

# LIBXSMM Samples

## CP2K Artificial Benchmark

The first code sample given for LIBXSMM was a performance reproducer exercising the same set of kernels usually generated for CP2K's SMM library. The code sample attempted to model the way "matrix stacks" are processed in CP2K, however there are two different code paths in CP2K: (1) the "main" code path used when processing stacks on the host-side, and (2) a code path targeting offload devices. Beside of the host-sided parallelization via MPI (and perhaps OpenMP), the secondly mentioned code path relies on an additional level of parallelization (which is obviously necessary to drive a potentially highly parallel offload device). Also, the additional level of parallelism is not exactly "nested" in the sense that it participates on sharing the same resources as the host-side. In fact, this "artificial benchmark" (cp2k code sample) is modeling a code path as utilized in the secondly mentioned case (offload device).

## 1D Dilated Convolutional Layer

This package contains the optimized kernels for the 1D dilated convolutional layer. The C++ implementation has code for both FP32 and BF16 formats. You can run this code on AVX-512 enabled CPUs. Ex. - Cascade Lake or Cooper lake.

### Install instructions

Install PyTorch in an anaconda or virtual environment before installing the package. Use GCC version 8.3.0 or higher.

```
conda activate environment          # Activate anaconda or virtual environment containing PyTorch

cd Conv1dOpti-extension/
python setup.py install            # Install package
cd ..
```

A user can either use run.sh script to run the torch\_example.py code, or he/she can follow the following commands.

```
export LD_LIBRARY_PATH={LIBXSMM_ROOT/lib}      # Set LD_LIBRARY_PATH
export OMP_NUM_THREADS=28                      # Set number of threads
export KMP_AFFINITY=compact,1,0,granularity=fine # Set KMP affinity

python torch_example.py                      # Run the pytorch example
```

In the previous example, we compare "nn.Conv1d" layer with our optimized "Conv1dOpti" layer. The example shows how "nn.Conv1d" can be replaced with "Conv1dOpti" layer in a neural network without requiring any other change. The optimized python layer can be imported using "from Conv1dOpti\_ext import Conv1dOpti" in python. The example checks the accuracy of the results and calculates the computation time of both layers.

### Limitations of the current version

- Keep padding=0 in the options. The current layer doesn't do padding. Explicit padding is needed for the optimized convolutional layer. You can use the example for reference.
- Optimized convolutional layer code can only run with stride = 1.
- Similarly, apply the nonlinearity (Ex. ReLU) separately.

To run code in BFloat16, set enable\_BF16 flag to True. BFloat16 code runs only when the parameters of Input width, number of filters and input channels to the layer are even number. Ex. - Filters = 16, Channels = 16, Input width = 60000, enable\_BF16 = True BF16 run If any of the previous parameter is odd number then code runs in FP32 format.

Keep batch size as multiple of unutilized cores (Ex. - 28, 56, 84, 128 .... on a 28 core cascade lake) for optimal performance with the Conv1dOpti layer. Each batch will run on a separate thread thus performance may go down if some core are not free, or batch size is not equal to the number of free cores. Keep the batch size as power of 2 with the MKLDNN backend (Conv1d) for optimal performance.

## Elementwise correctness- and performance tests

This folder contains tests for kernels, which work on each element of a given input separately. Examples for these operations are adding two matrices or vectors, or applying the square root to all elements individually.

*Disclosure: Performance tests haven't been implemented for all types yet.*

## Build

```
cd /path/to/libxsmm
make
or
make BLAS=0 LIBXSMM_NO_BLAS=1 STATIC=0 -j 64

cd /path/to/libxsmm/samples/eltwise
make -j 16
```

## Test specific kernels

To run a specific kernel, call one of the executable with its arguments. The arguments will be listed, when you call it without any.

## Test collections

In this directory, there are multiple bash files, which will execute multiple random tests for a specific type of operation. These collections call bash scripts from the subdirectory "kernel\_test", which will in turn call the executables in this directory.

## Compare performance between different architectures

If your machine supports multiple architectures like ARM ASIMD and ARM SVE, you can set the environment variable **ARCH1** to a second architecture. The performance tests will then run the kernels on both architectures, and compare them.

## Useful environment variables

When you want to test another architecture, specify **LIBXSMM\_TARGET**.

If you want more debugging information, set **LIBXSMM\_VERBOSE**. Setting it to -1 will print all debug information, and write the JIT-ed kernels into local files. # Hello LIBXSMM

This example is focused on a specific functionality but may be considered as "Hello LIBXSMM". Copy and paste the example code and build it either manually and as described in our main documentation (see underneath the source code), or use GNU Make:

```
cd /path/to/libxsmm
make

cd /path/to/libxsmm/samples/hello
make

./hello
```

Alternatively, one can use the Bazel build system. To further simplify, Bazelisk is used to boot-strap Bazel:

```
cd /path/to/libxsmm/samples/hello
bazelisk build //...

./bazel-bin/hello
```

The C/C++ code given here uses LIBXSMM in header-only form (`#include <libxsmm_source.h>`), which is in contrast to the code shown in the main documentation. The Fortran code (`hello.f`) can be manually compiled like `gfortran -I/path/to/libxsmm/include hello.f -L/path/to/libxsmm/lib -libxsmmf -lxsmm -lxsmmnoblas -o hello` or as part of the above described invocation of GNU Make.

## Magazine

### Overview

This collection of code samples accompany an article written for issue #34 of the magazine The Parallel Universe, an Intel publication. The articles focuses on Blaze-, Eigen-, and LIBXSMM-variants of Small Matrix Multiplications (SMMs). The set of sample codes now also includes a variant relying on BLAS and a variant that showcases LIBXSMM's explicit batch-interface.

The baseline requirements are libraries that can operate on column-major storage order, "zero copy" when using existing memory buffers, and an API that is powerful enough to describe leading dimensions. Typically a library-internal parallelization of matrix multiplication is desired. However, for the magazine sample collection there is no performance gain expected since the matrices are small, and nested parallelism may only add overhead. Hence library-internal parallelism is disabled (`BLAZE_USE_SHARED_MEMORY_PARALLELIZATION=0`, `EIGEN_DONT_PARALLELIZE`). LIBXSMM provides parallelization on a per-functions basis and no global toggle is needed.

The sample codes rely on the minimum programming language supported by the library in question (API): C++ in case of Blaze and Eigen, and C in case of LIBXSMM (both C++ and Fortran interfaces are available as well). For Blaze and Eigen, the build-system ensures to not map implementation into a BLAS library (normally desired but this would not test the library-native implementation).

### Results

To reproduce or repeat the performance measurements on a system of choice, all matrix operands are streamed by default. The file `magazine.h` can be edited to reproduce the desired combination (`STREAM_A`, `STREAM_B`, and `STREAM_C`). Whether or not matrix operands are streamed is motivated in publication. To reduce dependency on the compiler's OpenMP implementation, the benchmarks run single-threaded by default (`make OMP=1` can parallelize the batch of matrix multiplications). The outer/batch-level parallelization is also disabled to avoid accounting for proper first-touch memory population on multi-socket systems (NUMA). For the latter, the `init`-function (located in `magazine.h`) is not parallelized for simplicity.

```
cd libxsmm; make
cd samples/magazine; make
```

To run the benchmark kernels presented by the article:

```
./benchmark.sh
```

Please note that if multiple threads are enabled and used, an appropriate pin-strategy should be used (`OMP_PLACES=threads`, `OMP_PROC_BIND=TRUE`). To finally produce the benchmark charts:

```
./benchmark-plot.sh blaze
./benchmark-plot.sh eigen
./benchmark-plot.sh xsmm
```

The plot script relies at least on Gnuplot. ImageMagick (`mogrify`) can be also useful if PNGs are created, e.g., `./benchmark-plot.sh xsmm png 0` (the last argument disables single-file charts in contrast to multi-page PDFs created by default, the option also disables chart titles).

The set of kernels executed during the benchmark can be larger than the kernels presented by the plots: `benchmark.set` selects the kernels independent of the kernels executed (union).

## NEK Sample Collection

This directory contains kernels taken from Nek{Box,5000}. They aim to represent most of the matrix-matrix workloads.

Please note that the mxm\_std.f source code is protected by an (US) GOVERNMENT LICENSE, and under the copyright of the University of Chicago.

### stpm

Small tensor-product multiple (stpm) replicates the axhelm kernel, which computes the Laplacian with spectral elements. Usage:

```
./stpm m n k size1 size
```

The elements are m-by-n-by-k, mode picks the LIBXSMM interface used, and size scales the number of spectral elements.

### rstr

Restriction operator transforms elements from one size to another. This occurs in multi-grid, the convection operator, and, when the sizes are the same, the local Schwarz solves. Usage:

```
./rstr m n k mm nn kk size1 size
```

The input elements are m-by-n-by-k and the output elements are mm-by-nn-by-kk. When m=mm, n=nn, k=kk, this half of a Schwarz solve.

## SPECFEM Sample

This sample contains a dummy example from a spectral-element stiffness kernel taken from SPECFEM3D\_GLOBE.

It is based on a 4th-order, spectral-element stiffness kernel for simulations of elastic wave propagation through the Earth. Matrix sizes used are (25,5), (5,25) and (5,5) determined by different cut-planes through a three dimensional (5,5,5)-element with a total of 125 GLL points.

### Usage Step-by-Step

This example needs the LIBXSMM library to be built with static kernels, using MNK="5 25" (for matrix size (5,25), (25,5) and (5,5)).

### Build LIBXSMM

**General Default Compilation** In LIBXSMM root directory, compile the library with:

```
make MNK="5 25" ALPHA=1 BETA=0
```

**Additional Compilation Examples**    Compilation using only single precision version and aggressive optimization:

```
make MNK="5 25" ALPHA=1 BETA=0 PRECISION=1 OPT=3
```

For Sandy Bridge CPUs:

```
make MNK="5 25" ALPHA=1 BETA=0 PRECISION=1 OPT=3 AVX=1
```

For Haswell CPUs:

```
make MNK="5 25" ALPHA=1 BETA=0 PRECISION=1 OPT=3 AVX=2
```

For Knights Corner (KNC) (and thereby creating a Sandy Bridge version):

```
make MNK="5 25" ALPHA=1 BETA=0 PRECISION=1 OPT=3 AVX=1 \
OFFLOAD=1 KNC=1
```

Installing libraries into a sub-directory workstation/:

```
make MNK="5 25" ALPHA=1 BETA=0 PRECISION=1 OPT=3 AVX=1 \
OFFLOAD=1 KNC=1 \
PREFIX=workstation/ install-minimal
```

**Build SpecFEM example code**    For default CPU host:

```
cd sample/specfem
make
```

For Knights Corner (KNC):

```
cd sample/specfem
make KNC=1
```

Additionally, adding some specific Fortran compiler flags, for example:

```
cd sample/specfem
make FCFLAGS="-O3 -fopenmp" [...]
```

Note that steps 1 and 2 could be shortened by specifying a "specfem" make target in the LIBXSMM root directory:

```
make MNK="5 25" ALPHA=1 BETA=0 PRECISION=1 OPT=3 AVX=1 specfem
```

For Knights Corner, this would need two steps:

```
make MNK="5 25" ALPHA=1 BETA=0 PRECISION=1 OPT=3 AVX=1 OFFLOAD=1 KNC=1
make OPT=3 specfem_mic
```

## Run the Performance Test

For default CPU host:

```
./specfem.sh
```

For Knights Corner (KNC):

```
./specfem.sh -mic
```

## Results

Using Intel Compiler suite: icpc 15.0.2, icc 15.0.2, and ifort 15.0.2.

## **Sandy Bridge - Intel(R) Xeon(R) CPU E5-2670 0 @ 2.60GHz** Library compilation by (root directory):

```
make MNK="5 25" ALPHA=1 BETA=0 PRECISION=1 OPT=3 AVX=1
```

Single threaded example run:

```
cd sample/specfem
make; OMP_NUM_THREADS=1 ./specfem.sh
```

Output:

```
=====
average over          15 repetitions
timing with Deville loops    =    0.1269
timing with unrolled loops  =    0.1737 / speedup =   -36.87 %
timing with LIBXSMM dispatch =    0.1697 / speedup =   -33.77 %
timing with LIBXSMM prefetch =    0.1611 / speedup =   -26.98 %
timing with LIBXSMM static   =    0.1392 / speedup =    -9.70 %
=====
```

## **Haswell - Intel(R) Xeon(R) CPU E5-2680 v3 @ 2.50GHz** Library compilation by (root directory):

```
make MNK="5 25" ALPHA=1 BETA=0 PRECISION=1 OPT=3 AVX=2
```

Single threaded example run:

```
cd sample/specfem
make; OMP_NUM_THREADS=1 ./specfem.sh
```

Output:

```
=====
average over          15 repetitions
timing with Deville loops    =    0.1028
timing with unrolled loops  =    0.1385 / speedup =   -34.73 %
timing with LIBXSMM dispatch =    0.1408 / speedup =   -37.02 %
timing with LIBXSMM prefetch =    0.1327 / speedup =   -29.07 %
timing with LIBXSMM static   =    0.1151 / speedup =   -11.93 %
=====
```

Multi-threaded example run:

```
cd sample/specfem
make OPT=3; OMP_NUM_THREADS=24 ./specfem.sh
```

Output:

```
OpenMP information:
  number of threads =          24
```

[...]

```
=====
average over          15 repetitions
timing with Deville loops    =    0.0064
timing with unrolled loops  =    0.0349 / speedup =  -446.71 %
timing with LIBXSMM dispatch =    0.0082 / speedup =   -28.34 %
timing with LIBXSMM prefetch =    0.0076 / speedup =   -19.59 %
timing with LIBXSMM static   =    0.0068 / speedup =    -5.78 %
=====
```

## **Knights Corner - Intel Xeon Phi B1PRQ-5110P/5120D** Library compilation by (root directory):

```
make MNK="5 25" ALPHA=1 BETA=0 PRECISION=1 OPT=3 OFFLOAD=1 KNC=1
```

Multi-threaded example run:

```
cd sample/specfem
make FCFLAGS="-O3 -fopenmp -warn" OPT=3 KNC=1; ./specfem.sh -mic
```

Output:

```
OpenMP information:
  number of threads =          236
```

```
[...]
```

```
=====
average over          15 repetitions
timing with Deville loops    =    0.0164
timing with unrolled loops   =    0.6982 / speedup = -4162.10 %
timing with LIBXSMM dispatch =    0.0170 / speedup =   -3.89 %
timing with LIBXSMM static   =    0.0149 / speedup =    9.22 %
=====
```

## Matrix Transpose (TCOPY)

### Overview

This code sample aims to benchmark the performance of matrix transposes. The C/C++ and FORTRAN sample code differ slightly with the C/C++ code sample offering a richer set of command line options as well as build settings available inside of the translation unit.

The available command line options of the sample code may be reviewed by looking into the source code. Generally, the idea is to support the following:

```
transpose [<kind> [<m> [<n> [<ldi> [<ldo>]]]]]
transposef [<m> [<n> [<ldi> [<ldo>]]]]
```

Above, `m` and `n` specify the matrix shape, and `ldi` the leading dimension of the matrix. The argument `ldo` allows to specify an output dimension, which may differ from `ldi`. The transpose kind shall be either out-of-place (`o`) or in-place (`i`).

Running the C sample code may look like:

```
$ ./transpose.sh o 20000
m=20000 n=20000 ldi=20000 ldo=20000 size=3052MB (double, out-of-place)
    bandwidth: 18.8 GB/s
    duration: 159 ms
```

Instead of executing a wrapper script, one may affinitize the multi-threaded execution manually (OpenMP runtime). In case of an executable built using the Intel Compiler this may look like:

```
LIBXSMM_VERBOSE=2 KMP_AFFINITY=balanced,granularity=fine,1 \
./transpose o 20000
m=20000 n=20000 ldi=20000 ldo=20000 size=3052MB (double, out-of-place)
    bandwidth: 21.1 GB/s
    duration: 141 ms
```

```
Registry: 20 MB (gemm=0 mcopy=0 tcopy=1)
```

In the above case one can see from the verbose output (`LIBXSMM_VERBOSE=2`) that one kernel (`tcopy`) served transposing the entire matrix. To avoid duplicating JIT-kernels under contention (code registry), one may also consider `LIBXSMM_TRYLOCK=1`, which is available per API-call as well.

### OpenTuner

To tune the tile sizes ("block sizes") internal to LIBXSMM's transpose routine, the OpenTuner extensible framework for program autotuning can be used. In case of issues during the tuning phase ("no value has been set for this column"), please install the latest 1.2.x revision of SQLAlchemy (`pip install sqlalchemy==1.2.19`). A tuning script (`transpose_opentuner.py`) is provided, which accepts a range of matrix sizes as command line arguments.

```
transpose_opentuner.py <begin> <end> [nexpirments-per-epoch] [tile-size-m] [tile-size-n]
```

To start a tuning experiment for a new set of arguments, it is highly recommended to start from scratch. Otherwise the population of previously generated tuning results is fetched from a database and used to tune an eventually unrelated range of matrix shapes. To get reliable timings, the total time for all experiments per epoch is minimized (hence a different number of experiments per epoch also asks for an own database). Optionally, the initial block size can be seeded (`tile-size-m` and `tile-size-n`).

```
rm -rf opentuner.db
```

The script tunes matrices with randomized shape according to the specified range. The leading dimension is chosen tightly for the experiments. The optimizer not only maximizes the performance but also minimizes the value of  $M * N$  (which also helps to prune duplicated results due to an additional preference).

```
rm -rf opentuner.db
./transpose_opentuner.py --no-dups 1 1024 1000
```

```
rm -rf opentuner.db
./transpose_opentuner.py --no-dups 1024 2048 100
```

```
rm -rf opentuner.db
./transpose_opentuner.py --no-dups 2048 3072 20
```

```
rm -rf opentuner.db
./transpose_opentuner.py --no-dups 3072 4096 20
```

```
rm -rf opentuner.db
./transpose_opentuner.py --no-dups 4096 5120 16
```

```
rm -rf opentuner.db
./transpose_opentuner.py --no-dups 5120 6144 12
```

```
rm -rf opentuner.db
./transpose_opentuner.py --no-dups 6144 7168 8
```

```
rm -rf opentuner.db
./transpose_opentuner.py --no-dups 7168 8192 6
```

The tuning script uses the environment variables `LIBXSMM_TCOPY_M` and `LIBXSMM_TCOPY_N`, which are internal to `LIBXSMM`. These variables are used to adjust certain thresholds in `libxsmm_otrans` or to request a specific tiling-scheme inside of the `libxsmm_otrans_omp` routine.

## Dispatch

### Microbenchmark

This code sample benchmarks the performance of (1) the dispatch mechanism, and (2) the time needed to JIT-generate code for the first time. Both mechanisms are relevant when replacing GEMM calls (see Call Wrapper section of the reference documentation), or in any case of calling `LIBXSMM`'s native GEMM functionality.

### Command Line Interface (CLI)

- Optionally takes the number of dispatches/code-generations (default: 10000).
- Optionally takes the number of threads (default: 1).

### Measurements (Benchmark)

- Duration of an empty function call (serves as a reference timing).
- Duration to find an already generated kernel (cached/non-cached).
- Duration to JIT-generate a GEMM kernel.

In case of a multi-threaded benchmark, the timings represent a highly contended request (worst case). For thread-scaling, it can be observed that read-only accesses (code dispatch) stay roughly with a constant duration whereas write-accesses (code generation) are serialized and hence the duration scales linearly with the number of threads.

The Fortran example (`dispatch.f`) could use `libxsmm_dmmdispatch` (or similar) like the C code (`dispatch.c`) but intentionally shows the lower-level dispatch interface `libxsmm_xmmdispatch` and also omits using the `LIBXSMM` module. Not using the module confirms: the same task can be achieved by relying only on FORTRAN 77 language level.



## User-Data Dispatch

Further, another Fortran example about user-data dispatch is not exactly a benchmark. Dispatching user-data containing multiple kernels can obviously save multiple singular dispatches. The C interface for dispatching user-data is designed to follow the same flow as the Fortran interface.

## Scratch Memory Allocation (Microbenchmark)

This code sample aims to benchmark the performance of the scratch memory allocation. This facility is a viable option to satisfy the need for temporary memory when using the DNN domain of LIBXSMM (small convolutions). Although any kind of readable/writable buffer can be bound to a convolution handle, LIBXSMM's `libxsmm_aligned_scratch` features a thread-safe linear allocator mechanism which can help to lower allocation overhead.

## SMM Benchmark

This collection of code samples exercises different memory streaming cases when performing the matrix multiplication  $C_{m \times n} = \alpha \cdot A_{m \times k} \cdot B_{k \times n} + \beta \cdot C_{m \times n}$ : (1) streaming the matrices A, B, and C which is usually referred as batched matrix multiplication, (2) streaming the inputs A and B but accumulating C within cache, (3) streaming the A and C matrices while B is kept in cache, (4) streaming the B and C matrices while A is kept in cache, and (4) not streaming any of the operands but repeating the very same multiplication until the requested number of matrix multiplications has been completed.

Beside of measuring the duration of a test case, the performance is presented in GFLOPS/s. As an alternative metric, the memory bandwidth is given (the artificial "cached" case omits to present the cache-memory bandwidth). The "pseudo-performance" given in FLOPS/cycle is an artificial scoring, it not only uses a non-standard formula for calculating the FLOPS ( $2 * M * N * K - M * N$  rather than  $2 * M * N * K$ ) but also relies on (pseudo-)clock cycles:

```
$ ./specialized.sh 0
m=32 n=32 k=32 size=87381 memory=2048.0 MB (DP)
```

```
Batched (A,B,C)...
  pseudo-perf.: 10.7 FLOPS/cycle
  performance: 23.9 GFLOPS/s
  bandwidth: 11.1 GB/s
  duration: 239 ms
Finished
```

There are two sub collections of samples codes: (1) a collection of C++ code samples showing either BLAS, Compiler-generated code (inlined code), LIBXSMM/dispatched, LIBXSMM/specialized functions to carry out the multiplication, and (2) a Fortran sample code showing BLAS versus LIBXSMM including some result validation.

## C/C++ Code Samples: Command Line Interface (CLI)

- Takes an optional number (1st arg.) to select the streaming-case (0...8)
- Optionally takes the M, N, and K parameter of the GEMM in this order
- If only M is supplied, the N and K "inherit" the M-value
- Example I (A,B,C): `./specialized.sh 0 16 8 9`
- Example II (A,B): `./specialized.sh 6 16`

## Fortran Code Sample: Command Line Interface (CLI)

- Optionally takes the M, N, and K parameter of the GEMM in this order
- Optional problem size (in MB) of the workload; M/N/K must have been supplied
- Optional total problem size (in MB) implying the number of repeated run
- If only M is supplied, the N and K are "inheriting" the M-value
- Shows the performance of each of the streaming cases
- Example I: `./smm.sh 16 8 9 1024 16384`
- Example II: `./smm.sh 16`

## Wrapped DGEMM

This code sample is calling DGEMM and there is no dependency on the LIBXSMM API as it only relies on LAPACK/BLAS interface. Two variants are linked when building the source code: (1) code which is dynamically linked against LAPACK/BLAS, (2) code which is linked using `--wrap=symbol` as possible when using a GNU GCC compatible tool chain. For more information, see the Call Wrapper section of the reference documentation.

The same (source-)code will execute in three flavors when running `dgemm-test.sh`: (1) code variant which is dynamically linked against the originally supplied LAPACK/BLAS library, (2) code variant which is linked using the wrapper mechanism of the GNU GCC tool chain, and (3) the first code but using the LD\_PRELOAD mechanism (available under Linux).

### Command Line Interface (CLI)

- Optionally takes the number of repeated DGEMM calls
- Shows the performance of the workload (wall time)