

# Applying the Roofline Model

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## Abstract

This is the paper's abstract ...

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# 1 Introduction

'The free lunch is over' [10] In the past decades, the CPU manufactures were reliably able to increase the clock speed. However, this has become harder and harder due to not just one but several physical issues. To increase performance despite the limited clock speed, the CPUs became more complex.

From the perspective of software performance optimization, the increased complexity made performance observations harder to understand. Since the trend to more complex CPUs is likely to continue in the future, an insightful and easy-to-understand performance model would be of high value.

The roofline model [15] premises to fulfill these criteria. The key observation which led to this model is that, for the foreseeable future, the transfer bandwidth between CPU and Memory will often be the limiting factor of system performance.

If an algorithm manages to largely operate on data which can be held in the CPU caches, off-chip bandwidth will not be an issue, in contrast to an algorithm excessively accessing data directly from memory. The balance between memory transfer and floating point computation is described by the 'operational intensity', measuring the number of performed operations per transferred byte.

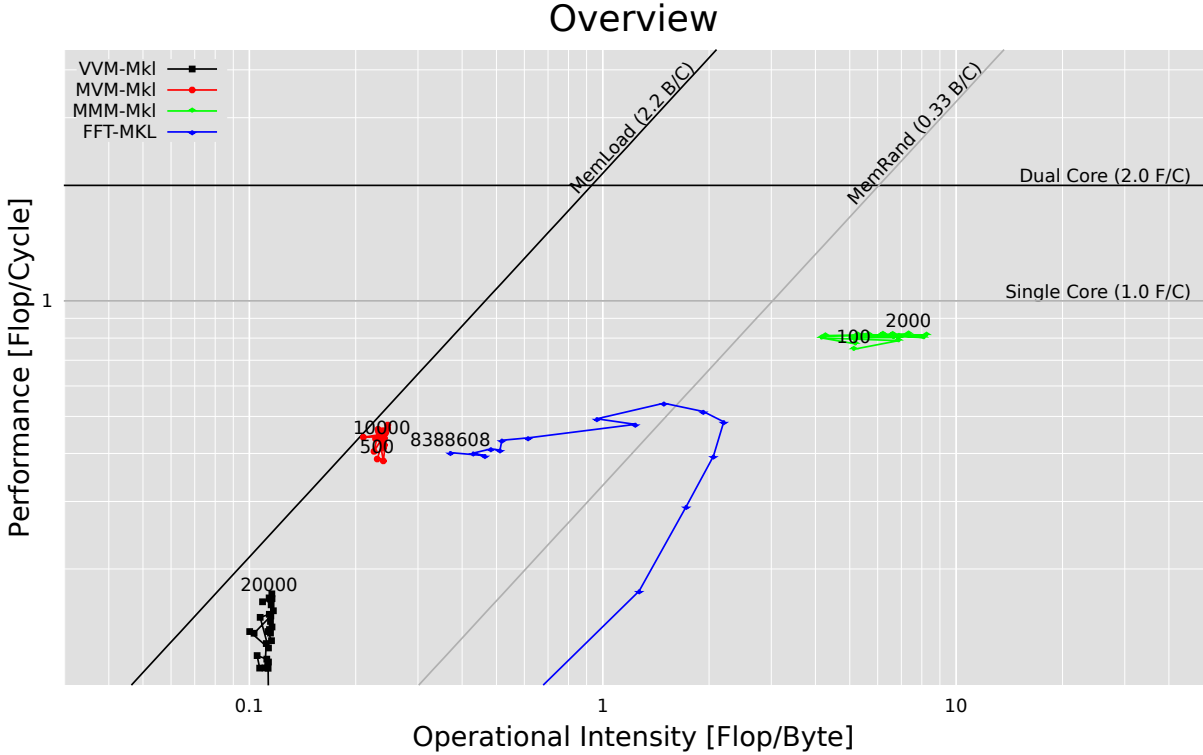


Figure 1: Yonah: Overview of different Kernels

The roofline model combines the operational intensity with the performance in a 2D graph (fig. 1). Each measurement results in a point on the plot. Multiple points are connected with a line to a series. The graph is on a log-log scale.

The peak floating point performance appears as a horizontal line. There can be different bounds depending on the technology or the number of cores used. The memory bandwidth forms a line of unit slope. There can again be multiple bounds, depending on the number of cores or the access pattern (random vs. linear).

The horizontal and diagonal lines give the roofline model its name. The point where the lines intersect is called the ridge point.

A roofline graph contains useful information for performance optimization. If the operational intensity of a kernel lies to the left of the ridge point, the kernel is memory bound. Peak floating point performance can only be reached by increasing the operational intensity. If the kernel lies to the right of the ridge point, memory bandwidth is no limiting factor. If the kernel does not reach the peak performance, there must be other performance limiting factors.

When comparing the roofline graphs of different machines, the position of the ridge point is an important clue of how difficult it is to reach a good performance. The further the ridge point lies to the right, the higher is the operational intensity required to achieve peak performance.

## 1.1 Goals for the Master Thesis

Since we did not find a tool capable of easily creating roofline plots, we decided to create one ourselves during this thesis. It should be able to measure the performance and operational intensity of a program, and to compose the results of different measurements into one roofline plot.

Code to be measured can come either in the form of a relatively isolated routine, typically containing a single kernel, or in the form of a larger program, containing multiple different kernels. While routines are treated as atomic units, it is desirable to split the larger program into its different algorithms and do the analysis for each algorithm separately. In the rest of this paper, we will use the term kernel for a routine or part of a program which is analyzed on its own.

To obtain the peak performance lines for the roofline model, we need to run micro benchmarks. To get the data points for a kernel, we need to measure the performance and the operational intensity.

Performance is defined as amount of work per unit of time. The amount of work and how it is defined is determined by the actual kernel and may not be needed to be measured directly by the measurement tool. The time required to do the work has to be measured.

Operational intensity is defined as operations per byte of data traffic. Since the operational intensity cannot be measured directly, we have to measure the operation count and the data traffic. Depending on the problem, different definitions of operation and data traffic make sense.

An operation could be a floating point operation, resulting in the well known "flops" unit, either single or double precision. But an operation could as well be defined as machine instruction, integer operation or others.

The point where data traffic is measured is typically between the last level cache of the processor and the DRAM, but it could be measured as well between the different cache levels or between L1 cache and processor.

The micro benchmarks are typically designed to either transfer as much data per unit of time or to execute as many operations per unit of time. Thus the measurement capabilities needed to evaluate the actual problems can be reused for the benchmarks.

In summary, we need to measure the following quantities:

- execution time

- memory traffic
- operation count

## 1.2 Performance Counters

Recent x86 CPUs contain typically two performance counters. Each can be configured to measure one performance event. There are many events, 119 on a CoreDuo. Examples are:

**INSTRUCTION RETIRED** occurs for every retired instruction

**DBUS BUSY** occurs for every cycle during which data bus is busy

**SSE PRE MISS** occurs when an SSE instruction misses all cache levels

**BR TAKEN RET** occurs for every retired taken branch instruction

When working with the linux operation system, the performance counters are configured and read using a kernel API. The kernel takes care of isolating different processes, such that each process can configure and use the counters according to the specific requirements, without interfering with other processes.

Using the performance counters, it is possible to measure execution time, memory traffic and operation count. For the execution time either the cycle counter or the system timer can be used. The memory traffic can be determined using the performance counters for counting cache misses and write back operations. An other option is to use the counters for bus transfers. Measuring the operation count depends heavily on the definition of operation, but is typically measurable with the performance counters, too.

## 2 Measurement Setup

All measurements are performed on an IBM X60 Thinkpad, featuring an Intel CoreDuo CPU (Family 6, Model 14). The CPU is based on the Yonah microarchitecture, which similar to the Pentium-M. The CPU contains two cores, each having a 32KB instruction and a 32KB data L1 cache, 8 ways set associative, with 64 bytes line size. The two cores share a 2MB unified L2 cache, again 8 ways set associative and with 64 bytes line size. The core frequency can scale between 1GHz and 1.83GHz. The bus frequency is 167MHz.

The main memory consists of two 2GB DDR2 modules, totaling in 4GB available memory. The theoretical throughput of the memory is 5.12 GB/s, which is 2.80 Bytes per core cycle, if the CPU runs at 1.83GHz.

We used XUbuntu 11.10, running a Linux 3.0.0-16 kernel in 32 bit mode, since the CPU does not support the 64 bit mode.

The performance counters are instrumented using the 'perf event' kernel interface [11], using libpfm4 [2] to generate the required parameters.

We used 'coreduo::UNHALTED\_CORE\_CYCLES' for measuring time. For the operation count, we used the following definitions for operation:

**SinglePrecisionFlop** SSE single precision operations.

```
'coreduo::SSE_COMP_INSTRUCTIONS_RETIRED:SCALAR_SINGLE'
+2*'coreduo::SSE_COMP_INSTRUCTIONS_RETIRED:PACKED_SINGLE'
```

**DoublePrecisionFlop** SSE double precision operations.

```
'coreduo::SSE_COMP_INSTRUCTIONS_RETIRED:SCALAR_DOUBLE'
+2*'coreduo::SSE_COMP_INSTRUCTIONS_RETIRED:PACKED_DOUBLE'
```

**CompInstr** Computational instructions retired. Counts SSE instructions and x87 instructions. Used for x87 code.

```
'coreduo::FP_COMP_INSTR_RET'
```

**SSEFlop** SSE operations, sum of SinglePrecisionFlop and DoublePrecisionFlop

We used two variants of measuring the memory transfer volume. The **MemBus** variant uses  $64 \times \text{'coreduo::BUS_TRANS\_MEM'}$ , which measures the transfers on the system bus. The **MemL2** variant uses the counters for the L2 cache line allocation and eviction, namely  $64 \times (\text{'coreduo::L2\_LINES\_IN:SELF'} + \text{'coreduo::L2\_LINES\_OUT:SELF'})$ , combined with  $8 \times \text{'coreduo::SSE\_NTSTORES\_RET'}$  to take non temporal stores into account.

## 2.1 Cache

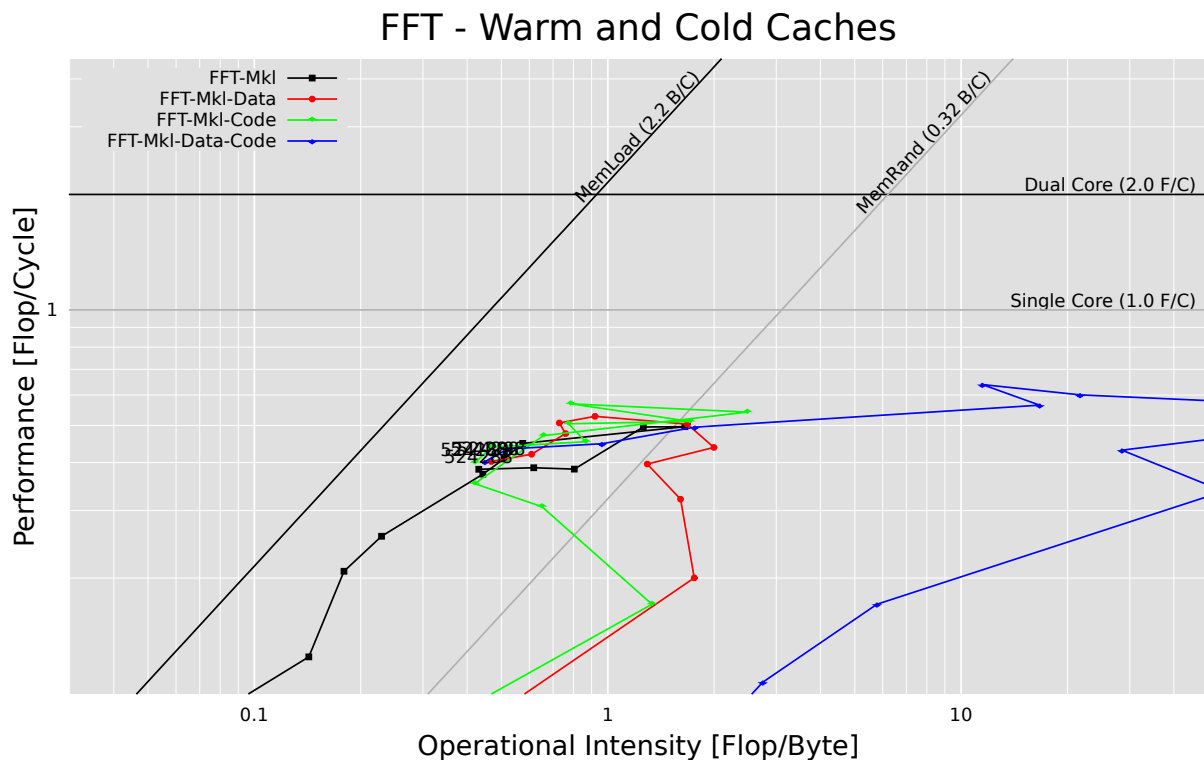


Figure 2: Yonah: Influence of the initial cache state

Specially for short running kernels, the initial state of the cache can have a big impact on the memory traffic and execution time. The impact can be controlled by making sure the caches are either warm or cold.

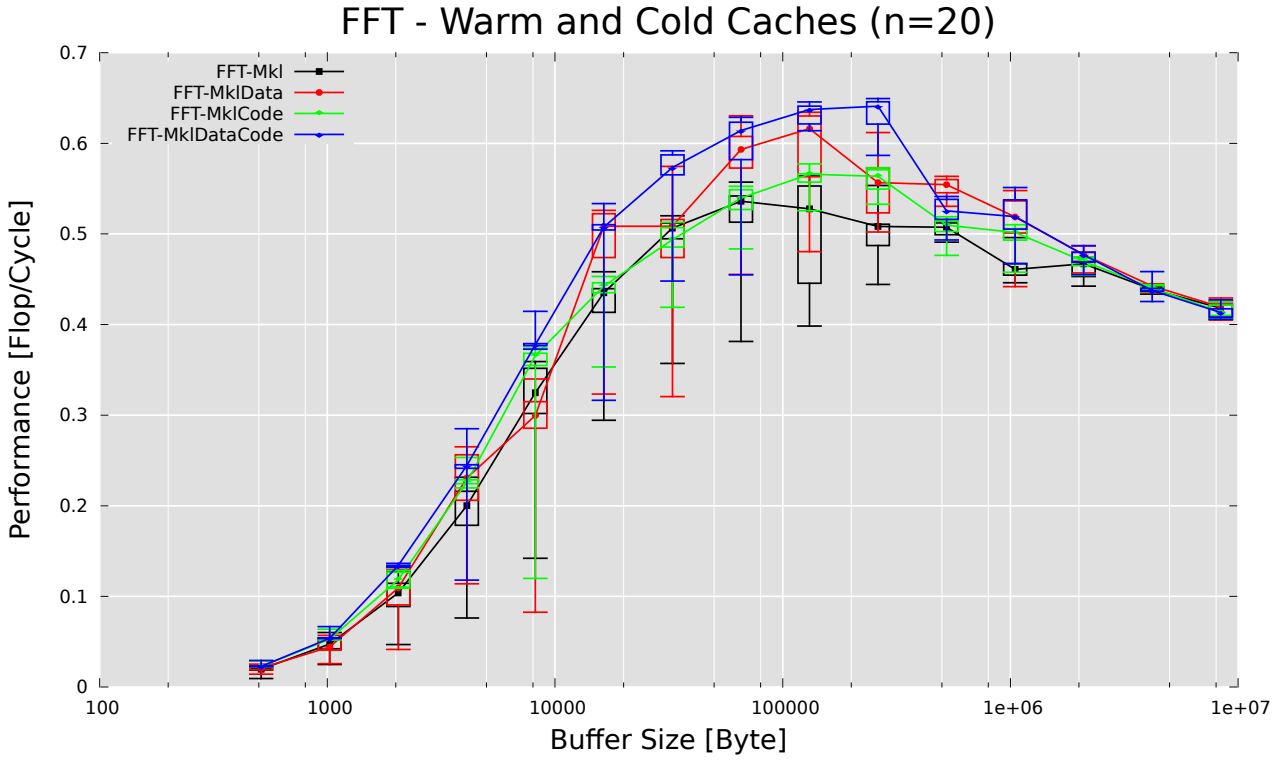


Figure 3: Yonah: Influence of the initial cache state on the Performance

In our tool, it is possible to specify the desired initial state of the code and the data separately. We used the fast fourier transformation implementation of the Intel Math Kernel Libraries as showcase. Figures 2 and 3 show the results when the cache is cold (FFT-Mkl), only the data is warmed up (FFT-Mkl-Data), only the code is warmed up (FFT-Mkl-Code) or both data and code is warmed up (FFT-Mkl-Data-Code).

The following snippet shows the relevant logic:

```

1 // should the code cache be warm?
  if (getWarmCode()) {
3     // Tell the kernel to warm the code cache,
      // which usually results in the kernel
5     // being executed once.
      getKernel()->warmCodeCache();

7
      // Should we clear the data?
9     if (!getWarmData()) {
        getKernel()->flushBuffers();
11    }
  } else { // Code cache should be cold.
13     // Access a large memory buffer and execute
      // a lot of code, this clears the code cache.
15     clearCaches();

17     // Should the data be warm?
      if (getWarmData()) {
19         // Warm the data cache by accessing each
          // cache line of the data buffer(s).
21         getKernel()->warmDataCache();
      } else {
23         // The data cache should be cold.
          getKernel()->flushBuffers();
25     }
  }
}

```

Getting cold caches can be quite tricky. See [12] section '3. CACHE FLUSHING METHODS WHEN TIMING ONE INVOCATION' for details.

To clear the code cache, we use the traditional method of accessing a large memory buffer and executing more than 32KB code to flush the L1 code cache.

In addition, the kernels report the buffers they allocated. This is used to flush these buffers with the 'clflush' instruction, not affecting code which is already in the cache. This is implemented by the `flushBuffers()` method in the above code snippet.

## 2.2 Frequency Scaling

The core frequency is not constant in current processors. Since the memory latencies and throughputs do not scale with the core frequency, a lower core frequency will generally cause a higher percentage of the peak performance to be reached by the kernel.

On Linux, frequency scaling is controlled so called governors. We used the 'performance' governor for all our measurements, which fixes the core frequency to the maximum.



### 3 Single Threaded Accuracy and Precision

First, let's recapitulate the definitions of accuracy and precision. [13] Accuracy of a measurement system is the closeness of the measurement results to the true value. Precision is the degree to which repeated measurements show the same result.

A standard technique to increase precision is to repeat a measurement and use a measure of tendency. This generally increases the precision of the result, but does not improve the accuracy in presence of systematic errors.

To analyze the results of single threaded measurements we designed three groups of measurements. Each group is focused on one specific quantity, namely time, transfer volume and operation count. We measured on an idle system. All measurements are executed with cold caches.

In all groups we used the following kernels:

**ADD** Repeat adding a constant to an accumulator. Everything is performed in registers. We use multiple accumulators and unroll the loop.

**Read** Read a buffer from memory

**Write** Overwrite a buffer in memory

**WriteStream** Overwrite a buffer in memory, using non temporal store instructions

**Triad** Perform  $a_i = b_i + k * c_i$ . This involves reading  $a$ ,  $b$  and  $c$  and writing  $a$  back.

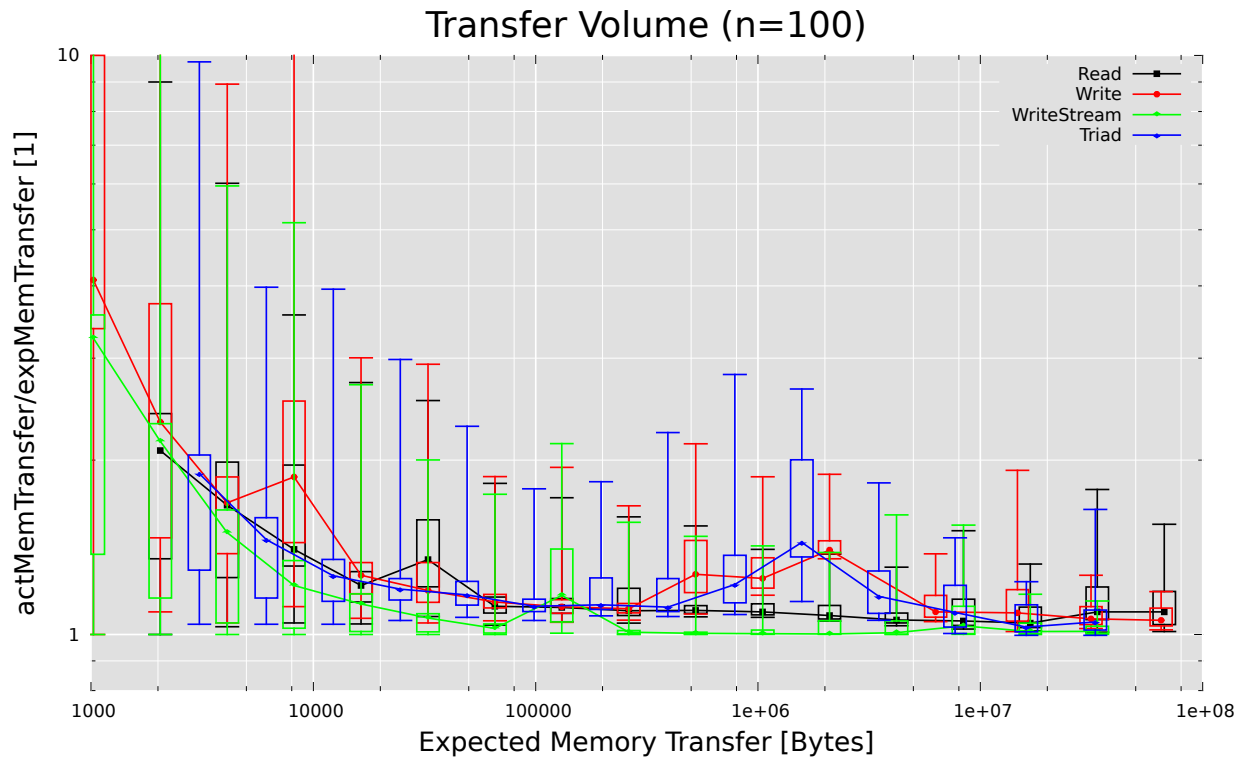
#### 3.1 Transfer Volume

We tried to estimate the amount of memory that has to be transferred. For pure reading, we expect to observe the whole buffer being transferred to the core. When writing is involved, we expect some of the writes to be held back in the cache. For the write kernel we presume that the whole cache is used for write back caching, and one third of the cache for the triad kernel, since there are three buffers. The streaming write kernel should write the whole buffer once.

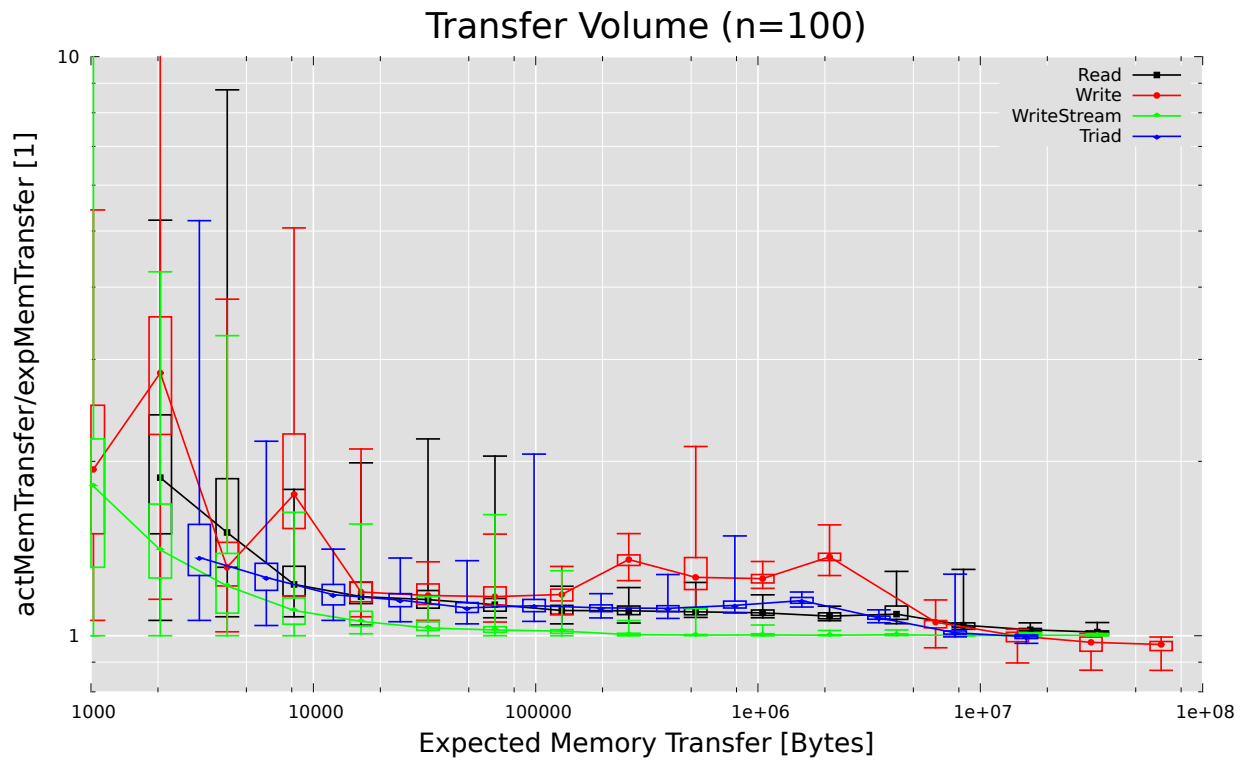
Figure 4 shows that we roughly observe the expected amount of memory transfer. Around an expected transfer volume of 2MB we overestimate the influence of the write back cache. The CPU seems to write data back to the memory before the cache is completely filled. The MemBus and MemL2 variants produce similar result. Note that the MemL2 variant measures less than the expected memory transfer for large buffer sizes.

The errors (see fig. 5) of the MemL2 variant are smaller than those of the MemBus variant.

To validate our assumption on the write back cache, we measured the memory transfer while flushing the cache using 'CLFLUSH' after the execution of the kernel completes. (fig. 6) There is a small overhead for the Read kernel. The data of the write kernel shows that almost the whole 2MB 2nd level cache is used for write back caching. For the Triad kernel one could suspect that each buffer receives about one third of the cache, which is affirmed by the data.

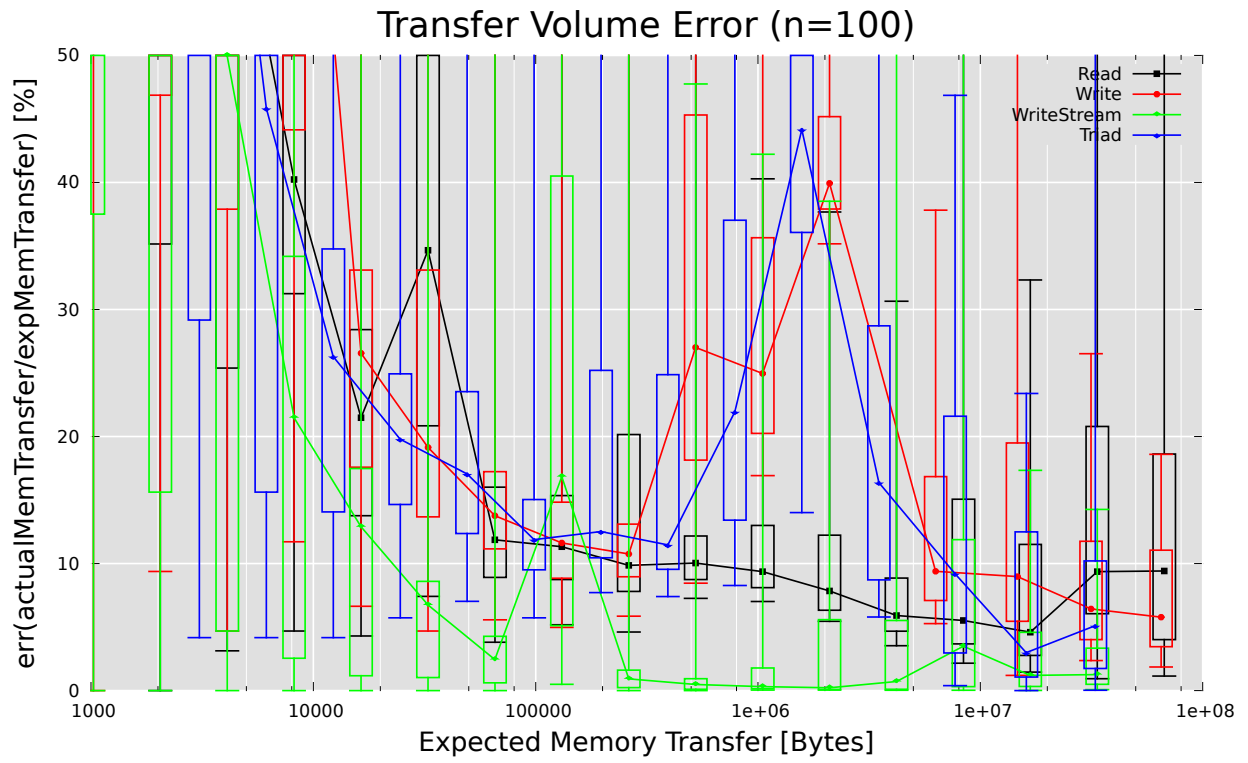


(a) MemBus

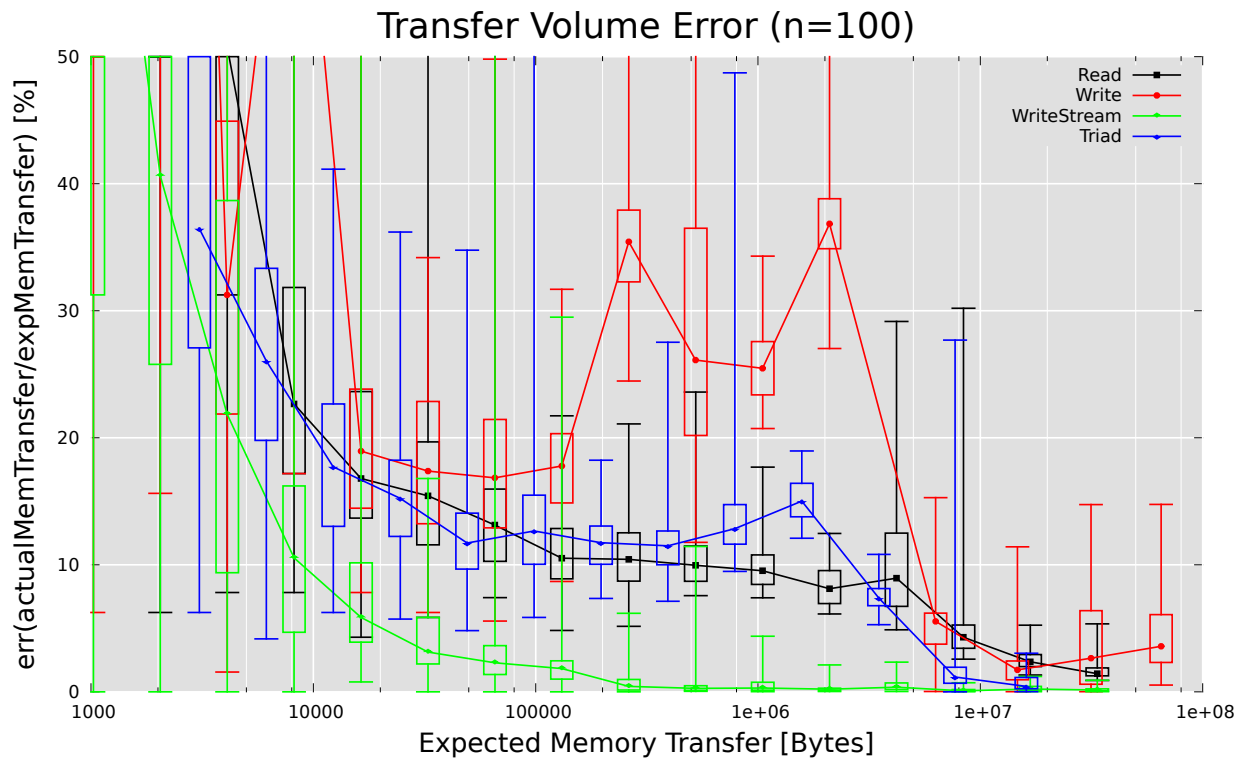


(b) MemL2

Figure 4: Transfer Volume



(a) MemBus



(b) MemL2

Figure 5: Error of Transferred Bytes

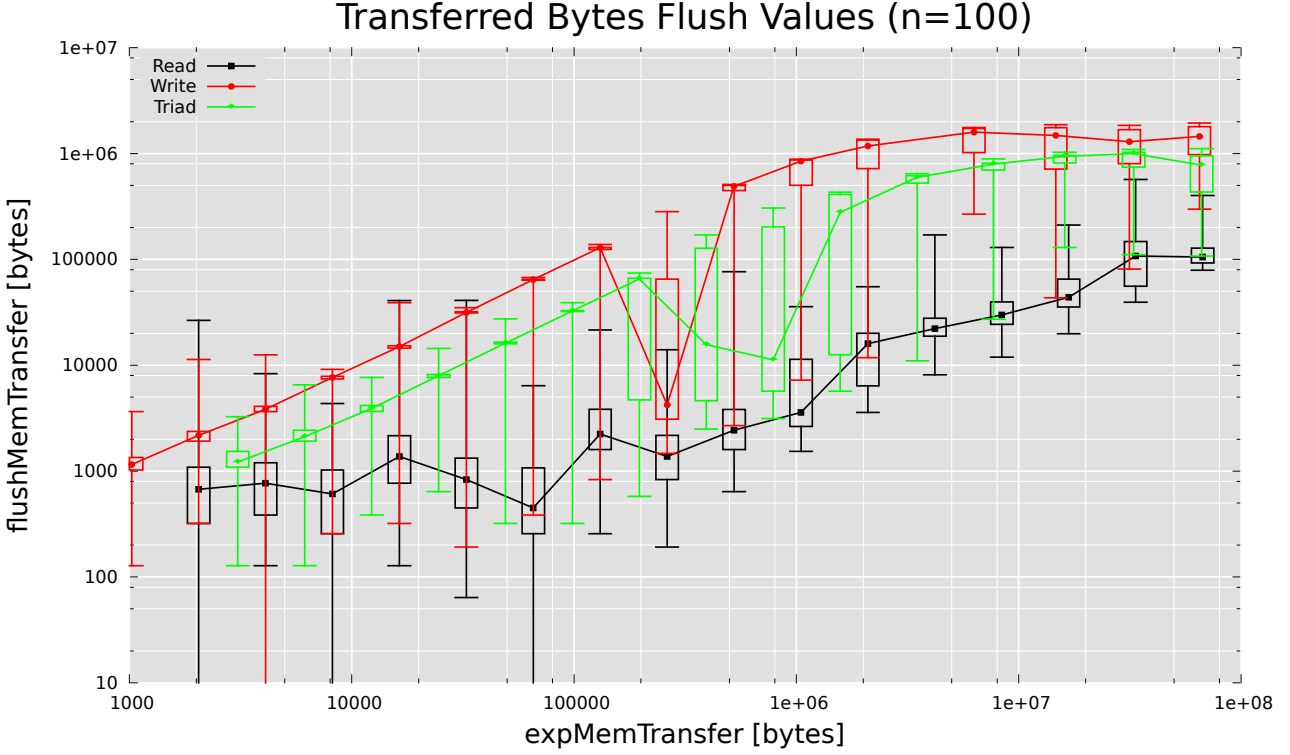


Figure 6: MemL2: Memory Transfer during Cache Flush after kernel execution

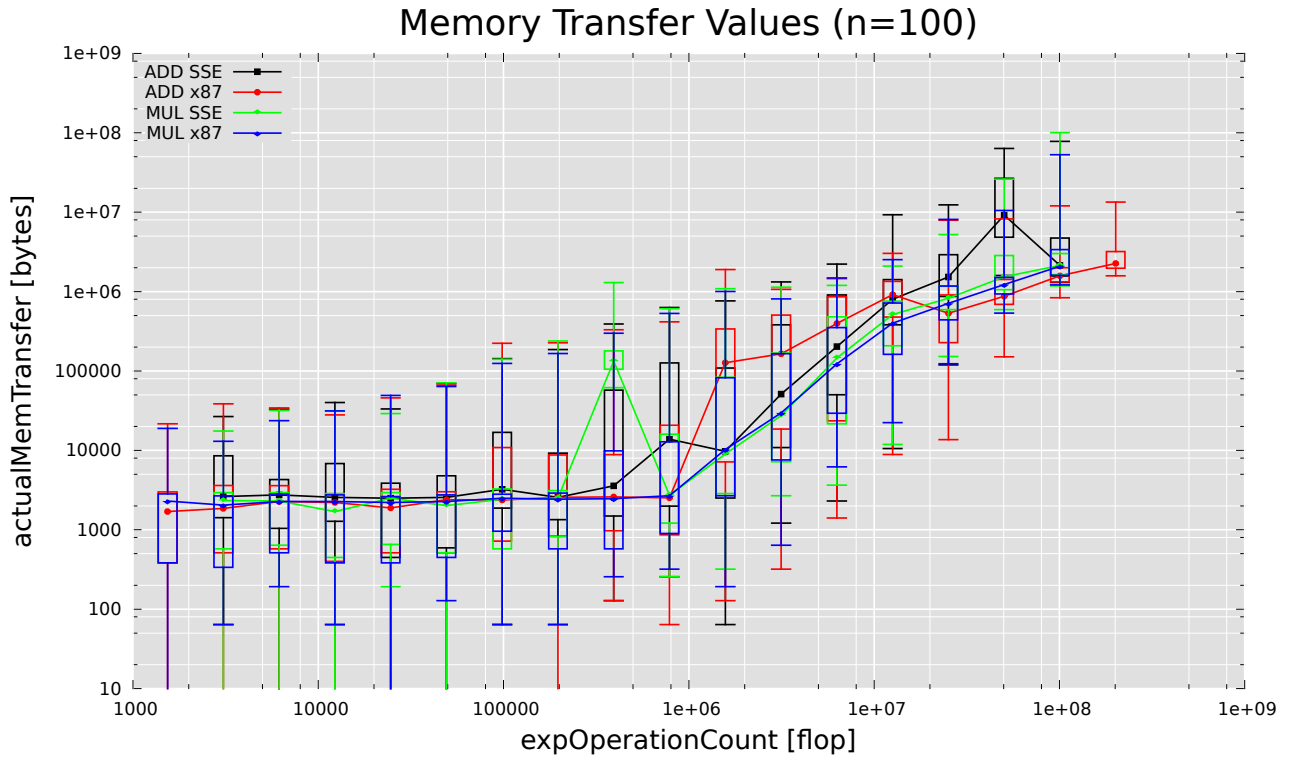
When measuring on an Intel Core, we observed a strange behaviour. While the Read and the Triad kernels behaved as expected, the we observed a memory transfer of half the buffer size for the write kernel, independent of the buffer size. We used the SSE intrinsics. Switching to the normal integer registers produced the expected results.

When measuring the memory transfer of the arithmetic kernels, we observe an overhead of around 2.5KB for for short running kernels. When the execution time exceeds 1ms to 10ms, the memory transfer starts to correlate with the execution time. There is a huge difference between the BusMem and BusL2 variants. The BusMem variant measures an overhed of around one byte every 20 cycles, while the BusL2 variant measures one byte every 300-1600 cycles (see fig. 7 and 8) This difference is plausible since the BusMem variant is likely to pick up any noise on the memory bus.

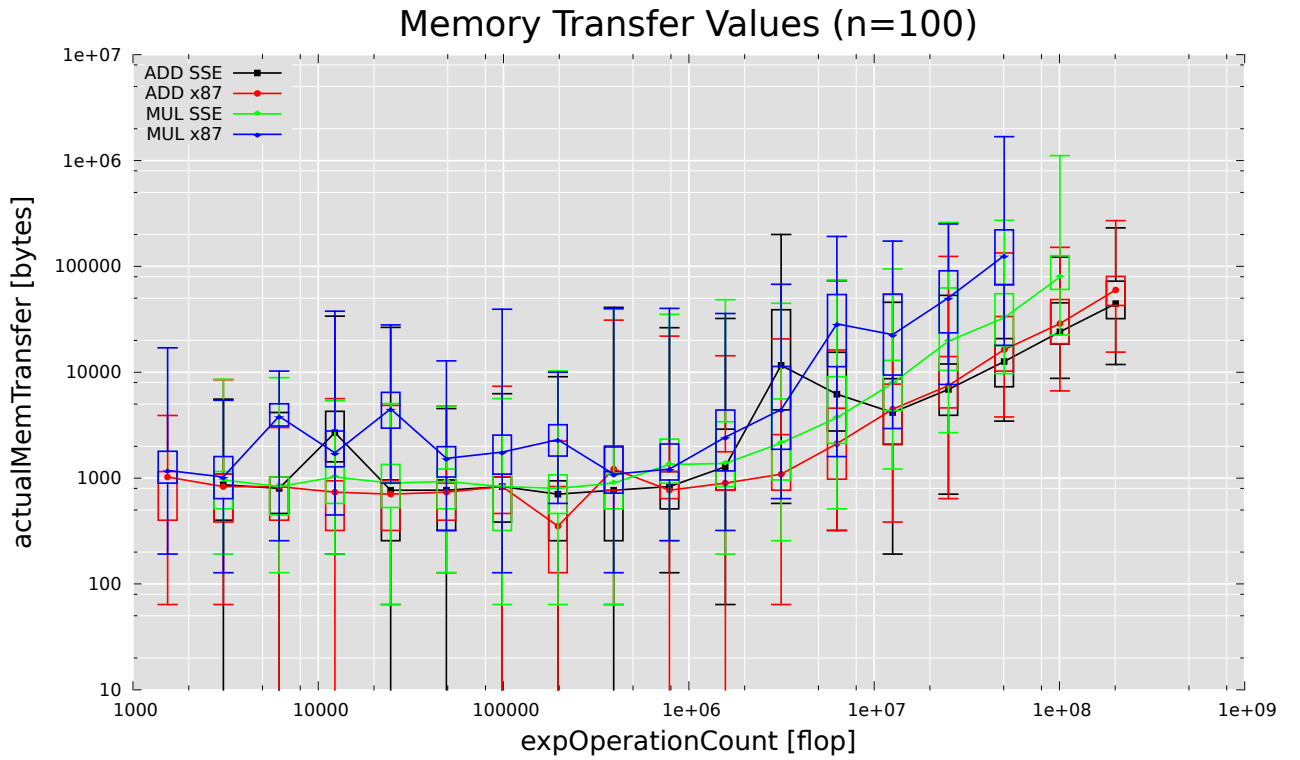
### 3.2 Time

For the ADD kernels, figure 8 shows that the execution time is around one cycle per operation and does not differ between SSE and x87, which is consistent with the information found in the Intel manual. The same applies for the MUL kernels, with a throughput of around 0.5 multiplications per cycle. The error is small for operation counts above 10000 (fig 9).

For the kernels causing memory transfer, we observe a strong correlation between expected memory transfer and execution time (fig. 10), but the errors far exceed those observed for the arithmetic kernels (fig. 11).



(a) MemBus



(b) MemL2

Figure 7: Transferred Bytes of the Arithmetic Kernels

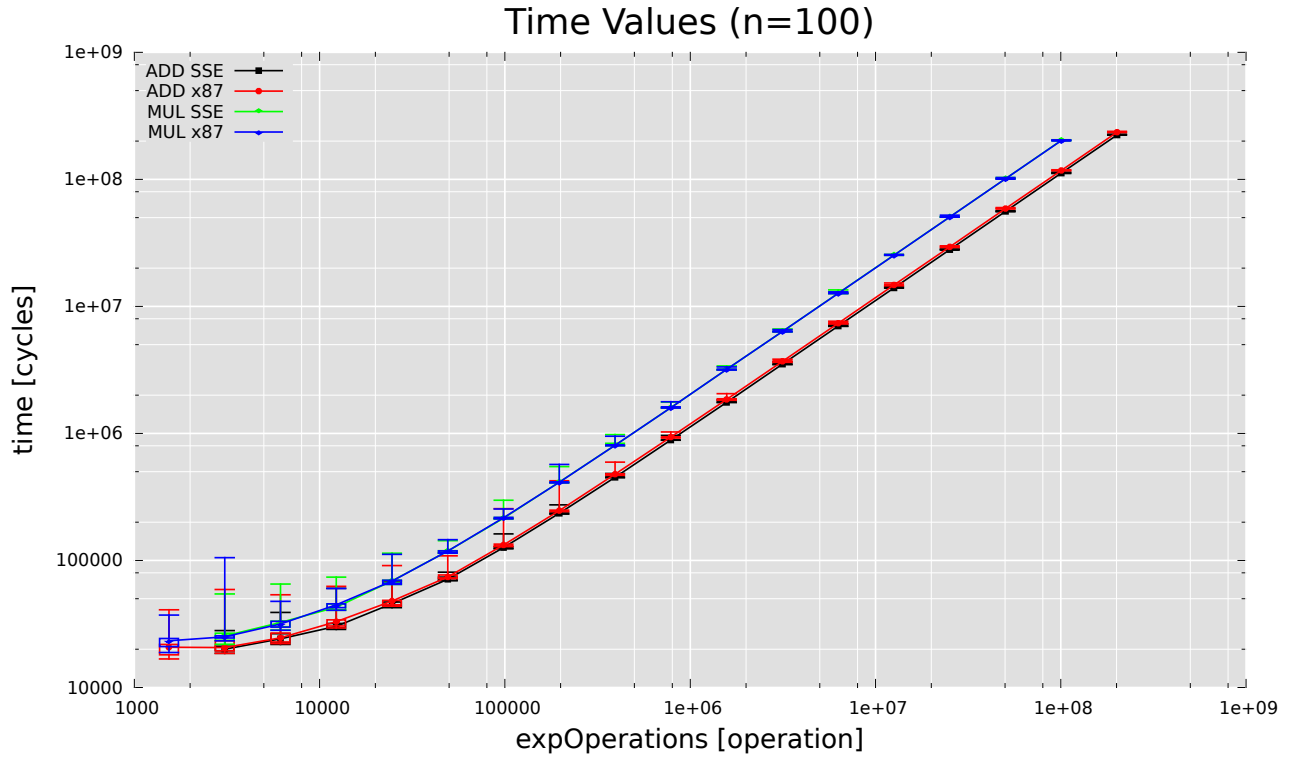


Figure 8: Execution Time of the ADD kernel

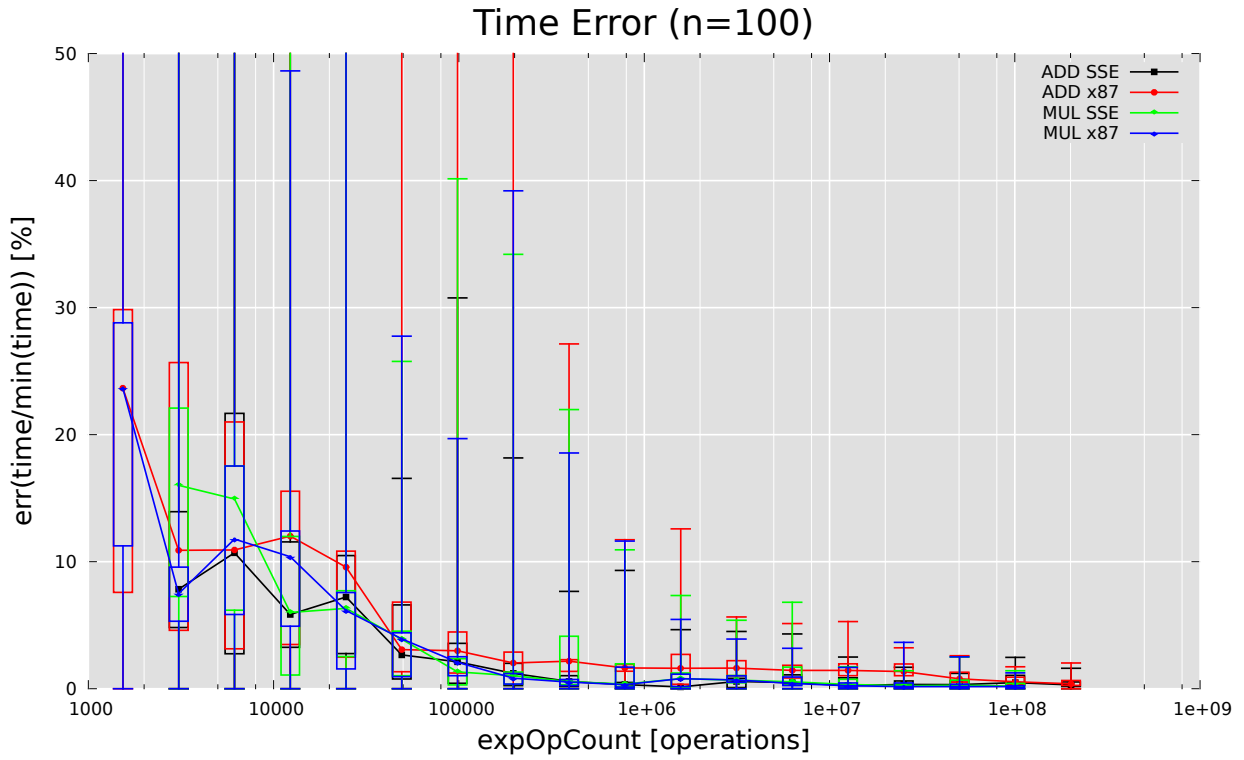


Figure 9: Error of the Execution Time of the ADD kernel

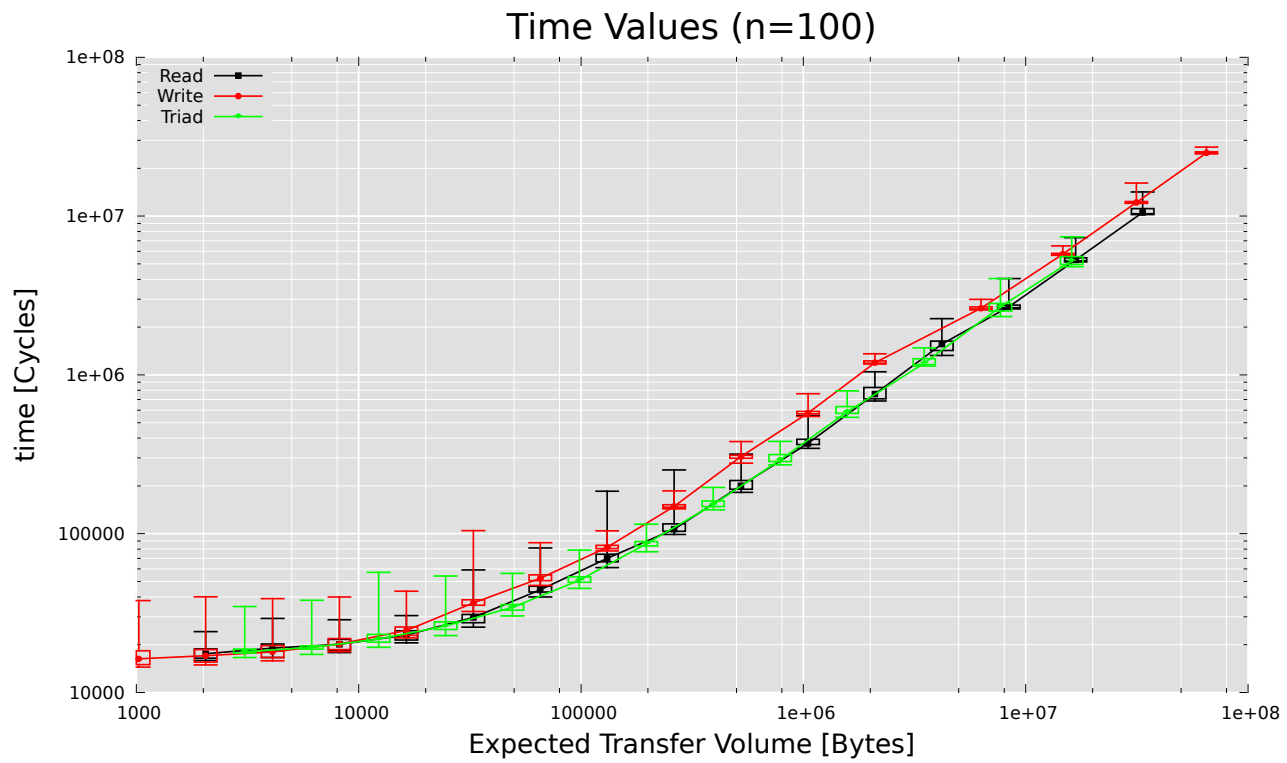


Figure 10: Execution Time of the memory kernels

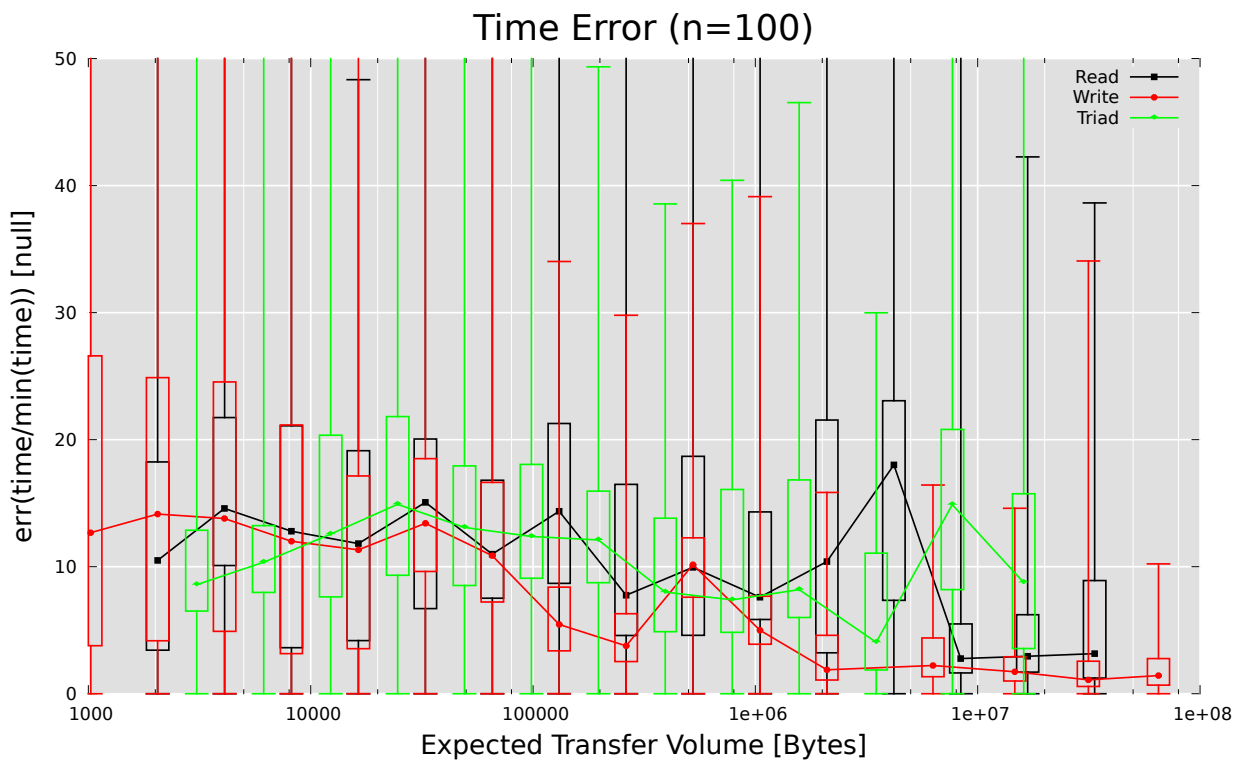


Figure 11: Error of the Execution Time of the memory kernels

### 3.3 Operation Count

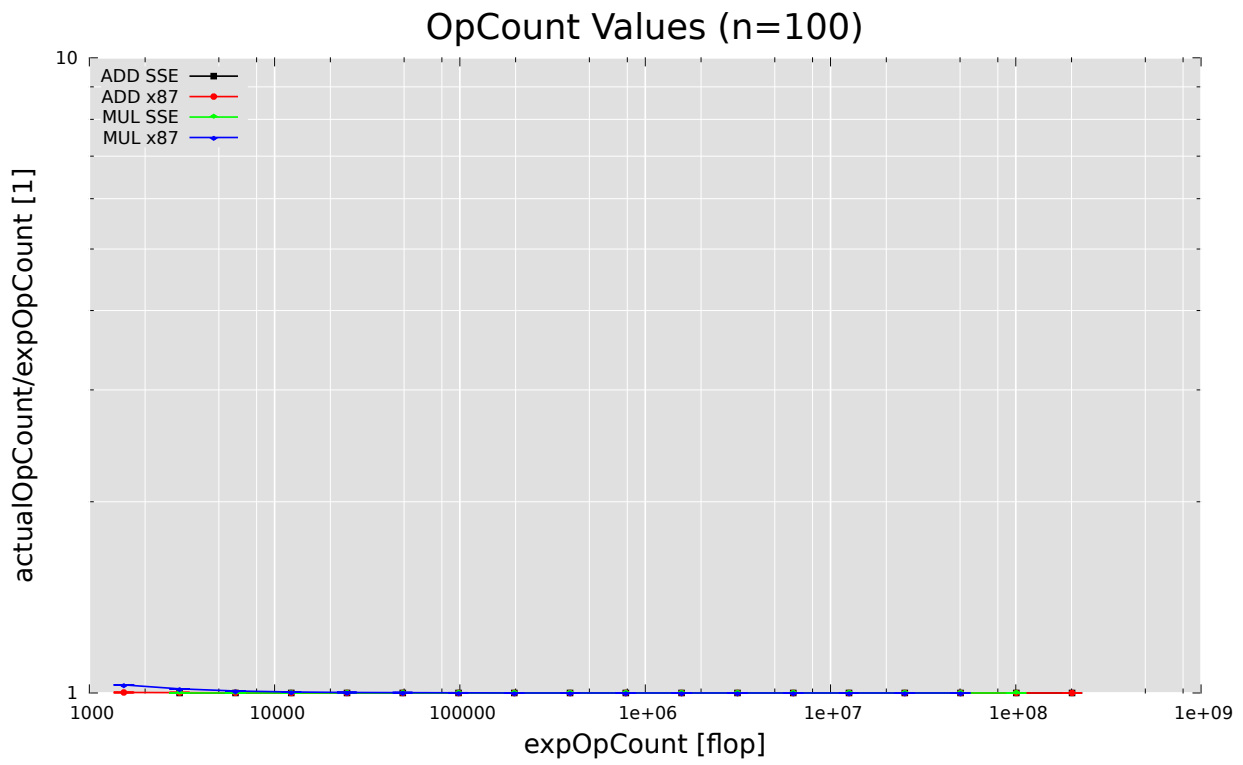


Figure 12: Operation Count

Figure 12 shows that we get almost perfect results for measuring the operation count. The error for the x87 ADD and MUL could be explained by an overhead of around 50 respectively 500 floating point instructions.



### 3.4 Handling the Variance

In the previous sections we saw that our measurements produce plausible results. But as soon as the kernels cause memory transfer, we observe a high variance. We presume this is due to various activities happening in the background during the measurement. (Task switches etc).

These activities cause events to be measured which are not related to the execution of the kernel. Fortunately, additional events only increase the measured execution time, memory transfer or operation count. Ideally, at least one execution does not include any overhead. In this case the true value is the minimum value observed.

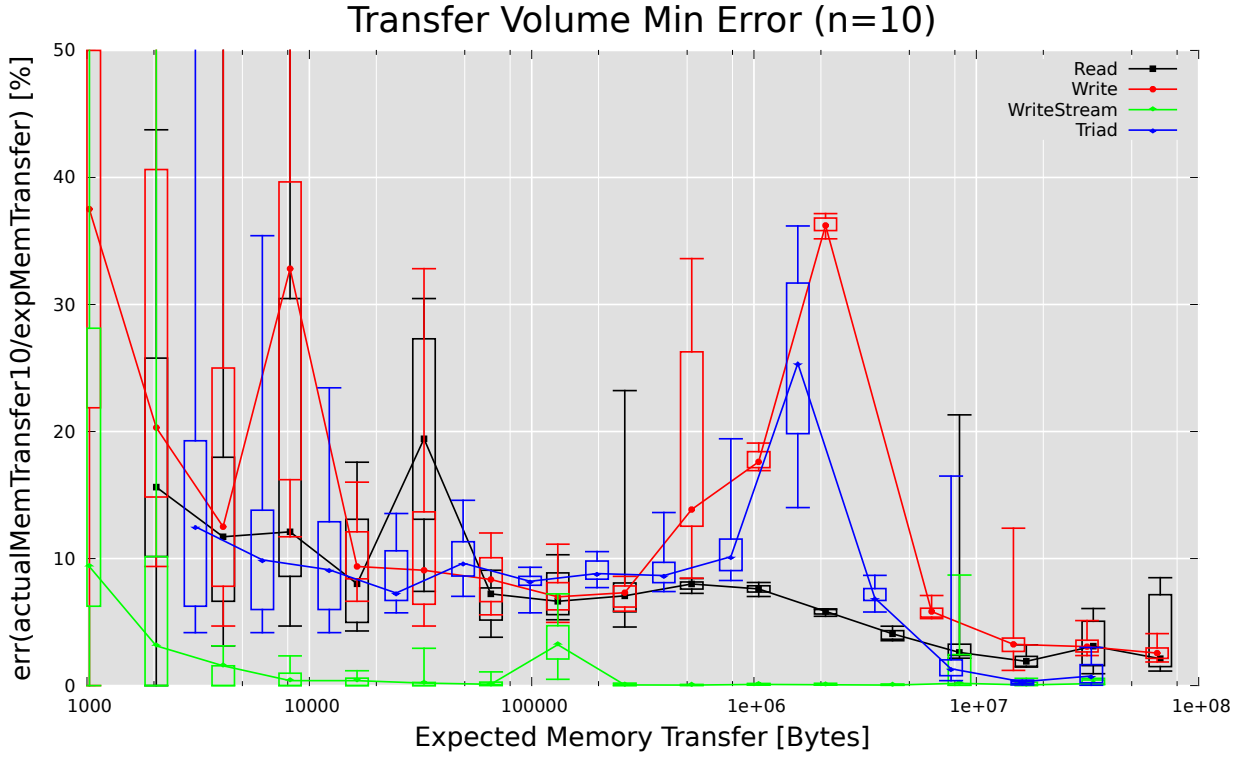
Based on these considerations, we repeat each measurement  $K$  times and discard all but the minimum value.

Using this scheme with  $K = 10$  for measuring the transfer volumes, the samples fall in a range of about 5%. The bias is under 10% except for transfer volumes under 20KB and with a peak of up to 40% around 2MB for the kernels involving writes. The difference in precision between MemBus and MemL2 disappeared almost completely. For large transfer volumes, the accuracy of the MemBus variant is superior. (fig. 13)

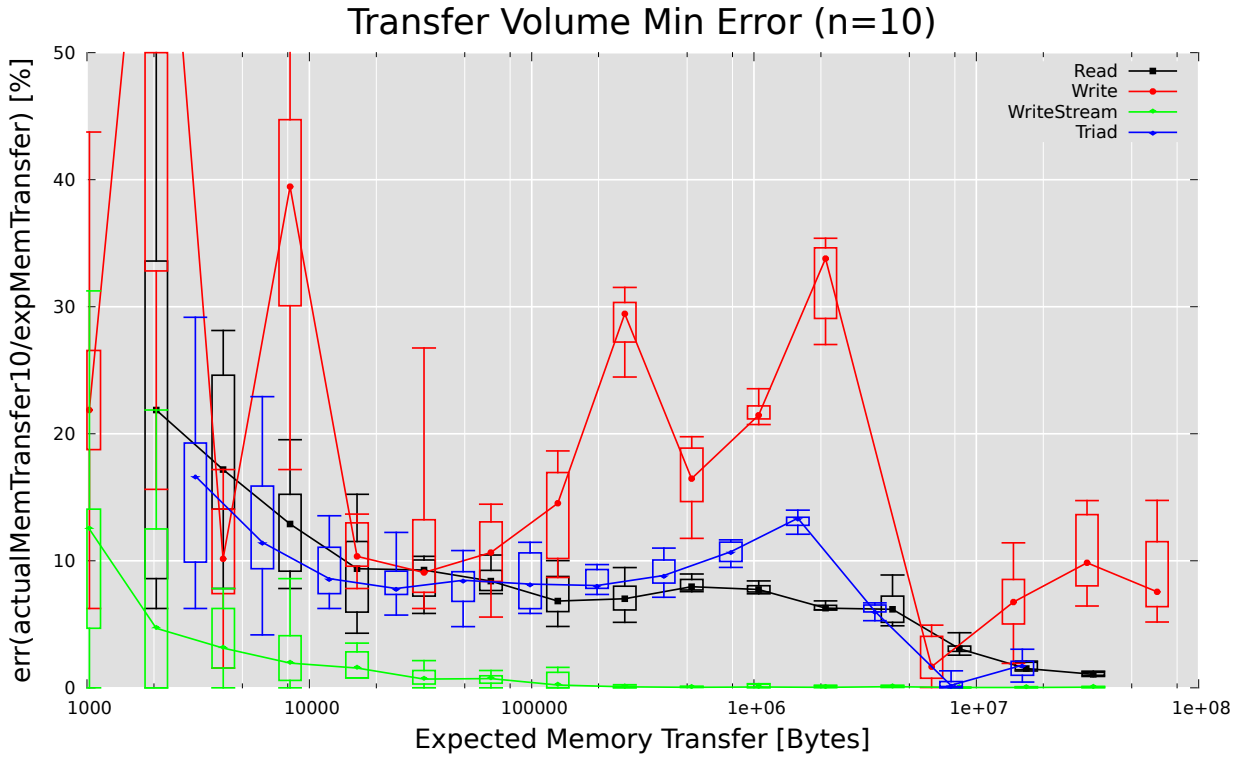
Applying the same scheme to measuring the execution time of the memory kernels yields a precision of about 10%. Since we cannot derive an expected value, we chose the minimum observed value as reference. (fig. 14)

Finally, figures 15 and 16 show that the arithmetic kernels do not pose any problems.

Summarizing our results, using the minimum of  $K$  scheme with  $K = 10$  the arithmetic kernels can be measured with high precision and accuracy. The results of measuring execution time and memory transfer of memory intensive kernels are scattered within 10% of the reference value. The memory transfer volume is overestimated by about 10% for transfer volumes under 10MB



(a) MemBus



(b) MemL2

Figure 13: Error of the Transfer Volume with  $K = 10$

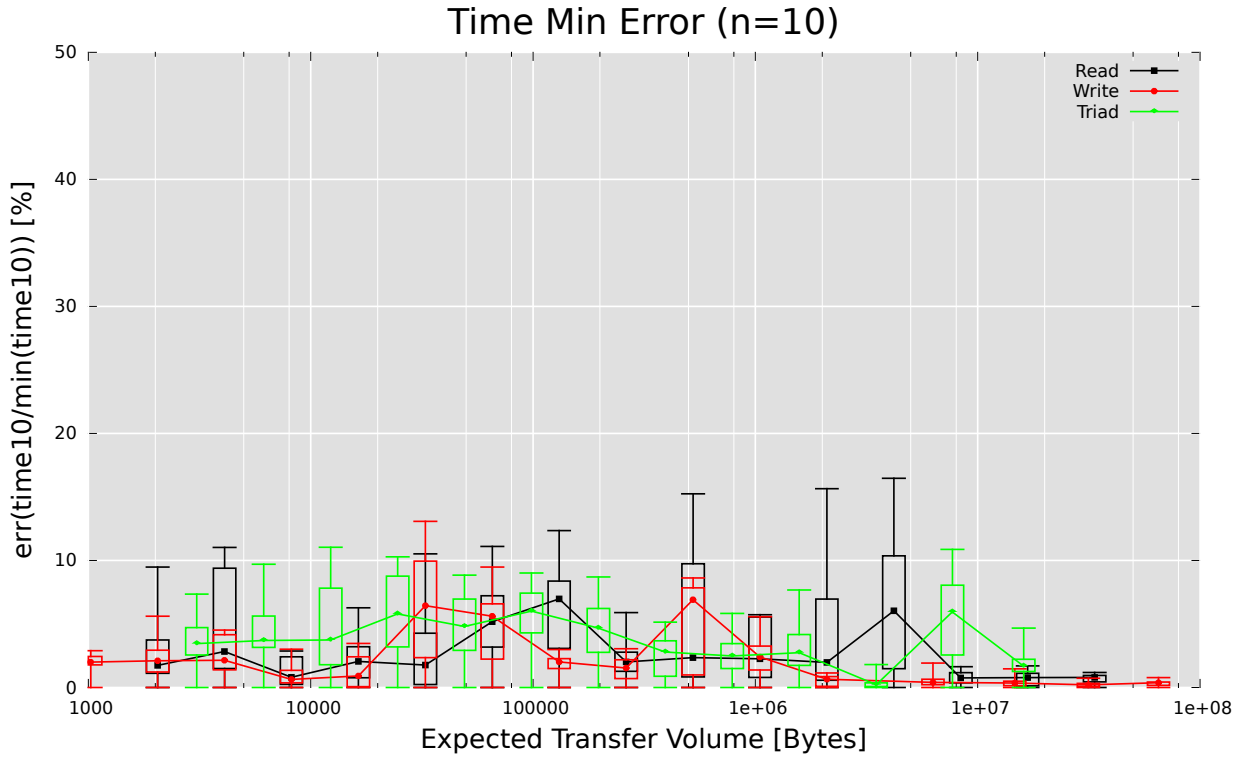


Figure 14: Yonah: Error of the Execution Time with  $K = 10$

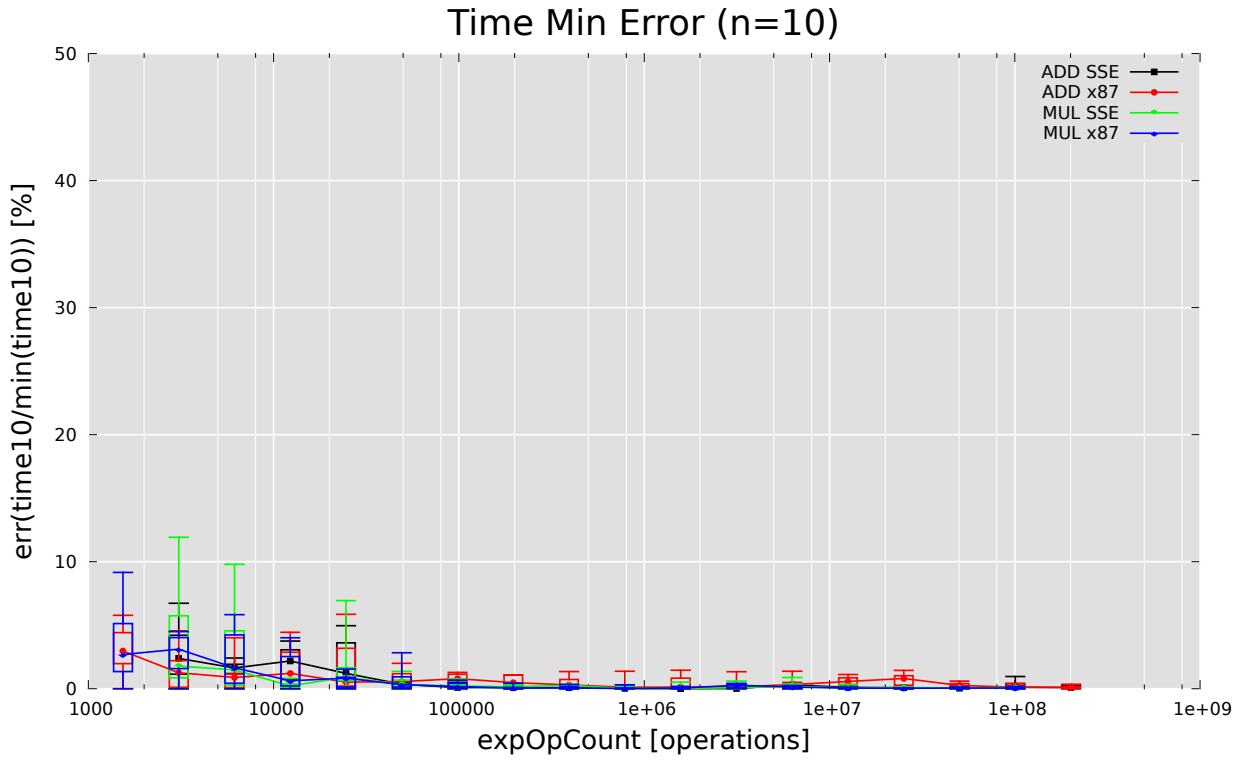


Figure 15: Yonah: Error of Execution Time with  $K = 10$

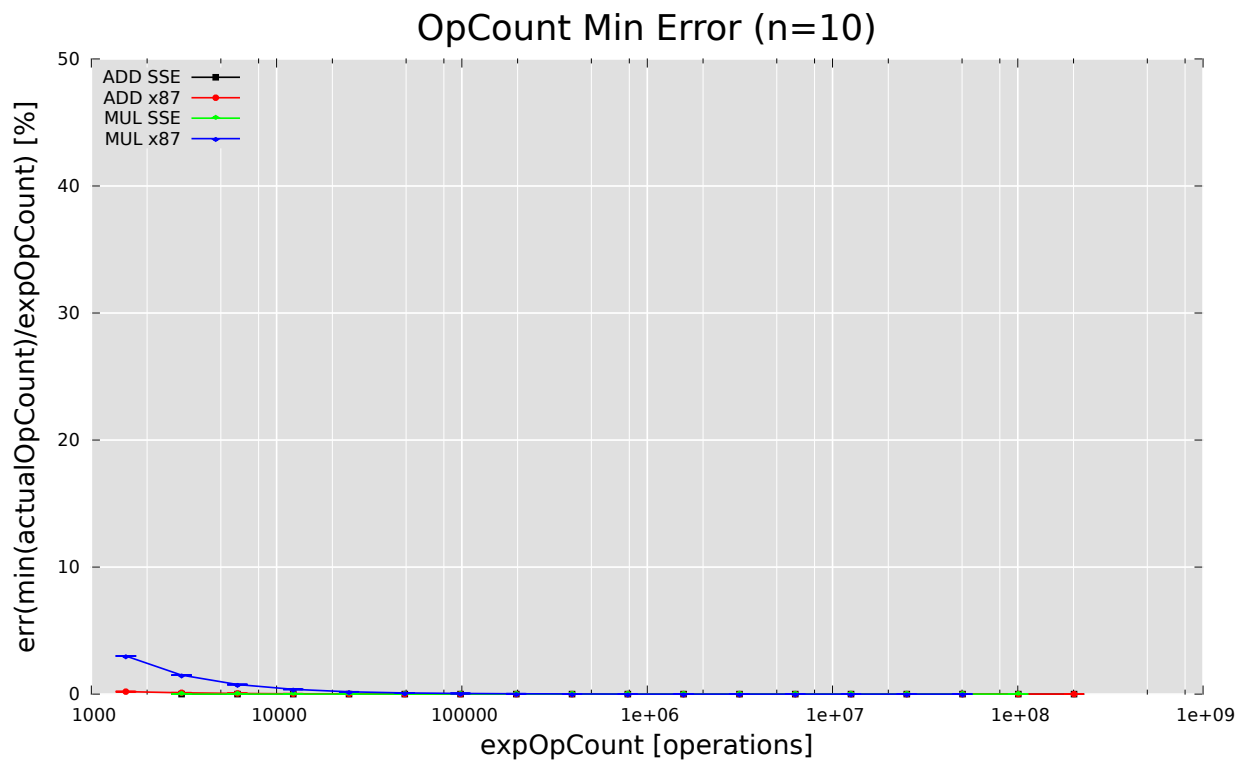


Figure 16: Yonah: Error of Operation Count with  $K = 10$

## 4 Multi Threaded Accuracy and Precision

For the validation of multithreaded measurements, we use the same measurements as for the single threaded validation, but run a separate workload instance on each core. Using a barrier, we make sure the two kernels start at the same time.

Since the Yonah does not utilize HyperThreading, we don't expect an arithmetic kernel running on one core affecting a memory intensive kernel on the other core. Therefore the workloads run in parallel are not mixed.

### 4.1 Transferred Volume

The MemBus variant measures all transfers on the bus. Therefore, the measurer of each workload should see the traffic of both kernels. The MemL2 variant should separate the traffic of the two cores. On figures 17, 18 and 19 we see the expected results for the MemL2 variant. The precision is comparable to the single threaded measurements, the overhead is slightly higher.

In contrast, the MemBus variant shows a huge variation. Choosing 4MB as representative buffer size, figures 20, 21 and 22 show the distribution of the results. There is a cluster around the expected result of twice the expected transfer volume (each workload seeing the transfer of both cores), but also a cluster around once the expected transfer volume. It seems that in about half of the measurement runs, the kernel only see their own traffic.

### 4.2 Time

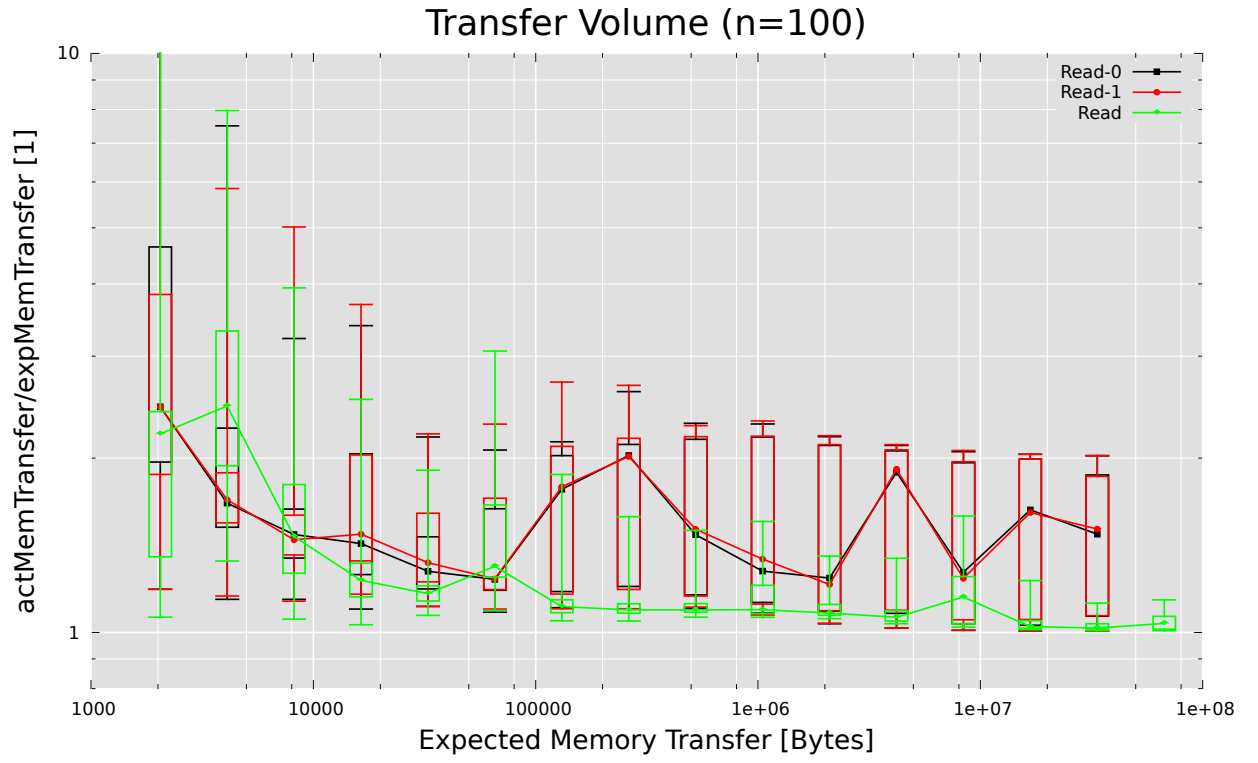
As expected, running two arithmetic kernels in parallel does not affect the measured execution time (fig. 23).

For the memory kernels we don't see much difference in execution time between the single threaded and the multithreaded results for expected transfer volumes below 1MB. We expected to observe a larger difference. For larger buffers the expected difference of about a factor of two can be observed, although outliers are frequent. (fig. 24 and 25)

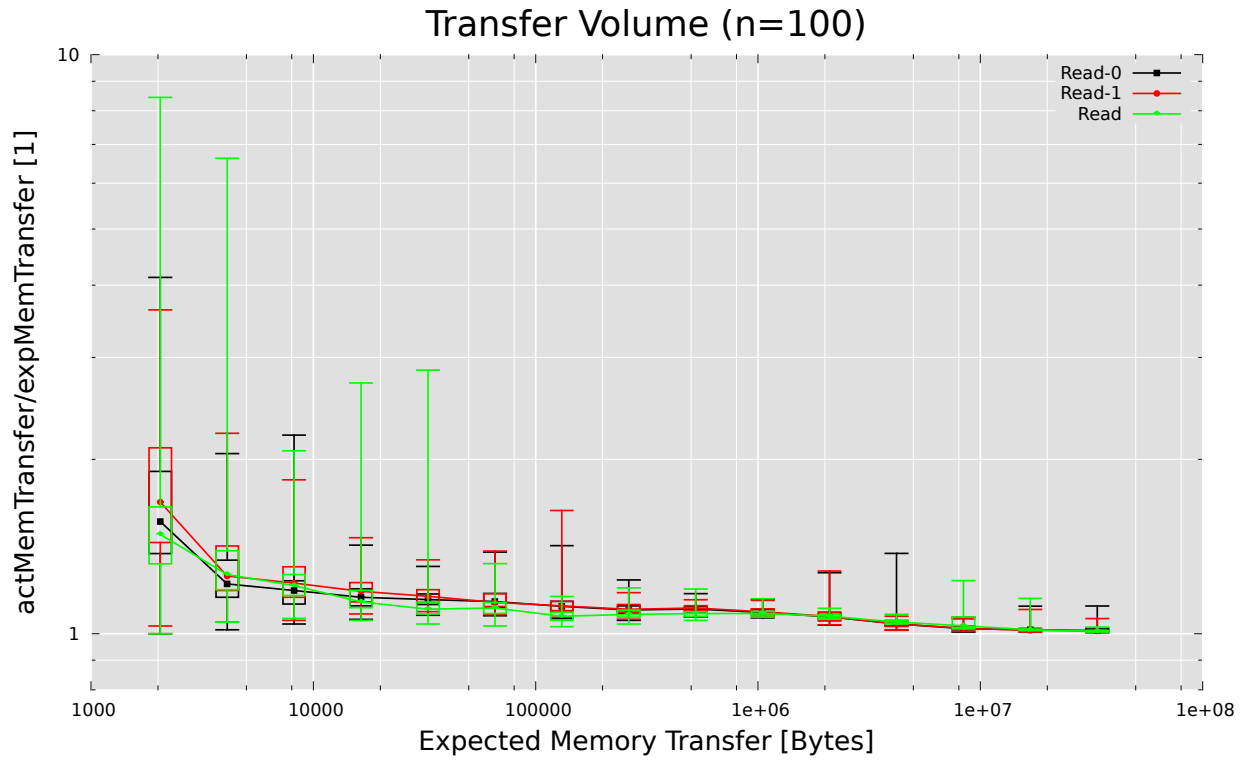
For the triad kernel there is almost no difference. (fig. 26)

### 4.3 Operation Count

As for the single threaded case, measuring the operation count does not pose any problems. (fig. 27)

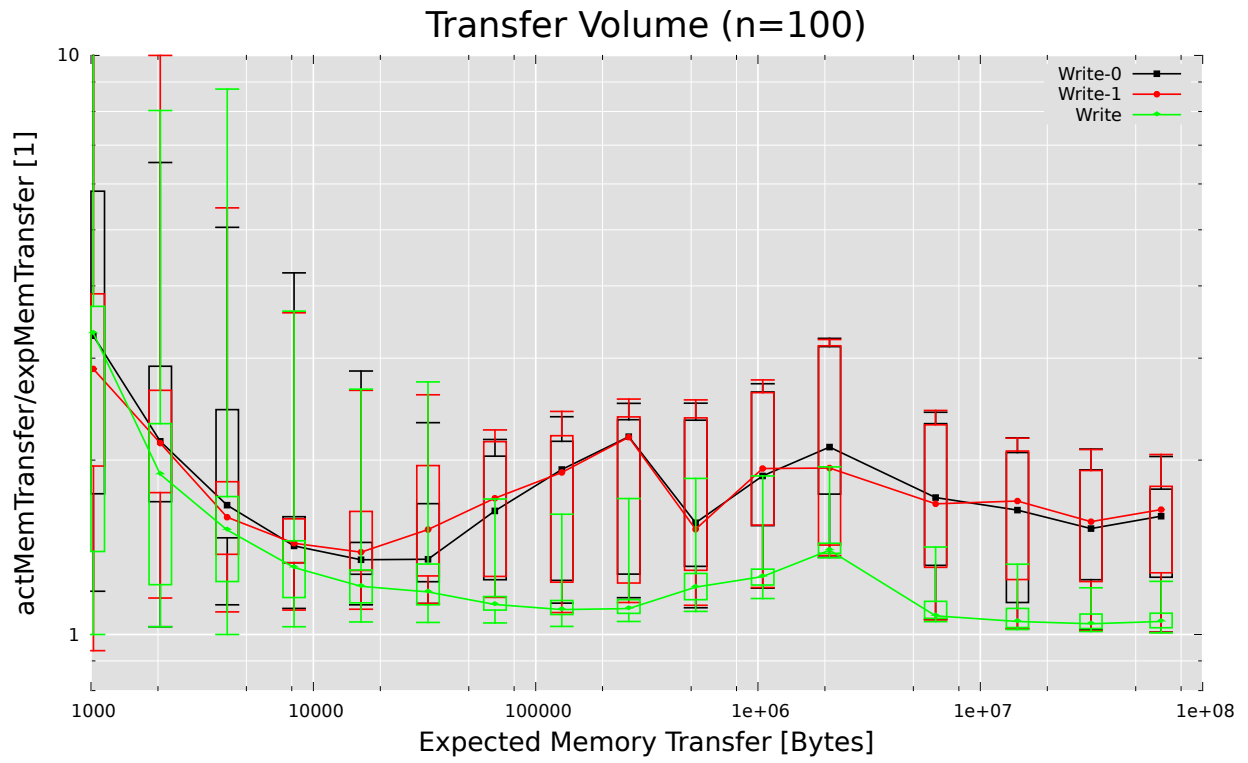


(a) MemBus

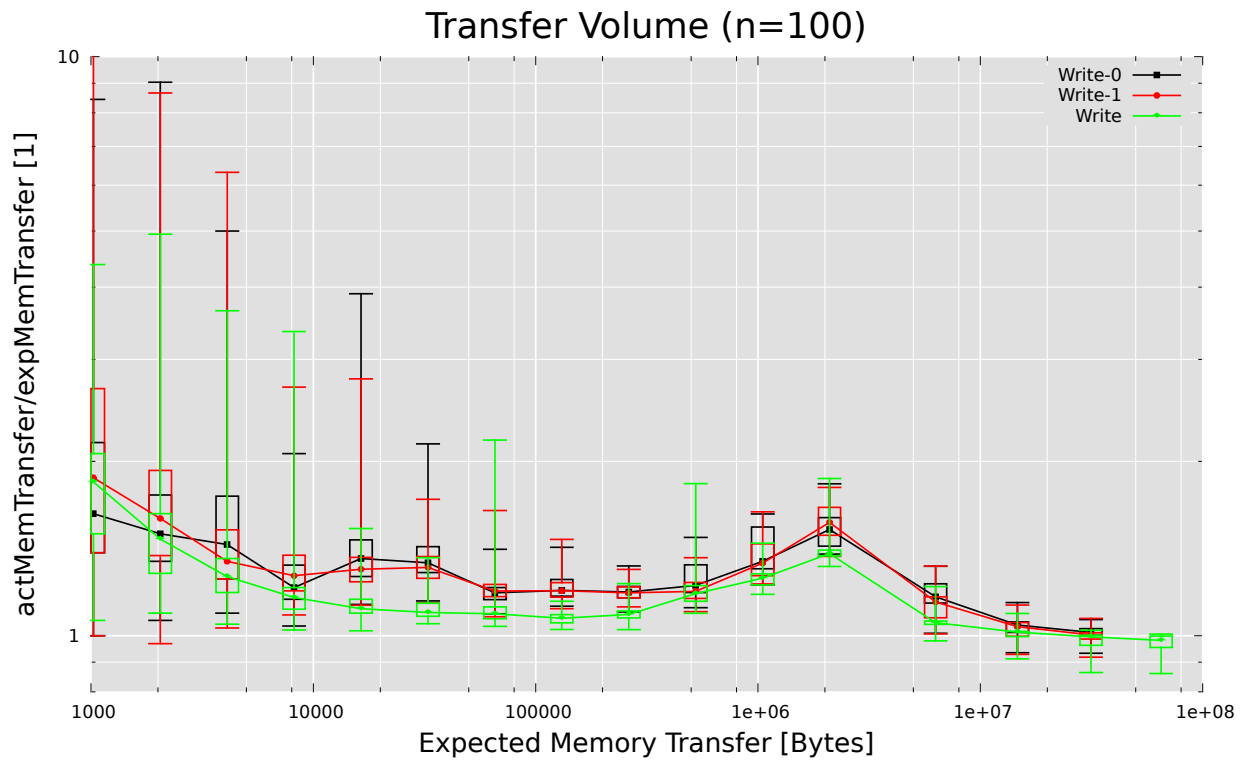


(b) MemL2

Figure 17: Transfer Volume of the Read Kernel

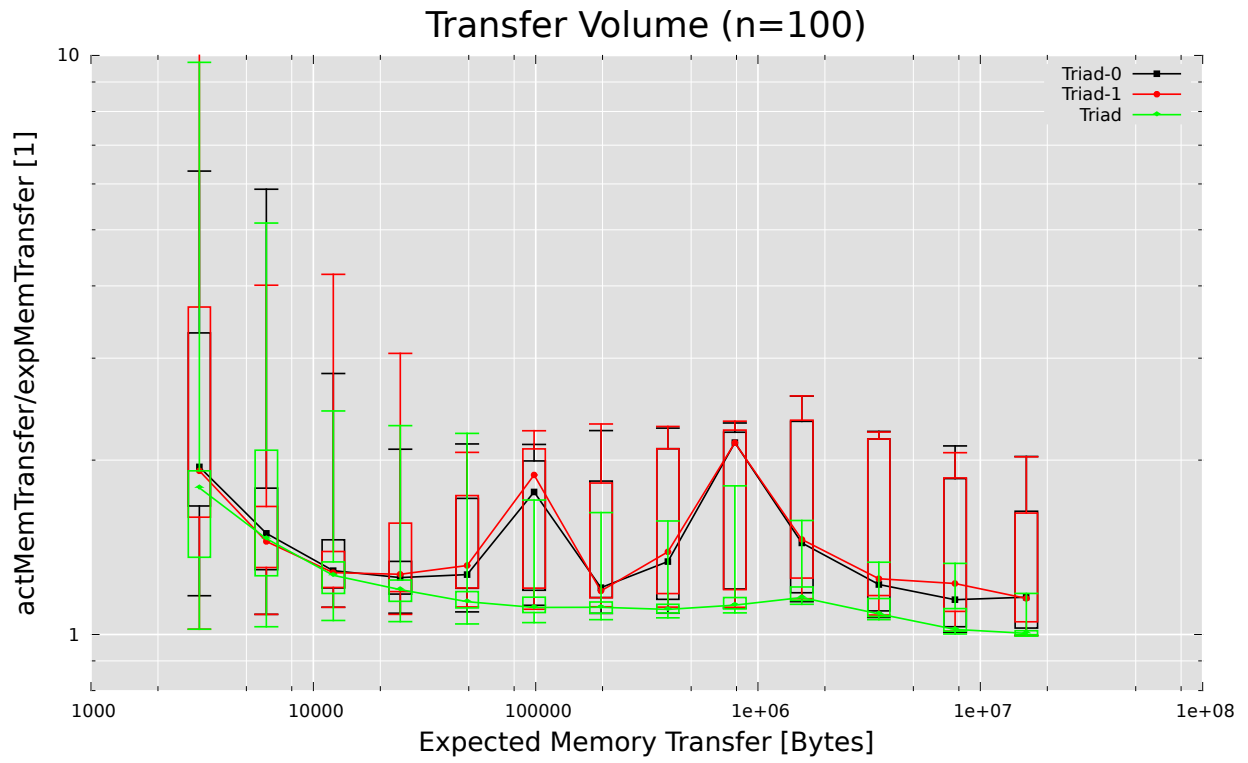


(a) MemBus

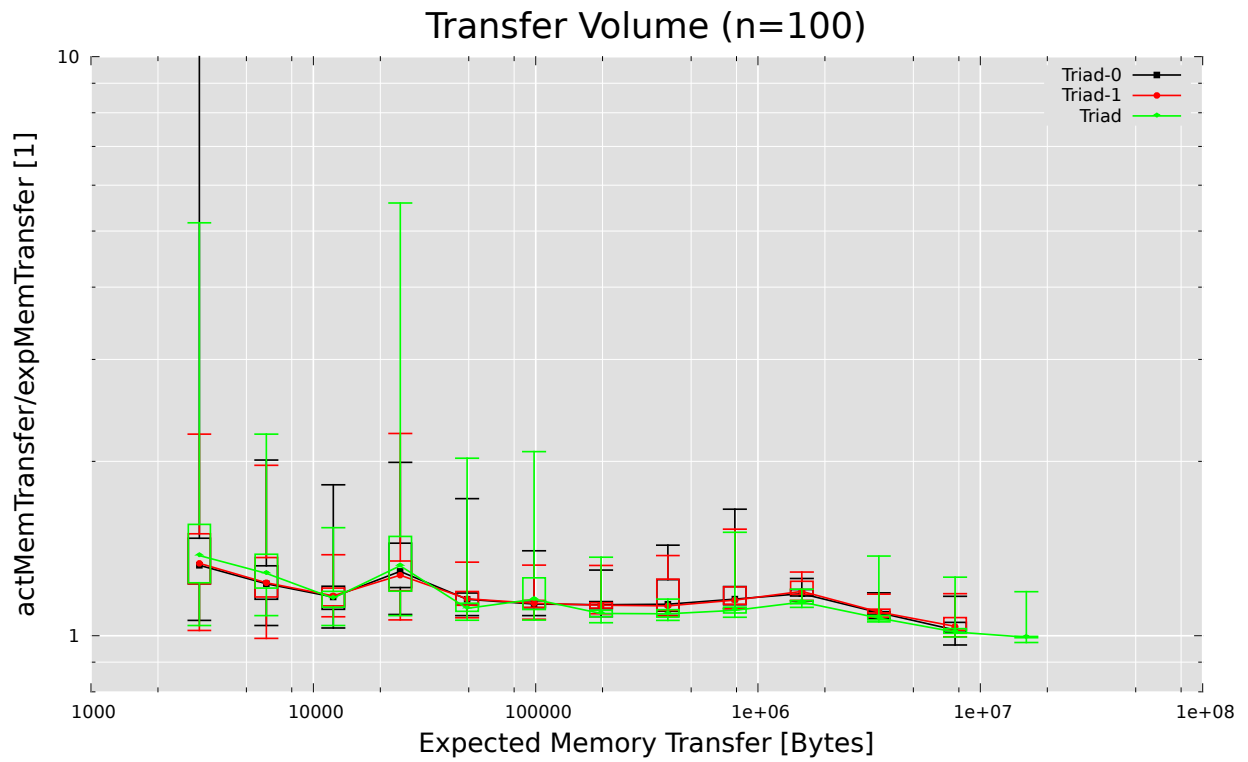


(b) MemL2

Figure 18: Transfer Volume of the Write Kernel



(a) MemBus



(b) MemL2

Figure 19: Transfer Volume of the Triad Kernel



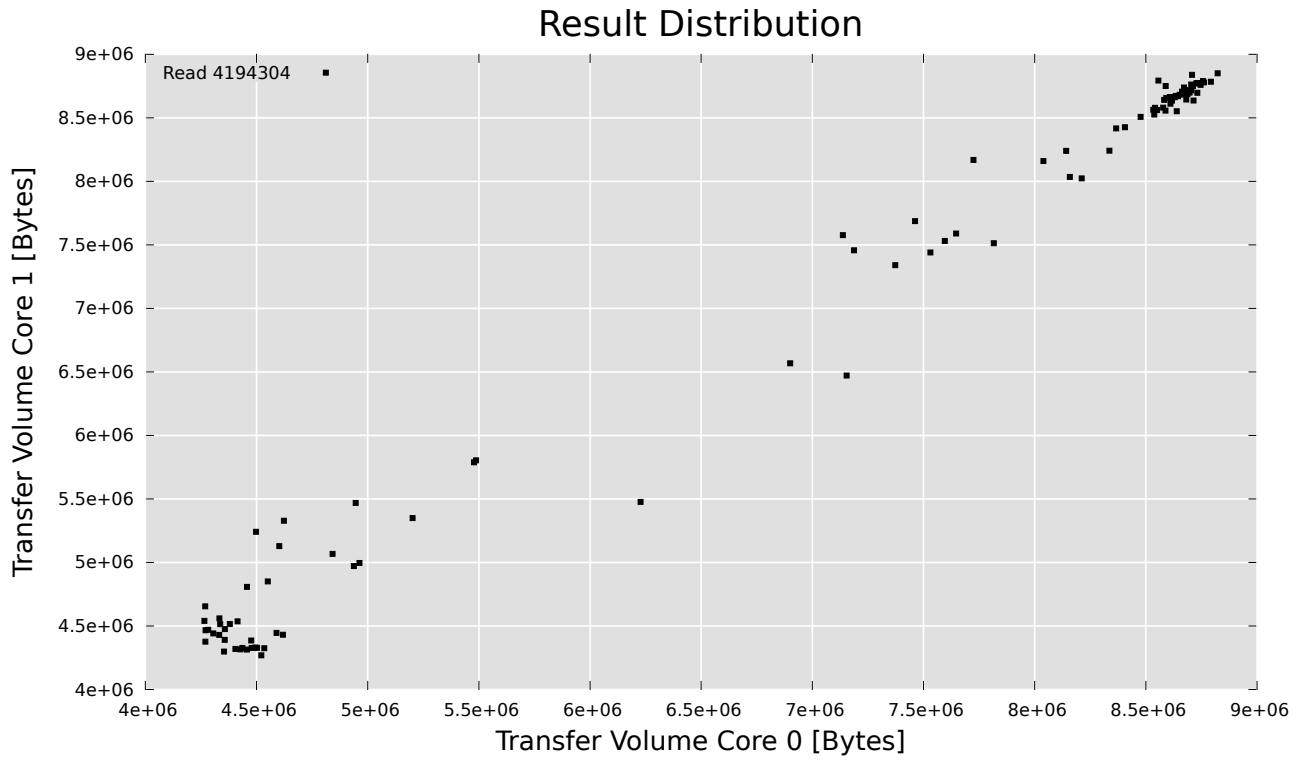


Figure 20: Distribution of the Results of the Read Kernel using MemBus

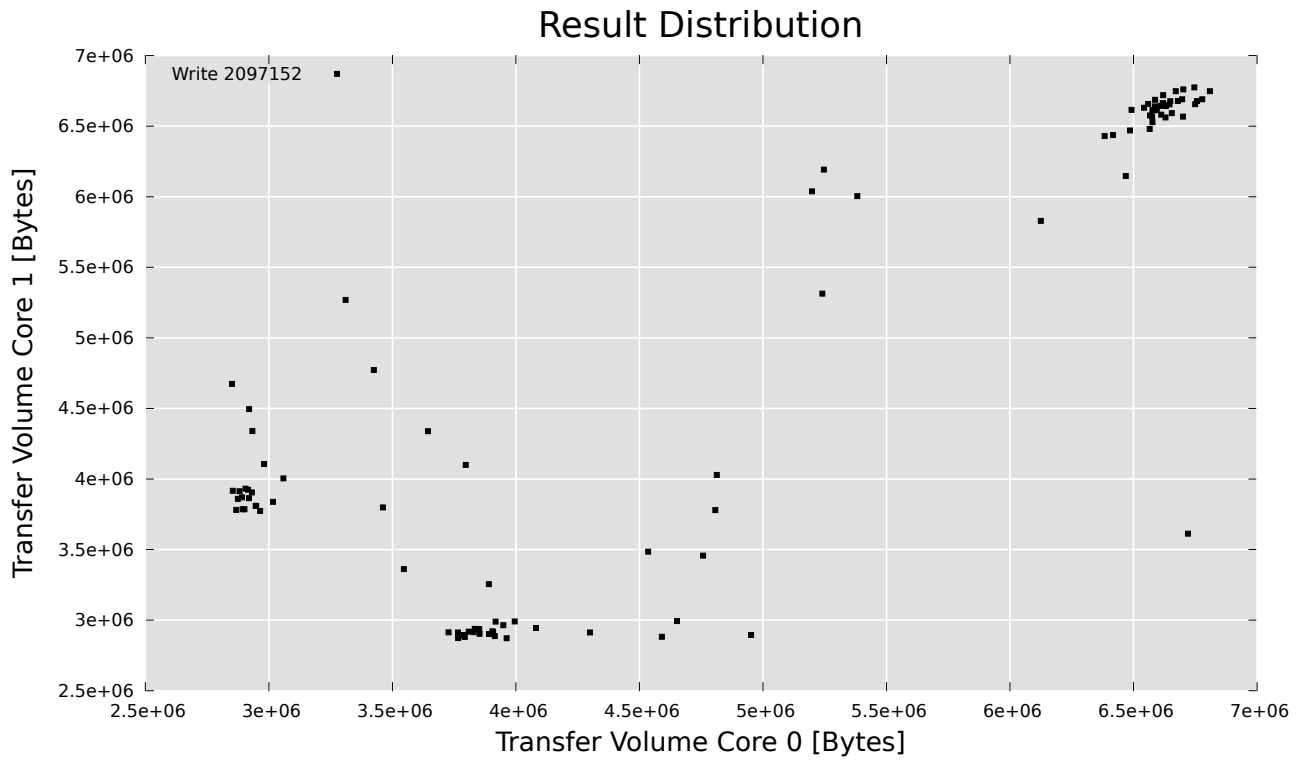


Figure 21: Distribution of the Results of the Write Kernel using MemBus

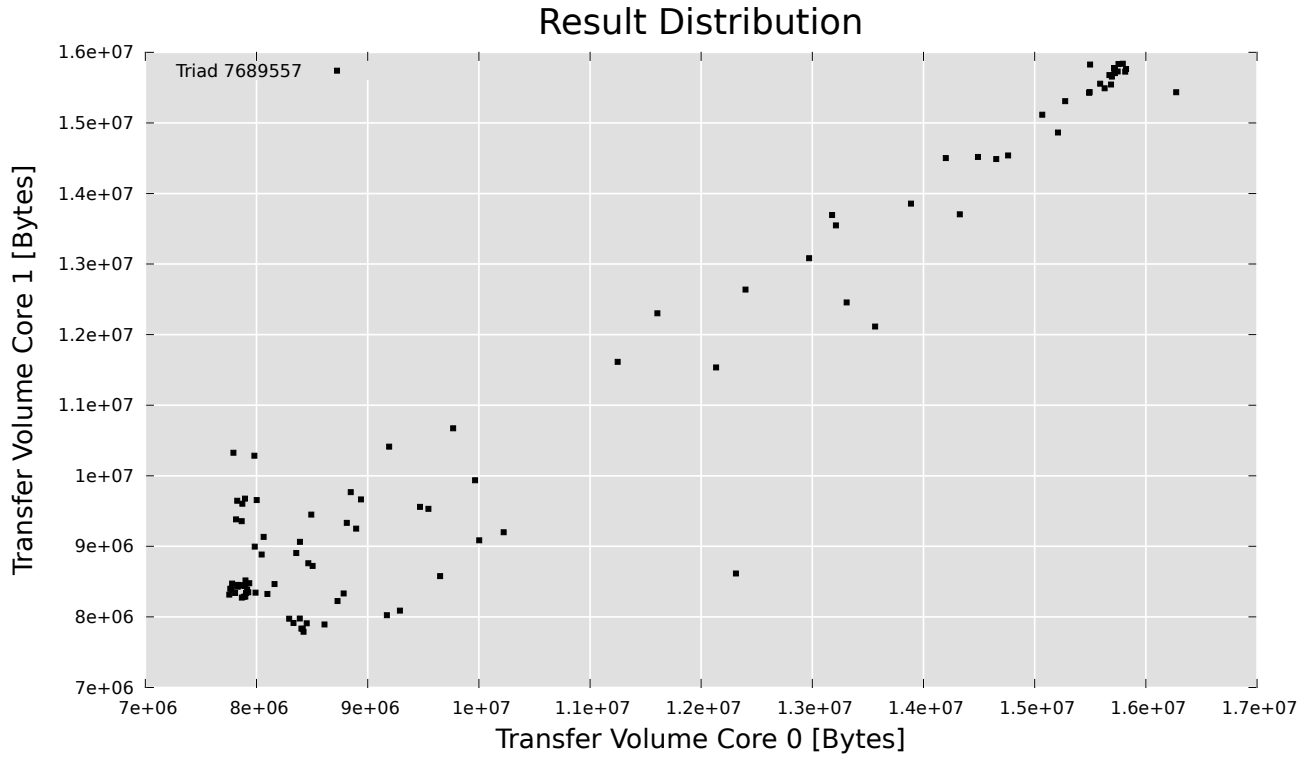


Figure 22: Distribution of the Results of the Triad Kernel using MemBus

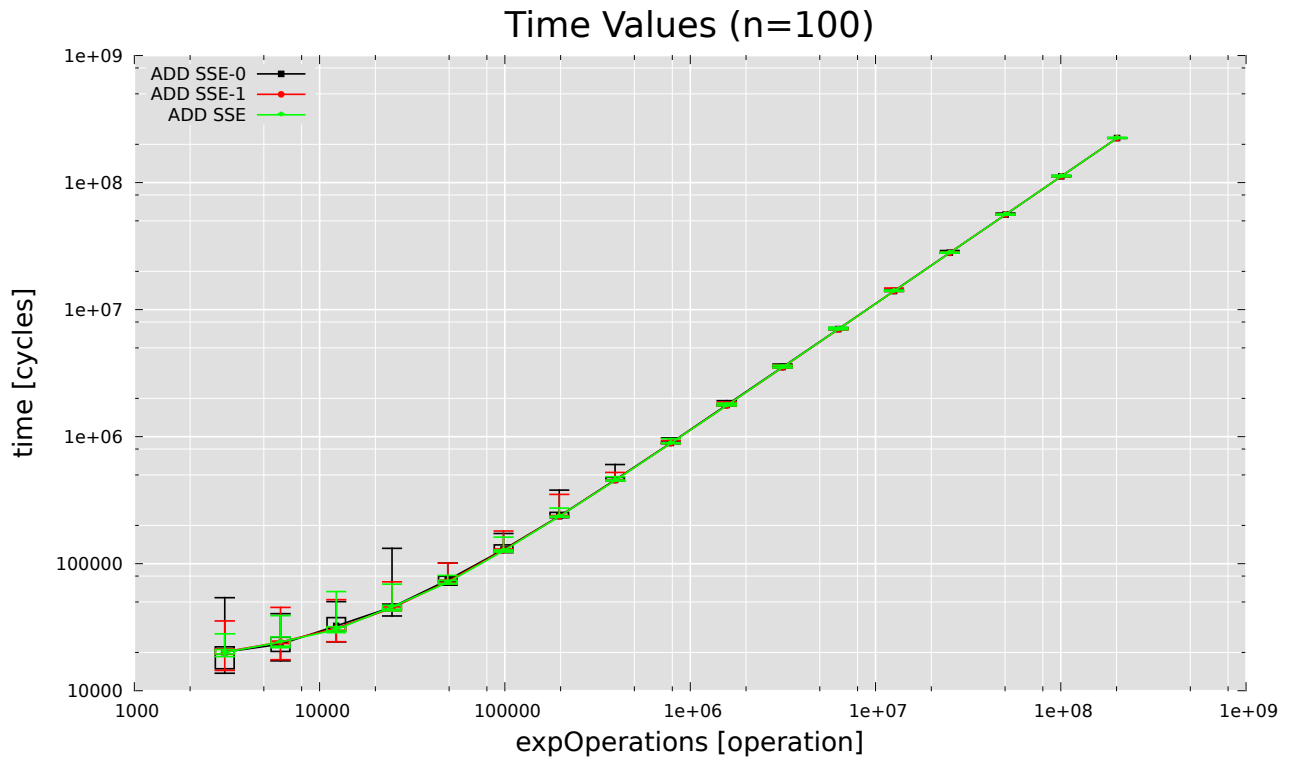


Figure 23: Execution Time of two ADD Kernels running at the same time

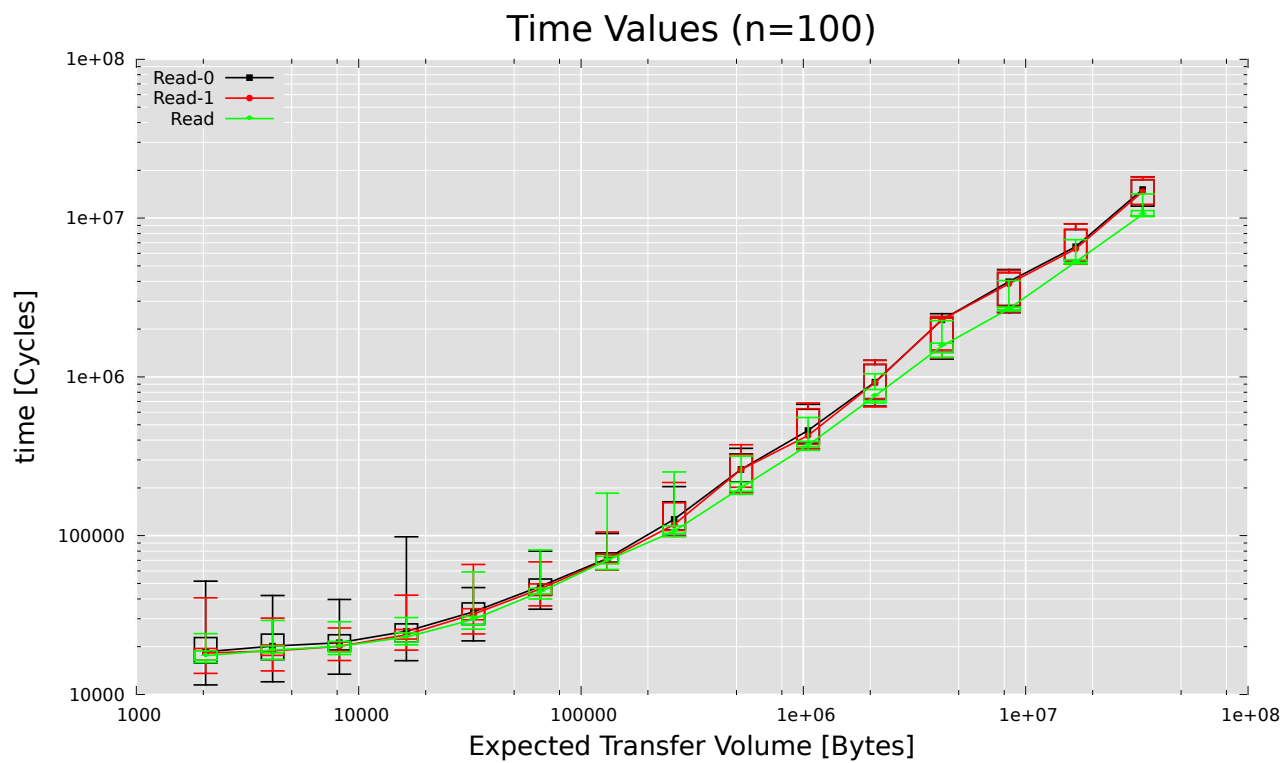


Figure 24: Execution Time of two Read Kernels running at the same time

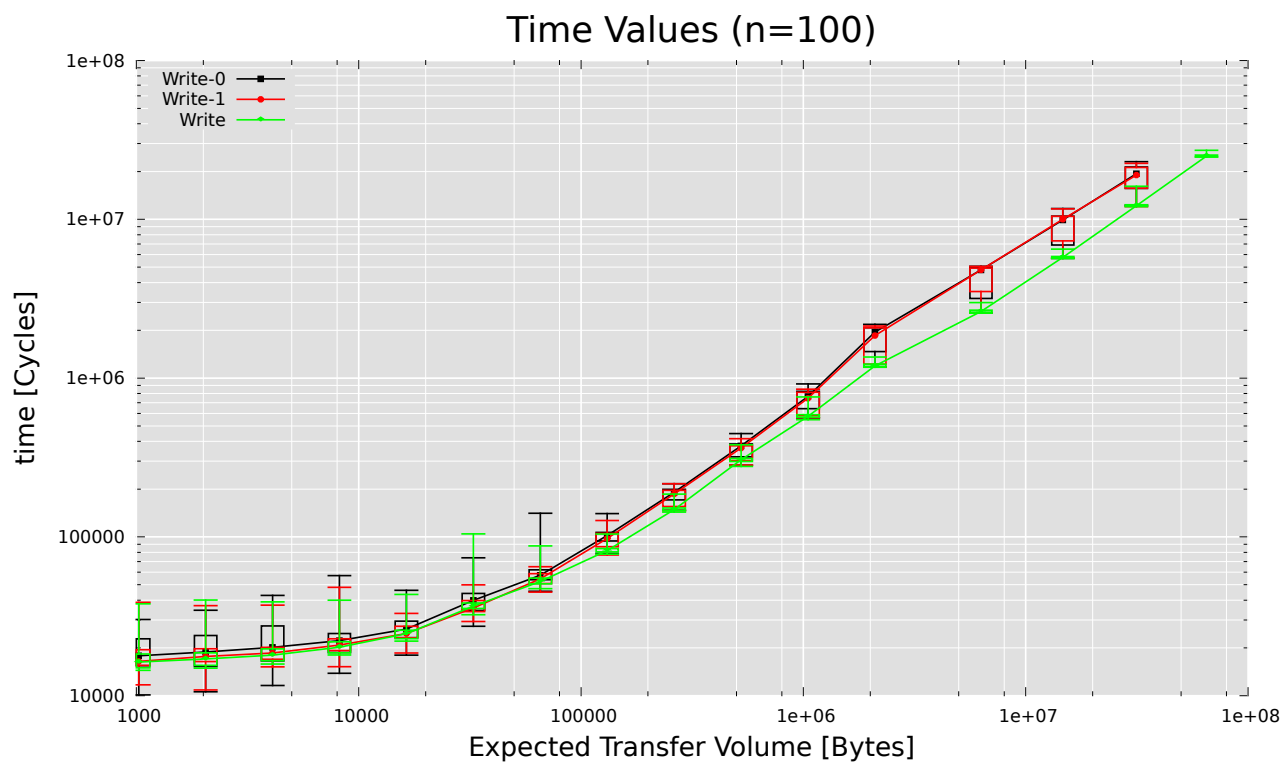


Figure 25: Execution Time of two Write Kernels running at the same time

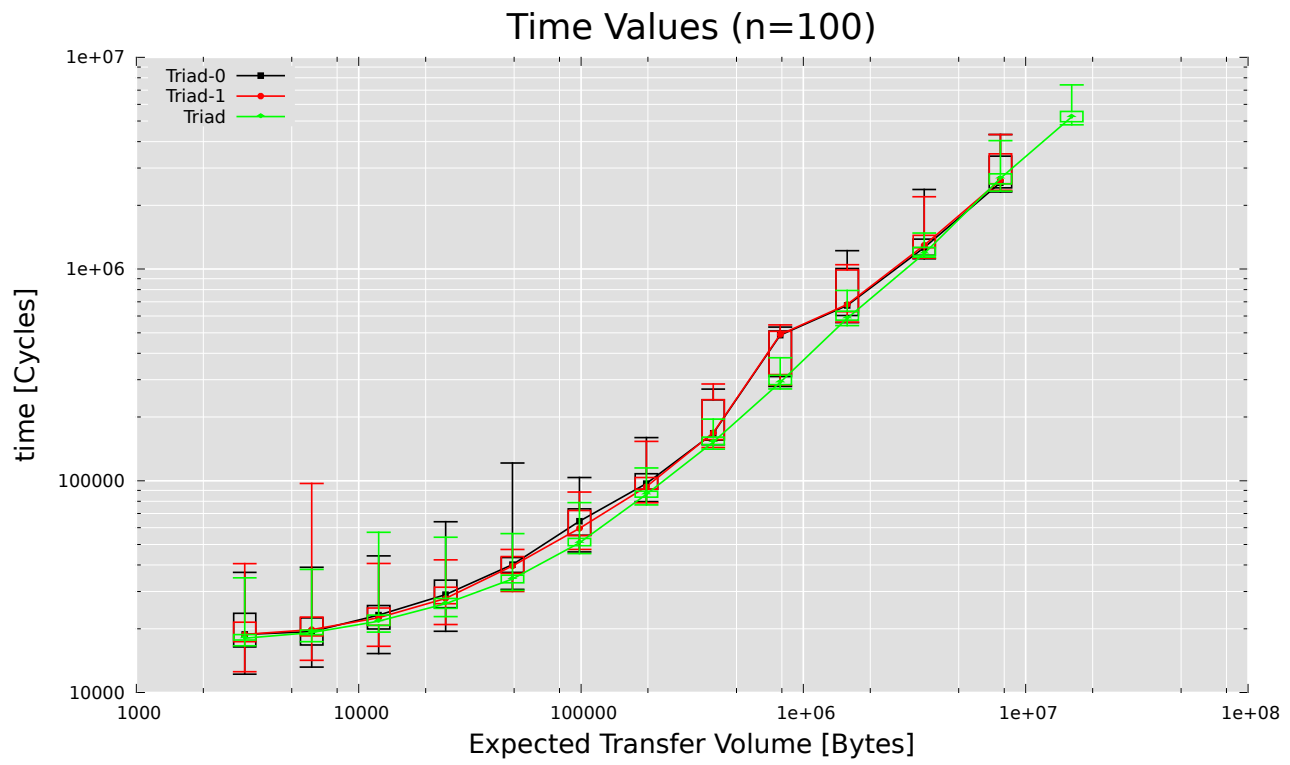


Figure 26: Execution Time of two Triad Kernels running at the same time

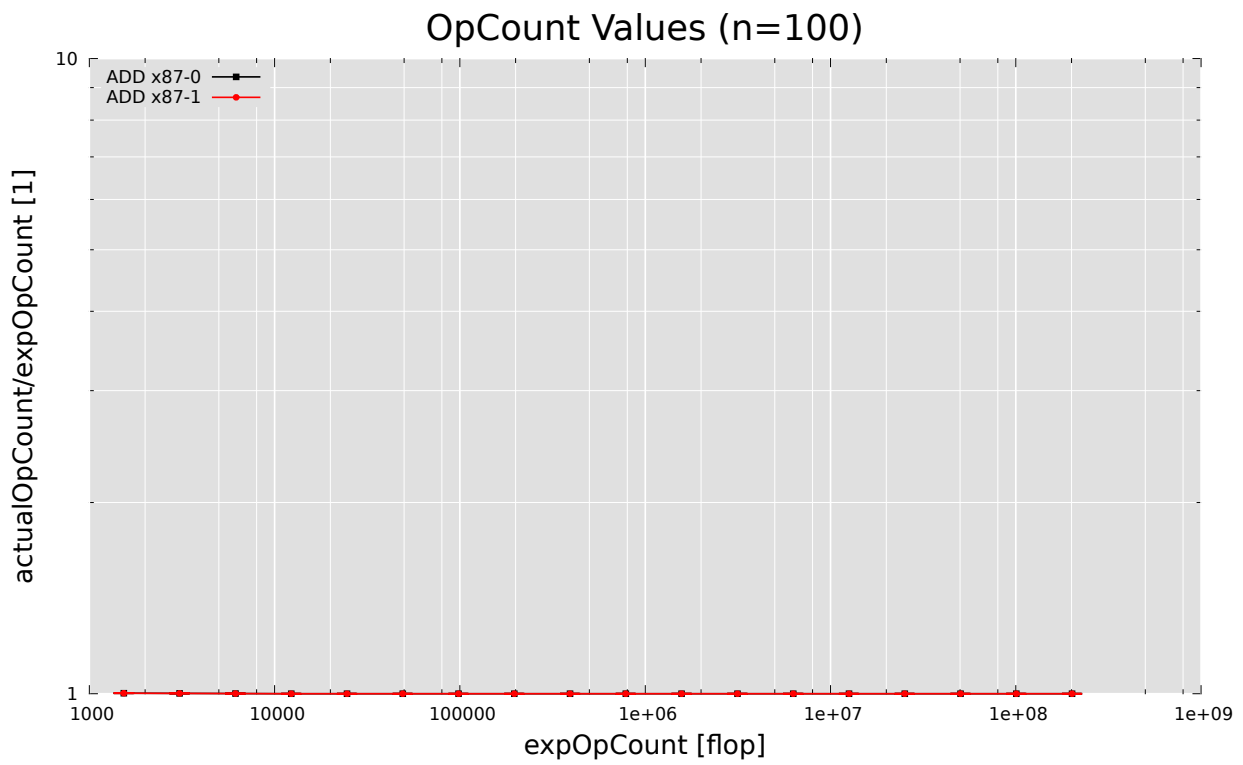


Figure 27: Operation Count

## 4.4 Handling the Variance

We again use the minimum of  $K = 10$  scheme. (see 3.4)

When measuring the transfer volume we achieve a variation below 10%. The overhead is around 20% for small buffers, and goes towards zero for transfer volumes exceeding 10MB. (figs 28, 29 and 30)

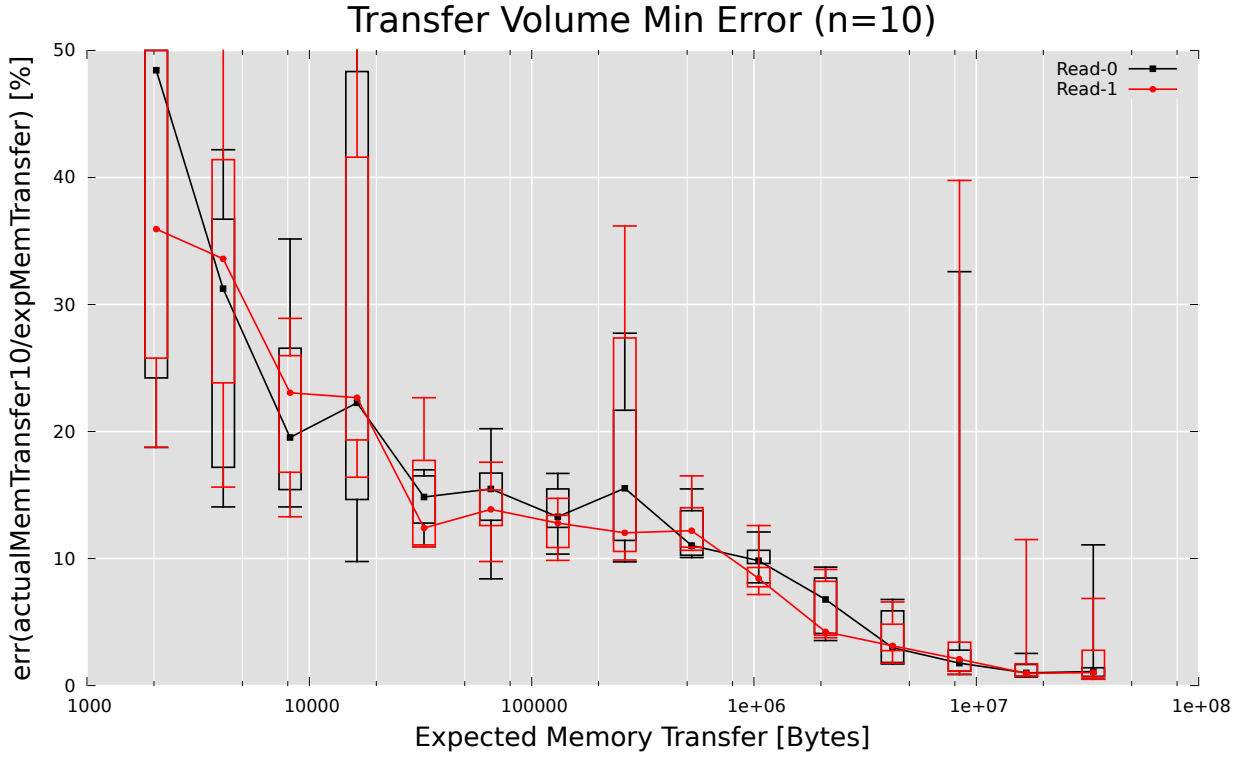
For the execution time, we observe huge variations for small buffer sizes. If the expected transfer volume exceeds 20KB, the variations drop to around 10% and become large again for transfer volumes exceeding 10MB. (figs. 31, 32 and 33)

The variations observed when running two ADD kernels in parallel are small except for iteration counts below 100000. (fig. 34)

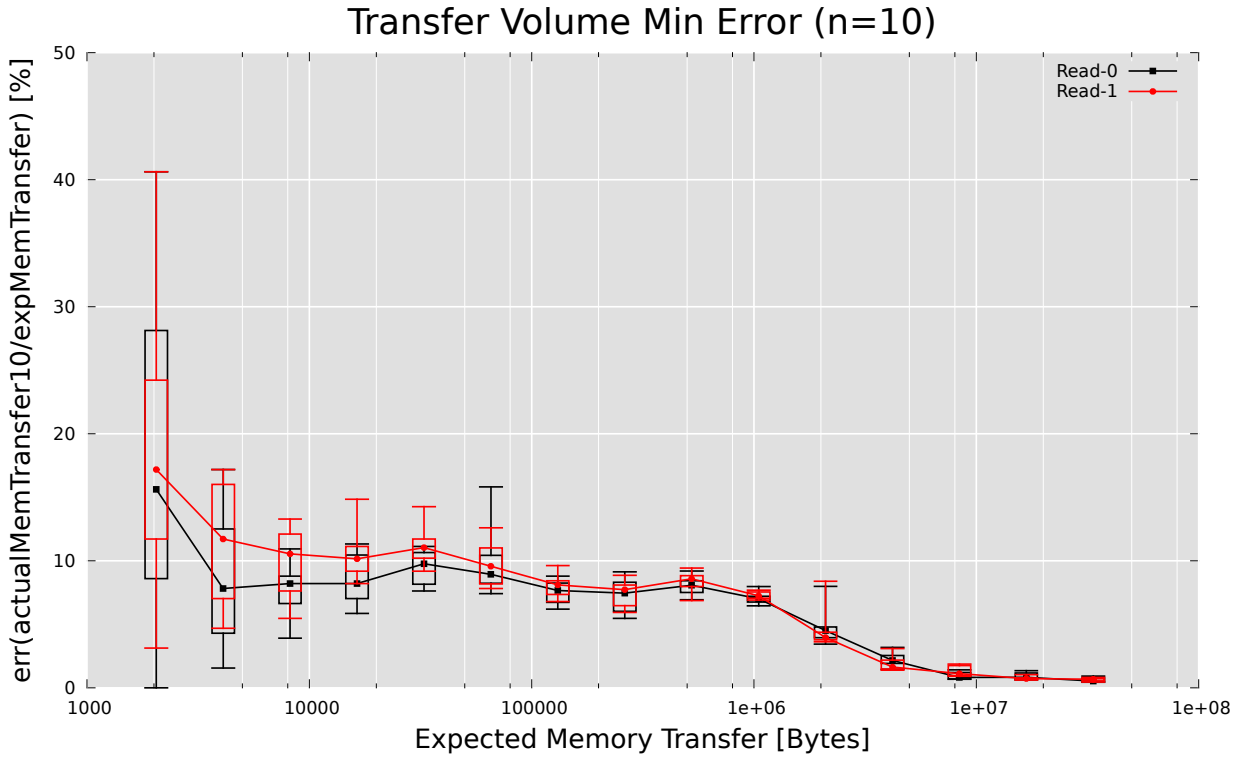
As expected, the results for the operation count are perfect (fig. 35)

Summarizing our results, using the minimum of  $K$  scheme with  $K = 10$  the arithmetic kernels can be measured with high precision and accuracy.

The results of measuring the transfer volume of memory intensive kernels are scattered within 10% of the reference value and overestimated by about 20% for transfer volumes below 10MB. The results of measuring the execution time have generally a high variance, except for transfer volumes between 20KB and 10MB.

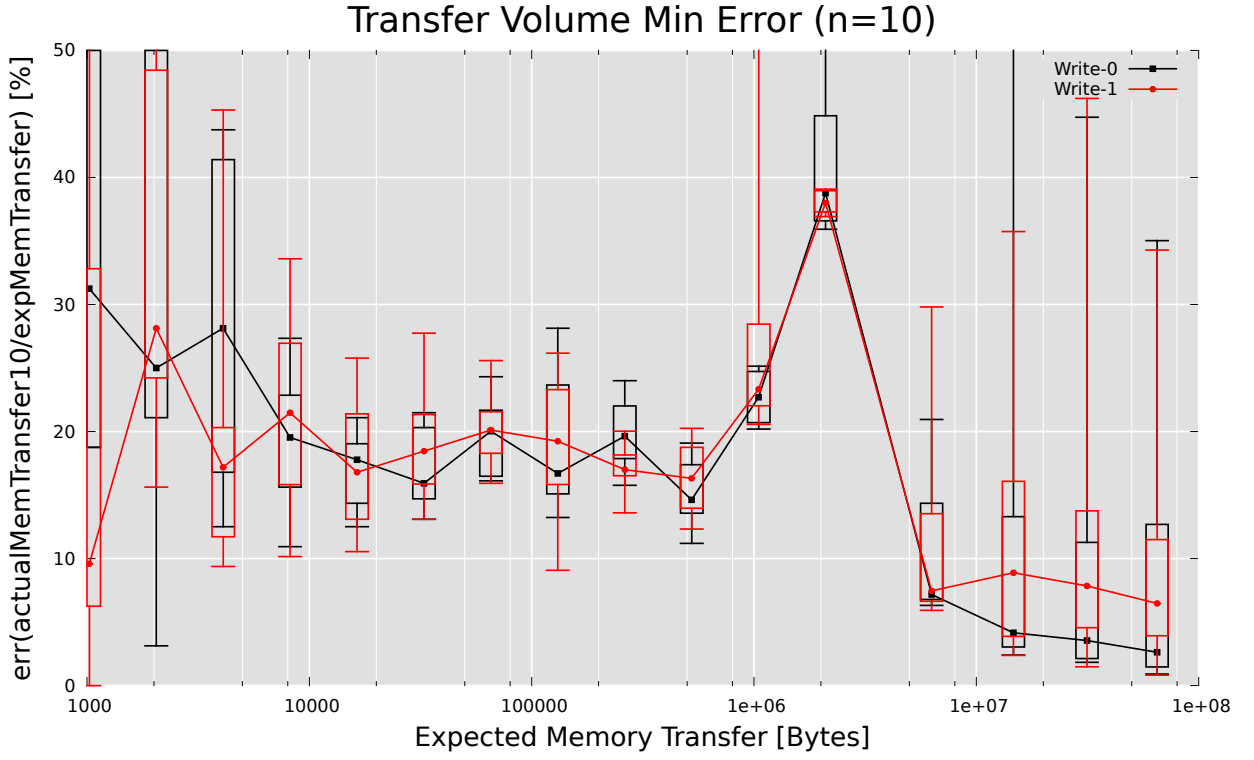


(a) MemBus

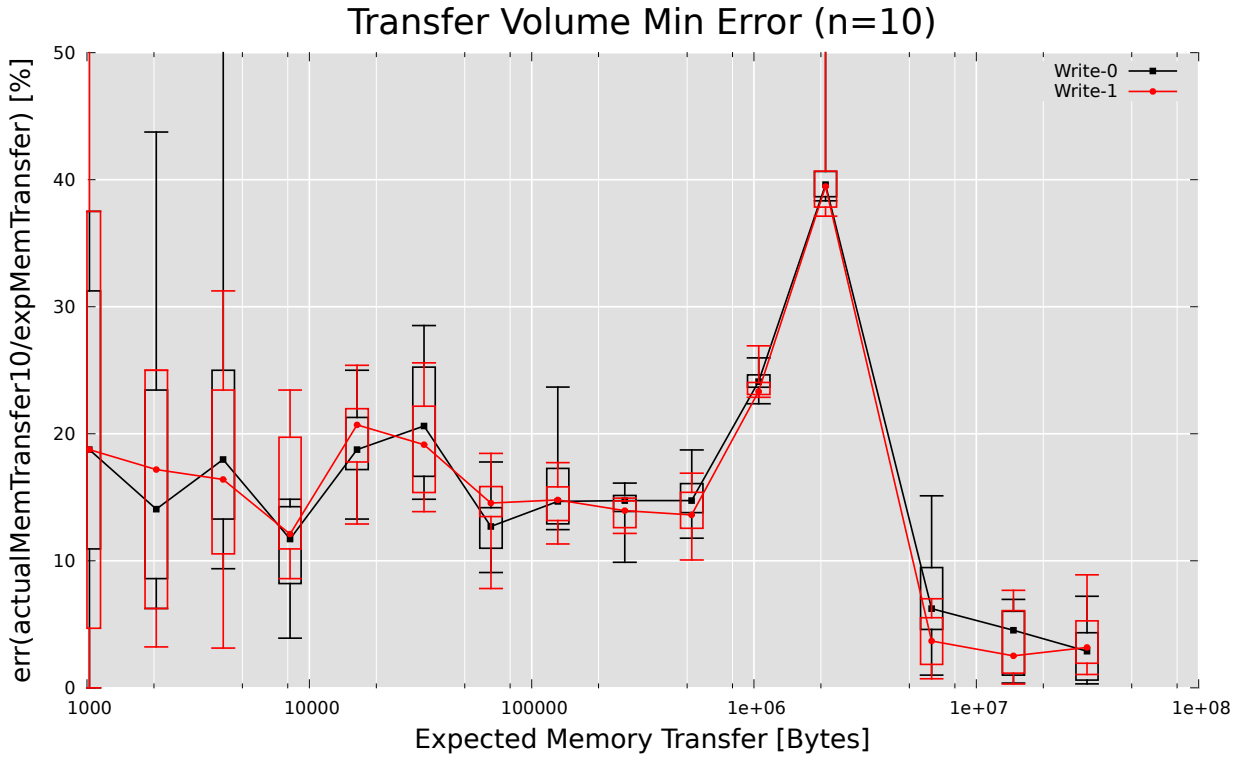


(b) MemL2

Figure 28: Error of the Transfer Volume of the Read Kernel with  $K = 10$

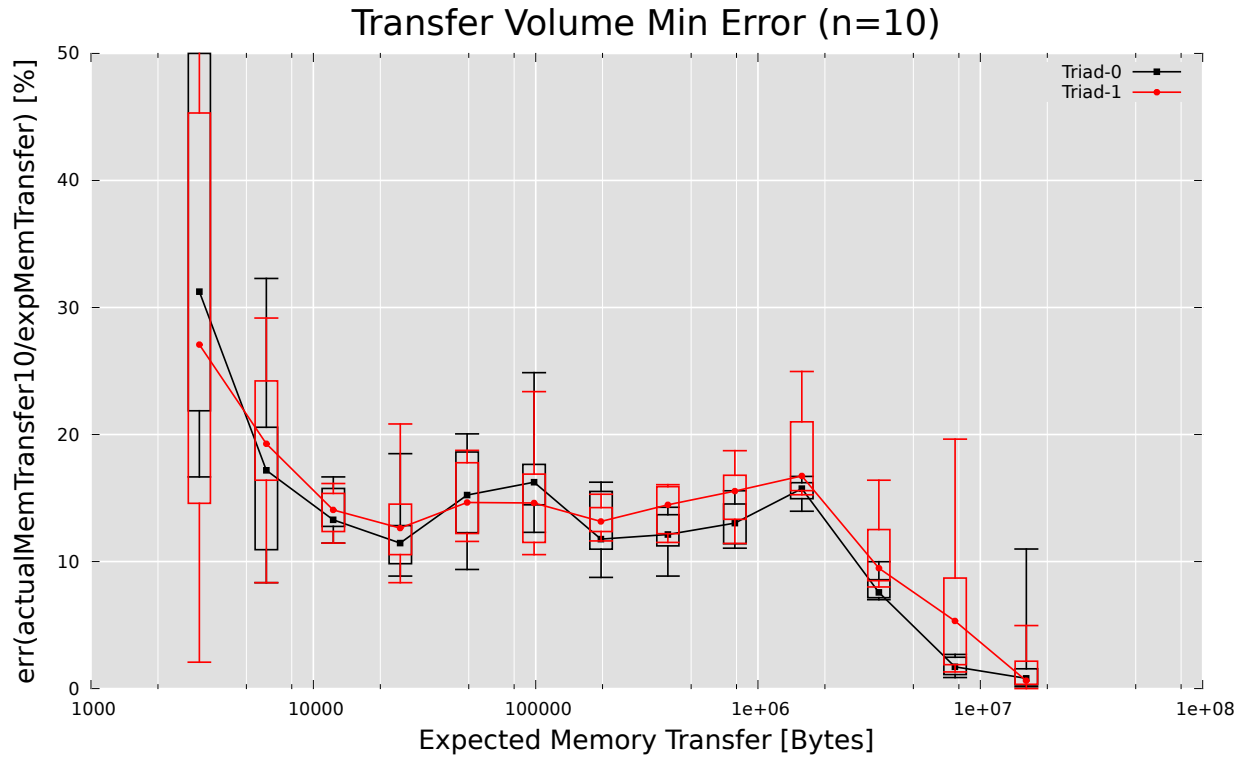


(a) MemBus

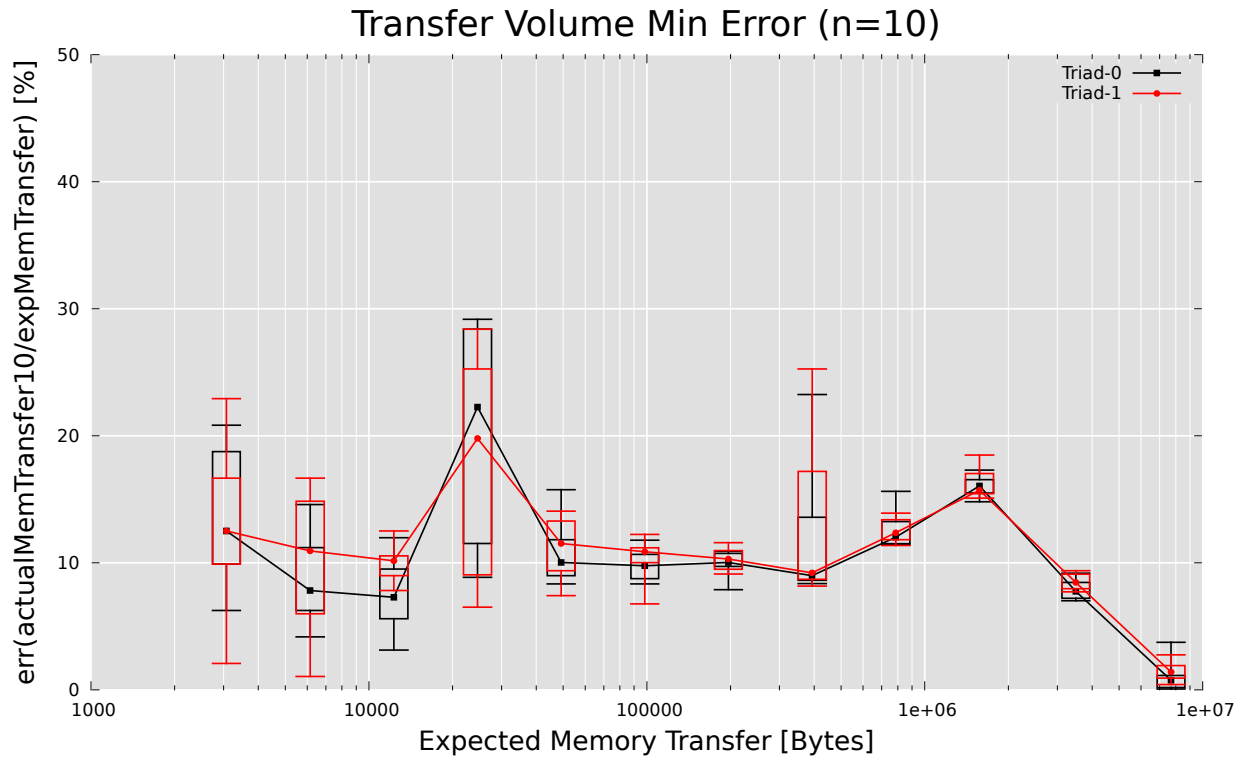


(b) MemL2

Figure 29: Error of the Transfer Volume of the Write Kernel with  $K = 10$



(a) MemBus



(b) MemL2

Figure 30: Error of the Transfer Volume of the Triad Kernel with  $K = 10$



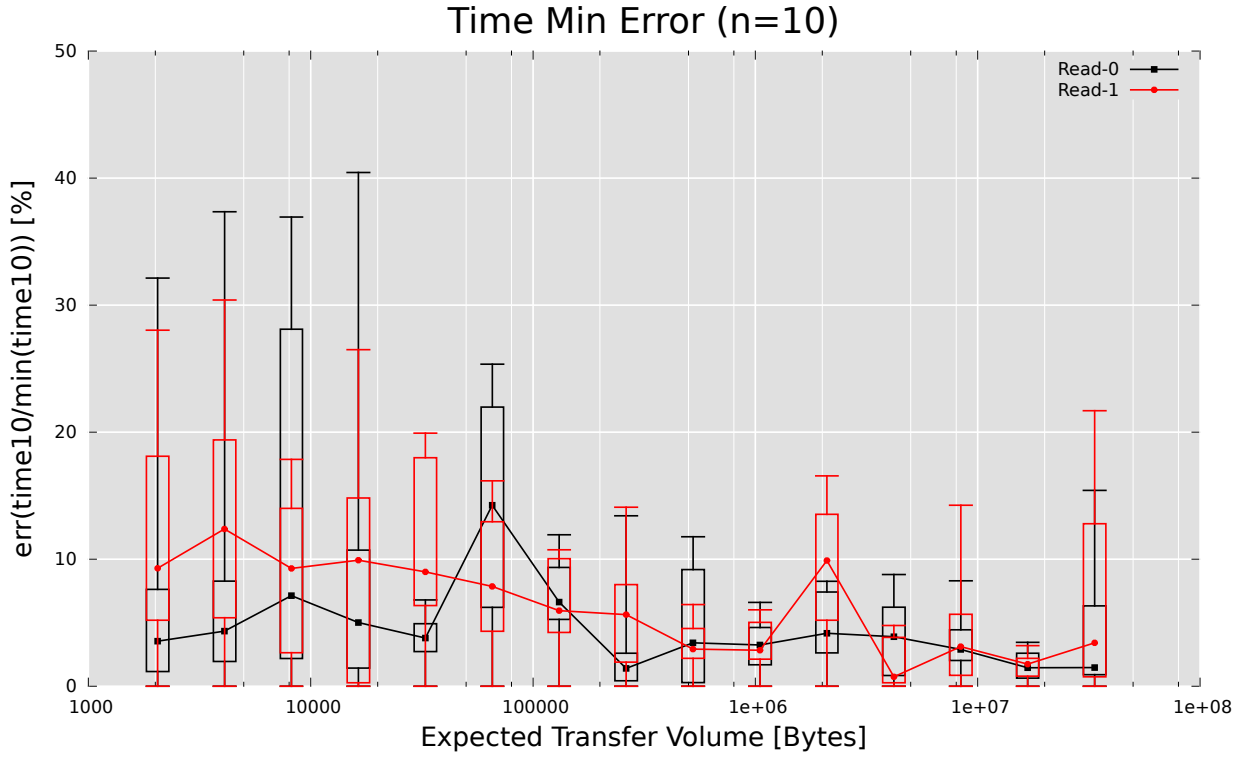


Figure 31: Error of the Execution Time of two Read Kernels running at the same time with  $K = 10$

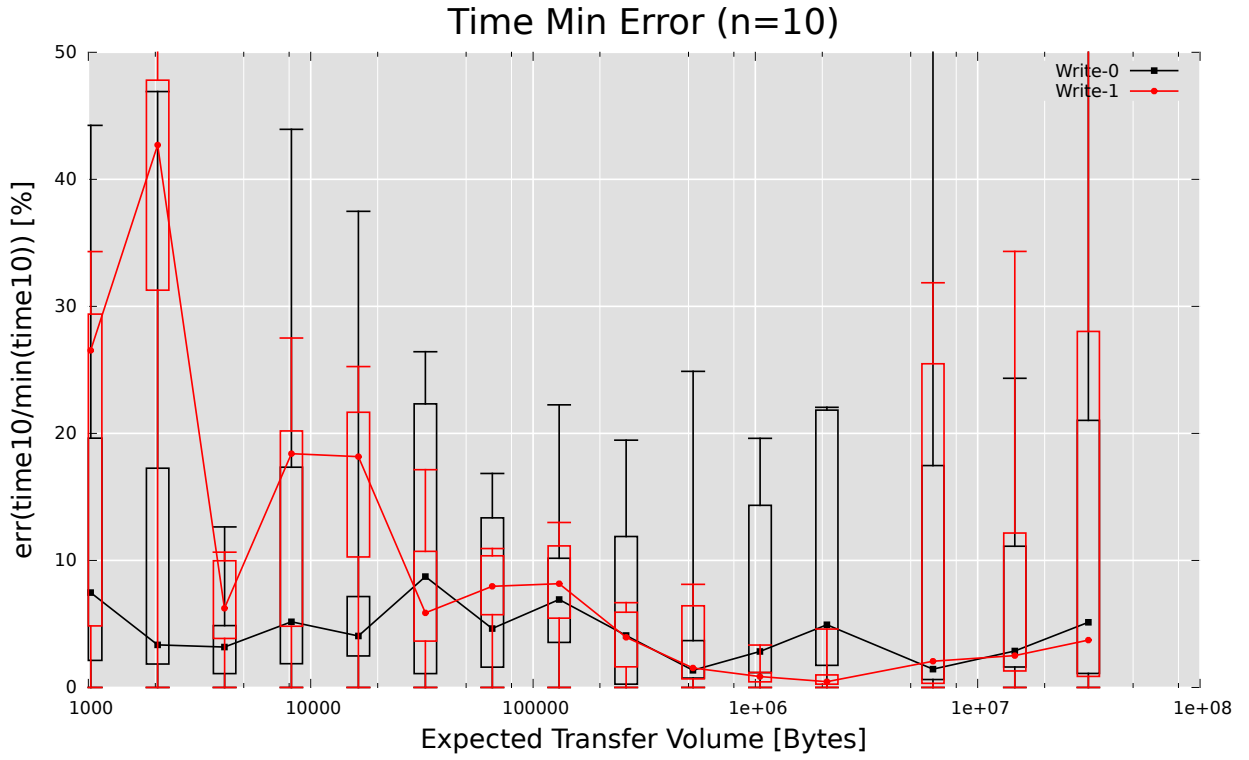


Figure 32: Error of the Execution Time of two Write Kernels running at the same time with  $K = 10$

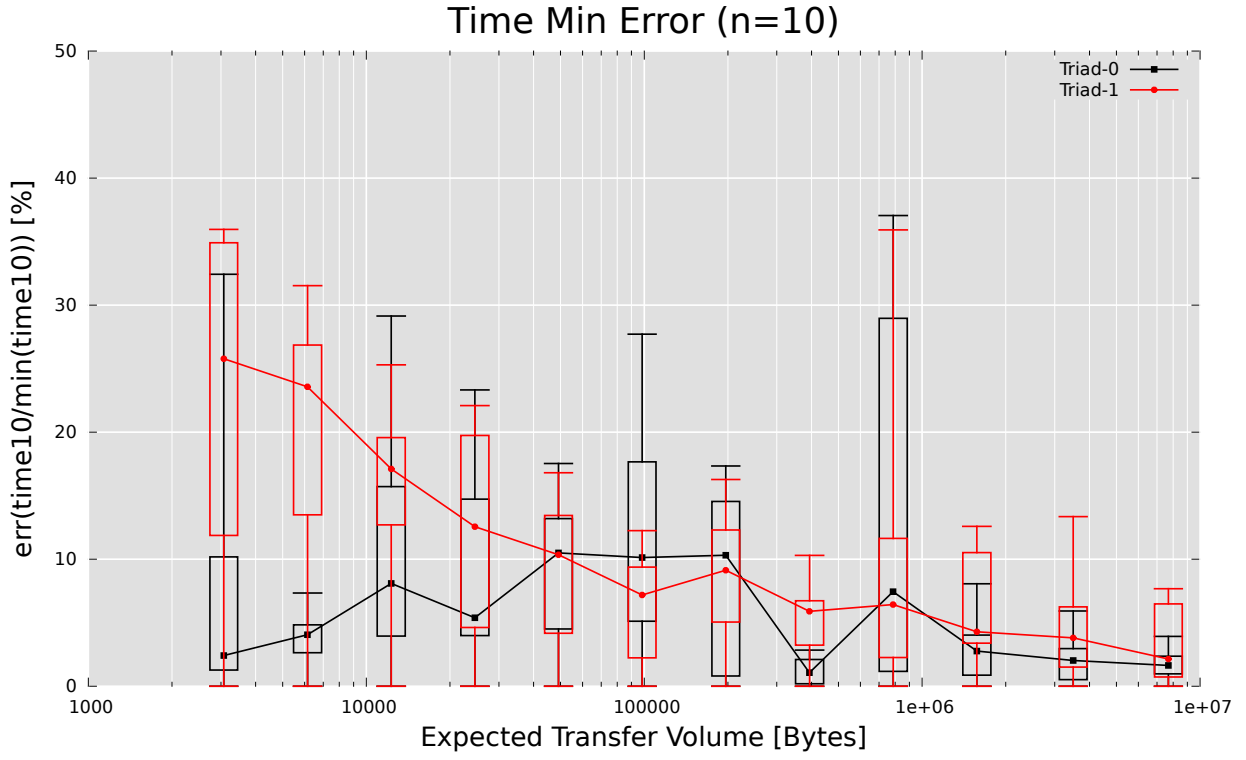


Figure 33: Error of the Execution Time of two Triad Kernels running at the same time with  $K = 10$

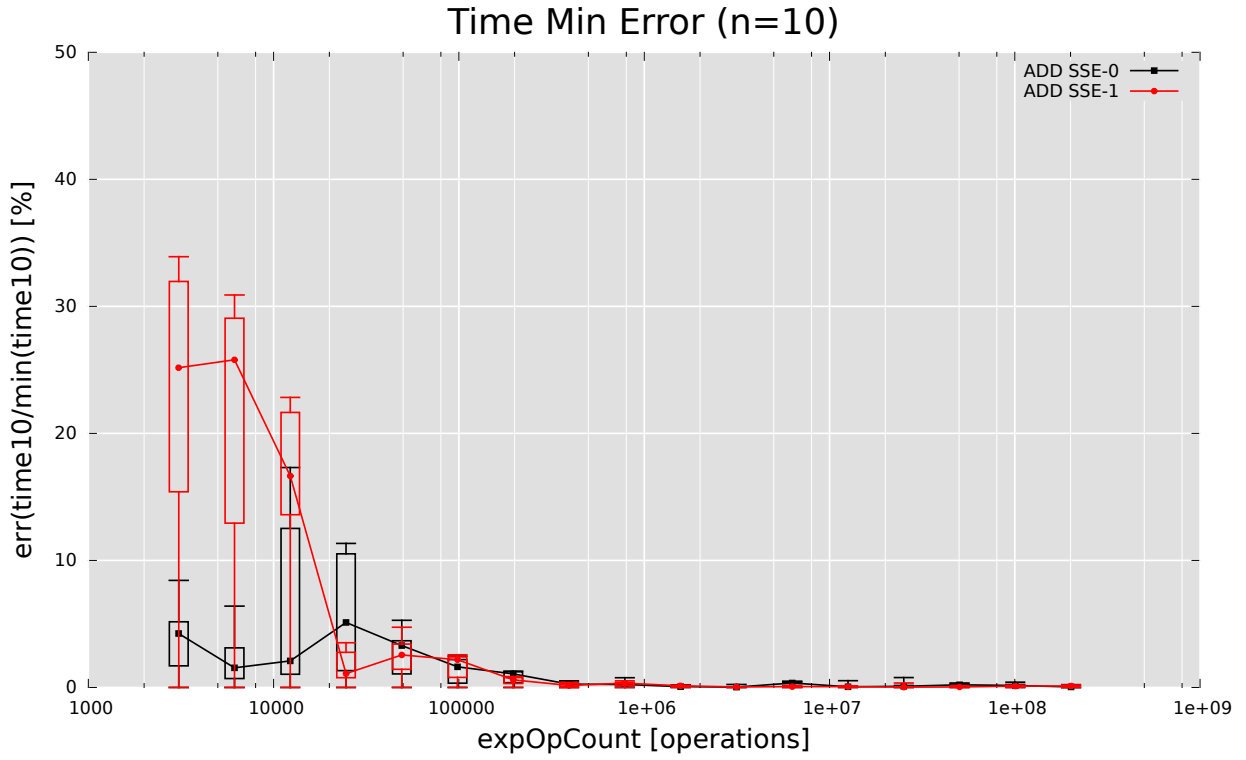


Figure 34: Error of the Execution Time of two ADD Kernels running at the same time with  $K = 10$

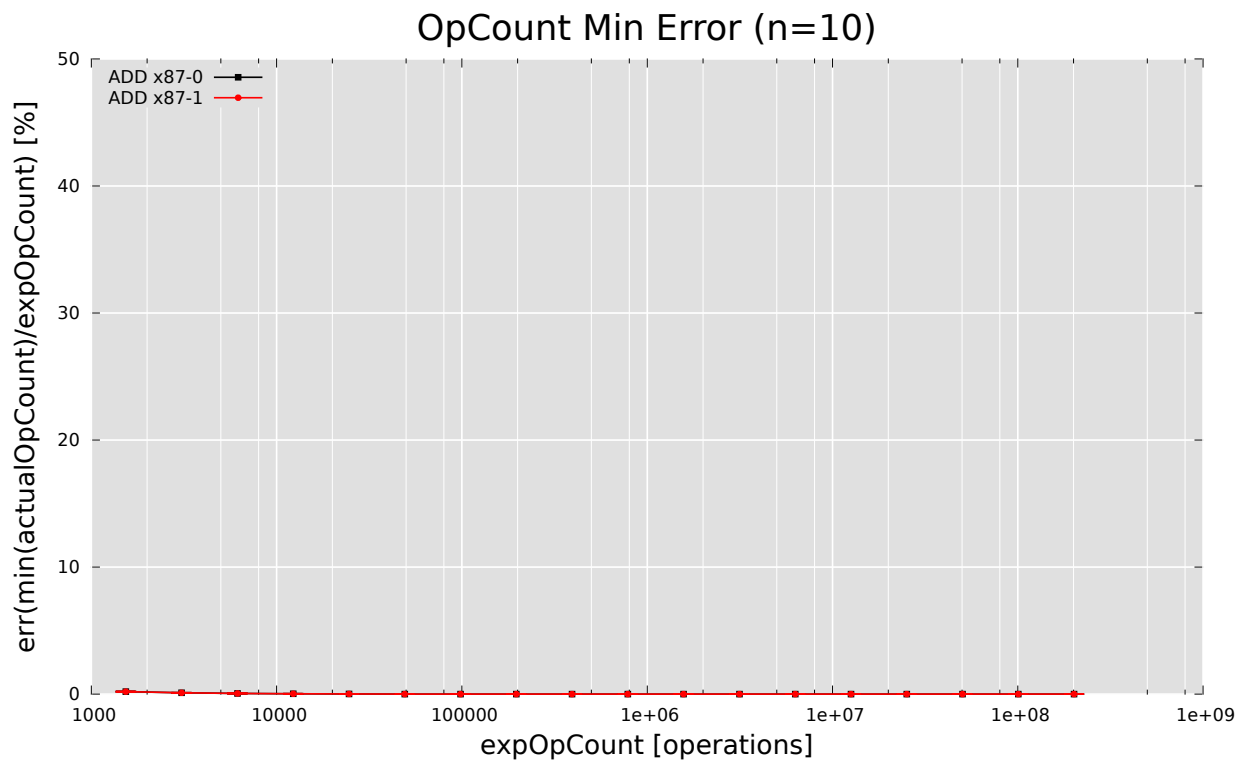


Figure 35: Error of the Operation Count with  $K = 10$

## 5 Experimental Results

We used our tool to measure various kernels. For each kernel we describe the kernel and the measurement setup and show the resulting roofline plot.

### 5.1 BLAS

Basic Linear Algebra Subprograms (BLAS) is a standard API for basic linear algebra operations. The functionality is divided into three levels:

**Level 1** Vector-Vector Operations

**Level 2** Matrix-Vector Operations

**Level 3** Matrix-Matrix Operations

For each level, we chose a representative operation and generated roofline plots using the Intel Math Kernel Library (MKL) [7] and the OpenBlas [3] implementations.

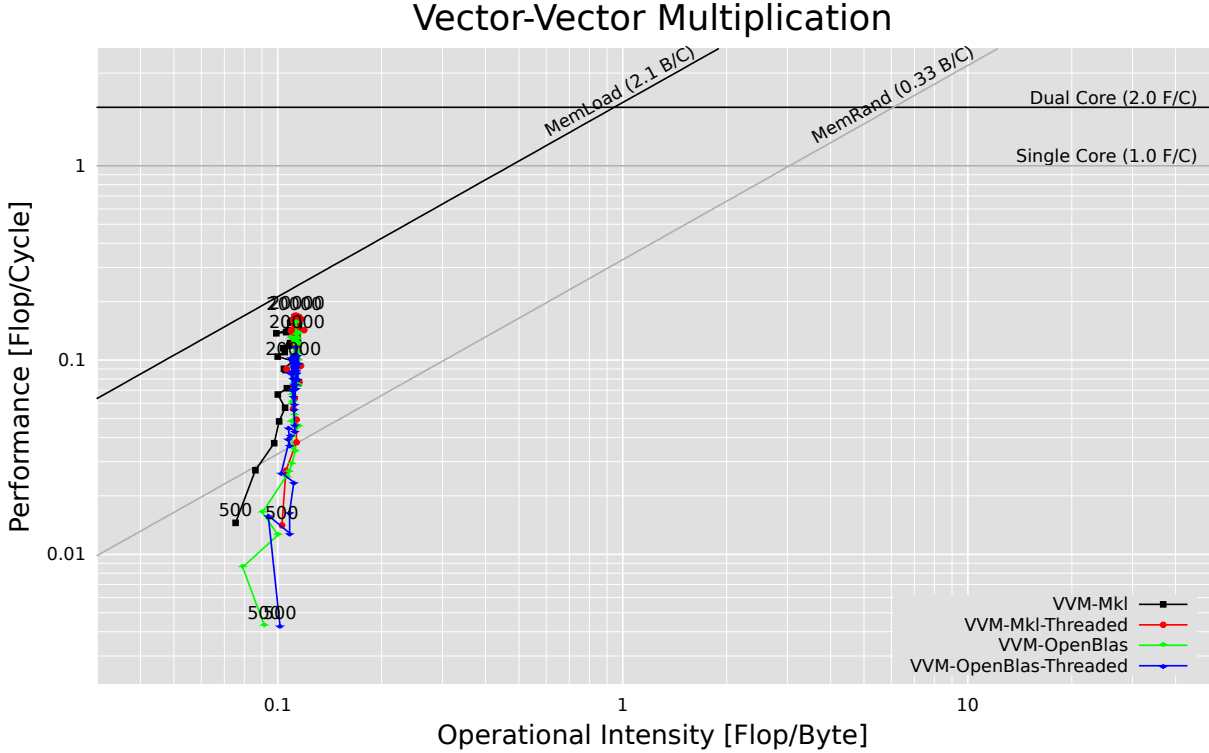


Figure 36: Roofline Plot of the Vector-Vector Multiplication (MemL2, DoublePrecisionFlop)

For level 1, we chose the 'daxpy' operation, defined as  $\mathbf{y} \leftarrow \alpha \mathbf{x} + \mathbf{y}$  with double vectors. There is no reuse in this kernel. For every vector element triple, two operations are performed. Since the vector sizes we measure fits into the last level cache, we don't have to take the write backs into account. The maximal operational intensity is  $2/(2 * 8) = 1/8 = 0.125$  which is confirmed by figure 36.

For level 2, we chose the 'dgemv' operation, defined as  $\mathbf{y} \leftarrow \alpha A \mathbf{x} + \beta \mathbf{y}$  with double vectors and matrices. For an  $n \times n$  matrix and vectors of size  $n$ , the

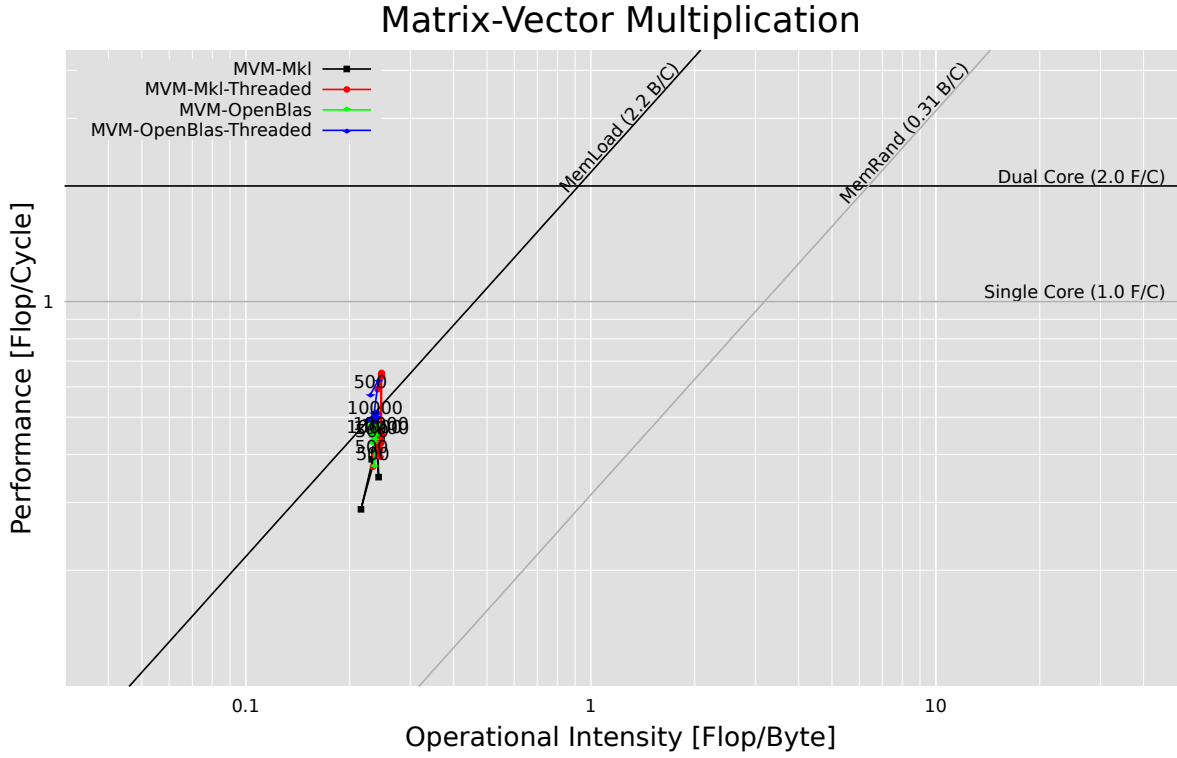


Figure 37: Roofline Plot of the Matrix-Vector Multiplication (MemL2, Double-PrecisionFlop)

operation count is  $2n$  for the vector scaling and  $2n^2$  for the multiplication of the matrix with the vector and the vector addition, totaling in  $2n^2 + 2n$ . The vector  $\mathbf{x}$  can be reused. Since the vector sizes we measure fit into the last level cache, the write backs are cached. The memory transfer is  $2n * 8$  bytes to load the vectors and  $n^2 * 8$  bytes to load the matrix. This results in a maximal operational intensity for large matrices of  $\approx 2/8 = 0.25$  which is confirmed by figure 37

For level 3, we chose the 'dgemm' operation, defined as  $C \leftarrow \alpha AB + \beta C$  with double matrices. For an  $n \times n$  matrix, the operation count is  $2n^2$  for the two scale operations and  $2n^3$  for the matrix-matrix multiplication and the addition to  $C$ .

The minimal memory transfer volume is  $3n^2 * 8$  bytes to load the matrices and  $\max(n^2 * 8 - k, 0)$  bytes to store the result (write back caching), where  $k$  is the size of the last level cache. In our measurement system  $k$  is 2MB.

The maximal operational intensity is  $(2n^3 + 2n^2)/(3n^2 * 8 + \max(n^2 * 8 - k, 0))$ . For large  $n$  this becomes  $(2n^3)/(4n^2 * 8) \approx n/16$ . This operational intensity cannot be reached since reuse is bound by the cache size. The intensity achieved in practice depends on the algorithm. In the following paragraphs we will analyze the triple loop and the blocked version. To simplify matters, we will ignore the effect of code and small parts of the working set on the cache.

The triple loop uses the following algorithm:

```

1 for (long i = 0; i < size; i++)
2   for (long j = 0; j < size; j++)
3     for (long k = 0; k < size; k++)
4       c[i * size + j] += a[i * size + k] * b[k * size + j]
```

If  $B$  fits into the cache, all matrices have to be loaded exactly once. In this case the transfer volume is  $3n^2 * 8$  to load the matrices. Since the space occupied by the reused matrix is not available for writeback caching,  $\max(n^2 * 8 - \max(k - n^2 * 8, 0), 0)$  bytes are written. Dropping lower order terms, the operational intensity is optimal ( $n/16$ ).

As soon as  $B$  does not fit into the cache ( $n^2 * 8 > k; n > 512$ ) it is loaded over and over. In addition, this trashes the the write back cache. The resulting memory transfer volume is  $(n^3 + 3n^2) * 8$  and, for large matrices, the operational intensity is  $1/4$ .

For very large matrices, the lines of  $A$  do not fit into the cache ( $n * 8 > k; n > 262144$ ).

The blocked version uses the following algorithm:

```

1  for (long i = 0; i < size; i += Nb)
2  for (long j = 0; j < size; j += Nb)
3  for (long k = 0; k < size; k += Nb)
4
5  for (long id = i; id < i + Nb; id += Mu)
6  for (long jd = j; jd < j + Nb; jd += Nu)
7  for (long kd = k; kd < k + Nb; kd += Ku)
8
9  for (long kdd = kd; kdd < kd + Ku; kdd++)
10 for (long idd = id; idd < id + Mu; idd++)
11 for (long jdd = jd; jdd < jd + Nu; jdd++)
12
13 c[idd * size + jdd] +=
14 a[idd * size + kdd] * b[kdd * size + jdd];

```

We chose  $N_b = 50$  and  $N_u = M_u = K_u = 2$ . For our discussion, only the blocking with  $N_b$  is relevant. It is presumed that  $N_b$  divides  $n$ .

If the matrix  $B$  fits completely into the cache ( $n^2 * 8 < k; n < 512$ ), we again have a memory transfer volume of  $3n^2 * 8 + \max(n^2 * 8 - \max(k - n^2 * 8, 0), 0)$ .

The blocking divides the matrices into block lines and block columns, each containing  $\frac{n}{N_b}$  blocks.

If the cache cannot hold the whole matrix but a whole block line fits into the cache ( $\frac{n}{N_b} N_b^2 * 8 = n N_b * 8 < k; n < 5243$ ), the blocks of  $A$  are reused. Thus  $A$  is loaded once while each block of  $B$  is loaded  $\frac{n}{N_b}$  times, once per block line of  $A$ . The memory transfers due to the loads is  $(2n^2 + \frac{n}{N_b} n^2) * 8 = (2n^2 + \frac{n^3}{N_b}) * 8$ . The effect of outstanding writes can be neglected. The writes cause an additional  $n^2 * 8$  bytes to be transferred. Dropping lower order terms, the operational intensity becomes  $2n^3 / (n^3 / N_b * 8) = N_b / 4 = 12.5$

For large matrices the block lines of  $A$  do not fit into the cache ( $n > 5243$ ). Each block of  $A$  is loaded once per block column of  $B$  and each block of  $B$  is loaded once per block row of  $A$ . Thus the memory transfer to load  $A$  and  $B$  is  $2 \frac{n}{N_b} n^2 * 8 = 2 \frac{n^3}{N_b} * 8$  and  $2 * n^2 * 8$  to load and store  $C$ . The resulting operational intensity is  $N_B / 8 = 6.25$ .

When comparing these models for the operational intensity of the triple loop and the blocked version, we observe a good match for matrix sizes up to  $n = 200$ . Past this size, the operational intensity of the triple loop rapidly falls to the value

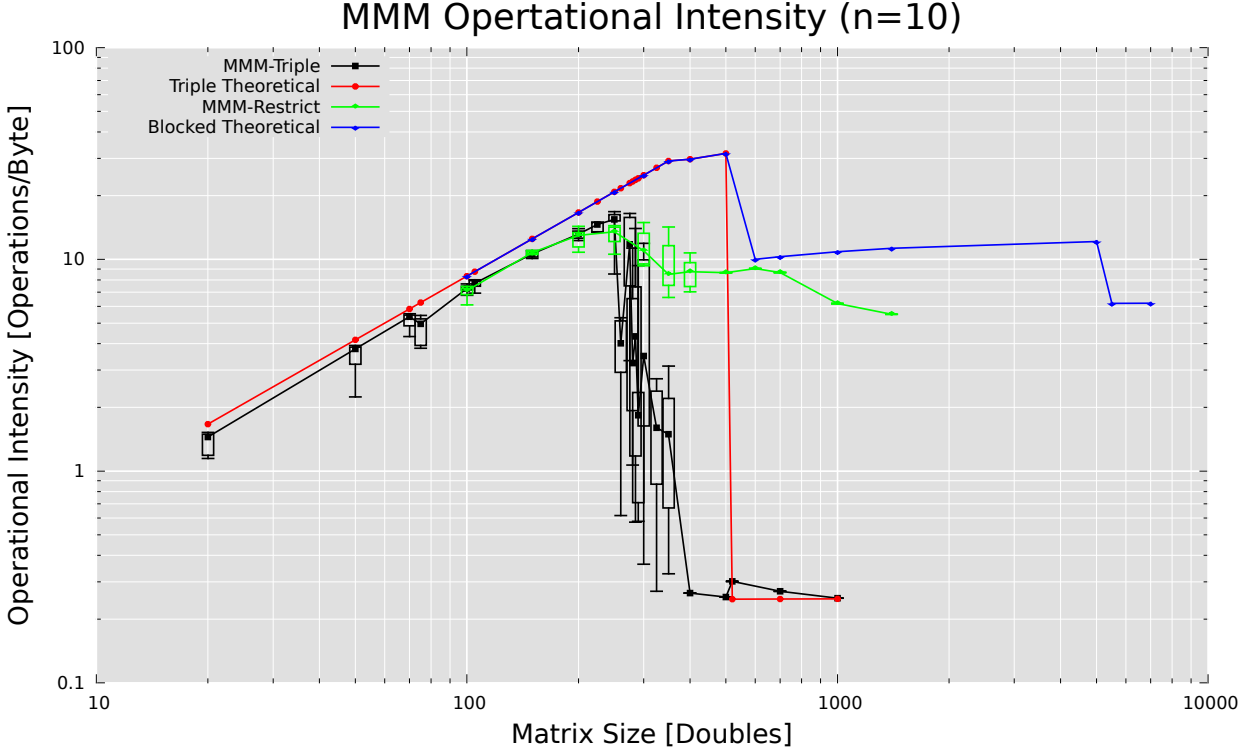


Figure 38: Matrix Matrix Multiplication: Operational Intensity

predicted for large matrices, but the drop begins too early. We predicted the fall when a single matrix occupies more memory than the L2 cache size, but the measured drop begins at half the cache size. (fig 38).

The model for the blocked version overestimates the measurement results as well. The initial drop begins too early. The operational intensity for large matrices is about half the predicted value.

In attempt to find the reason for the observed behavior we analyzed the TLB misses. The TLB has 128 entries. For the triple loop we predict  $3 * \frac{n^2 * 8}{4KB}$  TLB misses as long as one matrix fits into 128 pages ( $\frac{n^2 * 8}{4KB} < 128; n < \sqrt{128 * 4KB / 8} = 256$ ). If the matrices are larger, calculating a single element of the result requires reading one element of every row of  $B$ . If the rows of  $B$  are smaller than one page, multiple accessed elements will lie in the same page. If the rows are larger, one page is accessed per row. Thus the number of pages accessed to compute one element of the result is  $\min(n, n^2 * 8 / KB)$ . Since the TLB is trashed during accessing a column of  $B$ , there are  $n^2 \min(n, n^2 * 8 / KB)$  TLB misses to compute the  $n^2$  result elements, ignoring the TLB misses due to accessing  $A$  and  $C$ .

For the blocked version, we provide an analysis for a very restricted range only. If one line of a matrix is larger than one page ( $n * 8 > 4KB; n > 512$ ), each row within a block will lie in it's own page. If each block line fits within one page ( $N_b * 8 < 4KB; N_b < 512$ ) and the TLB is trashed during each block multiplication, there will be  $3 * N_b$  TLB misses per block multiplication,  $3 * (\frac{n}{N_b})^3 N_b = 3 \frac{n^3}{N_b^2}$  in total.

Figure 39 shows that the measurement results follow our predictions.

Figure 40 shows the roofline plot of the triple loop, the blocked version and the two libraries.

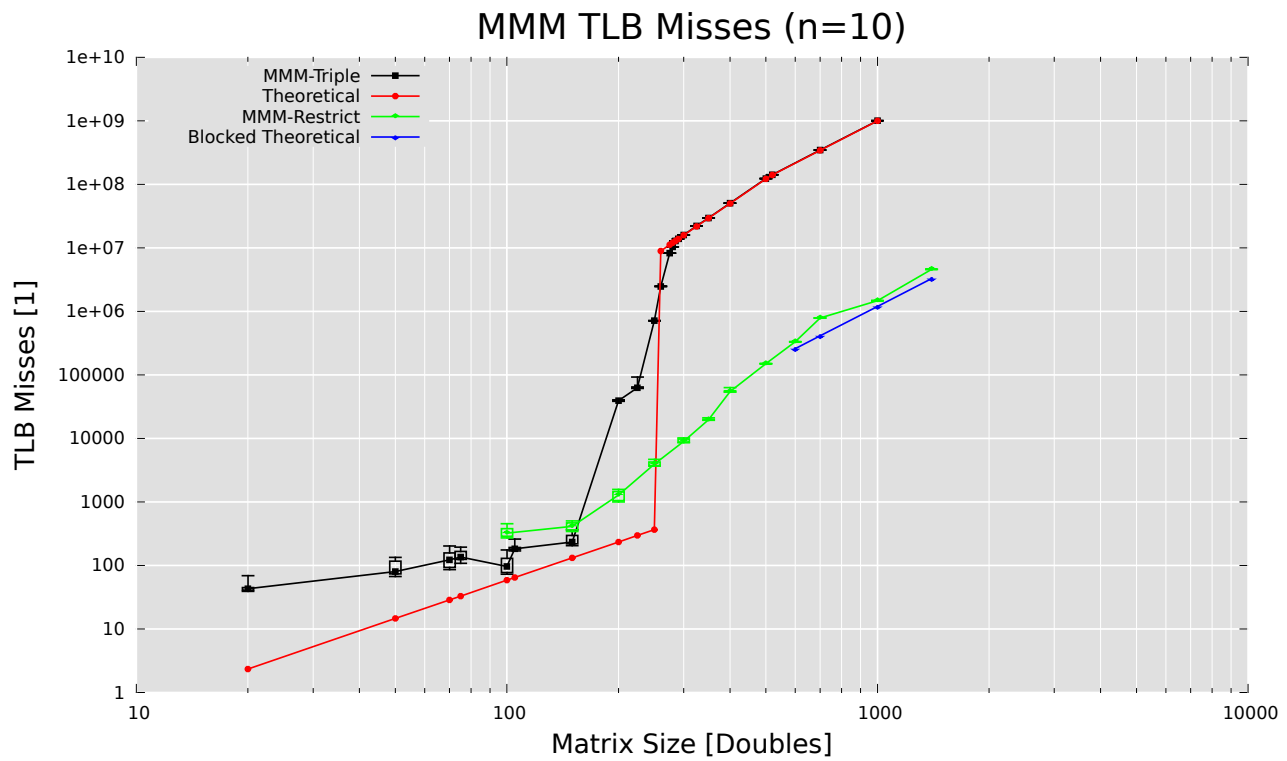


Figure 39: Matrix Matrix Multiplication: TLB Misses

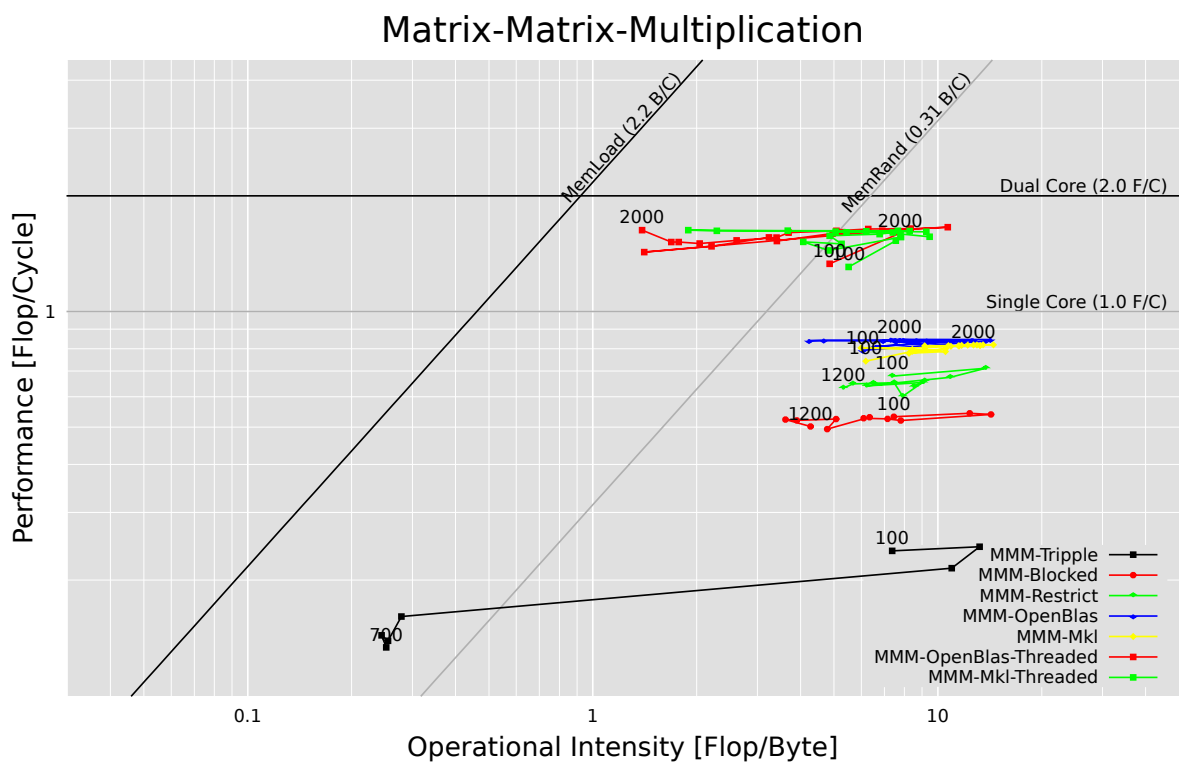


Figure 40: Roofline Plot of the Matrix-Matrix Multiplication





## 6 Measurement Tool Architecture

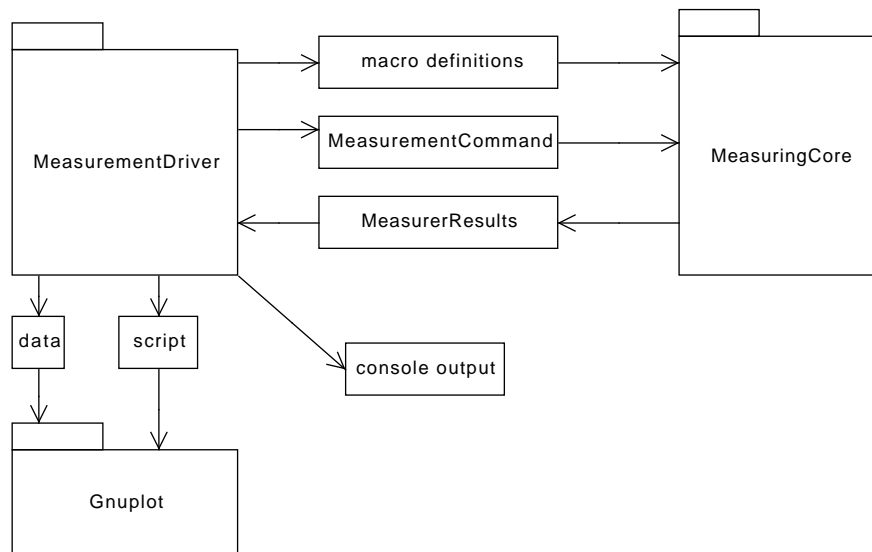
The tool consists of two main components: The Measuring Core, which performs the actual measurements, and the Measurement Driver, which controls the core.

High performance code is generally written in C or C++. Therefore the core is written in that language. To simplify development and maintenance, we tried to keep the amount of C++ code as small as possible. Therefore the measurement driver is written in Java.

A measurement is controlled by a measurement specific routine (one per measurement), which iterates through all parameter points to be examined, compiles and starts the Measuring Core and processes the results. This should result in straight forward code for controlling the measurements and, since the control code is written in Java, a minimal amount of new concepts has to be learned.

During the development of measurement control routines, it is expected that many changes do not affect the parameter points. To speed up repeated measurements after changes to the measurement driver, the measurement results are cached. Thus, as long as the measurement parameters are not changed, the measurement does not need to be repeated.

The measurement tool is used to generate and display measurement results. Often, the measurement results lead to changes to the tool itself. Thus, switches between using the tool and developing the tool are frequent. To support these switches, a frontend program is provided. It compiles the measurement driver and executes it. It can be started using a shell script called "rot". The result files of a measurement are placed in the current working directory.

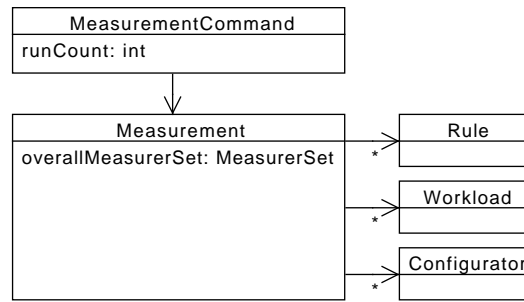


### 6.1 Component Collaboration

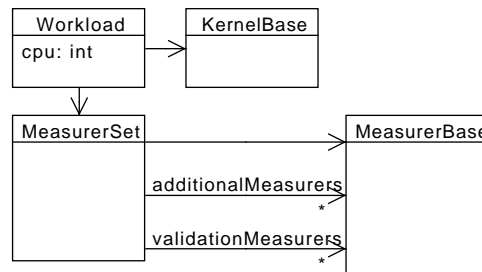
Data transfer between the measuring core and the measurement driver is achieved using serialized objects stored in files. Classes of these objects are used both from C++ and Java and therefore shared entities. They are described using XML. Source code for both languages is generated. For details, see [6.3](#)

The root class for describing a measurement is a **MeasurementCommand**. It contains the number of times the measurement should be repeated, as well as the

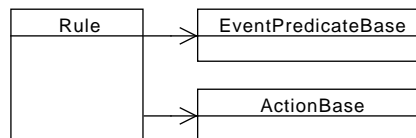
actual Measurement. The kernels are contained within the workloads, and rules allow to respond to various events happening during the measurement.



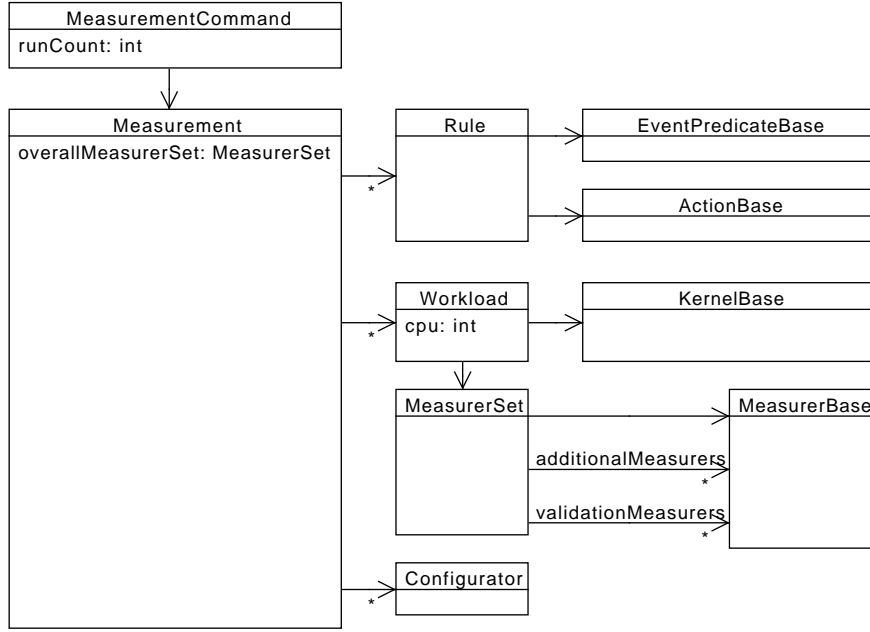
A workload describes what should be run and measured on one core. Each workload is run within a separate thread, which is optionally pinned to a fixed core. In this thread, the validation measurers are started, the caches are warmed up, the additional measurers are started, followed by the main measurer. Then the kernel is run and the measurers are stopped.



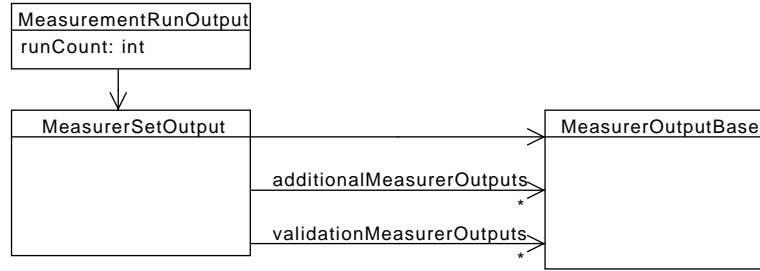
During the measurement, events are raised. For example: start of a workload, end of a workload, start of a thread etc. These events are matched against the event predicates stored in the rules. If a predicate matches, the action of the rule is executed.



The following diagram shows all classes describing a measurement together:

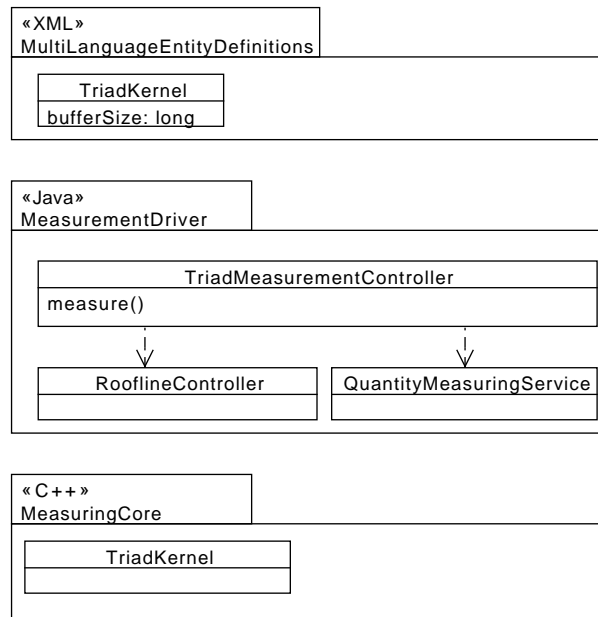


A measurement is usually repeated multiple times, to get an idea of the distribution of the results. Each repetition is called measurement run. In each run, the outputs of all measurers are collected. At the end of the measurement, the core serializes the results of all runs into a single file, which is read by the driver.



## 6.2 Tour of a Measurement

In this section, we'll look at the components specific to a measurement. To make sure you don't get lost, here is the tour map:



First, we'll look at the kernel. It is defined in an XML file:

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <derivedClass
    xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
4    xsi:noNamespaceSchemaLocation="../shared.xsd"
    name="TriadKernel" <!-- name of the class -->
6    baseType="KernelBase"
    cSuffix="Data"
8    comment="Kernel performing a=b+k*d
        on a memory buffer">
10   <field
        name="bufferSize"
12     type="long"
        comment="The size of the buffer"/>
14 </derivedClass>

```

Kernels are always derived from `KernelBase`, hence the `derivedClass` element on line 2 and the base type defined on line 6.

The `cSuffix` is given as 'Data' on line 7. This causes the generated class to be named 'TriadKernelData'. The measuring core implements 'TriadKernel', which derives from `TriadKernelData`. The serialization service will instantiate the derived class. This mechanism allows to use a derived class, optionally with additional code and data, to be used in the measuring core. This is how the actual algorithm is implemented. We'll look at this later.

On line 10 starts a field definition. Fields and getters/setters are generated for the field.

Next comes the class controlling the whole measurement.

```

package ch.ethz.ruediste.roofline.measurementDriver.
    measurementControllers;

```

2

```

public class TriadMeasurementController implements

```

```

4      IMeasurementController {
6          public String getName() {
            return "triad";
        }
8
9          public String getDescription() {
10             return "runs the triad kernel";
11         }
12
13         @Inject
14         public QuantityMeasuringService
            quantityMeasuringService;
15
16         @Inject
17         public RooflineController rooflineController;
18
19         public void measure(String outputName) throws
            IOException {
20             ...
21         }
22     }

```

The class implements `IMeasurementController` and has to be placed in the `measurementControllers` package. The `measure` command will instantiate the class and call the `measure()` method. The `getName()` method returns the name of the measurement, which is used to identify the measurement.

The two fields with the `@Inject` attribute are initialized by the dependency injection framework when the class is instantiated. The quantity measuring service allows to measure quantities like operation count, transferred bytes, performance etc. The roofline controller manages a roofline plot. We will see how these facilities are used when we look at the body of the `measure` function:

```

public void measure(String outputName){
2    rooflineController.setTitle("Triad");
    rooflineController.addDefaultPeaks();
4
5    for (long size = 10000; size < 100000; size += 10000) {
6        // initialize kernel
        TriadKernel kernel = new TriadKernel();
8        kernel.setBufferSize(size);
        kernel.setOptimization("-O3");
10
11        // add a roofline point
12        rooflineController.addRooflinePoint(
            "Triad", Long.toString(size),
14            kernel, Operation.CompInstr,
            MemoryTransferBorder.LlcRam);
15
16        // measure the throughput

```

```

18         Throughput throughput = quantityMeasuringService .
            measureThroughput (
                kernel , MemoryTransferBorder.LlcRam , ClockType .
                    CoreCycles );
20
21         // measure the operation count
22         OperationCount operations =
            quantityMeasuringService
                .measureOperationCount(kernel , Operation .
                    CompInstr );
24
25         // print throughput and operation count
26         System.out.printf(" size %d: throughput: %s
            operations: %s\n" , size ,
                throughput , operations );
28     }
30     rooflineController .plot ( );
    }

```

First the roofline plot is initialized with the title and the default peaks. Then, for each buffer size, the kernel is initialized. For each kernel, the optimization flags used to compile the kernel have to be specified.

Then the roofline controller is instructed to add a roofline point to the plot. The first argument is the series name, next the label of the data point. Points with the same series name are connected with a line in the plot. The rest of the arguments specify the kernel and how the required quantities should be measured.

In the rest of the loop, the throughput and the operation count are measured and printed to the console. This is an example of how to use the quantity measuring service.

The last statement of the `measure()` body causes the plot to be output to a file in the current directory. This involves the invocation of `gnuplot`.

During the invocation of `addRooflinePoint()` and the quantity measuring service a lot was going on under the hood. First a measurement was created from the kernel and the measurers required to measure the requested quantities. Then was checked if there is already a result for the measurement in the cache. If not, the measurement was serialized, the measuring core was configured, built and started. Then the result of the core was parsed and stored in the cache. And finally, the requested quantities were calculated.

The only measurement specific part involved in this process is the implementation of the kernel. First the header:

```

1  class TriadKernel : public TriadKernelData{
    double *a,*b,*c;
3
    protected:
5        std::vector<std::pair<void*,long> > getBuffers ( );
7
    public:
        void initialize ( );

```

```

9      void run();
      void dispose();
11 };

```

The kernel requires three buffers. All declared methods override methods from the KernelBase. The buffers are allocated and initialized in initialize() and freed in dispose(). getBuffers() returns the buffers along with their sizes. This is used to clear the or warm the caches. run() contains the actual algorithm.

```

1  void TriadKernel::initialize() {
      srand48(0);
3      size_t size = getBufferSize() * sizeof(double);

5      // allocate the buffers
      a = (double*) malloc(size);
7      b = (double*) malloc(size);
      c = (double*) malloc(size);

9      // initialize the buffers
11     for (long i=0; i<getBufferSize(); i++){
          a[i]=drand48();
13         b[i]=drand48();
          c[i]=drand48();
15     }
16 }

17 std::vector<std::pair<void*, long> > TriadKernel::
    getBuffers() {
19     size_t size = getBufferSize() * sizeof(double);

21     std::vector<std::pair<void*, long> > result;
        result.push_back(std::make_pair((void*) a, size));
23     result.push_back(std::make_pair((void*) b, size));
        result.push_back(std::make_pair((void*) c, size));
25     return result;
26 }

27 void TriadKernel::run() {
29     for (long p = 0; p < 1; p++) {
          for (long i = 0; i < getBufferSize(); i++) {
31             a[i] = b[i] + 2.34 * c[i];
          }
33     }
34 }

35 void TriadKernel::dispose() {
37     free(a);
        free(b);
39     free(c);
40 }

```



## 6.3 Multi Language Infrastructure

The shared entities are used from both C++ and Java. To avoid having to manually synchronize two versions of the same class, the source code for the C++ and the Java implementation is generated from an XML definition by the Shared Entity Generator. The XML definition contains class and field definitions only, no code. If class specific code is needed, it has to be implemented separately for each language and merged with the field definitions using inheritance.

The shared entity definitions, written in XML, are parsed using a serialization library called XStream. XStream maps classes to an XML representation. The classes used to define the shared entities are shown in [Figure 42](#).

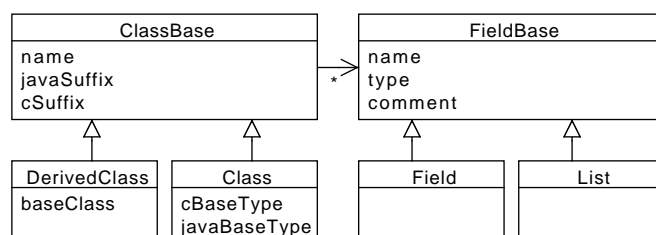


Figure 42: Classes representing a multi language class definition

The following is an example of a class definition:

```

<?xml version="1.0" encoding="UTF-8"?>
<class name="MultiLanguageTestClass"
  cBaseType="MultiLanguageObjectBase"
  javaBaseType=""
  comment="Multi Language Class used for unit tests">

  <field
    name="longField"
    type="long"
    comment="test field with type 'long'"/>
  <list
    name="referenceList"
    type="MultiLanguageTestClass"
    comment="list referencing full classes"/>
  <field
    name="referenceField"
    type="MultiLanguageTestClass"
    comment="field referencing another class"/>
</class>
  
```

After the definitions are loaded, Velocity templates are used to generate all source code.

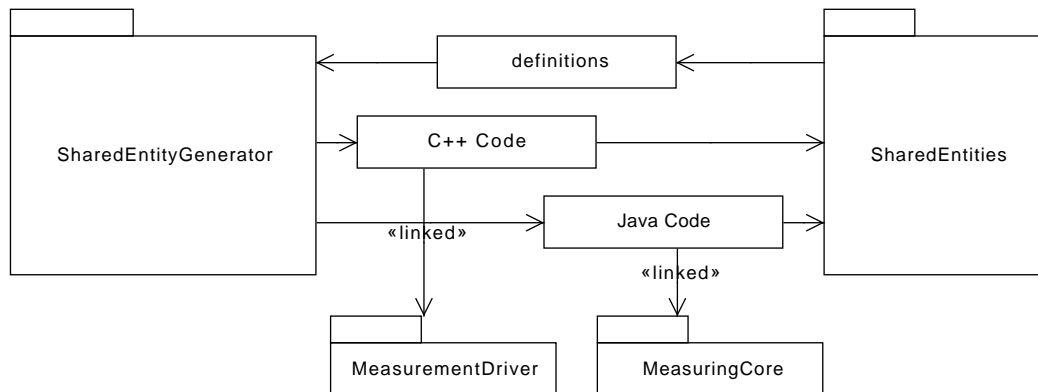
A normal entity has a C and a Java base type. The C base type has to directly or indirectly inherit from SharedEntityBase, which is a polymorphic class. This allows to use the RTTI (RunTime Type Information). Java base types have no

such constraint (due to the implicit common base class `Object`). The base types are just included in the generated source code, but have no other effect on the code generation.

A derived entity names another entity as base type. The C and Java base types are set to that class. The fields of the base class are included in the serialization process. If just the C and Java base types would be set to the shared entity used as base class, the generated class would still derive from the base class, but the fields of the base class would not be included in the serialization process.

Often it is necessary to mix hand written code with the generated code. To support this, a suffix can be specified, which is added to the name of the generated class. Only the name of the generated class is affected, not the type name used for references to the class. A class named without the specified suffix has to be provided manually, and should derive from the generated class. Any additional code as well as additional fields can be included in the hand written class.

The class definitions and the generated code is located in the Multi Language Classes project. The generated Java code is linked by the Measurement Driver project. The generated C code is linked by the Measuring Core. The following Diagram shows these dependencies:



### 6.3.1 Serialization and Deserialization

Along with the source code for each class, a service serializing and deserializing multi language objects to/from a simple text based format is generated for both languages. It supports the following primitive types:

- double
- integer
- long integer
- boolean
- string

References to other shared entities are supported. The serializer can handle general object graphs.

Lists containing one of the supported primitive types as well as containing references to other shared entities are supported.

The service implementations for both languages follow the same structure. Each has two methods, one for serialization and one for deserialization.

The serialization method receives an object and an output stream. The method body contains an if for each known serializable class, which checks if the class of the object received is equal to the serializable class. If true, the value of all fields of the class and it's base classes get serialized. For references, the serialization method is called recursively with the same output stream and the referenced object as parameters.

The deserialization method works analogous to the serialization method. It receives an input stream. The method body contains an if for each known serializable class, which checks if the next line of the input names the serializable class. If true, a new instance of the class is created and the value of all fields are read from the input and set on the created instance, including all fields declared in a base class. If a reference is encountered, the deserialization method is called recursively with the same input, and the returned instance is used as field value.

## 6.4 Frontend

The measurement tool is a console tool controlled using command line options. Measurement results are either directly displayed on the console, dumped to a data file or processed, usually for generating a graph. The graph is typically stored as a file. But unlike normal tools, the source code is expected to change frequently, and the user likely switches often between coding and using the tool.

To support this usage pattern, the build process has been integrated into the normal tool operation. The frontend is used to first trigger the build process and then invoke the measurement driver. Otherwise, the user would have to keep to console windows open, one for building and one for measuring, and not to forget building to see the changes made to the source code.

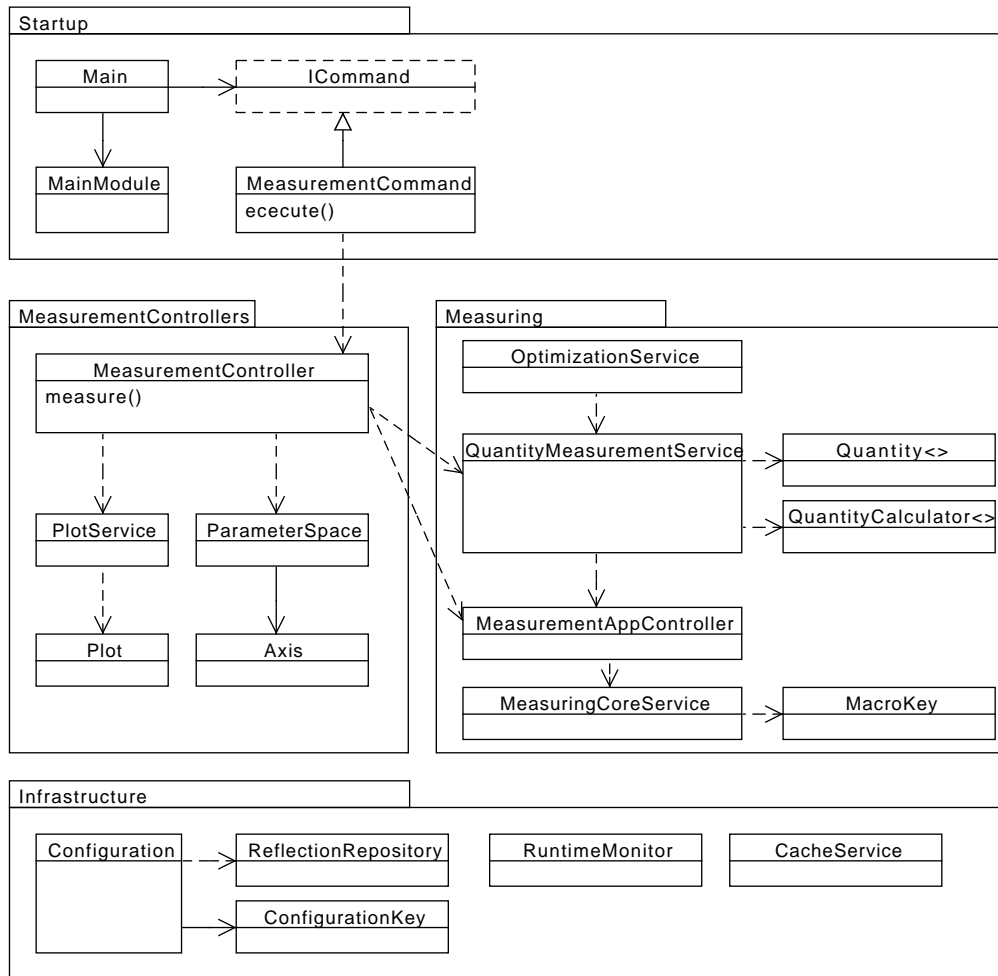
After building, the frontend starts the measurement driver, forwarding it's own command line. Certain flags are used to control the operation of the frontend. These are not forwarded.

The frontend has a configuration system. The known configuration keys are defined at the top of the Main class. There are three configuration sources. The default configuration stored in a configuration file. It contains templates which are expanded during the build process. The result is included as resource in the generated JAR file. Flags of the default configuration can be overwritten using a user configuration file, which is located by default under " / .roofline / frontendconfig ". This location can be changed using a command line argument. Finally, the command line options known by the frontend are used to modify the configuration flags after they have been loaded.

## 6.5 Measurement Driver

For the design of the measurement driver, we used software engineering best practice, namely unit testing (junit), mocks (jmock), and dependency injection (guice). Further a domain model (DOM), controllers, repositories and stateless services as described in [6]. Describing all these concepts lies beyond the scope of this report. It is assumed that the reader has a basic understanding of the mentioned concepts.

The following diagram shows an overview of the driver:



In the following paragraphs, we will have a quick look at the look at the different parts.

The entry point of the driver is the **Main** class. First, the dependency injection framework is initialized. This is accomplished using the **MainModule**. It's **configure()** method uses the **ClassFinder** to find all compiled classes and configures how they are instantiated, mainly based on naming conventions.

Then the command line arguments are parsed. If command line auto completion is desired (indicated by the '-autocomplete' flag), the auto completion process starts.

Otherwise the configuration is initialized, using the flags specified at the command line and the configuration files (default configuration stored in the jar and user configuration from the home directory of the user).

The last step in the initialization sequence is to set up log4j, the logging framework.

Then the class for the command given on the command line is instantiated and the **execute()** method on the resulting **ICommand** is called.

When a 'measure' command is given, a **MeasurementCommandController** is instantiated. The command controller looks at the next command line argument, instantiates the corresponding measurement controller and calls the **measure()** method.

The measurement controller will typically create multiple **Measurements** with different parameters. The **ParameterSpace** facilitates iterating over all possible parameter combinations. Each parameter is associated to an **Axis**. For each axis, one or multiple values can be given. The `getAllPoints()` returns a **Coordinate** for each possible value combination. Iterating over the points in the space, the measurement controller can construct a measurement for each point.

The results of the constructed measurements can be either printed to the console, or stored in one of various **Plots**. When all data is gathered, the plot can be rendered and written to an output file using the **PlotService**.

Although it is possible to directly create the **Measurers** required to measure something, most of the time the intent is to measure a certain **Quantity** (**OperationCount**, **TransferredBytes**, **Performance** etc). The **QuantityMeasuringService** can be used to obtain a **QuantityCalculator** for a quantity. The calculator can be queried for the list of measurers which are required to calculate the quantity. When the results of all required measurers are known, they can be passed to the calculator, which will return the desired quantity. In addition, the quantity measuring service provides convenience methods for working with the quantity calculators.

Once the **Measurement** is constructed, the `measure()` method of the **MeasurementAppController** is used to perform the measurement. First it is checked if a cached result is available for the measurement (using the **CacheService**). If not, the **MeasuringCoreService** is used to build the core for the measurement and to start the core.

The **Kernels** can define macros. During build preparation, all macro definitions present in the measurement are collected and written to generated header files within the core.

During the execution of the measurement driver, the run time used for the various tasks is collected using the **RuntimeMonitor**. At the end of the execution, the times spent for the tasks is printed to the console.

### 6.5.1 Dependency Injection Configuration

Generally, a convention over configuration approach was chosen for the configuration of the dependency injection. The conventions as well as optional exceptions are defined in the **MainModule**. The conventions are:

**Services** all classes in the services packages are bound to themselves as singletons

**Repositories** all classes in the repositories packages are bound to themselves as singletons

**Application Controllers** all classes in the 'appControllers' package are bound to themselves as singletons

**Measurement Series** all classes deriving from **IMeasurementSeries** in the measurement series package are bound to the **IMeasurementSeries** interface annotated with their name

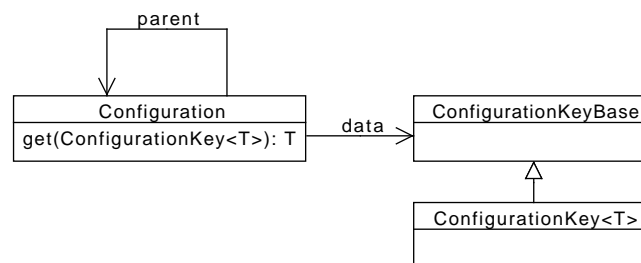
**Commands** all classes deriving from  **ICommand** in the commands package are bound to the  **ICommand** interface annotated with their name

**Measurement Controllers** all classes deriving from `IMeasurementController` in the measurement controller package are bound to the `IMeasurementController` interface annotated with their name

### 6.5.2 Configuration

The design goal was to create a configuration system which

- allows to set configuration flags from the command line and from configuration files
- can manage some form of comment for the flags
- makes the available flags transparent
- supports user specific configuration



The central class of our solution is the **ConfigurationKey**. A configuration key contains a string key which identifies the configuration flag it represents. In addition, it contains a description and the default value of the flag. It has a template parameter which defines the data type of the flag. This removes the necessity to use type casts when reading configuration flags. Configuration keys should be stored in public static variables. The help command scans all classes of the measurement driver for such configuration keys and prints the key string and the description. After the configuration is loaded, it is checked if a configuration key is defined for each configuration flag specified. If a configuration key for a flag is missing (or more likely, a configuration flag has been misspelled in the configuration) an error is generated.

The values associated with configuration keys are stored in **Configurations**. Configurations can be chained together using the parent links. If no value is found in a configuration or all of its ancestors, the default value stored in the configuration key is used.

The state of a configuration can be saved on a stack using `push()` and restored using `pop()`. All modifications to a configuration after a push are undone by the pop. This can be used to temporarily change the configuration.

The following paragraphs describe the sources of configuration flag definitions in order of decreasing precedence.

The command line is scanned for arguments starting with a dash. Such arguments are expected to be in the form of `"-<flag key>=<value>"` and specifies that the configuration with the specified flag key should have the specified value. Configuration flag definitions on the command line have highest precedence.

Next come two configuration files. They both have the same format: each line consists of the flag key, followed by an equal sign and the flag value.

The first file is the user configuration file. By default it is located under `~/roofline/config`, but this can be changed using the "userConfigFile" configuration flag, in particular by overwriting the flag on the command line.

The second file is the default configuration. It is located in the source code of the measurement driver, and can be loaded from the classpath. It contains some placeholders, which are expanded during the build process.

Finally, the flag definitions with lowest precedence are the default values given in the configuration keys.

### 6.5.3 Auto Completion

#### 6.5.4 Commands

A command is represented by a class deriving from  `ICommandController`  and should be placed in the commands package. A command has a name and a description, which should be the return value of the  `getName()`  respectively  `getDescription()`  methods of the command. The measurement driver expects a command name as first argument. The name is matched against the names of all available commands. If a command matches, the  `execute()`  method of a new instance of the corresponding class is called with the remaining command line arguments as parameter.

#### 6.5.5 Measurement Controllers

The operation of the measurement driver is controlled by the measurement controllers. They define which measurements to perform and how to process the output. The measure command instantiates a measurement controller and calls the  `measure()`  method.

#### 6.5.6 Parameter Space

When implementing measurement controllers, one often has to iterate over all possible combinations of some parameters. The **ParameterSpace** was designed to support this.

Every parameter is identified by an **Axis**. For each axis, one or multiple values are specified. After the desired values are specified, all possible parameter combinations can be generated, represented by **Coordinate** objects. The points are generated implicitly when iterating over the space.

Example:

```
1 space.add(systemLoadAxis , SystemLoad.Idle );
   space.add(systemLoadAxis , SystemLoad.DiskOther );
3 space.add(systemLoadAxis , SystemLoad.DiskAll );
   space.add(systemLoadAxis , SystemLoad.AddOther );
5 space.add(systemLoadAxis , SystemLoad.AddAll );

7 space.add(clockTypeAxis , ClockType.CoreCycles );
   space.add(clockTypeAxis , ClockType.ReferenceCycles );
```

```

9  space.add(clockTypeAxis , ClockType.uSecs);

11 for (Coordinate coordinate : space) {

13     ClockType clockType
        = coordinate.get(clockTypeAxis);
15     SystemLoad systemLoad
        = coordinate.get(systemLoadAxis);
17     ...
}

```

To facilitate the initialization of measurements, the classes of the measurement description have an `initialize()` method which takes a coordinate as parameter. Depending on the kernel or measurer at hand, some fields are set to the value of an axis given by the coordinate.

The most common axes are defined in the **Axes** class.

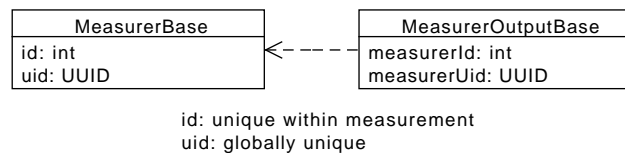
### 6.5.7 Retrieving Outputs

To process the results of a measurement, it is frequently necessary to retrieve the output of a specific measurer.

The straight forward approach would be to give each measurer an unique id, and to store the id of the measurer with the measurer output. Measurers are newly created with each invocation of the measurement driver, possibly leading to new ids. But for caching, the ids of the measurers do not matter.

To overcome these problems, two ids are generated for each measurer. One identifier uniquely identifying each instantiated measurer. And an id which is unique within one measurement. When loading a result from cache, the unique identifiers of the loaded result are set to the identifiers of the measurement at hand.

To retrieve the output of a measurer, the **MeasurementResult** and the **MeasurementRunOutput** provide several methods which take a measurer as argument and return it's output.



### 6.5.8 Plotting

### 6.5.9 The MeasurementAppController

The measurement application controller is the entry point for performing measurements. It is the sole client to the **MeasuringCoreService**, which provides the low level control over the measuring core, and keeps track of the measurement the core is compiled for.

In addition, it uses the **MeasurementHashRepository** to keep track of measurements which have equal measuring cores.

The main method of the controller is `measure()`. Functionality in pseudo Code:



```

MeasurementResult measure(measurement , numberOfRuns)
2  "prepare measurement"
  runOutputs=[]
4  if (useCachedResult || "measurement has been seen")
    loaded="load stored results"
6    if (loaded!=null)
      if (!shouldCheckCoreHash
8        || currentCoreHash==loaded.coreHash)
        runOutputs=loaded
10
11  if ("more results needed")
12    newResult=performMeasurement()
    "merge and store loaded and new run outputs"
14
    "build and return MeasurementResult with the desired
      number of run outputs"

```

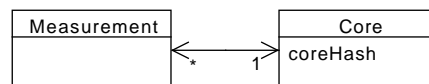
The method first tries to load a measurement result from the result cache. If not enough run outputs are loaded (or none at all), the measurement is performed to get the remaining measurement run outputs.

Finally, a measurement result with exactly the requested number of runs is constructed and returned.

It is possible to disable loading stored results by setting the `useCachedResults` configuration key to false. The measurement is performed and existing results are overwritten.

The hash code of the core is stored along with the measurement result. This allows to check if the currently compiled core is equal to the core which was used during the measurement. By default, if the core changed since the results were generated, the results are not used and new results are generated using the current measuring core. By setting `shouldCheckCoreHash` to false, this check can be skipped.

Preparing and building the measuring core are expensive operations in term of runtime. Therefore, the measurement application controller keeps track of as much information about the measurements and the cores needed to perform them as possible. The **MeasurementHashRepository** is used for this purpose. It has the following internal Model:



The **Core** class is private and does not leave the repository.

The model is exposed through the following methods

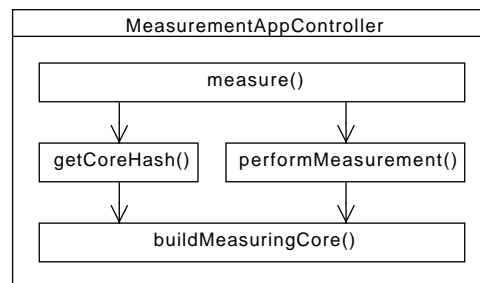
- `areCoresEqual(measurementA, measurementB): bool`
- `setHaveEqualCores(measurementA, measurementB)`
- `setCoreHash(measurement,coreHash)`
- `getCoreHash(measurement): CoreHash`

Before building, the controller asks the repository if the core for the new measurement is the same as the currently built one. (using `areCoresEqual()`) If the cores are the same, no building is required.

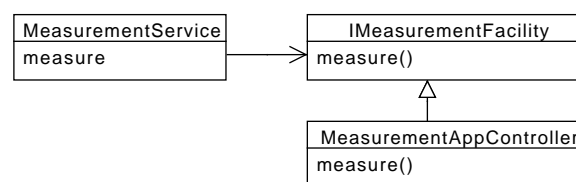
During the build preparation the controller and the **MeasuringCoreService** monitor changes to the core. If no changes were necessary, the repository is notified using `setHaveEqualCores()`. The cores of the two measurements are merged.

When a core hash is required (for example to check if the current core is the same as the one used to generate a stored result), the controller first asks the repository for it using `getCoreHash()`. If the hash is not known, the core is built for the measurement, the hash is calculated from the core and stored in the repository using `setCoreHash()`. This could again lead to a merging of two cores, if a core with the same hash is present already.

Building the measuring core can become necessary when the core hash of a measurement has to be known, or when a measurement is to be performed. This is reflected in the call graph of the methods within the application controller:



Since it makes sense that services can start measurements, the **MeasurementService** provides a `measure()` method. The service knows an instance of **IMeasurementFacility** which provides `measure()`, and forwards all calls to its own `measure()` method to the measurement facility. The facility is implemented by the **MeasurementAppController** controller. Therefore the service ultimately forwards all calls to `measure()` to the application controller.



#### 6.5.10 Architecture Specific Behavior

The measurement driver supports multiple system architectures. Currently, the system architecture is identified by the available PMUs. When a performance event is to be read, a list with the event for each architecture is passed to the `getAvailableEvent()` method of the **SystemInfoService**. The method returns the available event. In other cases, the presence of a PMU is checked directly.

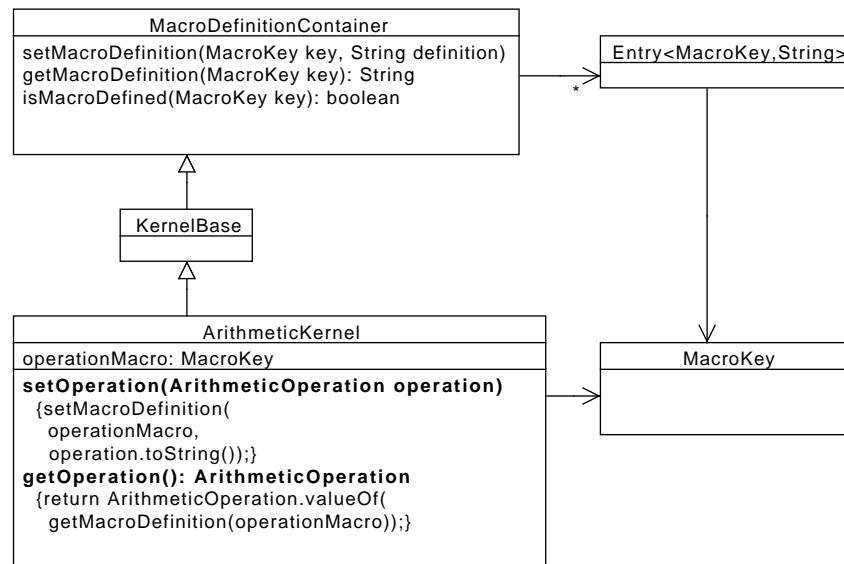
For further development, it might become beneficial to use the specification pattern.

### 6.5.11 Preprocessor Macros

Preprocessor macros are used to allow flexible compile time parameterization of the measuring core. The macros are defined by the measurement driver. Before the compilation of the measuring core, the measurement driver writes the definition of each macro to a separate include file. This allows the build system to track macro definition changes for and to recompile only the required parts.

In the measurement driver, each macro is identified by a macro key, which contains the macro name, a description and the default value. The macro definitions are stored in classes deriving from `MacroDefinitionContainer`. The classes should define macro keys by placing them in private static variables. To access the macro definition, getters and setters have to be provided.

When the measuring core is configured to perform a measurement, the macro keys are collected from the classes of the measurement driver using reflection. Then the macro definitions are extracted from the measurement definition and referenced objects. If no definition is given for a macro, the default definition found in the macro key is used. If contradicting definitions are found, an error is raised.



### 6.5.12 Measurement Result Caching

The measurement controllers mix the definition of the measurement parameters and the processing of the output. Thus, if the output processing logic needs to be modified, the measurements have to be performed again. This causes a delay, which is avoided by caching the measurement results.

All parameters of a measurement are contained within the measurement description and the referenced objects. Therefore, if the measurement description is identical to a measurement description of a previous measurement, the result of the previous measurement can be reused.

The cache mechanism works using a hash function on the XML representation of the measurement description. After a measurement has been performed, a file named after the hash value of the measurement description of the measurement is created and the measurement results are stored therein. Before a measurement

is performed, the hash value is computed. If a corresponding file is found, the previous measurement results are reused.

## 6.6 Measuring Core

The measuring core is based on the object graph constructed by the driver. The classes are extended with code and data.

### 6.6.1 Core Architecture

To fully utilize multi core systems, applications have to be implemented with multiple threads or processes. Measuring such applications is considerably more difficult than measuring single threaded applications. If the thread management is implemented specifically for the measurement at hand, the measuring code can be weaved into it by hand. But if the threads or processes are created within legacy or closed source code, the measuring tool has to take care of detecting the creation of threads and install the necessary measurers. For the roofline measuring tool we will only consider multi threaded applications.

To gain full control over the kernel code, the measurement tool starts the kernel within a child process. The parent process attaches to the child using ptrace. This causes the child to be stopped when certain events occur and the parent is notified. The events include thread creation and breakpoints.

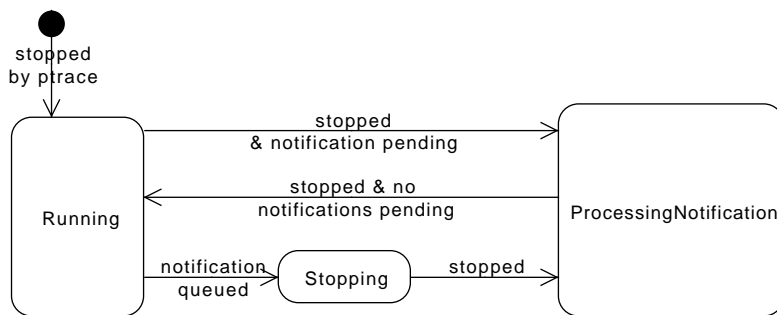
Every kernel thread can raise events at any point. The events include thread creation, breakpoints, starting and stopping of workloads etc. Whenever an event occurs, the rule list has to be searched and the matching actions have to be executed. The rule list is always searched in the thread which raised the event. If the event caused the thread to be stopped and the parent thread to be notified, the parent restarts the thread with a notification of the event which occurred. The thread will search the rule list and continue execution.

It is important to distinguish the events from notifications in this context. An event is handled by the rule list of the child and typically generated by the child process as well. A notification is used to communicate between the child process and the parent process. However, the parent can notify (using a notification) the child of a certain observation, which causes the child to generate an event.

The rule list is always searched in the thread generating the event. If an action has to be executed in another thread, it has to be queued using `ChildThread::queueAction()`

The technically most challenging problem is to interrupt another thread and make it execute some action. There are two approaches to this problem, either using a signal handler of the thread or using ptrace to call code within the thread. Since installing a signal handler in a thread could cause unwanted side effects, we use the ptrace approach. SIGTRAP is sent to the target thread, which will cause it to be stopped. The parent modifies the thread state of the stopped thread. When the thread resumes execution, it executes some event handling code and then return to the location the thread was interrupted.

## 6.6.2 Child Thread States



The parent process manages a state for each child thread. When a child thread starts, ptrace will immediately stop it with SIGSTOP. If the notification system is ready, a ThreadStarted notification will be sent to the child.

While a notification is being processed by the child, its state is set to processing. When no more notifications are pending, the state is set to running. If a notification is queued from one thread to another and the state of the receiving thread is running, a SIGTRAP is sent to the receiving thread and the state of the receiving thread is set to stopping. The stopping state indicates that the thread will stop eventually.

A thread can exit at any time. When this is detected by the parent process, the state and the notification queue are erased.

## 6.7 Thread Representation in the Child Process

In the child process, threads are represented as **ChildThread** objects. Since every **Workload** runs in its own thread, a child thread is associated with every workload.

When a new thread is spawned, it will be stopped by ptrace. The parent sends the ThreadStarted notification to the child. In the handler, the child will instantiate the **ChildThread**. If the started thread is a workload thread, the startup routine of the workload will associate the instantiated child thread with the workload.

Actions can be sent from one thread to another using `ChildThread::queueAction()`.

### 6.7.1 Building

Each measurement can be performed with different compiler optimization flags and macro definitions. Therefore, the measuring core has to be rebuilt for each measurement, which makes rebuilding the measuring core a frequent operation. It should therefore be as fast as possible. This is achieved by carefully tracking all build dependencies and by using ccache.

CCache is a compiler cache. Whenever the compiler is run, ccache hashes all input files, together with the compiler flags. It then checks if its cache already contains an entry for the hash value. If this is not the case, ccache runs the compiler and stores the output together with the hash value of the input in its cache. If the

hash value is present already, it does not run the compiler but uses the compiler output stored in it's cache. This considerably speeds up recompilations.

But ccache still has to build the hash values and copy the compiler output, which takes some time. This is where tracking the build dependencies comes in. The following parameters can change between measurements:

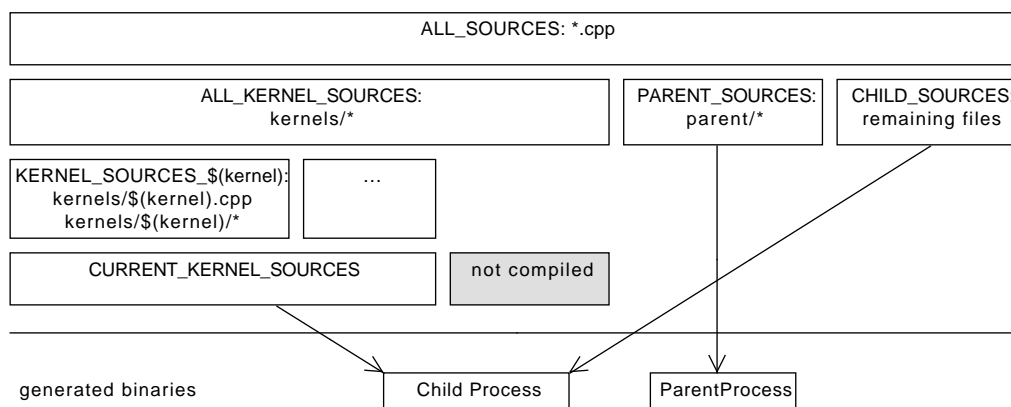
**Macro definitions** Each macro definition is stored in a separate file, which is only updated by the measurement driver if the macro definition changes. Every source file which needs a macro definition includes the corresponding file. These inclusions are tracked and allow to only recompile the affected source files.

**Compiler flags** Each kernel specifies it's own optimization flags. The compiler flags used for the rest of the measuring core do not affect the measurement results. The compiler flags are stored in a separate file. Whenever it is changed, the parts affected are recompiled.

**Compiled Kernels** For each measurement, only the kernels actually used are compiled. The measurement driver writes the kernel names into a separate file. The child binary is recompiled when it changes.

The build process is controlled using the gnu make utility [9]. Make automatically determines which parts of a program have to be recompiled, based on rules stored in a makefile. Each rule consists of target files, prerequisite files and a recipe. Make checks the modification times of the target and the prerequisite files. If any prerequisite is newer than any target, the recipe is executed in order to update the target files. The recipe is a sequence of shell commands.

The following diagram shows how the source files are categorized and compiled:



The makefile used for the measuring core first instructs make to use the find utility to get a list of all source files (with .cpp extension) in the measuringCore/src and measuringCore/generated directories (ALL\_SOURCES).

Using the filter functions of make, the kernel sources are set to the subset of ALL\_SOURCES which is located in src/kernels or generated/kernels. These are all sources related to kernels. (ALL\_KERNEL\_SOURCES).

The sources of the parent process are the subset of ALL\_SOURCES which is located in src/parent(PARENT\_SOURCES).

The source files of ALL\_SOURCES not contained in ALL\_KERNEL\_SOURCES or PARENT\_SOURCES are stored in CHILD\_SOURCES.

The names of all present kernels are stored by the measurement driver in generated/kernelNames.mk. For each of the kernels named there, the source file named after the kernel and all source files in the subdirectory named after the kernel collected in a variable (KERNEL\_SOURCES\_\$(kernel)). They are compiled with the optimization flags of the compiler, which are stored under generated/kernelOptimization.

The sources of all current sources are collected and form, together with the CHILD\_SOURCES, the sources of the child process.

The parent process is compiled from the PARENT\_SOURCES.

There is a rule without recipe with the kernel objects as target and the file containing the measurement specific optimization flags as prerequisite. This causes the file containing the optimization flags to be added as prerequisite for each kernel object file.

In the C programming language, it is possible to include other files in a source file. Of course, the compiled code depends on the contents of the included files, too. To track these build dependencies, the compiler is instructed to generate rules without recipes with the object file as target and the source file together with the included files as prerequisites. The generated rules are stored in .d files in the build directory and are included in the makefile.

If special compilation flags are required for a source file, a rule should be added near the end of the makefile.

### 6.7.2 System Initialization

We chose a modular approach to initialize the measuring core. Whenever a system part needs to run code when the program starts or shuts down, it can instantiate a class derived from SystemInitializer.

This is preferably achieved by declaring a global static variable named dummy in a .cpp file. Example:

```
// define and register a system initializer.
static class FooInitializer: public SystemInitializer{
    void start(){
        // code to be executed on startup
    }

    void stop(){
        // code to be executed on shutdown
    }
} dummy;
```

It is important to give every initializer subclass an individual name. Use the name of the file the initializer is declared in as prefix. If two initializer classes have the same name, they don't work correctly (instances of the wrong classes are created)

Whenever a SystemInitializer is instantiated, the instance is registered in a static global list. On system startup and shutdown, the start() respective stop() method of all registered SystemInitializers is called.

## 7 How To

### 7.1 Installation

see INSTALL file in tool directory

### 7.2 Create a New Kernel

First, you have to create an XML description of the new kernel in `sharedEntities/definitions/kernels`. Look at some of the other files in that directory and choose one as starting point for your own. Copy the chosen file and give it the name of your kernel. It must end with 'Kernel'. The file name is taken as class name for your kernel description.

Next, run `'rot help'` to generate the source code from your XML description. In case your class defines a `'javaSuffix'`, the compilation following the source generation will fail. Create the Java code of your kernel class in `measurementDriver/src/ch/ethz/ruediste/roofline/sharedEntities/Kernel` and make it inherit from the generated class with the suffix. (see other kernels for examples)

The Java part of your kernel is now ready. You can use it in a measurement. But we are still missing the implementation in the measuring core. To implement the kernel, it is indispensable to specify a `'cSuffix'` in your kernel description.

Create a class in `measuringCore/src/sharedEntities/kernels`, include the generated header file (filename contains the suffix) and derive from the generated class. Add fields for all the data buffers you plan to use (if any). Override and implement the following methods:

**initialize()** Allocate and initialize the required buffers.

**getBuffers()** Return the list of all buffers along with their size. This is used to automatically clear or warm the caches.

**run()** Run the kernel.

**dispose()** Free all buffers

In case you have additional code, you can place it in a subdirectory with the same name as your kernel, without the 'Kernel' suffix. All '.cpp' files will be compiled and linked with the measuring core.

### 7.3 Use the Driver as a Library

You can use the measurement driver as a library. First, run `'./gradlew -daemon measurementDriver:runnableJar'` to create a jar containing the driver together with all dependencies. It will be located in `'measurementDriver/build/distributions/measurementDriver.jar'`. Include the jar in your project.

During the startup of your application, call `LibraryMain.initialize()`. Now you can use the driver. You can directly instantiate entities and use `Instantiator.instance.getInstance()` to retrieve service instances.



## 7.4 Create New Measurement

- create new class in measurementDriver/measurements
- implement IMeasurement

## 7.5 Add Configuration Key

The configuration is used to set various flags in the measurement driver.

- add public static field of type ConfigurationKey to any class within the measurement driver.

## 7.6 Generate Annotated Assembly

- in Eclipse, hit build (Ctrl+B)
- change the kernel header file (make it recompile)
- build again
- from the console window, copy the compiler invocation for MeasurementSchemeRegistration.cpp
- open a terminal and go to tool/measuringCore/Debug.
- paste the compiler invocation
- insert "-Wa,-ahl=ass.s", check optimization flags
- issue command
- the annotated assembly code can be found in tool/measuringCore/Debug/ass.s
- open the annotated assembly code in Eclipse

# 8 ===WORK IN PROGRESS===

## 9 Measuring Execution Time

- 0x40000000 UNHALTED\_CORE\_CYCLES 30Ah  
CPU\_CLK\_UNHALTED.CORE
- 0x40000025 UNHALTED\_REFERENCE\_CYCLES 30Bh  
CPU\_CLK\_UNHALTED.REF
- 0x400000ad THERMAL\_TRIP 3Bh C0h
- 0x400000ae CPU\_CLK\_UNHALTED
- 0x400001a9 ix86arch::UNHALTED\_CORE\_CYCLES
- 0x400001aa ix86arch::INSTRUCTION\_RETIRED
- 0x400001ab ix86arch::UNHALTED\_REFERENCE\_CYCLES

## 9.1 Experiments

To gain insight into the accuracy and precision of the timers available, we run the addition kernel with an exponentially increasing iteration count. The largest iteration count should result in a runtime of about 0.5s. We expect the precision to be high for small iteration counts, a peak variance at around 5 ms due to the task switches, and an increasing precision for higher iteration counts. The accuracy of the minimum should be high for small iteration counts, and include a small overhead if multiple task switches occur during the measurement.

### 9.2 Experiment 1

The goal of this experiment is to show the effects of task switches and disk IO on measuring execution time. As far as possible, we'd like to exclude the effects of shared memory bandwidth.

We measure the arithmetic add kernel. Iteration count is increased until total execution time is about half a second. We measure at both the minimal and maximal CPU frequency. We measure on an idle system, when another arithmetic kernel runs or when heavy disk IO is performed. We let the system load threads run on all of the system's CPU. Separate measurements for core cycles, bus cycles, `gettimeofday()`, times (user time)

We estimate the execution time for one iteration. We take the time for the highest iteration count where we can still get measurement runs without any interrupts. This time is divided by the respective iteration count.

Graphs (idle, disk, arithmetic):

- X: exp exec time [ms, cycles] Y: rel error V: box plots
- X: exp exec time [ms, cycles] Y: ints V: box plots
- X: exp exec time [ms, cycles] Y: task sw V: box plots

### 9.3 Experiment 2

Investigate the effects of task switches on a memory intensive kernel. Repeat experiment 1 with both a memory load and write kernel

### 9.4 Experiment 3

Measure the influences of shared memory bandwidth on the runtime. Depending on the system architecture, we expect to measure shared bandwidth effects. We measure a memory load and a memory write kernel. We measure on idle system and while running memory load and write kernel on the other CPUs. Buffer sizes are larger than cache size. Measure core cycles. Measure at min and max frequency. Buffer size chosen such that execution time is around half a scheduling time segment.

One plot per kernel combination (load/load, load/write, write/load, write/write)

- X: cpu map Y: time[cycles]

## 9.5 Experiment 4

Unfortunately, even on a very lightly loaded system, any task can be executed on any other core. Caused by the shared memory bandwidth, this could affect short running kernels, and result in wrong measurement results of a whole measurement series. We show this by starting two memory intensive, short running kernels simultaneously. Solution: introduce sleeps between measurement runs, to make sure they are independently measured.

with and without sleep: X: measurement number Y: time[cycles]

## 9.6 Experiment 5

For long running measurements, it is sufficient to make sure that the average system load is low. The side effects of code running on other kernels will be smoothed out. This is shown on various average loads (none, 1 2 3 5 10 20 40 50 75 100)

X: system load Y: rel error X: system load Y: variance

We measure using the following counters: - core cycles - bus cycles - gettimeofday() - times(): user time

We measure the following kernels: +- arithmetic:add \*- mem: load \*- mem: write

We measure at \*+- max frequency +- min frequency

We measure use the following kernels to generate system load +- arithmetic:add \*- mem: load \*- mem: write +- io: file - io: network - io: graphics

We measure at different load levels (\*+none, 25, 50, 75, \*+100)

Measure at different load switch durations (0.1,1,5,10,15,50,100 ms)

We measure with any core combination. same core / +core2 core \*+0 \*+1 \*+2 \*+3

## 10 Measuring Memory Traffic

- 0x40000027 LLC\_MISSES
- 0x40000040 SSE\_PRE\_EXEC 07h03h SSE\_PRE\_EXEC.L2
- 0x40000059 L2\_DBUS\_BUSY\_RD
- 0x4000005c L2\_LINES\_IN 24h
- 0x4000006a L2\_M\_LINES\_OUT 27h
- 0x400000cb SSE\_PRE\_MISS 4Bh 00h/01h/02h
- 62h BUS\_DRDY\_CLOCKS

### 10.1 Experiments

To gain insight into the accuracy and precision of the memory transfer methods, we run the addition kernel with an exponentially increasing iteration count. The largest iteration count should result in a runtime of about 0.5s. We expect the

precision to be high for small iteration counts, a peak variance at around 5 ms due to the task switches, and an increasing precision for higher iteration counts. The accuracy of the minimum should be high for small iteration counts, and include a small overhead if multiple task switches occur during the measurement.

## 10.2 Experiment 1

The first series of measurements is about the overhead of task switches on the measured memory transfer. We measure an arithmetic kernel and mem load and write, with buffer sizes which fit into the cache and which do not fit. We measure on an idle system, and with an arithmetic kernel on the other CPUs.

X: iteration count Y: rel error X: iteration count Y: ints X: iteration count Y: task switches

## 10.3 Experiment 2

The second measurement series is about the separation of measuring transfer volume of different threads. We measure mem load and write with large buffers. We measure on an idle system and with mem kernels on the other CPUs. Execution time: about .5 s

X: cpu map Y: rel error

We measure using the following counters: - bus transactions - cache misses / writebacks / non-prefetching load/store instructions

We measure the following kernels: - arithmetic:add - mem: load: small - mem: write: small - mem: load: large - mem: write: large

We measure at - max frequency

We measure use the following kernels to generate system load - arithmetic: add - mem: load - mem: write - io: file - io: network - io: graphics

We measure at different load levels (none, 25, 50, 75, 100)

Measure at different load switch durations (0.1,1,5,10,15,50,100 ms)

We measure with any core combination. same core / +core2 core 0 1 2 3

# 11 Effects Affecting the Measurement of Multiple Quantities

While each of the measurements required to produce a roofline plot has it's own subtleties, there are some effects affecting multiple measurements, which we will discuss in the following sections.

## 11.1 Context Switches

Unless a special operating system is used, we have to deal with context switches during measurement. On current operating systems, a context switch typically occurs every 10ms due to the timer interrupt. Following the lines of [5], there are two ways to deal with them:

If the execution time of the kernel is small, the operating system will eventually execute the whole kernel without interruption. This can be exploited using

the best k measurement scheme. The kernel is repeatedly executed until the k measurements with the smallest execution times show a variation below a certain threshold. These executions were apparently not affected by a context switch, since a context switch would have increased execution time. The HW\_INT\_RCV performance counter could possibly be used as well to detect context switches.

If a single execution of the kernel takes longer than the period of time between two timer interrupts, it will always be affected by a context switch. In this case, the proposed solution is to execute the kernel in a loop until many context switches occurred. The effect of the context switches can be compensated for by reducing the measured time by a certain factor. The factor depends on the actual system.

The linux kernel offers the possibility to count performance events only during the time a thread actually executes, omitting events happening during kernel execution or while other threads run. This was not treated in the book above, and offers interesting new options.

## 11.2 System Load

Specially if the measurement includes context switches, the system load has a big impact on the measurement result. But due to caching effects, even the k best measurement scheme might be affected by the system load. Since we can control the system the measurements are performed on, we can control system load. But none the less, it should be recorded along with the measurement, in case something goes wrong with the measurement system setup.

## 11.3 Multi Threading

Our kernels and benchmarks will use multi threading. This has to be supported by the measurement tool. Since some caches as well as part of the memory bandwidth might be shared among different cores, multi threading can have various effects on the amount of transferred memory and the available bandwidth.

In case of hyper threading, some functional units of a processor core are shared among two threads. This influences the peak performance of the core.

It is possible that the operating system moves a thread from one core to another. Since the overhead of a switching the core is large, it is generally avoided by the scheduler of the operating system. But it can occur, and we have to be prepared for it.

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