# Joint Matrix: A Unified SYCL Extension for Matrix Hardware Programming

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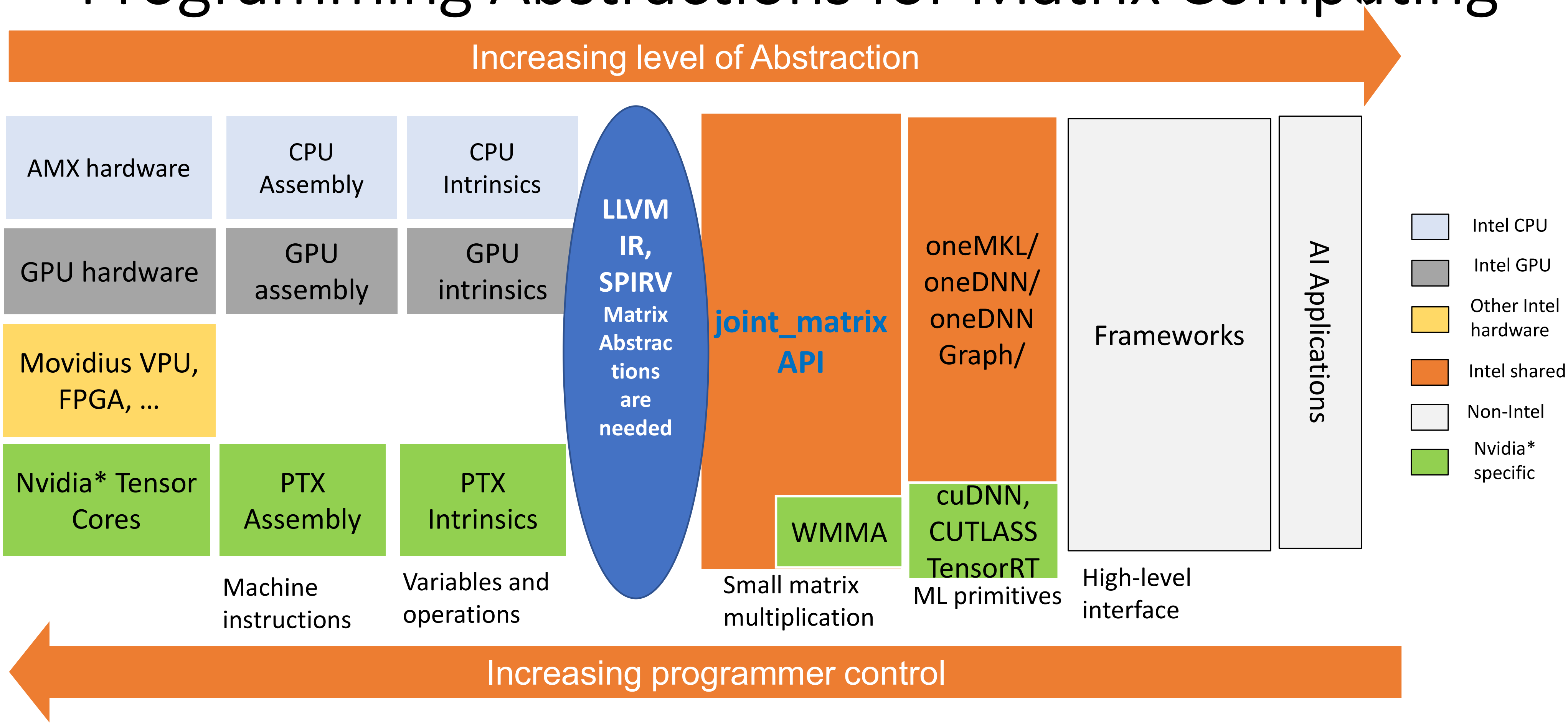
Collaborating with many colleagues from Intel and Codeplay

# Executive Summary

- Goal
  - Deliver unified SYCL matrix interface across matrix hardware: Intel AMX, Intel XMX and Nvidia Tensor Cores
    - Programmer productivity: Allow the customer to express their applications for matrix hardware with minimal changes
    - Performance: Maps directly to low-level intrinsics/assembly for maximum performance
- Status
  - Implementation: Unified interface will be part of oneAPI 2023.1 release (March 21st)
  - Current Users: Code porting from CUDA wmma, MLIR SPIRV-based joint matrix code generation

# Programming Abstractions for Matrix Computing




Ninja programmer - Focus on performance through hardware

Application programmer - Focus on algorithmic improvements

# Lead Users

**Performance portability across all hardware without extra effort of optimizations for specific hardware**


## AI Scientists

- New operations such as tensor contractions, BRGEMM, quantized gemm, fused operations

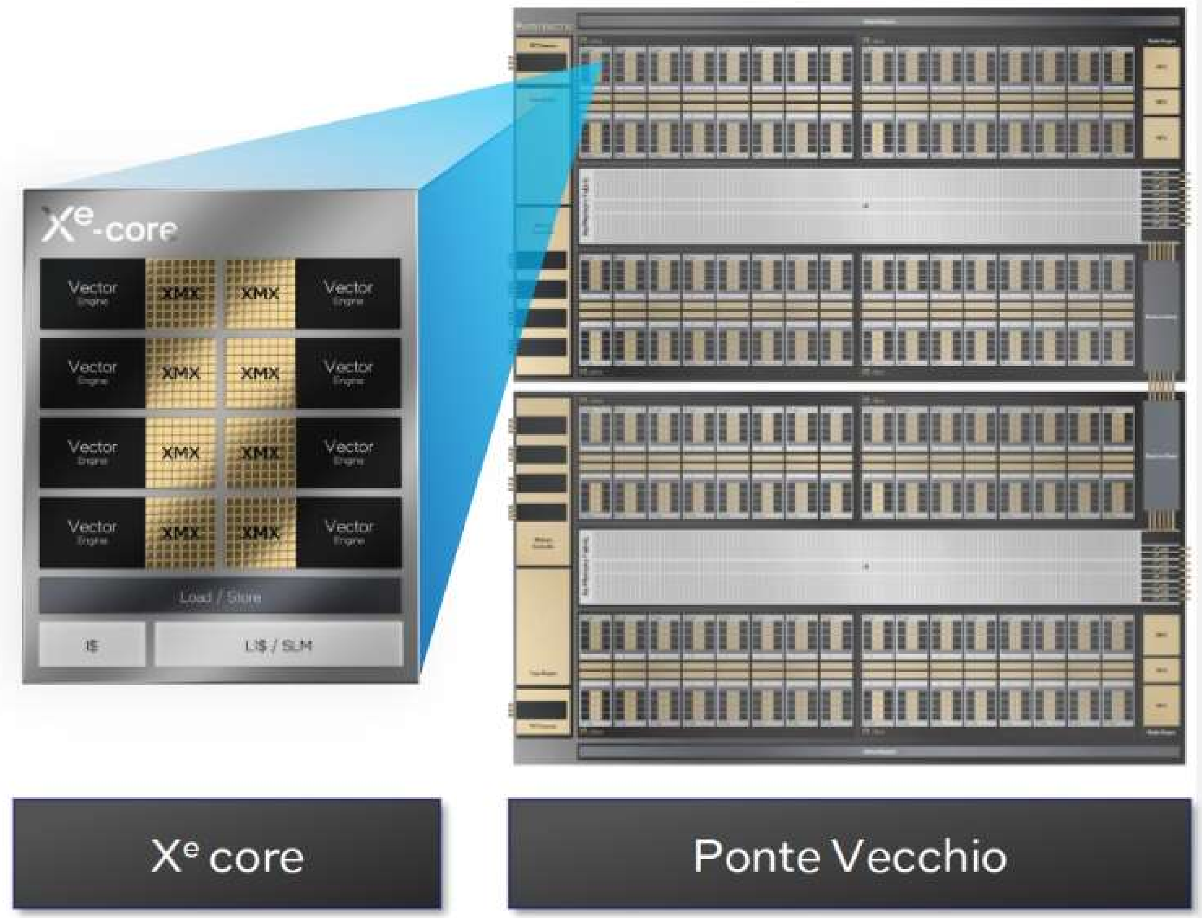
## Library Developers

- Different DNN and BLAS libraries

# Matrix Hardware

# Intel XMX in Intel® Data Center GPU Max Series

- Code-named Ponte Vecchio (PVC)
- Xe -HPC 2-Stack Ponte Vecchio GPU
- 8 slices
- Xe slice contains 16 Xe core
- An Xe -core contains 8 vector and 8 matrix engines

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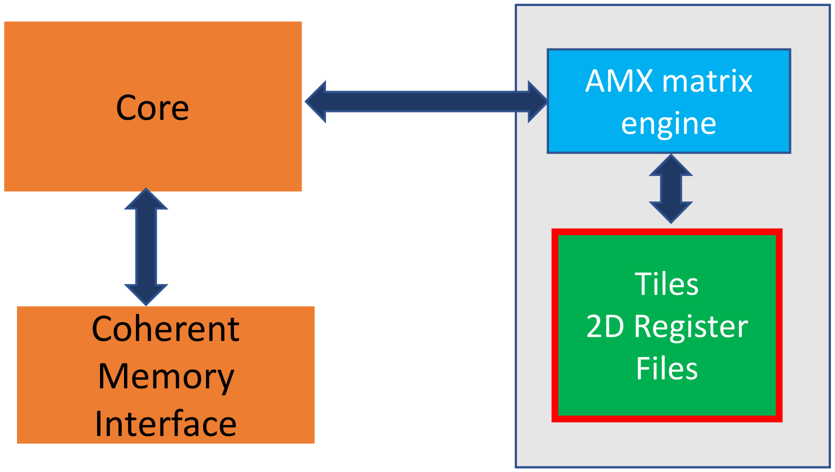
# Intel AMX High-Level Architecture

- Intel® Xeon® processor codenamed Sapphire Rapids
- Intel AMX, an Intel x86 extension for multiplication of matrices of bf16/int8 elements



# SYCL Joint Matrix Extension

# SYCL Matrix Extension

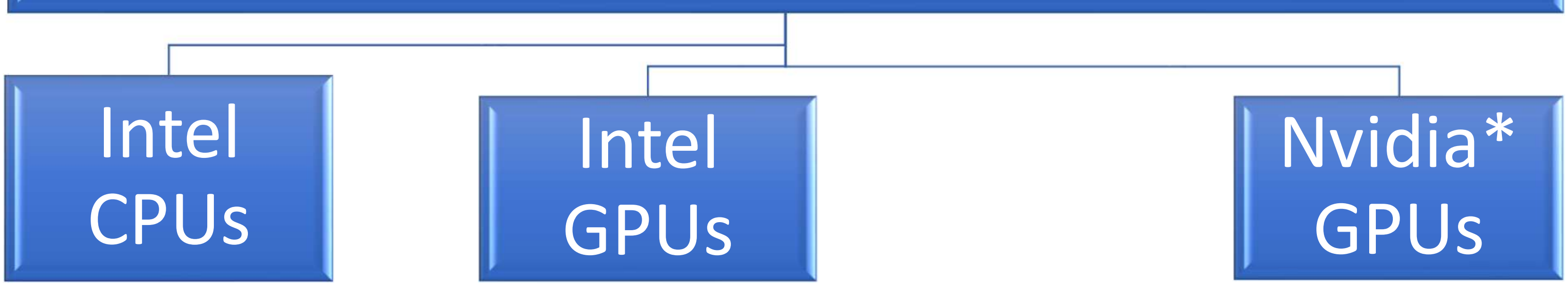
| | |
|---|---|
| Namespace | namespace sycl::ext::oneapi::experimental::matrix |
| - New matrix data type with group scope (WG or SG)<br>- Defined with a specified type, use (a, b, accumulator), size, and layout. | template <typename Group, typename T, use Use, size_t Rows, size_t Cols, layout Layout = layout::dynamic><br>struct joint_matrix;<br>enum class use { a, b, accumulator}; |
| - Separate memory operations from the compute<br>- enum class layout {row_major, col_major, dynamic };<br>- Group execution scope → *joint, Group as argument* | • joint_matrix_fill(Group g, joint_matrix<>&dst, T v);<br>• void joint_matrix_load(Group g, joint_matrix<>dst, T *base, unsigned stride, Layout layout);<br>• void joint_matrix_store(Group g, joint_matrix<>src, T *base, unsigned stride, Layout layout); |
| - Multiply and add<br>- Element-wise ops<br>- Extensible to add more operations | • joint_matrix<> joint_matrix_mad(Group g, joint_matrix<>A, joint_matrix<>B, joint_matrix<>C);<br>• void joint_matrix_apply(Group g, joint_matrix<>A, F&& func); |

# SYCL joint_*matrix* *Example*

```
using namespace sycl::ext::oneapi::experimental::matrix;
queue q;
range<2> G = {M/tM, N/tN * SG_SIZE};
range<2> L = {1, SG_SIZE};
auto bufA = sycl::buffer{memA, sycl::range{M*K}};
auto bufB = sycl::buffer{memB, sycl::range{K*N}};
auto bufC = sycl::buffer{memC, sycl::range{M*N}};
q.submit([&](sycl::handler& cgh) {
  auto accA = sycl::accessor{bufA, cgh, sycl::read_only};
  auto accB = sycl::accessor{bufB, cgh, sycl::read_only};
  auto accC = sycl::accessor{bufC, cgh, sycl::read_write};
  cgh.parallel_for(nd_range<2>(G, L), [=](nd_item<2> item) {
     const auto sg_startx = item.get_global_id(0) - item.get_local_id(0);
     const auto sg_starty = item.get_global_id(1) - item.get_local_id(1);
     sub_group sg = item.get_sub_group();
     joint_matrix<sub_group, int8_t, use::a, tM, tK, layout::row_major> subA;
     joint_matrix<sub_group, int8_t, use::b, tK, tN, layout::row_major> subB;
     joint_matrix<sub_group, int32_t, use::accumulator, tM, tN> subC;
     joint_matrix_fill(sg, subC, 0);
     for (int k = 0; k < K; k += tk) {
       joint_matrix_load(sg, subA, accA + sg_startx * tM * K + k, K);
       joint_matrix_load(sg, subB, accB + k * N + sg_starty, N);
       subC = joint_matrix_mad(sg, subA, subB, subC);
     }
     joint_matrix_apply(sg, subC, [=](T &x) { Relu(x); });
     joint_matrix_store(sg, subC, accC + sg_startx * tM * N + sg_starty, N, row_major);
  });
});
q.wait;
```

# oneAPI 2023.1: One Joint Matrix Code to Run on Intel AMX, Intel XMX and Nvidia* Tensor Cores

```
joint_matrix<sub_group, int8_t, use::a, tM, tK, layout::row_major> subA;
joint_matrix<sub_group, int8_t, use::b, tK, tN, layout::row_major> subB;
joint_matrix<sub_group, int32_t, use::accumulator, tM, tN> subC;
sub_group sg = item.get_sub_group();
joint_matrix_fill(sg, subC, 0);
for (int k = 0; k < K; k += tK) {
  joint_matrix_load(sg, subA, accA + sg_startx * tM * K + k, K);
  joint_matrix_load(sg, subB, accB + k * N + sg_starty/SG_SIZE*tN, N);
  subC = joint_matrix_mad(sg, subA, subB, subC);
}
joint_matrix_apply(sg, subC, [=](T x) { x *= alpha; });
joint_matrix_store(sg, subC, accC + sg_startx * tM * N + sg_starty/SG_SIZE*tN, N, layout::row_major);
```



# SYCL Matrix Extension: Intel Specific Features

**CUDA Syntax**

```
wmma::fragment<wmma::accumulator, 16, 16, 16, float> frag;
for(int t=0; t<frag.num_elements; t++)
  frag.x[t] *= alpha;
```

**SYCL namespace**

```
namespace sycl::ext::intel::experimental::matrix
```

- Element-wise ops using indexing into work item slice of the joint matrix
- Mapping of WI element to original joint matrix element is implementation defined

→ get_coord()

```
• wi_data<> get_wi_data(Group g, joint_matrix<>C);
• class wi_data {
     size_t length();
     wi_element<> operator[](size_t i);
  };
• class wi_element {
     std::tuple<size_t, size_t> get_coord();
  };
```

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# SYCL joint_matrix Indexing with Coordinates Example

- Element wise ops that apply to a set of elements of the matrix → Mapping is required
- Example: Quantization Calculations
- *A*B + sum_rows_A + sum_cols_B + scalar_zero_point*
- *sum_rows_A* returns a single row of A

```
using namespace sycl::ext::oneapi::experimental::matrix;

void sum_rows_A(joint_matrix<T, rows, cols>& subA)
{
  auto data = ext::intel::experimental::matrix::get_wi_data(sg, subA);
  for (int i = 0; i < data.length(); ++i) {
    auto [row, col] = data[i].get_coord();
    global_index = row + global_idx * rows;
    sum_local_rows[global_index] += data[i];
  }
}
```

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# Matrix Query Interface

# AMX Supported Combinations

| A type | Btype | Ctype | M | N | K |
|---|---|---|---|---|---|
| (u)int8_t | (u)int8_t | int32_t | <=16 | <=16 | <=64 |
| bf16 | bf16 | float | <=16 | <=16 | <=32 |

# Intel XMX Supported Combinations

| A type | Btype | Ctype | M | N | K |
|---|---|---|---|---|---|
| (u)int8_t | (u)int8_t | int32_t | <=8 | 8 (ATS-M)<br>16 (PVC) | 32 |
| fp16 | fp16 | float | <=8 | 8 (ATS-M)<br>16 (PVC) | 16 |
| bf16 | bf16 | float | <=8 | 8 (ATS-M)<br>16 (PVC) | 16 |
| tf32 | tf32 | float | <=8 | 16 (PVC) | |

# Nvidia* Tensor Cores Supported Combinations

| A type | Btype | Accumulator type | M | N | K |
|---|---|---|---|---|---|
| half | half | float | 16 | 16 | 16 |
| | | | 32 | 8 | 16 |
| | | | 8 | 32 | 16 |
| half | half | half | 16 | 16 | 16 |
| | | | 32 | 8 | 16 |
| | | | 8 | 32 | 16 |
| bfloat16 | bfloat16 | float | 16 | 16 | 16 |
| | | | 32 | 8 | 16 |
| | | | 8 | 32 | 16 |
| tf32 | tf32 | float | 16 | 16 | 8 |
| (u)int8_t | (u)int8_t | int32_t | 16 | 16 | 16 |
| | | | 32 | 8 | 16 |
| | | | 8 | 32 | 16 |

# Matrix Query

| Namespace | namespace sycl::ext::oneapi::experimental::matrix |
| --- | --- |

Provide a default shape if user does not provide a combination in a *constexpr* way

```
template<sycl::ext::oneapi::experimental::architecture Dev, typename Ta, typename Tb,
  typename Taccumulator>
struct matrix_params {
  static constexpr size_t M = /* implementation defined */;
  static constexpr size_t N = /* implementation defined */;
  static constexpr size_t K = /* implementation defined */;

  template <typename Group, layout Layout>
  using joint_matrix_a = joint_matrix<Group, Ta, use::a, M, K, Layout>;

  template <typename Group, layout Layout>
  using joint_matrix_b = joint_matrix<Group, Tb, use::b, K, N, Layout>;

  template <typename Group>
  using joint_matrix_accumulator = joint_matrix<Group, Taccumulator, use::accumulator, M, N>;
};
```

# SYCL joint_*matrix Using the Default Query*

```
using namespace sycl::ext::oneapi::experimental::matrix;
using myparams = matrix_params<sycl::ext::oneapi::experimental::architecture::intel_gpu_pvc,
                               int8_t, int8_t, int>;
constexpr int tM = myparams::M;
constexpr int tN = myparams::N;
constexpr int tK = myparams::K;
range<2> G = {M/tM, N/tN * SG_SIZE};
range<2> L = {1, SG_SIZE};
// buffers
q.submit([&](sycl::handler& cgh) {
  // accessors
  cgh.parallel_for(nd_range<2>(G, L), [=](nd_item<2> item) {
    const auto sg_startx = item.get_global_id(0) - item.get_local_id(0);
    const auto sg_starty = item.get_global_id(1) - item.get_local_id(1);
    sub_group sg = item.get_sub_group();
    myparams::joint_matrix_a<sub_group, layout::row_major> tA;
    myparams::joint_matrix_b<sub_group, layout::row_major> tB;
    myparams::joint_matrix_accumulator<sub_group> tC;
    joint_matrix_fill(sg, tC, 0);
    for (int k = 0; k < K; k += tk) {
     joint_matrix_load(sg, tA, memA + sg_startx * tM * K + k, K);
     joint_matrix_load(sg, tB, memB + k * N + sg_starty, N);
     tC = joint_matrix_mad(sg, tA, tB, tC);
   }
   joint_matrix_store(sg, tC, memC + sg_startx * tM * N + sg_starty, N, row_major);
  });
});
```

# SYCL joint_matrix

```
// inputA is MxK, inputB is KxN, inputC is MxN
#define tM=16  tN=16  tK=16


void gemm(size_t global_idx, size_t global_idy, size_t local_idx, size_t local_idy, sub_group sg)  {

  joint_matrix<sub_group, half, use::a, tM, tK, row_major> matA;
  joint_matrix<sub_group, half, use::b, tK, tN, row_major> matB;
  joint_matrix<sub_group, float, use::accumulator, tM, tN> matC;

  const auto sg_startx = global_idx - local_idx;
  const auto sg_starty = global_idy - local_idy;

  joint_matrix_fill(matC, 0.0f);

  for (int step = 0; step < K; step += tK) {

   uint AStart = sg_startx * tM * K + step;
   uint BStart = step * N + sg_starty;
   joint_matrix_load(sg, matA, inputA + AStart, K);
   joint_matrix_load(sg, matB, inputB + BStart, N);
   matC = joint_matrix_mad(sg, matA, matB, matC);

  }


  joint_matrix_apply(sg, matC, [=](T& x) { x *= alpha; });

  joint_matrix_store(sg, matC, output + sg_startx * tM * N + sg_starty, N, row_major);

}
```

# CUDA Fragments

```
// inputA is MxK, inputB is KxN, inputC is MxN
#define tM=16 tN=16 tK=16


__global__ void wmma_ker(blockidx) {

  fragment<matrix_a, 16, 16, 16, half, col_major> a_frag;
  fragment<matrix_b, 16, 16, 16, half, row_major> b_frag;
  fragment<accumulator, 16, 16, 16, float> c_frag;

  uint row = (blockIdx%x - 1)*tM + 1
  uint col = (blockIdx%y - 1)*tN + 1

  fill_fragment(c_frag, 0.0f);

  for (uint step = 0; step < K; step += matrixDepth) {

     uint AStart = row * rowStrideA + step;
     uint BStart = col * colStrideB + step;

     load_matrix_sync(matA, inputA + AStart, K);

     load_matrix_sync(matB, inputB + BStart, N);

     mma_sync(matC, matA, matB, matC);

   }

   for(int t=0; t<matC.num_elements; t++)

     matC.x[t] *= alpha;

   store_matrix_sync(inputC+row*N+col, matC, N, mem_row_major);

}
```

# Current Users of Joint Matrix

| | |
|---|---|
| GEMM code using joint_matrix | • AMX, XMX (ATS-M and PVC) high-performant GEMM using SYCL joint matrix |
| Porting code from wmma to joint_matrix | • Porting an earthquake simulation code that makes direct use of the tensor cores through wmma from CUDA and wmma to SYCL and joint matrix |
| SYCL-DNN – By CodePlay | • Using joint_matrix for enabling Nvidia Tensor Cores in SYCL-DNN |
| SYCL-BLAS – By CodePlay | • Using joint_matrix for enabling Nvidia Tensor Cores in SYCL-BLAS GEMM |
| SPIRV MLIR Dialect | • XMX Support using MLIR SPIRV dialect by adding SPIRV joint_matrix |

# Conclusion and Next Steps

- Full support of SYCL joint matrix extension on Intel AMX, Intel XMX, and Nvidia Tensor Cores
- Extensions to LLVM IR and SPIRV
- Effective usage in MLIR integration and CUDA code migration
- Next steps:
  - Standardization of SYCL joint matrix to Khronos SYCL
  - Standardization of SPIRV joint matrix to Khronos SPIRV
- Contributions/feedback are welcome

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