
WorkloadActual   4: 8388608 op, 853952748.76 ns, 101.7991 ns/op
WorkloadActual   5: 8388608 op, 853756867.81 ns, 101.7757 ns/op
WorkloadActual   6: 8388608 op, 855847475.79 ns, 102.0250 ns/op
WorkloadActual   7: 8388608 op, 858974634.24 ns, 102.3978 ns/op
WorkloadActual   8: 8388608 op, 852780105.63 ns, 101.6593 ns/op
WorkloadActual   9: 8388608 op, 854761046.71 ns, 101.8955 ns/op
WorkloadActual  10: 8388608 op, 854717113.88 ns, 101.8902 ns/op
WorkloadActual  11: 8388608 op, 854827111.11 ns, 101.9033 ns/op
WorkloadActual  12: 8388608 op, 855137613.80 ns, 101.9403 ns/op
WorkloadActual  13: 8388608 op, 875801237.32 ns, 104.4036 ns/op
WorkloadActual  14: 8388608 op, 857909676.09 ns, 102.2708 ns/op
WorkloadActual  15: 8388608 op, 862315841.35 ns, 102.7961 ns/op
```

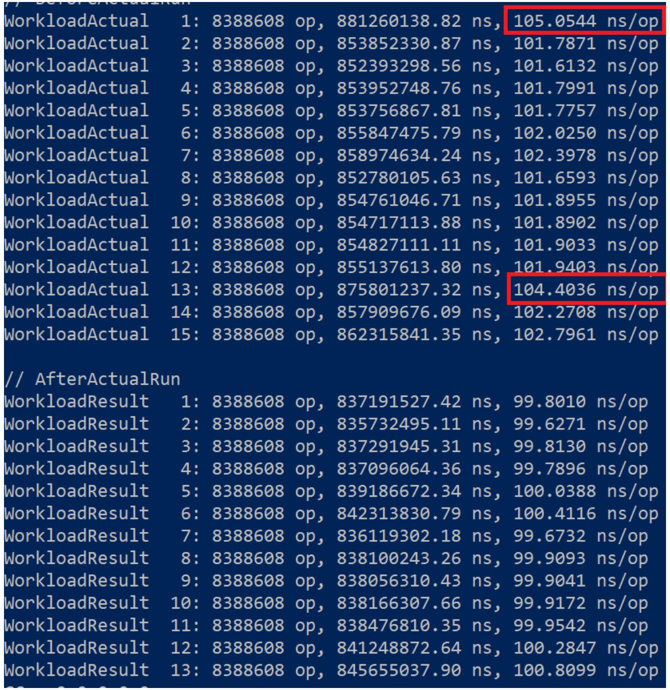
```
job.WithTargetCount(count)
```

Heuristic

Results



```
WorkloadResult   1: 8388608 op, 837191527.42 ns, 99.8010 ns/op
WorkloadResult   2: 8388608 op, 835732495.11 ns, 99.6271 ns/op
WorkloadResult   3: 8388608 op, 837291945.31 ns, 99.8130 ns/op
WorkloadResult   4: 8388608 op, 837096064.36 ns, 99.7896 ns/op
WorkloadResult   5: 8388608 op, 839186672.34 ns, 100.0388 ns/op
WorkloadResult   6: 8388608 op, 842313830.79 ns, 100.4116 ns/op
WorkloadResult   7: 8388608 op, 836119302.18 ns, 99.6732 ns/op
WorkloadResult   8: 8388608 op, 838100243.26 ns, 99.9093 ns/op
WorkloadResult   9: 8388608 op, 838056310.43 ns, 99.9041 ns/op
WorkloadResult  10: 8388608 op, 838166307.66 ns, 99.9172 ns/op
WorkloadResult  11: 8388608 op, 838476810.35 ns, 99.9542 ns/op
WorkloadResult  12: 8388608 op, 841248872.64 ns, 100.2847 ns/op
WorkloadResult  13: 8388608 op, 845655037.90 ns, 100.8099 ns/op
```



```
WorkloadActual   1: 8388608 op, 881260138.82 ns, 105.0544 ns/op
WorkloadActual   2: 8388608 op, 853852330.87 ns, 101.7871 ns/op
WorkloadActual   3: 8388608 op, 852393298.56 ns, 101.6132 ns/op
WorkloadActual   4: 8388608 op, 853952748.76 ns, 101.7991 ns/op
WorkloadActual   5: 8388608 op, 853756867.81 ns, 101.7757 ns/op
WorkloadActual   6: 8388608 op, 855847475.79 ns, 102.0250 ns/op
WorkloadActual   7: 8388608 op, 858974634.24 ns, 102.3978 ns/op
WorkloadActual   8: 8388608 op, 852780105.63 ns, 101.6593 ns/op
WorkloadActual   9: 8388608 op, 854761046.71 ns, 101.8955 ns/op
WorkloadActual  10: 8388608 op, 854717113.88 ns, 101.8902 ns/op
WorkloadActual  11: 8388608 op, 854827111.11 ns, 101.9033 ns/op
WorkloadActual  12: 8388608 op, 855137613.80 ns, 101.9403 ns/op
WorkloadActual  13: 8388608 op, 875801237.32 ns, 104.4036 ns/op
WorkloadActual  14: 8388608 op, 857909676.09 ns, 102.2708 ns/op
WorkloadActual  15: 8388608 op, 862315841.35 ns, 102.7961 ns/op

// AfterActualRun
WorkloadResult   1: 8388608 op, 837191527.42 ns, 99.8010 ns/op
WorkloadResult   2: 8388608 op, 835732495.11 ns, 99.6271 ns/op
WorkloadResult   3: 8388608 op, 837291945.31 ns, 99.8130 ns/op
WorkloadResult   4: 8388608 op, 837096064.36 ns, 99.7896 ns/op
WorkloadResult   5: 8388608 op, 839186672.34 ns, 100.0388 ns/op
WorkloadResult   6: 8388608 op, 842313830.79 ns, 100.4116 ns/op
WorkloadResult   7: 8388608 op, 836119302.18 ns, 99.6732 ns/op
WorkloadResult   8: 8388608 op, 838100243.26 ns, 99.9093 ns/op
WorkloadResult   9: 8388608 op, 838056310.43 ns, 99.9041 ns/op
WorkloadResult  10: 8388608 op, 838166307.66 ns, 99.9172 ns/op
WorkloadResult  11: 8388608 op, 838476810.35 ns, 99.9542 ns/op
WorkloadResult  12: 8388608 op, 841248872.64 ns, 100.2847 ns/op
WorkloadResult  13: 8388608 op, 845655037.90 ns, 100.8099 ns/op
```

```
job.WithRemoveOutliers(false)
or --outliers
```

IsOutlier

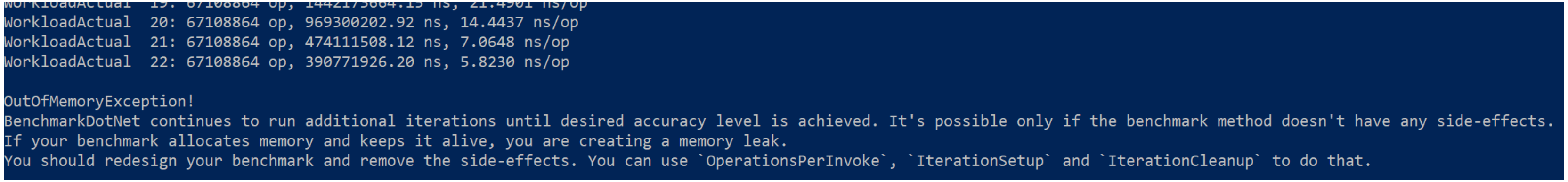
Customizing the heuristic

- job.WithIterationTime(timeInterval)
- job.WithMinIterationTime(timeInterval)
- job.WithMinInvokeCount(int)
- job.WithMaxRelativeError(double)
- job.WithMaxAbsoluteError(timeInterval)

The trap

```
public class ListBenchmarks
{
    private List<int> list = new List<int>();

    [Benchmark]
    public void Add() => list.Add(1234);

    [Benchmark]
    public void AddLoop()
    {
        list.Clear();

        for (int i = 0; i < 1000; i++)
            list.Add(1234);
    }
}
```

OOM



```
WorkloadActual  19: 67108864 op, 1442173684.15 ns, 21.4901 ns/op
WorkloadActual  20: 67108864 op, 969300202.92 ns, 14.4437 ns/op
WorkloadActual  21: 67108864 op, 474111508.12 ns, 7.0648 ns/op
WorkloadActual  22: 67108864 op, 390771926.20 ns, 5.8230 ns/op

OutOfMemoryException!
BenchmarkDotNet continues to run additional iterations until desired accuracy level is achieved. It's possible only if the benchmark method doesn't have any side-effects.
If your benchmark allocates memory and keeps it alive, you are creating a memory leak.
You should redesign your benchmark and remove the side-effects. You can use `OperationsPerInvoke`, `IterationSetup` and `IterationCleanup` to do that.
```

Stages: Summary

- Using statistics to get stable results
- Users don’t need to worry about specifying invocation count
- Results don’t contain overhead
- **It takes time to do all of that**
- User can specify invocation/iteration/warmup/target count
- User can customize the heuristic
- Benchmarks should not have side-effects

Setup & Cleanup

```
public class SetupAndCleanupExample
{
    [GlobalSetup]
    public void GlobalSetup() { }

    [IterationSetup] // sets 1 iteration = 1 invocation
    public void IterationSetup() { }

    [Benchmark]
    public void Benchmark() { }

    [IterationCleanup]
    public void IterationCleanup() { }

    [GlobalCleanup]
    public void GlobalCleanup() { }
}
```

More info

Iteration (pseudo code)

```
public Measurement RunIteration(IterationData data)
{
    IterationSetupAction();
    GcCollect();

    var clock = Clock.Start();
    action(invokeCount / unrollFactor);
    var clockSpan = clock.GetElapsed();

    IterationCleanupAction();
    GcCollect();
 }
```

```
job.WithGcForce(false)
```

Inlining

```
[Benchmark(Baseline = true)]
public void OneWay() { /* one way to solve the problem */ }
[Benchmark]
public void AnotherWay() { /* another way to solve the problem */ }
```

What if one of the methods get inlined?

How to prevent inlining without modifying the code?

```
public delegate Span<byte> TargetDelegate();

private TargetDelegate targetDelegate = BenchmarkedMethod;
```

How to minimize loop overhead?

```
private void MainMultiAction(long invokeCount)
{
    for (long i = 0; i < invokeCount; i++)
        targetDelegate();
}
```

```
private void MainMultiAction(long invokeCount)
{
    for (long i = 0; i < invokeCount / unrollFactor; i++)
    {
        targetDelegate(); targetDelegate(); targetDelegate(); targetDelegate();
        targetDelegate(); targetDelegate(); targetDelegate(); targetDelegate();
        targetDelegate(); targetDelegate(); targetDelegate(); targetDelegate();
        targetDelegate(); targetDelegate(); targetDelegate(); targetDelegate();
    }
}
```

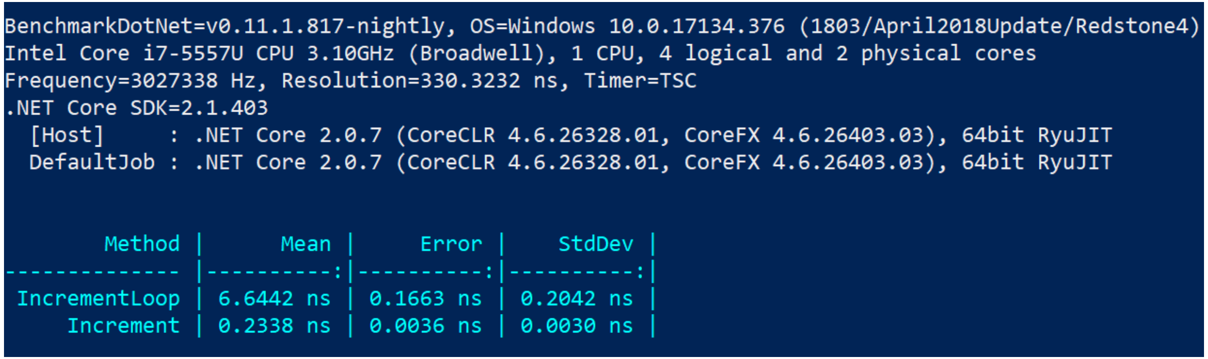
```
job.WithUnrollFactor(count) or --unrollFactor
```

More info

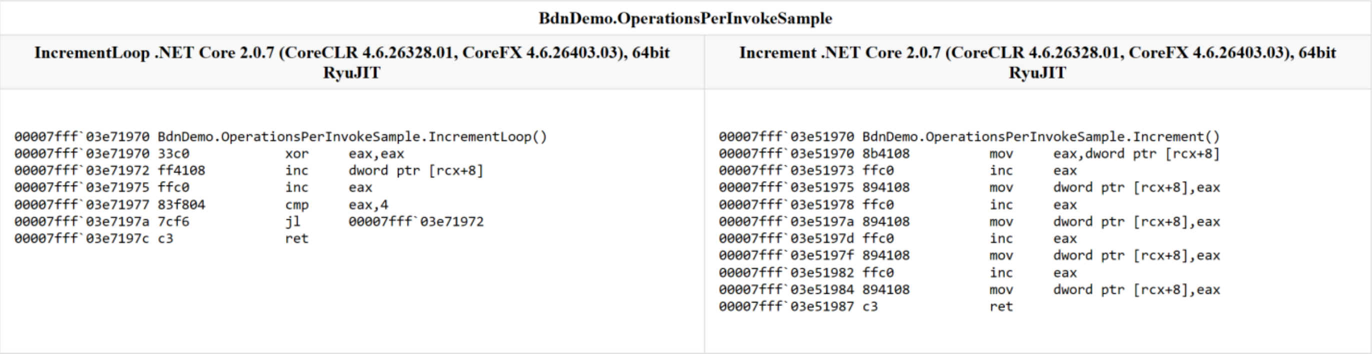
OperationsPerInvoke

```
[DisassemblyDiagnoser]
public class OperationsPerInvokeSample
{
    private int a;

    [Benchmark]
    public void IncrementLoop()
    {
        for (int i = 0; i < 4; i++)
            a++;
    }

    [Benchmark(OperationsPerInvoke = 4)]
    public void Increment()
    {
        a++; a++; a++; a++;
    }
}
```

Loop has an overhead!



```
BenchmarkDotNet=v0.11.1.817-nightly, OS=Windows 10.0.17134.376 (1803/April2018Update/Redstone4)
Intel Core i7-5557U CPU 3.10GHz (Broadwell), 1 CPU, 4 logical and 2 physical cores
Frequency=3027338 Hz, Resolution=330.3232 ns, Timer=TSC
.NET Core SDK=2.1.403
  [Host]     : .NET Core 2.0.7 (CoreCLR 4.6.26328.01, CoreFX 4.6.26403.03), 64bit RyuJIT
  DefaultJob : .NET Core 2.0.7 (CoreCLR 4.6.26328.01, CoreFX 4.6.26403.03), 64bit RyuJIT


        Method |      Mean |     Error |    StdDev |
-------------- |----------:|----------:|----------:|
 IncrementLoop | 6.6442 ns | 0.1663 ns | 0.2042 ns |
     Increment | 0.2338 ns | 0.0036 ns | 0.0030 ns |
```



BdnDemo.OperationsPerInvokeSample

IncrementLoop .NET Core 2.0.7 (CoreCLR 4.6.26328.01, CoreFX 4.6.26403.03), 64bit RyuJIT

```
00007fff`03e71970 BdnDemo.OperationsPerInvokeSample.IncrementLoop()
00007fff`03e71970 33c0            xor     eax,eax
00007fff`03e71972 ff4108          inc     dword ptr [rcx+8]
00007fff`03e71975 ffc0            inc     eax
00007fff`03e71977 83f804          cmp     eax,4
00007fff`03e7197a 7cf6            jl      00007fff`03e71972
00007fff`03e7197c c3              ret
```

Increment .NET Core 2.0.7 (CoreCLR 4.6.26328.01, CoreFX 4.6.26403.03), 64bit RyuJIT

```
00007fff`03e51970 BdnDemo.OperationsPerInvokeSample.Increment()
00007fff`03e51970 8b4108          mov     eax,dword ptr [rcx+8]
00007fff`03e51973 ffc0            inc     eax
00007fff`03e51975 894108          mov     dword ptr [rcx+8],eax
00007fff`03e51978 ffc0            inc     eax
00007fff`03e5197a 894108          mov     dword ptr [rcx+8],eax
00007fff`03e5197d ffc0            inc     eax
00007fff`03e5197f 894108          mov     dword ptr [rcx+8],eax
00007fff`03e51982 ffc0            inc     eax
00007fff`03e51984 894108          mov     dword ptr [rcx+8],eax
00007fff`03e51987 c3              ret
```

How to prevent from Out-of-order execution?

```
private void MainMultiAction(long invokeCount)
{
    for (long i = 0; i < invokeCount / unrollFactor; i++)
    {
        consumer.Consume(targetDelegate()); consumer.Consume(targetDelegate());
        consumer.Consume(targetDelegate()); consumer.Consume(targetDelegate());
        consumer.Consume(targetDelegate()); consumer.Consume(targetDelegate());
        consumer.Consume(targetDelegate()); consumer.Consume(targetDelegate());
        consumer.Consume(targetDelegate()); consumer.Consume(targetDelegate());
        consumer.Consume(targetDelegate()); consumer.Consume(targetDelegate());
        consumer.Consume(targetDelegate()); consumer.Consume(targetDelegate());
        consumer.Consume(targetDelegate()); consumer.Consume(targetDelegate());
    }
}
```

Consumer

```
public class Consumer
{
    private volatile byte byteHolder;
    // (more types skipped for brevity)
    private string stringHolder;
    private object objectHolder;

    [MethodImpl(MethodImplOptions.AggressiveInlining)]
    public void Consume(ulong ulongValue)
       => Volatile.Write(ref ulongHolder, ulongValue);
}
```

Iteration: Summary

- Use Global/Iteration Setup/Cleanup attributes
- Delegates:
  - prevent from inlining
  - Allow ref returning benchmark
  - Allow stackonly types returning benchmarks
- Unroll factor – to minimize the overhead of loop
- Use Volatile.Write to prevent from reordering
- As the end user you just need to return the result

Architecture

- Host Process (console app)
  - Generates
  - Builds (Roslyn/dotnet cli)
  - Executes Child Process
- Child Process (console app)
  - **Executes benchmark**
  - Signals events to Host
  - Reports results to Host

See: IToolchain, IGenerator, IBuilder and IExecutor

Why Process-level Isolation?

- We want to have stable and repeatable results
- Order of executing benchmarks should not affect the results
  - Benchmarks can have side effects
  - GC is self-tuning (generation size can change over time)
  - We need a clean CPU cache
  - CLR can apply some optimizations
- [InProcessToolchain] does **not** spawn new process

Generating new project

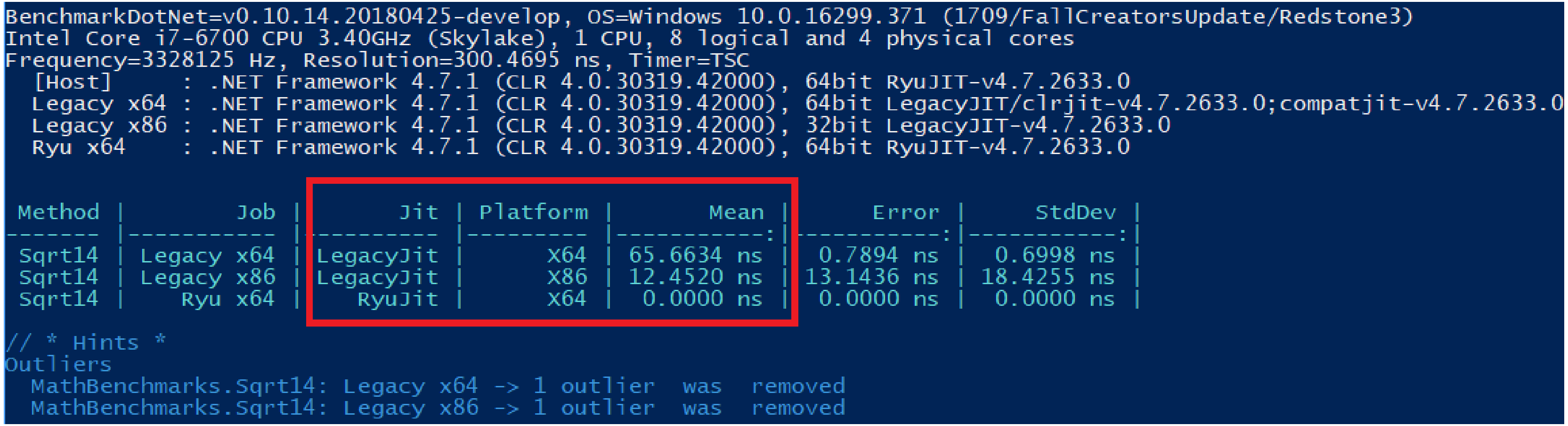
- Benchmark.not**cs** (customized for every benchmark)
- Benchmark.**csproj**
  - Architecture (Job.Env.Platform)
  - Optimizations: ALWAYS on
- Benchmark**.config -** derives from Host.config file, except of:
  - GC Mode (Job.Env.Gc)
  - JIT: Legacy/RyuJIT/LLVm (Job.Env.Jit, *LLVM only for Mono)
  - & more: GCCpuGroup, gcAllowVeryLargeObjects
- Use [KeepBenchmarkFiles] to see what is generated

See: AppConfigGenerator, Generator, EnvMode, GcMode

Run benchmark for all JITs

```
[Config(typeof(JitsConfig))]
public class MathBenchmarks
{
    private class JitsConfig : ManualConfig
    {
        public JitsConfig()
        {
            Add(Job.Default.With(Jit.LegacyJit).With(Platform.X86).WithId("Legacy x86"));
            Add(Job.Default.With(Jit.LegacyJit).With(Platform.X64).WithId("Legacy x64"));
            Add(Job.Default.With(Jit.RyuJit).With(Platform.X64).WithId("Ryu x64"));
        }
    }

    [Benchmark]
    public double Sqrt14()
        => Math.Sqrt(1) + Math.Sqrt(2) + Math.Sqrt(3) + Math.Sqrt(4) +
           Math.Sqrt(5) + Math.Sqrt(6) + Math.Sqrt(7) + Math.Sqrt(8) +
           Math.Sqrt(9) + Math.Sqrt(10) + Math.Sqrt(11) + Math.Sqrt(12) +
           Math.Sqrt(13) + Math.Sqrt(14);
}
```

LegacyJit vs RyuJit



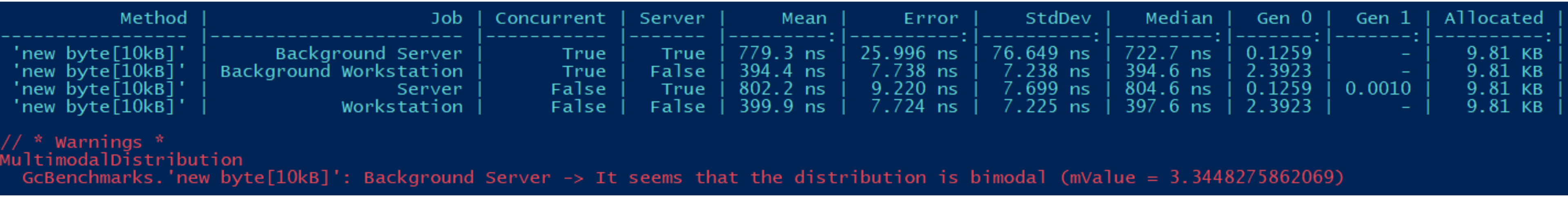
```
BenchmarkDotNet=v0.10.14.20180425-develop, OS=Windows 10.0.16299.371 (1709/FallCreatorsUpdate/Redstone3)
Intel Core i7-6700 CPU 3.40GHz (Skylake), 1 CPU, 8 logical and 4 physical cores
Frequency=3328125 Hz, Resolution=300.4695 ns, Timer=TSC
  [Host]     : .NET Framework 4.7.1 (CLR 4.0.30319.42000), 64bit RyuJIT-v4.7.2633.0
  Legacy x64 : .NET Framework 4.7.1 (CLR 4.0.30319.42000), 64bit LegacyJIT/clrjit-v4.7.2633.0;compatjit-v4.7.2633.0
  Legacy x86 : .NET Framework 4.7.1 (CLR 4.0.30319.42000), 32bit LegacyJIT-v4.7.2633.0
  Ryu x64    : .NET Framework 4.7.1 (CLR 4.0.30319.42000), 64bit RyuJIT-v4.7.2633.0


 Method |        Job |       Jit | Platform |       Mean |      Error |     StdDev |
------- |----------- |---------- |--------- |-----------:|-----------:|-----------:|
 Sqrt14 | Legacy x64 | LegacyJit |      X64 | 65.6634 ns |  0.7894 ns |  0.6998 ns |
 Sqrt14 | Legacy x86 | LegacyJit |      X86 | 12.4520 ns | 13.1436 ns | 18.4255 ns |
 Sqrt14 |    Ryu x64 |    RyuJit |      X64 |  0.0000 ns |  0.0000 ns |  0.0000 ns |

// * Hints *
Outliers
  MathBenchmarks.Sqrt14: Legacy x64 -> 1 outlier  was  removed
  MathBenchmarks.Sqrt14: Legacy x86 -> 1 outlier  was  removed
```

`Why 0ns for RyuJIT?!? Is it a bug?`

Different GC modes

```
[Config(typeof(GcConfig))]
public class GcBenchmarks
{
    private class GcConfig : ManualConfig
    {
        public GcConfig()
        {
            Add(Job.Default.With(new GcMode { Server = true, Concurrent = true }).WithId("Background Server"));
            Add(Job.Default.With(new GcMode { Server = true, Concurrent = false }).WithId("Server"));
            Add(Job.Default.With(new GcMode { Server = false, Concurrent = true }).WithId("Background Workstation"));
            Add(Job.Default.With(new GcMode { Server = false, Concurrent = false }).WithId("Workstation"));

            Add(MemoryDiagnoser.Default);
        }
    }

    [Benchmark(Description = "new byte[10kB]")]
    public byte[] Allocate() => new byte[10000];
}
```

Different GC modes



```
           Method |                  Job | Concurrent | Server |     Mean |     Error |    StdDev |   Median |  Gen 0 |  Gen 1 | Allocated |
----------------- |--------------------- |----------- |------- |---------:|----------:|----------:|---------:|-------:|-------:|----------:|
 'new byte[10kB]' |    Background Server |       True |   True | 779.3 ns | 25.996 ns | 76.649 ns | 722.7 ns | 0.1259 |      - |   9.81 KB |
 'new byte[10kB]' | Background Workstation |     True |  False | 394.4 ns |  7.738 ns |  7.238 ns | 394.6 ns | 2.3923 |      - |   9.81 KB |
 'new byte[10kB]' |               Server |      False |   True | 802.2 ns |  9.220 ns |  7.699 ns | 804.6 ns | 0.1259 | 0.0010 |   9.81 KB |
 'new byte[10kB]' |          Workstation |      False |  False | 399.9 ns |  7.724 ns |  7.225 ns | 397.6 ns | 2.3923 |      - |   9.81 KB |

// * Warnings *
MultimodalDistribution
  GcBenchmarks.'new byte[10kB]': Background Server -> It seems that the distribution is bimodal (mValue = 3.3448275862069)
```

- More settings available:
  - CpuGroups
  - AllowVeryLargeObjects
  - RetainVM
  - NoAffinitize
  - HeapAffinitizeMask
  - HeapCount

Build

- For .NET and Mono we use *Roslyn*
- For .NET Core and CoreRT we use *dotnet cli*
- Build 1 exe per runtime settings (0.11.0)
- Build is done in paralell

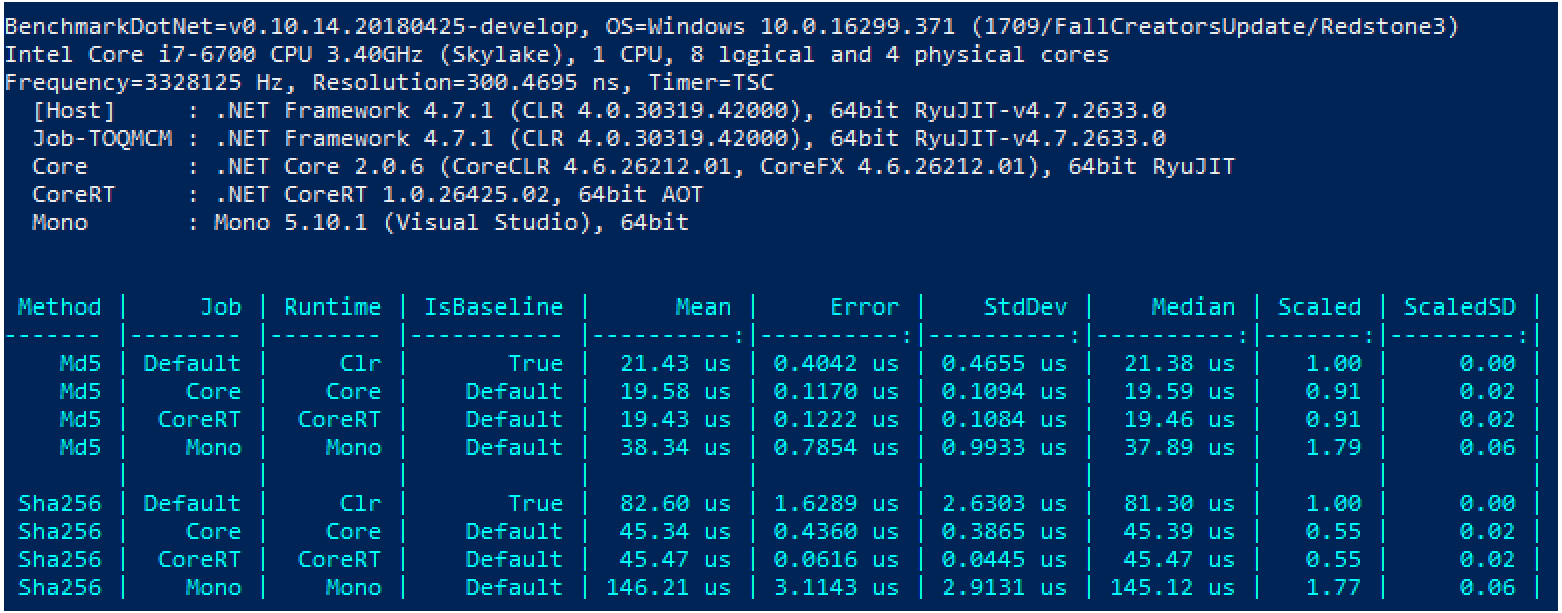
- **Any** target framework: .NET Core vs .NET vs Mono vs CoreRT

See: Builder, CsProjBuilder

Compare frameworks

```
[ClrJob(isBaseline: true), MonoJob, CoreJob, CoreRtJob]
public class Algo_Md5VsSha256
{
    private readonly byte[] data;
    private readonly MD5 md5 = MD5.Create();
    private readonly SHA256 sha256 = SHA256.Create();

    public Algo_Md5VsSha256()
    {
        data = new byte[10000];
        new Random(42).NextBytes(data);
    }

    [Benchmark]
    public byte[] Md5() => md5.ComputeHash(data);

    [Benchmark]
    public byte[] Sha256() => sha256.ComputeHash(data);
}
```

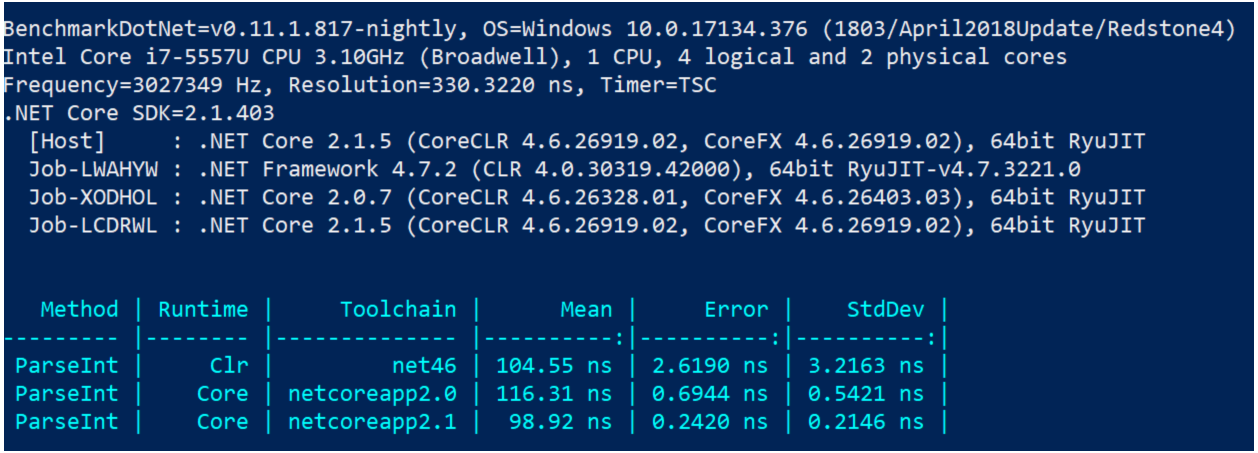
.NET Core vs .NET vs Mono vs CoreRT



```
BenchmarkDotNet=v0.10.14.20180425-develop, OS=Windows 10.0.16299.371 (1709/FallCreatorsUpdate/Redstone3)
Intel Core i7-6700 CPU 3.40GHz (Skylake), 1 CPU, 8 logical and 4 physical cores
Frequency=3328125 Hz, Resolution=300.4695 ns, Timer=TSC
  [Host]     : .NET Framework 4.7.1 (CLR 4.0.30319.42000), 64bit RyuJIT-v4.7.2633.0
  Job-TOQMCM : .NET Framework 4.7.1 (CLR 4.0.30319.42000), 64bit RyuJIT-v4.7.2633.0
  Core       : .NET Core 2.0.6 (CoreCLR 4.6.26212.01, CoreFX 4.6.26212.01), 64bit RyuJIT
  CoreRT     : .NET CoreRT 1.0.26425.02, 64bit AOT
  Mono       : Mono 5.10.1 (Visual Studio), 64bit


 Method |     Job | Runtime | IsBaseline |      Mean |      Error |     StdDev |    Median | Scaled | ScaledSD |
------- |-------- |-------- |----------- |----------:|-----------:|-----------:|----------:|-------:|---------:|
    Md5 | Default |     Clr |       True |  21.43 us | 0.4042 us | 0.4655 us |  21.38 us |   1.00 |     0.00 |
    Md5 |    Core |    Core |    Default |  19.58 us | 0.1170 us | 0.1094 us |  19.59 us |   0.91 |     0.02 |
    Md5 |  CoreRT |  CoreRT |    Default |  19.43 us | 0.1222 us | 0.1084 us |  19.46 us |   0.91 |     0.02 |
    Md5 |    Mono |    Mono |    Default |  38.34 us | 0.7854 us | 0.9933 us |  37.89 us |   1.79 |     0.06 |
        |         |         |            |           |            |            |           |        |          |
 Sha256 | Default |     Clr |       True |  82.60 us | 1.6289 us | 2.6303 us |  81.30 us |   1.00 |     0.00 |
 Sha256 |    Core |    Core |    Default |  45.34 us | 0.4360 us | 0.3865 us |  45.39 us |   0.55 |     0.02 |
 Sha256 |  CoreRT |  CoreRT |    Default |  45.47 us | 0.0616 us | 0.0445 us |  45.47 us |   0.55 |     0.02 |
 Sha256 |    Mono |    Mono |    Default | 146.21 us | 3.1143 us | 2.9131 us | 145.12 us |   1.77 |     0.06 |
```

--runtimes

--runtimes net46 netcoreapp2.0 netcoreapp2.1



```
BenchmarkDotNet=v0.11.1.817-nightly, OS=Windows 10.0.17134.376 (1803/April2018Update/Redstone4)
Intel Core i7-5557U CPU 3.10GHz (Broadwell), 1 CPU, 4 logical and 2 physical cores
Frequency=3027349 Hz, Resolution=330.3220 ns, Timer=TSC
.NET Core SDK=2.1.403
  [Host]     : .NET Core 2.1.5 (CoreCLR 4.6.26919.02, CoreFX 4.6.26919.02), 64bit RyuJIT
  Job-LWAHYW : .NET Framework 4.7.2 (CLR 4.0.30319.42000), 64bit RyuJIT-v4.7.3221.0
  Job-XODHOL : .NET Core 2.0.7 (CoreCLR 4.6.26328.01, CoreFX 4.6.26403.03), 64bit RyuJIT
  Job-LCDRWL : .NET Core 2.1.5 (CoreCLR 4.6.26919.02, CoreFX 4.6.26919.02), 64bit RyuJIT


   Method | Runtime |      Toolchain |       Mean |      Error |     StdDev |
--------- |-------- |--------------- |-----------:|-----------:|-----------:|
 ParseInt |     Clr |          net46 | 104.55 ns | 2.6190 ns | 3.2163 ns |
 ParseInt |    Core | netcoreapp2.0 | 116.31 ns | 0.6944 ns | 0.5421 ns |
 ParseInt |    Core | netcoreapp2.1 |  98.92 ns | 0.2420 ns | 0.2146 ns |
```

Executor

- *Process.Start* for .NET and Mono and CoreRT
- *dotnet $benchmark.dll* for .NET Core
- Communication is done over std in/out (KISS)
- Custom processor affinity can be set (--affinity)
- Benchmarks are run **sequentially, not in parallel**

Architecture: Summary

- Host process generates, builds and runs .exe per benchmark
- It helps us to get repeatable results
- It allows the users to compare different settings:
  - Legacy vs RyuJit
  - GC Workstation vs GC Server
  - .NET vs Mono vs Core vs CoreRT
- It limits us to only known frameworks
- InProcessToolchain runs in process (-i)

Diagnosers

- Plugins that allow to get some extra diagnostic information
- Can attach to the child proces:
  - Before anything else
  - Before Main run
  - After Main run
  - After all
  - Separate logic
- Few types: extra run / no overhead / separate logic

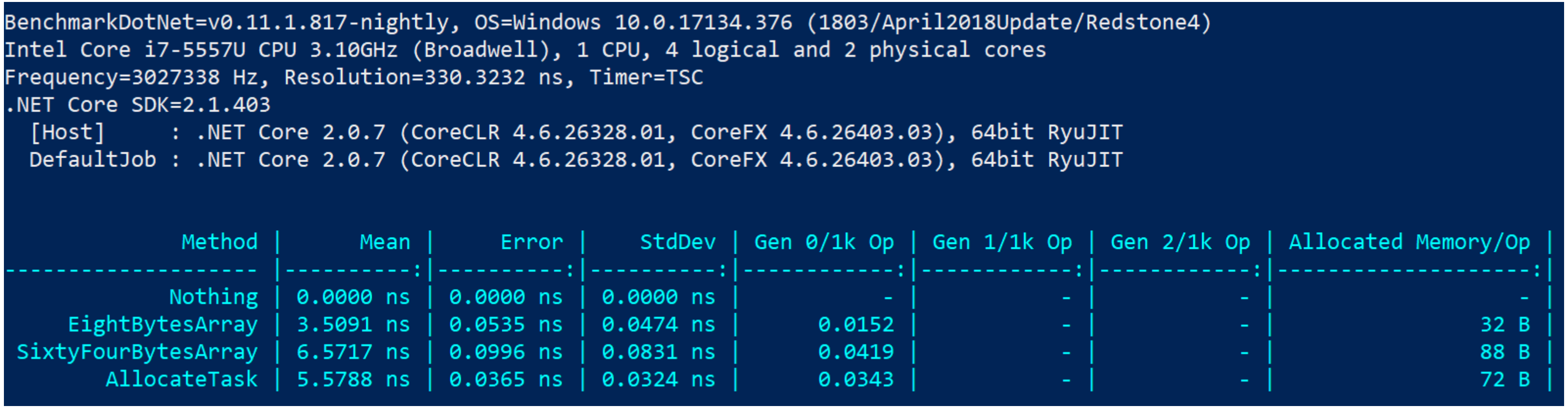
Memory Diagnoser

- Peforms an extra iteration at the end of Target Stage
- Uses available API:
  - `AppDomain.CurrentDomain.MonitoringTotalAllocatedMemorySize`
  - GC.GetAllocatedBytesForCurrentThread()
  - No API for Mono
- Accuracy limited to the APIs and GC allocation quantum

Memory Diagnoser sample

```
[MemoryDiagnoser]
public class AccurateAllocations
{
    [Benchmark] public void Nothing() { }
    [Benchmark] public byte[] EightBytesArray() => new byte[8];
    [Benchmark] public byte[] SixtyFourBytesArray() => new byte[64];

    [Benchmark] public Task<int> AllocateTask()
                     => Task.FromResult(default(int));
}
```

Memory Diagnoser results



```
BenchmarkDotNet=v0.11.1.817-nightly, OS=Windows 10.0.17134.376 (1803/April2018Update/Redstone4)
Intel Core i7-5557U CPU 3.10GHz (Broadwell), 1 CPU, 4 logical and 2 physical cores
Frequency=3027338 Hz, Resolution=330.3232 ns, Timer=TSC
.NET Core SDK=2.1.403
  [Host]     : .NET Core 2.0.7 (CoreCLR 4.6.26328.01, CoreFX 4.6.26403.03), 64bit RyuJIT
  DefaultJob : .NET Core 2.0.7 (CoreCLR 4.6.26328.01, CoreFX 4.6.26403.03), 64bit RyuJIT


              Method |      Mean |     Error |    StdDev | Gen 0/1k Op | Gen 1/1k Op | Gen 2/1k Op | Allocated Memory/Op |
-------------------- |----------:|----------:|----------:|------------:|------------:|------------:|--------------------:|
             Nothing | 0.0000 ns | 0.0000 ns | 0.0000 ns |           - |           - |           - |                   - |
     EightBytesArray | 3.5091 ns | 0.0535 ns | 0.0474 ns |      0.0152 |           - |           - |                32 B |
 SixtyFourBytesArray | 6.5717 ns | 0.0996 ns | 0.0831 ns |      0.0419 |           - |           - |                88 B |
        AllocateTask | 5.5788 ns | 0.0365 ns | 0.0324 ns |      0.0343 |           - |           - |                72 B |
```

Hardware Performance Counters

- Performs an extra run
- Uses TraceEvent, which uses ETW to get the PMCs
- Requires to run as Admin, no virtualization support
- Windows only

Hardware Counters Sample

```
[HardwareCounters(HardwareCounter.BranchMispredi
ctions, HardwareCounter.BranchInstructions)]
public class Cpu_BranchPerdictor
{
    private static int Branch(int[] data)
    {
        int sum = 0;
        for (int i = 0; i < N; i++)
            if (data[i] >= 128)
                sum += data[i];
        return sum;
    }

    private static int Branchless(int[] data)
    {
        int sum = 0;
        for (int i = 0; i < N; i++)
        {
            int t = (data[i] - 128) >> 31;
            sum += ~t & data[i];
        }
        return sum;
    }
```

```
[Benchmark]
public int SortedBranch()
        => Branch(sorted);

[Benchmark]
public int UnsortedBranch()
        => Branch(unsorted);

[Benchmark]
public int SortedBranchless()
        => Branchless(sorted);

[Benchmark]
public int UnsortedBranchless()
        => Branchless(unsorted);
```

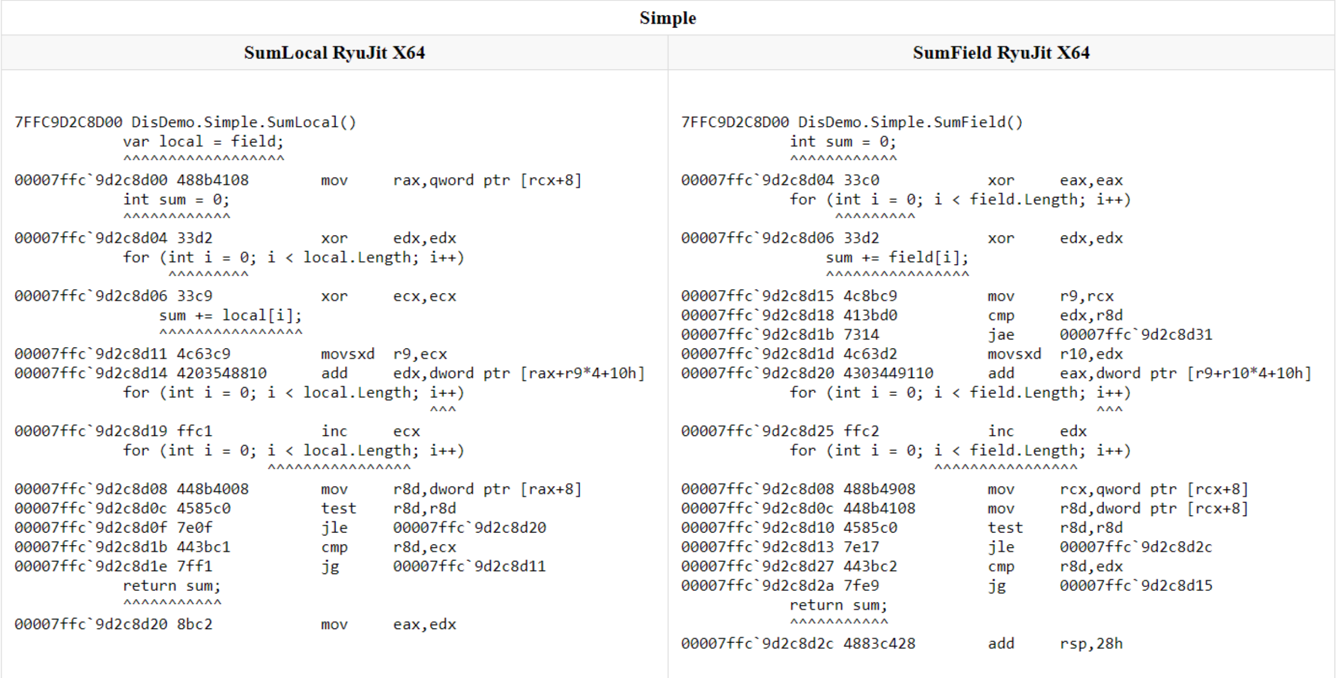
Harware Counters Result

Method	Mean	Mispredict rate	BranchInstructions /Op	BranchMispredictions /Op
SortedBranch	21.4539 us	0,04%	70121	24
UnsortedBranch	136.1139 us	**23,70%**	68788	16301
SortedBranchless	28.6705 us	0,06%	35711	22
UnsortedBranchless	28.9336 us	0,05%	35578	17

Disassembly Diagnoser

- Attaches at the end (no extra run)
- Uses ClrMD to get the ASM, Mono.Cecil for IL
- 32 and 64 bit exe embeded in the resources
- Supports:
    - desktop .NET: LegacyJit (32 & 64 bit), RyuJIT (64 bit)
    - .NET Core 2.0+ for RyuJIT (64 & 32 bit)
    - Mono: 32 & 64 bit, **including LLVM**
    - Does not work for CoreRT **(yet)**

Disassembly Diagnoser: Sample



Simple

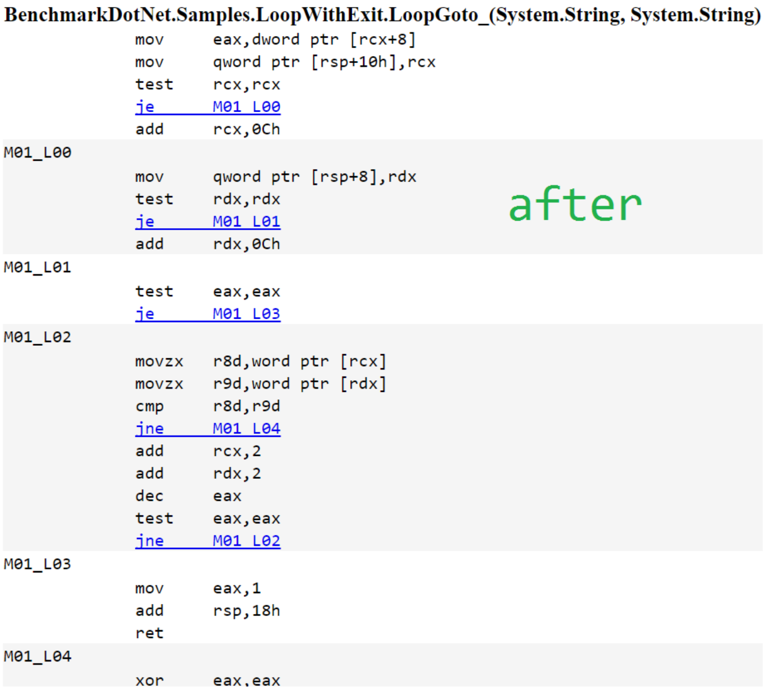
SumLocal RyuJit X64

```
7FFC9D2C8D00 DisDemo.Simple.SumLocal()
            var local = field;
            ^^^^^^^^^^^^^^^^^^
00007ffc`9d2c8d00 488b4108        mov     rax,qword ptr [rcx+8]
            int sum = 0;
            ^^^^^^^^^^^^
00007ffc`9d2c8d04 33d2            xor     edx,edx
            for (int i = 0; i < local.Length; i++)
                 ^^^^^^^^^
00007ffc`9d2c8d06 33c9            xor     ecx,ecx
                sum += local[i];
                ^^^^^^^^^^^^^^^^
00007ffc`9d2c8d11 4c63c9          movsxd  r9,ecx
00007ffc`9d2c8d14 4203548810      add     edx,dword ptr [rax+r9*4+10h]
            for (int i = 0; i < local.Length; i++)
                                              ^^^
00007ffc`9d2c8d19 ffc1            inc     ecx
            for (int i = 0; i < local.Length; i++)
                            ^^^^^^^^^^^^^^^^
00007ffc`9d2c8d08 448b4008        mov     r8d,dword ptr [rax+8]
00007ffc`9d2c8d0c 4585c0          test    r8d,r8d
00007ffc`9d2c8d0f 7e0f            jle     00007ffc`9d2c8d20
00007ffc`9d2c8d1b 443bc1          cmp     r8d,ecx
00007ffc`9d2c8d1e 7ff1            jg      00007ffc`9d2c8d11
            return sum;
            ^^^^^^^^^^^
00007ffc`9d2c8d20 8bc2            mov     eax,edx
```

SumField RyuJit X64

```
7FFC9D2C8D00 DisDemo.Simple.SumField()
            int sum = 0;
            ^^^^^^^^^^^^
00007ffc`9d2c8d04 33c0            xor     eax,eax
            for (int i = 0; i < field.Length; i++)
                 ^^^^^^^^^
00007ffc`9d2c8d06 33d2            xor     edx,edx
                sum += field[i];
                ^^^^^^^^^^^^^^^^
00007ffc`9d2c8d15 4c8bc9          mov     r9,rcx
00007ffc`9d2c8d18 413bd0          cmp     edx,r8d
00007ffc`9d2c8d1b 7314            jae     00007ffc`9d2c8d31
00007ffc`9d2c8d1d 4c63d2          movsxd  r10,edx
00007ffc`9d2c8d20 4303449110      add     eax,dword ptr [r9+r10*4+10h]
            for (int i = 0; i < field.Length; i++)
                                              ^^^
00007ffc`9d2c8d25 ffc2            inc     edx
            for (int i = 0; i < field.Length; i++)
                            ^^^^^^^^^^^^^^^^
00007ffc`9d2c8d08 488b4908        mov     rcx,qword ptr [rcx+8]
00007ffc`9d2c8d0c 448b4108        mov     r8d,dword ptr [rcx+8]
00007ffc`9d2c8d10 4585c0          test    r8d,r8d
00007ffc`9d2c8d13 7e17            jle     00007ffc`9d2c8d2c
00007ffc`9d2c8d27 443bc2          cmp     r8d,edx
00007ffc`9d2c8d2a 7fe9            jg      00007ffc`9d2c8d15
            return sum;
            ^^^^^^^^^^^
00007ffc`9d2c8d2c 4883c428        add     rsp,28h
```

Sample HTML raport

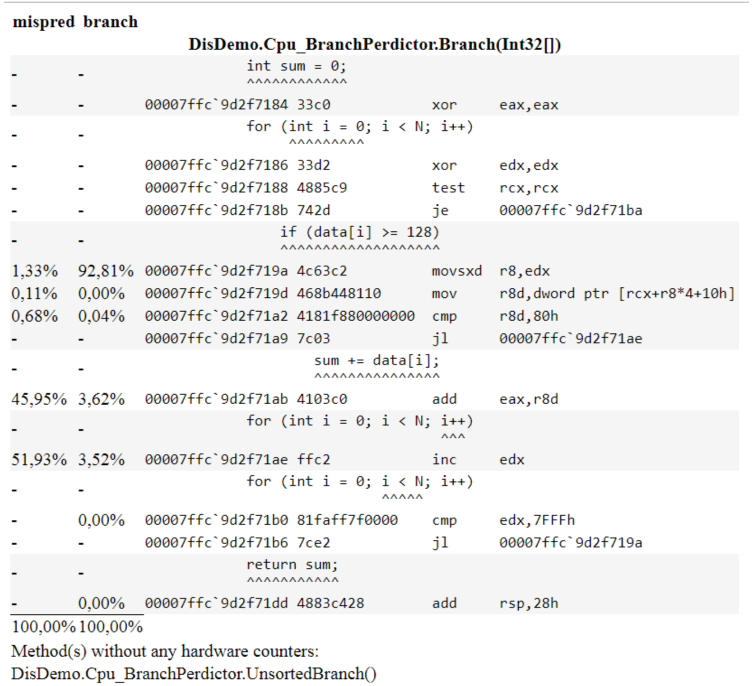


BenchmarkDotNet.Samples.LoopWithExit.LoopGoto_(System.String, System.String)

```
              mov      eax,dword ptr [rcx+8]
              mov      qword ptr [rsp+10h],rcx
              test     rcx,rcx
              je       M01_L00
              add      rcx,0Ch
M01_L00
              mov      qword ptr [rsp+8],rdx
              test     rdx,rdx
              je       M01_L01
              add      rdx,0Ch
M01_L01
              test     eax,eax
              je       M01_L03
M01_L02
              movzx    r8d,word ptr [rcx]
              movzx    r9d,word ptr [rdx]
              cmp      r8d,r9d
              jne      M01_L04
              add      rcx,2
              add      rdx,2
              dec      eax
              test     eax,eax
              jne      M01_L02
M01_L03
              mov      eax,1
              add      rsp,18h
              ret
M01_L04
              xor      eax,eax
```

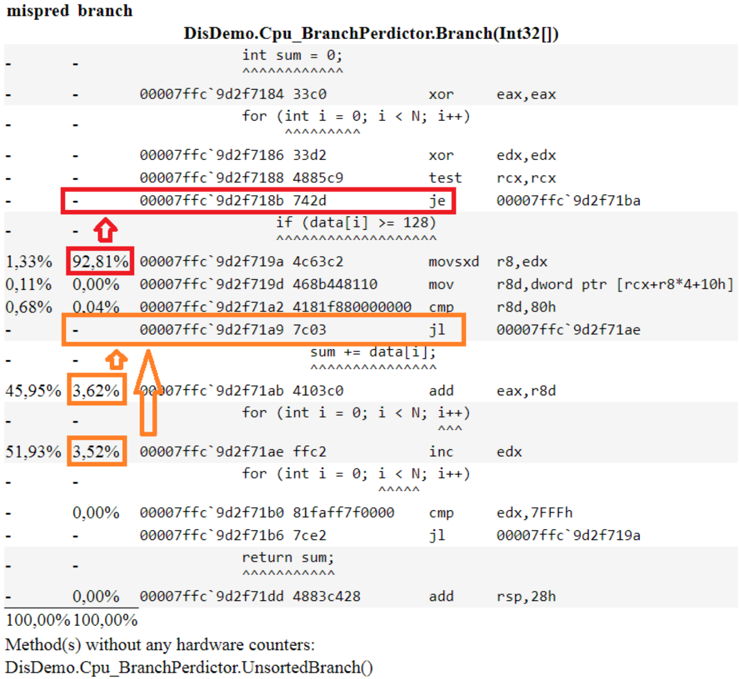
after

PMC + ASM



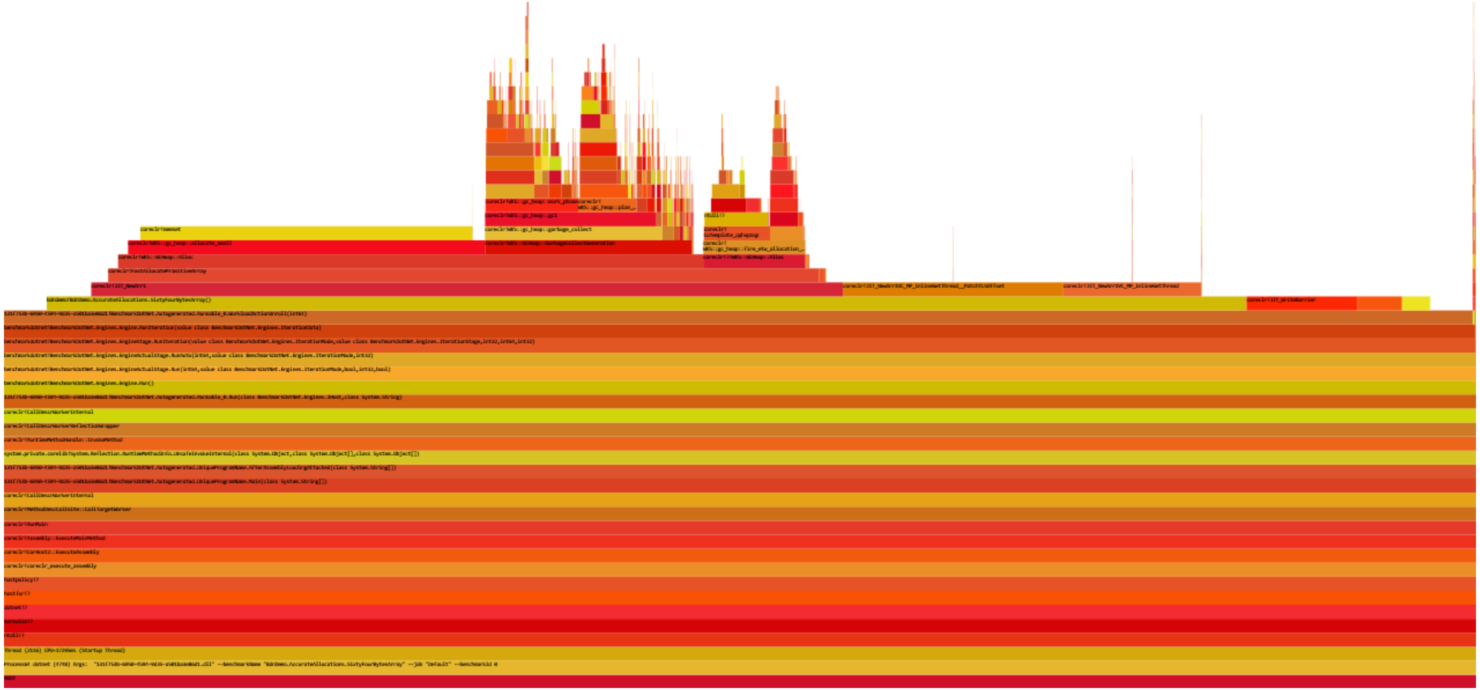
```
mispred  branch
                       DisDemo.Cpu_BranchPerdictor.Branch(Int32[])
-        -                          int sum = 0;
                                    ^^^^^^^^^^^^
-        -        00007ffc`9d2f7184 33c0            xor     eax,eax
-        -                          for (int i = 0; i < N; i++)
                                         ^^^^^^^^^
-        -        00007ffc`9d2f7186 33d2            xor     edx,edx
-        -        00007ffc`9d2f7188 4885c9          test    rcx,rcx
-        -        00007ffc`9d2f718b 742d            je      00007ffc`9d2f71ba
-        -                              if (data[i] >= 128)
                                        ^^^^^^^^^^^^^^^^^^^
1,33%    92,81%   00007ffc`9d2f719a 4c63c2          movsxd  r8,edx
0,11%    0,00%    00007ffc`9d2f719d 468b448110      mov     r8d,dword ptr [rcx+r8*4+10h]
0,68%    0,04%    00007ffc`9d2f71a2 4181f880000000  cmp     r8d,80h
-        -        00007ffc`9d2f71a9 7c03            jl      00007ffc`9d2f71ae
-        -                                  sum += data[i];
                                            ^^^^^^^^^^^^^^^
45,95%   3,62%    00007ffc`9d2f71ab 4103c0          add     eax,r8d
-        -                          for (int i = 0; i < N; i++)
                                                           ^^^
51,93%   3,52%    00007ffc`9d2f71ae ffc2            inc     edx
-        -                          for (int i = 0; i < N; i++)
                                                    ^^^^^
-        0,00%    00007ffc`9d2f71b0 81faff7f0000    cmp     edx,7FFFh
-        -        00007ffc`9d2f71b6 7ce2            jl      00007ffc`9d2f719a
-        -                          return sum;
                                    ^^^^^^^^^^^
-        0,00%    00007ffc`9d2f71dd 4883c428        add     rsp,28h
100,00%  100,00%
Method(s) without any hardware counters:
DisDemo.Cpu_BranchPerdictor.UnsortedBranch()
```

PMC + ASM = skids ;(



```
mispred  branch
                            DisDemo.Cpu_BranchPerdictor.Branch(Int32[])
                                  int sum = 0;
-        -                        ^^^^^^^^^^^^
-        -        00007ffc`9d2f7184 33c0            xor     eax,eax
                                  for (int i = 0; i < N; i++)
-        -                             ^^^^^^^^^^
-        -        00007ffc`9d2f7186 33d2            xor     edx,edx
-        -        00007ffc`9d2f7188 4885c9          test    rcx,rcx
-        -        00007ffc`9d2f718b 742d            je      00007ffc`9d2f71ba
                                      if (data[i] >= 128)
-        -                            ^^^^^^^^^^^^^^^^^^^
1,33%    92,81%   00007ffc`9d2f719a 4c63c2          movsxd  r8,edx
0,11%    0,00%    00007ffc`9d2f719d 468b448110      mov     r8d,dword ptr [rcx+r8*4+10h]
0,68%    0,04%    00007ffc`9d2f71a2 4181f880000000  cmp     r8d,80h
-        -        00007ffc`9d2f71a9 7c03            jl      00007ffc`9d2f71ae
                                          sum += data[i];
-        -                                ^^^^^^^^^^^^^^^
45,95%   3,62%    00007ffc`9d2f71ab 4103c0          add     eax,r8d
                                  for (int i = 0; i < N; i++)
-        -                                               ^^^
51,93%   3,52%    00007ffc`9d2f71ae ffc2            inc     edx
                                  for (int i = 0; i < N; i++)
-        -                                        ^^^^^
-        0,00%    00007ffc`9d2f71b0 81faff7f0000    cmp     edx,7FFFh
-        -        00007ffc`9d2f71b6 7ce2            jl      00007ffc`9d2f719a
                                  return sum;
-        -                        ^^^^^^^^^^^
-        0,00%    00007ffc`9d2f71dd 4883c428        add     rsp,28h
100,00% 100,00%
Method(s) without any hardware counters:
DisDemo.Cpu_BranchPerdictor.UnsortedBranch()
```

ETW Profiler



Diagnosers: Summary

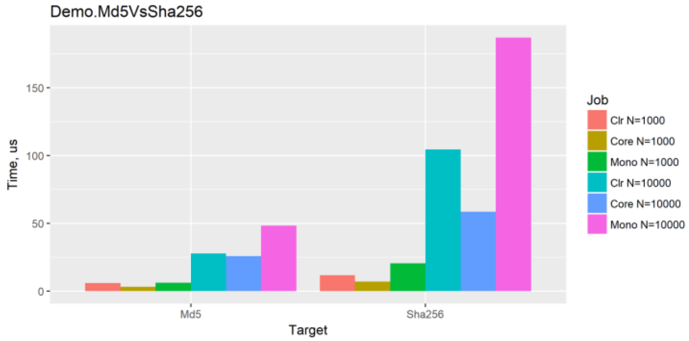
- MemoryDiagnoser - accurate total size of allocated memory
- DisassemblyDiagnoser - get ASM, IL and C# for any .NET
- PmcDiagnoser – Hardware Counters on Windows
- We can combine PMC & ASM
- EtwProfiler – to profile the benchmarked code
- InliningDiagnoser uses ETW to get info about inlining
- TailCallDiagnoser uses ETW to get info about Tail Call opt
- Architecture allows for more (like integration with profilers)

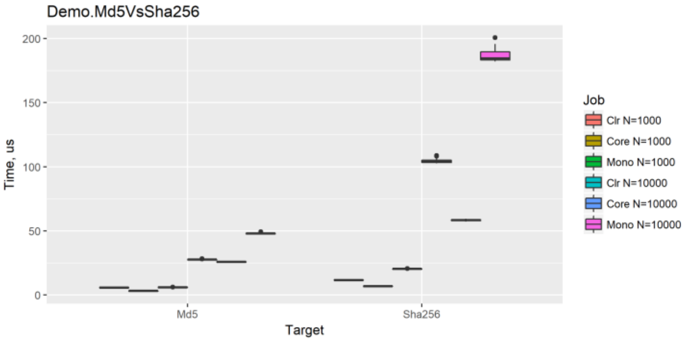
Exporters

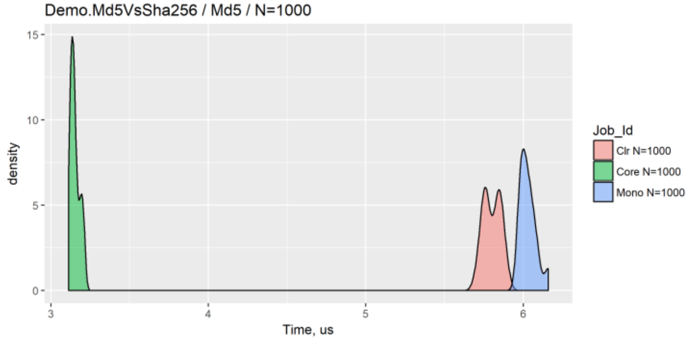
- HTML
- Markdown: GitHub, StackOverflow
- CSV
- RPlot (requires R)
- XML
- JSON

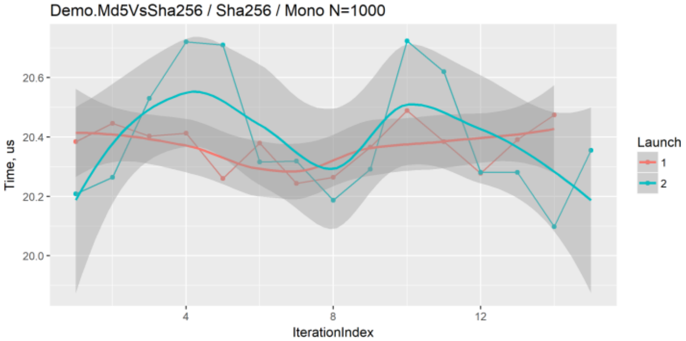
```
[AsciiDocExporter]
[CsvExporter]
[CsvMeasurementsExporter]
[HtmlExporter]
[PlainExporter]
[RPlotExporter]
[JsonExporterAttribute.Brief]
[JsonExporterAttribute.BriefCompressed]
[JsonExporterAttribute.Full]
[JsonExporterAttribute.FullCompressed]
[MarkdownExporterAttribute.Default]
[MarkdownExporterAttribute.GitHub]
[MarkdownExporterAttribute.StackOverflow]
[MarkdownExporterAttribute.Atlassian]
[XmlExporterAttribute.Brief]
[XmlExporterAttribute.BriefCompressed]
[XmlExporterAttribute.Full]
[XmlExporterAttribute.FullCompressed]
public class IntroExporters
```

RPlot Sample



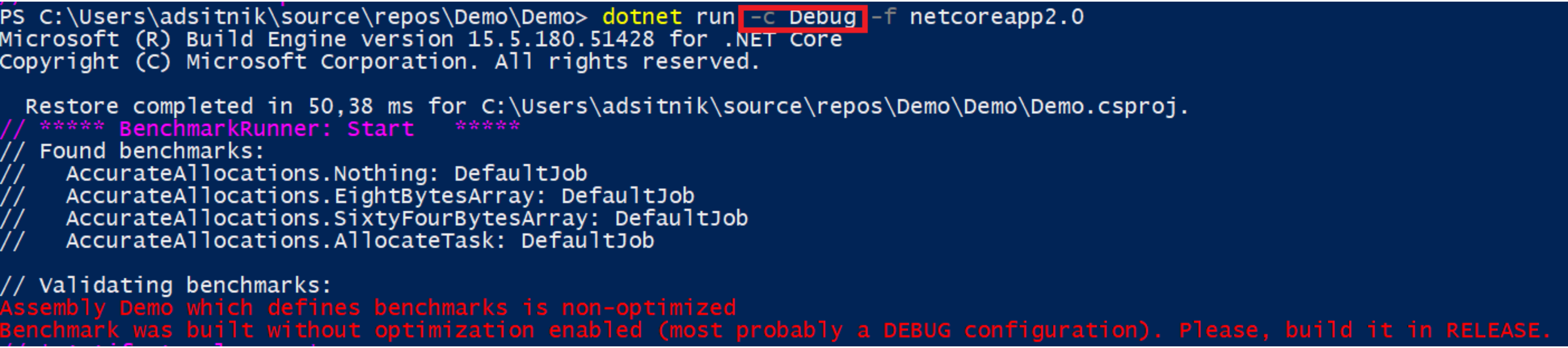






Validators

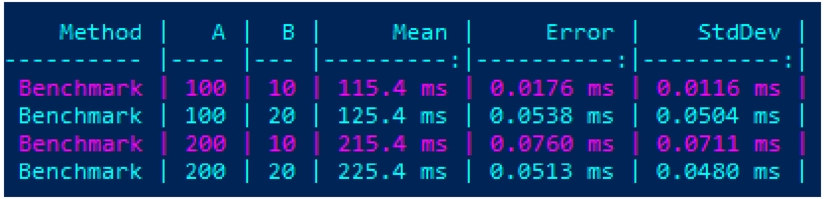
- Prevent the users from doing stupid things



```
PS C:\Users\adsitnik\source\repos\Demo\Demo> dotnet run -c Debug -f netcoreapp2.0
Microsoft (R) Build Engine version 15.5.180.51428 for .NET Core
Copyright (C) Microsoft Corporation. All rights reserved.

  Restore completed in 50,38 ms for C:\Users\adsitnik\source\repos\Demo\Demo\Demo.csproj.
// ***** BenchmarkRunner: Start   *****
// Found benchmarks:
//   AccurateAllocations.Nothing: DefaultJob
//   AccurateAllocations.EightBytesArray: DefaultJob
//   AccurateAllocations.SixtyFourBytesArray: DefaultJob
//   AccurateAllocations.AllocateTask: DefaultJob

// Validating benchmarks:
Assembly Demo which defines benchmarks is non-optimized
Benchmark was built without optimization enabled (most probably a DEBUG configuration). Please, build it in RELEASE.
```

Params

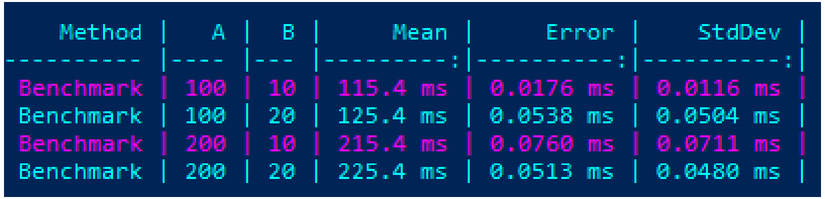
```
public class IntroParams
{
    [Params(100, 200)]
    public int A { get; set; }

    [Params(10, 20)]
    public int B { get; set; }

    [Benchmark]
    public void Benchmark()
        => Thread.Sleep(A + B + 5);
}
```



```
    Method |   A |  B |      Mean |      Error |     StdDev |
---------- |---- |--- |----------:|-----------:|-----------:|
 Benchmark | 100 | 10 |  115.4 ms |  0.0176 ms |  0.0116 ms |
 Benchmark | 100 | 20 |  125.4 ms |  0.0538 ms |  0.0504 ms |
 Benchmark | 200 | 10 |  215.4 ms |  0.0760 ms |  0.0711 ms |
 Benchmark | 200 | 20 |  225.4 ms |  0.0513 ms |  0.0480 ms |
```

ParamsSource

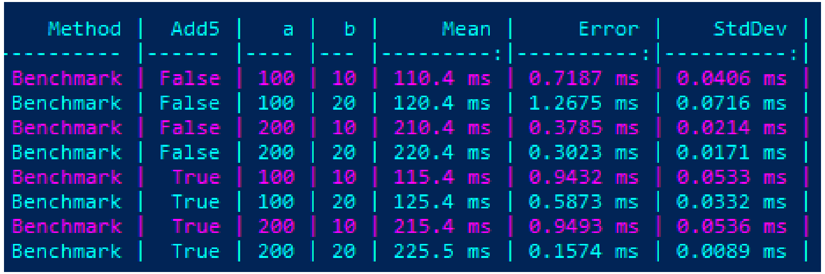
```
public class IntroParamsSource
{
    [ParamsSource(nameof(ValuesForA))]
    public int A { get; set; }

    [ParamsSource(nameof(ValuesForB))]
    public int B;

    public IEnumerable<int> ValuesForA
        => new[] { 100, 200 };

    public static IEnumerable<int> ValuesForB()
        => new[] { 10, 20 };

    [Benchmark]
    public void Benchmark()
        => Thread.Sleep(A + B + 5);
}
```



```
    Method |   A |  B |      Mean |      Error |     StdDev |
---------- |---- |--- |----------:|-----------:|-----------:|
 Benchmark | 100 | 10 |  115.4 ms |  0.0176 ms |  0.0116 ms |
 Benchmark | 100 | 20 |  125.4 ms |  0.0538 ms |  0.0504 ms |
 Benchmark | 200 | 10 |  215.4 ms |  0.0760 ms |  0.0711 ms |
 Benchmark | 200 | 20 |  225.4 ms |  0.0513 ms |  0.0480 ms |
```

Arguments

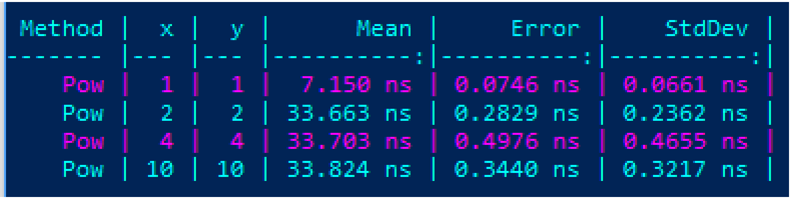
```
public class IntroArguments
{
    [Params(true, false)]
    public bool Add5;

    [Benchmark]
    [Arguments(100, 10)]
    [Arguments(100, 20)]
    [Arguments(200, 10)]
    [Arguments(200, 20)]
    public void Benchmark(int a, int b)
    {
        if (Add5)
            Thread.Sleep(a + b + 5);
        else
            Thread.Sleep(a + b);
    }
}
```



```
    Method |  Add5 |   a |  b |     Mean |     Error |    StdDev |
---------- |------ |---- |--- |---------:|----------:|----------:|
 Benchmark | False | 100 | 10 | 110.4 ms | 0.7187 ms | 0.0406 ms |
 Benchmark | False | 100 | 20 | 120.4 ms | 1.2675 ms | 0.0716 ms |
 Benchmark | False | 200 | 10 | 210.4 ms | 0.3785 ms | 0.0214 ms |
 Benchmark | False | 200 | 20 | 220.4 ms | 0.3023 ms | 0.0171 ms |
 Benchmark |  True | 100 | 10 | 115.4 ms | 0.9432 ms | 0.0533 ms |
 Benchmark |  True | 100 | 20 | 125.4 ms | 0.5873 ms | 0.0332 ms |
 Benchmark |  True | 200 | 10 | 215.4 ms | 0.9493 ms | 0.0536 ms |
 Benchmark |  True | 200 | 20 | 225.5 ms | 0.1574 ms | 0.0089 ms |
```

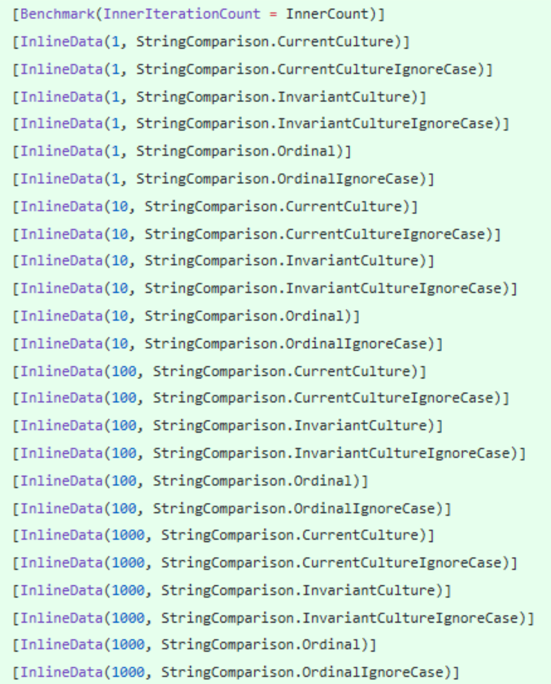
ArgumentsSource

```
public class IntroArgumentsSource
{
    [Benchmark]
    [ArgumentsSource(nameof(Numbers))]
    public double Pow(double x, double y)
         => Math.Pow(x, y);

    public IEnumerable<object[]> Numbers()
    {
        yield return new object[] { 1.0, 1.0 };
        yield return new object[] { 2.0, 2.0 };
        yield return new object[] { 4.0, 4.0 };
        yield return new object[] { 10.0, 10.0 };
    }
}
```

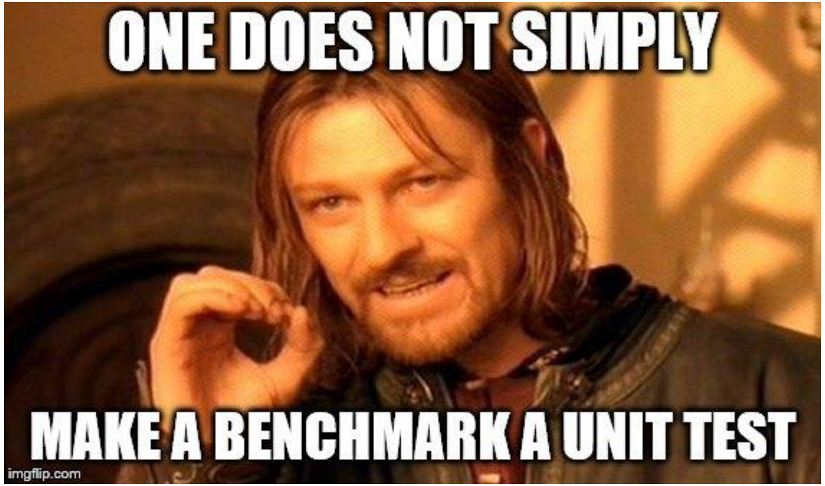


```
 Method |  x |  y |      Mean |     Error |    StdDev |
------- |--- |--- |----------:|----------:|----------:|
    Pow |  1 |  1 |  7.150 ns | 0.0746 ns | 0.0661 ns |
    Pow |  2 |  2 | 33.663 ns | 0.2829 ns | 0.2362 ns |
    Pow |  4 |  4 | 33.703 ns | 0.4976 ns | 0.4655 ns |
    Pow | 10 | 10 | 33.824 ns | 0.3440 ns | 0.3217 ns |
```

Avoid having too many arguments!



```
[Benchmark(InnerIterationCount = InnerCount)]
[InlineData(1, StringComparison.CurrentCulture)]
[InlineData(1, StringComparison.CurrentCultureIgnoreCase)]
[InlineData(1, StringComparison.InvariantCulture)]
[InlineData(1, StringComparison.InvariantCultureIgnoreCase)]
[InlineData(1, StringComparison.Ordinal)]
[InlineData(1, StringComparison.OrdinalIgnoreCase)]
[InlineData(10, StringComparison.CurrentCulture)]
[InlineData(10, StringComparison.CurrentCultureIgnoreCase)]
[InlineData(10, StringComparison.InvariantCulture)]
[InlineData(10, StringComparison.InvariantCultureIgnoreCase)]
[InlineData(10, StringComparison.Ordinal)]
[InlineData(10, StringComparison.OrdinalIgnoreCase)]
[InlineData(100, StringComparison.CurrentCulture)]
[InlineData(100, StringComparison.CurrentCultureIgnoreCase)]
[InlineData(100, StringComparison.InvariantCulture)]
[InlineData(100, StringComparison.InvariantCultureIgnoreCase)]
[InlineData(100, StringComparison.Ordinal)]
[InlineData(100, StringComparison.OrdinalIgnoreCase)]
[InlineData(1000, StringComparison.CurrentCulture)]
[InlineData(1000, StringComparison.CurrentCultureIgnoreCase)]
[InlineData(1000, StringComparison.InvariantCulture)]
[InlineData(1000, StringComparison.InvariantCultureIgnoreCase)]
[InlineData(1000, StringComparison.Ordinal)]
[InlineData(1000, StringComparison.OrdinalIgnoreCase)]
```



Strategies

- Throughput – default, perfect for microbenchmarks with a steady state
- Monitoring
  - no Pilot stage
  - no Overhead evaluation
  - Outliers remain untouched
  - 1 iteration = 1 benchmark invocation
- Coldstart – no warmup, no pilot stage

BenchmarkDotNet: Summary

- Accurate, Repeatable and Stable Results
- **Powerful** Statistics
- Rich support:
  - C#, F#, VB
  - .NET 4.6+, .NET Core 2.0+, Mono, CoreRT
  - Windows, Linux, MacOS
- Great User Experience
- Strong community
- Very good test coverage

Do you still want to write your own harness using Stopwatch?

Questions?

Thank you!

Docs: http://benchmarkdotnet.org/

Code: https://github.com/dotnet/BenchmarkDotNet