Just-in-time compilation: Speeding up small linear algebra operations

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Intel® Math Kernel Library (Intel® MKL)

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Outline

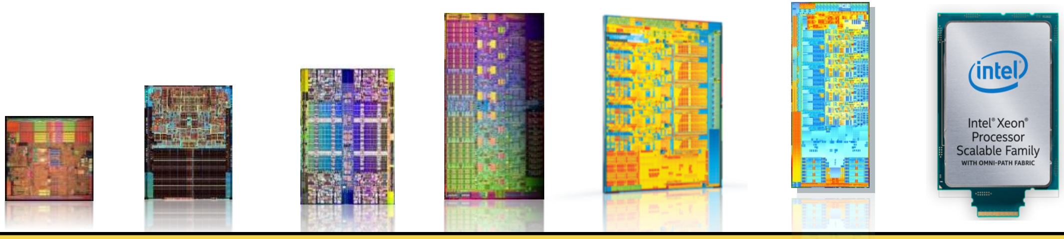
- Motivation
- Problem statement and solutions
- Simple example
- Performance comparison

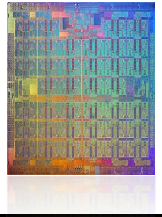
Motivation

- Partial differential equations
- FEM solvers
- Block sparse matrices
- Earthquake simulations
- Astrophysics
- Molecular dynamics
- Tensor contractions
- Machine learning
- Autonomous driving

Processor improvements

More cores → More Threads → Wider vectors





	Intel® Xeon® Processor 64-bit	Intel® Xeon® Processor 5100 series	Intel® Xeon® Processor 5500 series	Intel® Xeon® Processor 5600 series	Intel® Xeon® Processor E5-2600 v2 series	Intel® Xeon® Processor E5-2600 v3 series v4 series	Intel® Xeon® Scalable Processor[1]	Intel® Xeon Phi™ x200 Processor (KNL)
Up to Core(s)	1	2	4	6	12	18-22	28	72
Up to Threads	2	2	8	12	24	36-44	56	288
SIMD Width	128	128	128	128	256	256	512	512
Vector ISA	Intel® SSE3	Intel® SSE3	Intel® SSE4-4.1	Intel® SSE 4.2	Intel® AVX	Intel® AVX2	Intel® AVX-512	Intel® AVX-512

1. Product specification for launched and shipped products available on ark.intel.com.

Optimization Notice

Overheads for small sizes

- Low vectorization
- Low parallelization
- Loop trip count
- Non-local data access for large leading dimensions
- Error checking
- High function call overheads
  - Dispatching to ISA-specific codepath

Methods for improving performance for small sizes

- Specific kernels
- Compile-time optimizations
- Just-in-time (run-time) compilation
- Batching operations together
    - Modifying data layout

JIT compilers

- Xbyak (https://github.com/herumi/xbyak)
  - Used in Intel MKL and Intel MKL-DNN
- libxsmm back-end (https://github.com/hfp/libxsmm)
  - Used in libxsmm
- LLVM (https://llvm.org/docs/index.html)
- Others

Xbyak syntax

- Similar to Intel syntax:
  - mov eax, ebx → mov(eax, ebx);
  - vaddps xmm1, xmm2, xmm3 → vaddps(xmm1, xmm2, xmm3);
- Registers:
  - Xmm xmm0; Zmm zmm31; Reg32 eax; Zmm(i)
- Addressing:
  - mov(eax, ptr [ebx + ecx]); test(byte [esp], 4)
- Labels:
  - L(“L1”); //create label
  - jmp(“L1”); //jump to that label

Simple example: saxpy with unit increments
y = alpha * x + y

```
void saxpy_unit(int n, float alpha, float* x, float* y) {
    for (int i = 0; i < n; i++) {
        y[i] += alpha * x[i];
    }
}
```

JIT-ing saxpy_unit

- What parameter(s) will the generator take?
- What is the API for the generated kernel?

```
saxpy_unit_jit jc(n);
void (*saxpy_kernel)(float, float*, float*) =
       jc.getCode<void(*)(float, float*, float*)>();
saxpy_kernel(alpha, x, y);
```

Xbyak saxpy_unit - setup

```
#define ELE_IN_REG 16
class saxpy_unit_jit: public Xbyak::CodeGenerator {
    public: saxpy_unit_jit(int n): Xbyak::CodeGenerator()
{
    // convenience register variables
    auto reg_alpha = xmm0; // 1st parameter (alpha)
    auto reg_x = rdi;      // 2nd parameter (pointer to x)
    auto reg_y = rsi;      // 3rd parameter (pointer to y)
    auto alpha = zmm2;     // holds broadcasted alpha

    // broadcast alpha
    vbroadcastss(alpha, reg_alpha);
```

Xbyak saxpy_unit - main loop

```
// loop over full vector registers
for (int i = 0; i < (n / ELE_IN_REG); i++) {
    vmovups(zmm0, ptr[reg_x + sizeof(float)*(i*ELE_IN_REG)]);
    vmovups(zmm1, ptr[reg_y + sizeof(float)*(i*ELE_IN_REG)]);
    vfmadd231ps(Zmm(1), Zmm(0), alpha);
    vmovups(ptr[reg_y + sizeof(float)*(i*ELE_IN_REG)], zmm1);
}
```

Xbyak saxpy_unit - tail

```
 // finish off tail using masks
if ( n % ELE_IN_REG ) {
    auto full_regs = n / ELE_IN_REG;
    auto mask = (1 << (n % ELE_IN_REGISTER)) - 1;
    mov(eax, mask);
    kmovw(k1, eax);
    vmovups(zmm0 | k1, ptr[reg_x + sizeof(float)*(full_regs*ELE_IN_REG)]);
    vmovups(zmm1 | k1, ptr[reg_y + sizeof(float)*(full_regs*ELE_IN_REG)]);
    vfmadd231ps(zmm1, zmm0, alpha);
    vmovups(ptr[reg_y] | k1, zmm1);
}
```

Generated code

n = 32

```
vbroadcastss zmm2, xmm0
vmovups zmm0, zmmword ptr [rdi]
vmovups zmm1, zmmword ptr [rsi]
vfmadd231ps zmm1, zmm0, zmm2
vmovups zmmword ptr [rsi], zmm1
vmovups zmm0, zmmword ptr [rdi+0x40]
vmovups zmm1, zmmword ptr [rsi+0x40]
vfmadd231ps zmm1, zmm0, zmm2
vmovups zmmword ptr [rsi+0x40], zmm1
```

n = 42

```
vbroadcastss zmm2, xmm0
vmovups zmm0, zmmword ptr [rdi]
vmovups zmm1, zmmword ptr [rsi]
vfmadd231ps zmm1, zmm0, zmm2
vmovups zmmword ptr [rsi], zmm1
vmovups zmm0, zmmword ptr [rdi+0x40]
vmovups zmm1, zmmword ptr [rsi+0x40]
vfmadd231ps zmm1, zmm0, zmm2
vmovups zmmword ptr [rsi+0x40], zmm1
mov eax, 0x3ff
kmovw k1, eax
vmovups zmm0{k1}, zmmword ptr [rdi+0x80]
vmovups zmm1{k1}, zmmword ptr [rsi+0x80]
vfmadd231ps zmm1, zmm0, zmm2
vmovups zmmword ptr [rsi+0x80]{k1}, zmm1
```

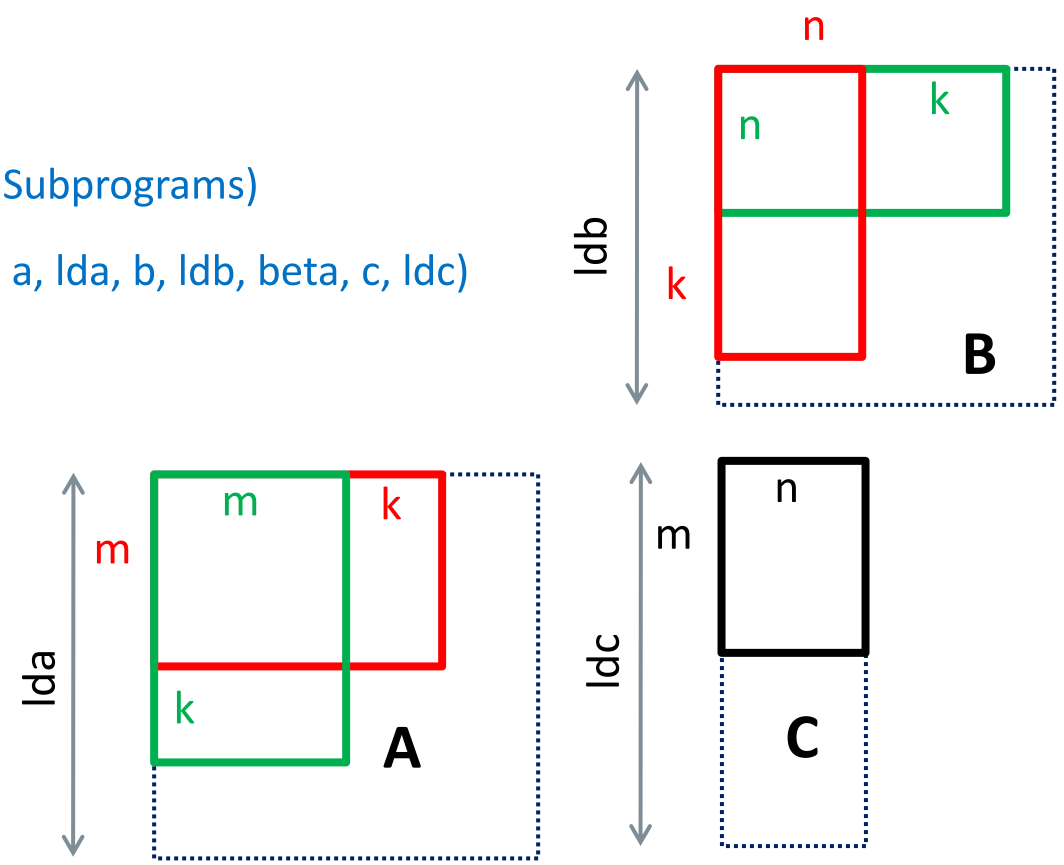
Matrix-matrix multiply

- Part of the BLAS (Basic Linear Algebra Subprograms)
- *GEMM(transa, transb, m, n, k, alpha, a, lda, b, ldb, beta, c, ldc)

C = *alpha* op(**A**) * op(**B**) + *beta* **C**

op(**X**) = **X** or $\mathbf{X}^T$

```
C = beta*C
DO i=1,M
 DO j=1,N
  DO kk=1,K
   C(i,j) += alpha*A(i,kk)*B(kk,j)
  END DO
 END DO
END DO
```



Direct call compilation flags for Intel MKL

Define the preprocessor macro MKL_DIRECT_CALL or MKL_DIRECT_CALL_SEQ

- Instead of calling a library function, a C implementation may be used
- Starting from Intel MKL 2018.1, compiler intrinsics may be used for some kernels

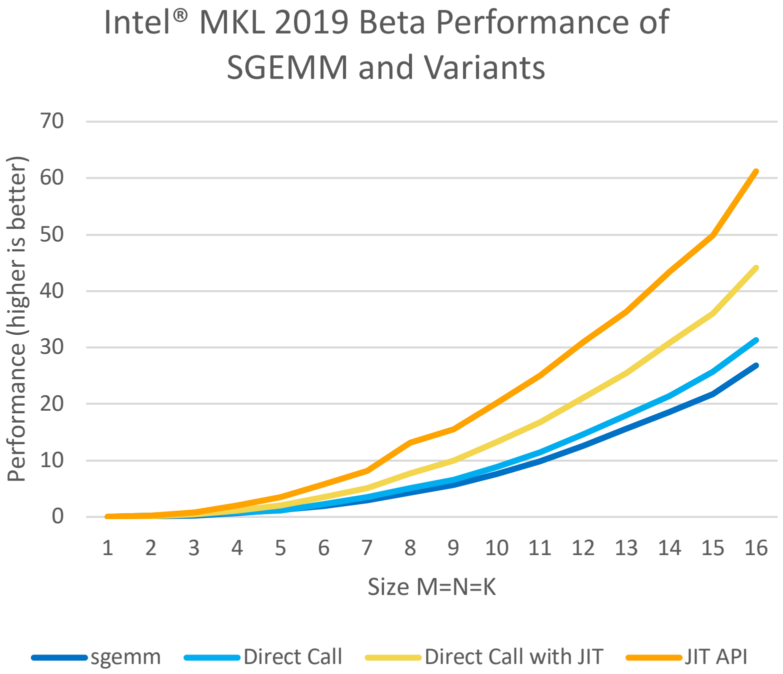
Starting from Intel MKL 2019 Beta: MKL_DIRECT_CALL_JIT or MKL_DIRECT_CALL_SEQ_JIT

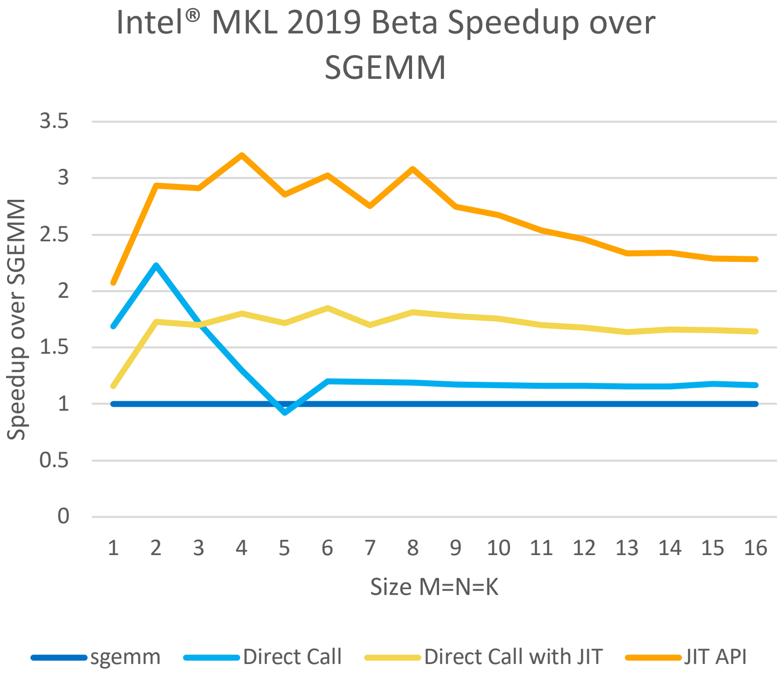
- A JIT-ted kernel may be used

```
// compile with: icc -DMKL_DIRECT_CALL …
#include <mkl.h>
void main(void) {
    dgemm(…);
}
```

```
! compile with: ifort -DMKL_DIRECT_CALL -fpp …
#     include “mkl_direct_call.fi”
      program DGEMM_MAIN
      DGEMM(…)
```

Performance of SGEMM on Intel® Xeon® Platinum





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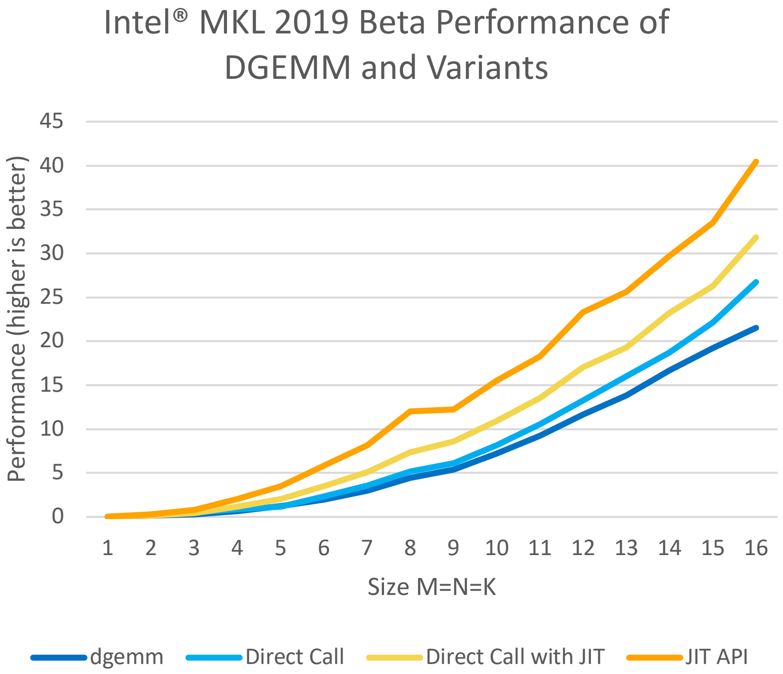
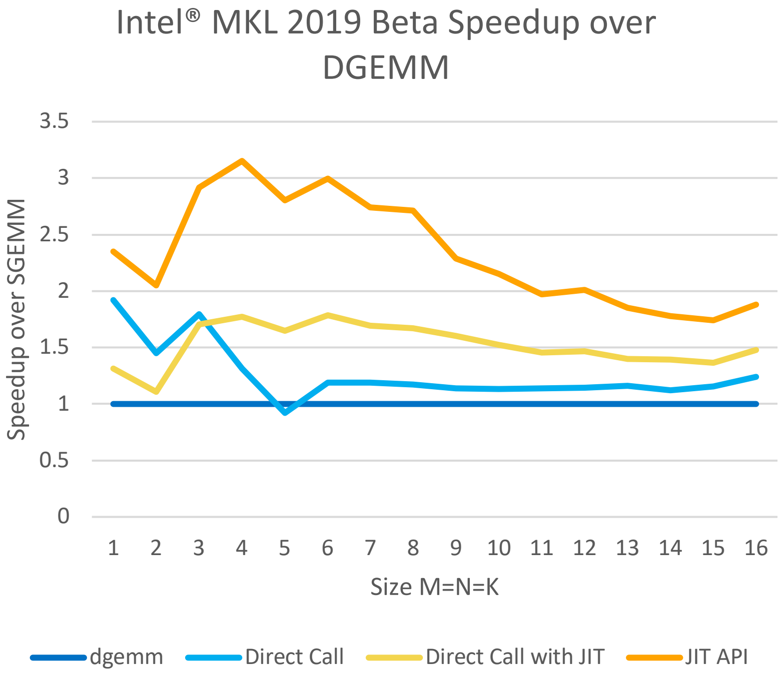
Performance of DGEMM on Intel® Xeon® Platinum





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Summary

- Small linear algebra problems:
  - Are ubiquitous
  - Suffer performance overheads
- Just-in-time compilation can help:
  - Generator can create customized kernels for any parameters
- Performance gains can be significant

Resources

- Intel MKL Developer Reference: https://software.intel.com/en-us/articles/mkl-reference-manual
- Intel MKL Forum: https://software.intel.com/en-us/forums/intel-math-kernel-library
- No cost option for Intel MKL: https://software.intel.com/en-us/articles/free-mkl
- Intel MKL-DNN: https://github.com/01org/mkl-dnn
- Xbyak: https://github.com/herumi/xbyak
- libxsmm: https://github.com/hfp/libxsmm

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