10-414/714 – Deep Learning Systems: Algorithms and Implementation

GPU Acceleration

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Outline

GPU programming

Case study: matrix multiplication on GPU

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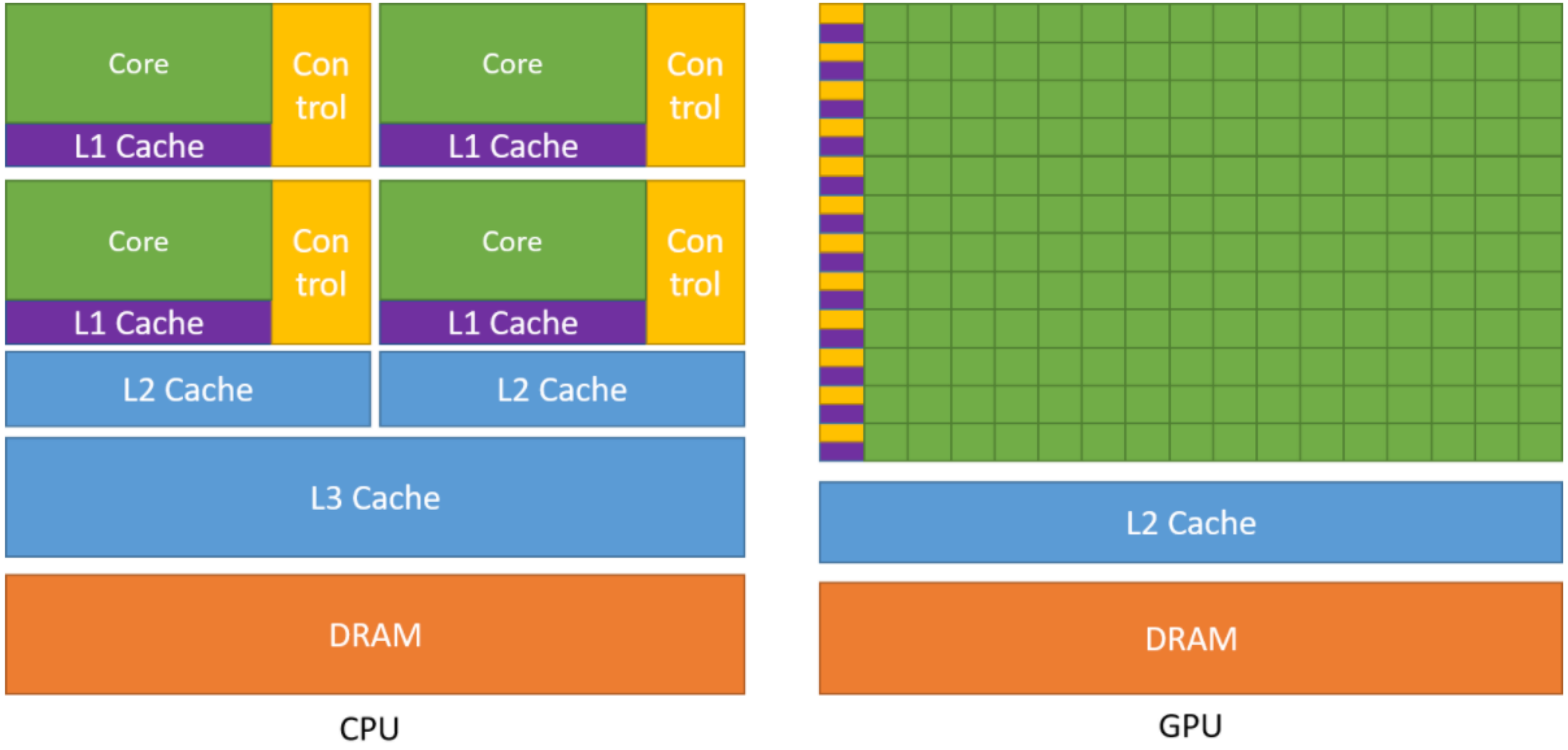
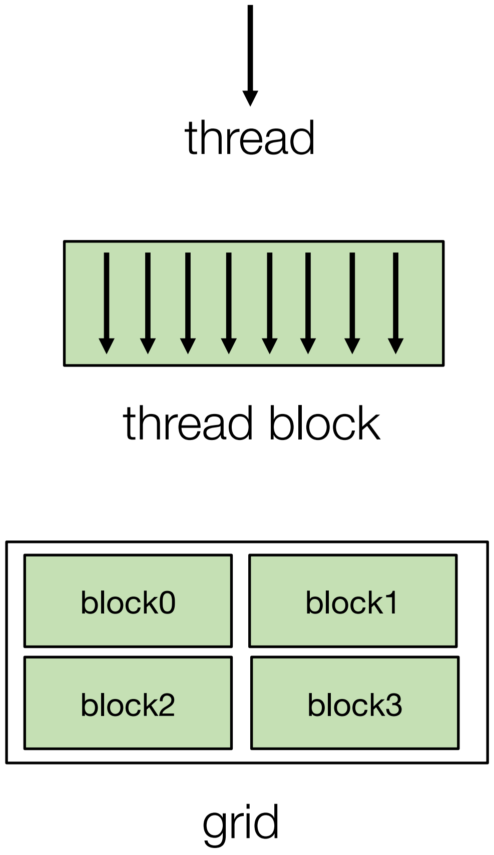
What is a GPU



Massive parallel computing units

Source: CUDA Programming guide

GPU programming mode: SIMT



- Single instruction multiple threads (SIMT)
- All threads executes the same code, but can take different path
- Threads are grouped into blocks
  - Thread within the same block have shared memory
- Blocks are grouped into a launch grid
- A kernel executes a grid

NOTE: we will be using the CUDA's terminology in this lecture. But usually there is a direct mapping of these concepts in other gpu programming models (opencl, sycl, metal)

Example: vector add

```
void VecAddCPU(float* A, float *B, float* C, int n) {
  for (int i = 0; i < n; ++i) {
    C[i] = A[i] + B[i];
  }
}
```

```
__global__ void VecAddKernel(float* A, float *B, float* C, int n) {
int i = blockDim.x * blockIdx.x + threadIdx.x;
  if (i < n) {
    C[i] = A[i] + B[i];
  }
}
```

Example: vector add

`i (global offset)`	0	1	2	3	4	5	6	7
`threadIdx.x`	0	1	2	3	0	1	2	3
`blockIdx.x`	0				1			

Suppose each block includes 4 threads: blockDim.x = 4

```
__global__ void VecAddKernel(float* A, float *B, float* C, int n) {
  int i = blockDim.x * blockIdx.x + threadIdx.x;
  if (i < n) {
    C[i] = A[i] + B[i];
  }
}
```

Example: vector add host side

```
__global__ void VecAddKernel(float* A, float *B, float* C, int n) {
  int i = blockDim.x * blockIdx.x + threadIdx.x;
  if (i < n) {
    C[i] = A[i] + B[i];
  }
}

void VecAddCUDA(float* Acpu, float *Bcpu, float* Ccpu, int n) {
  float *dA, *dB, *dC;
  cudaMalloc(&dA, n * sizeof(float));
  cudaMalloc(&dB, n * sizeof(float));
  cudaMalloc(&dC, n * sizeof(float));
  cudaMemcpy(dA, Acpu, n * sizeof(float), cudaMemcpyHostToDevice);
  cudaMemcpy(dB, Bcpu, n * sizeof(float), cudaMemcpyHostToDevice);
  int threads_per_block = 512;
  int nblocks = (n + threads_per_block - 1) / threads_per_block;
  VecAddKernel<<<nblocks, thread_per_block>>>(dA, dB, dC, n);
  cudaMemcpy(Ccpu, dC, n * sizeof(float), cudaMemcpyDeviceToHost);
  cudaFree(dA); cudaFree(dB); cudaFree(dC);
}
```

Demonstrate the host side launch and device memory allocation. Unlike this example, real applications usually keep data in gpu memory as long as possible.

Example of other GPU Programming Models

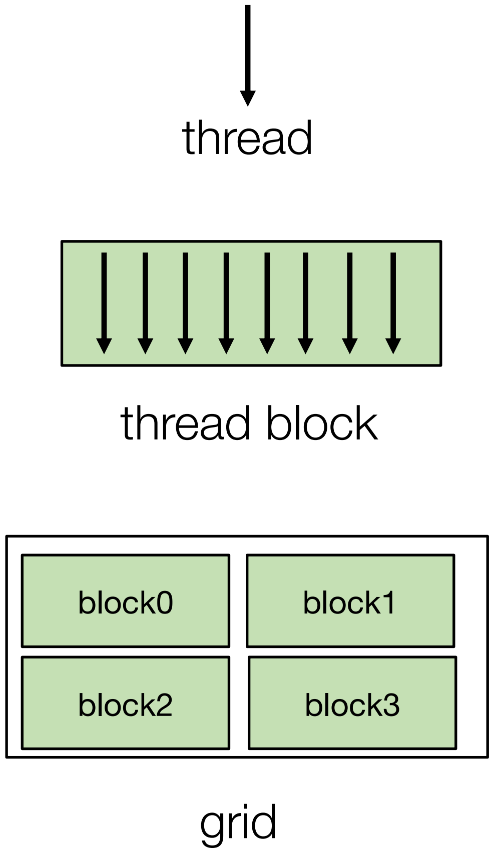
OpenCL (used in ARM GPU)

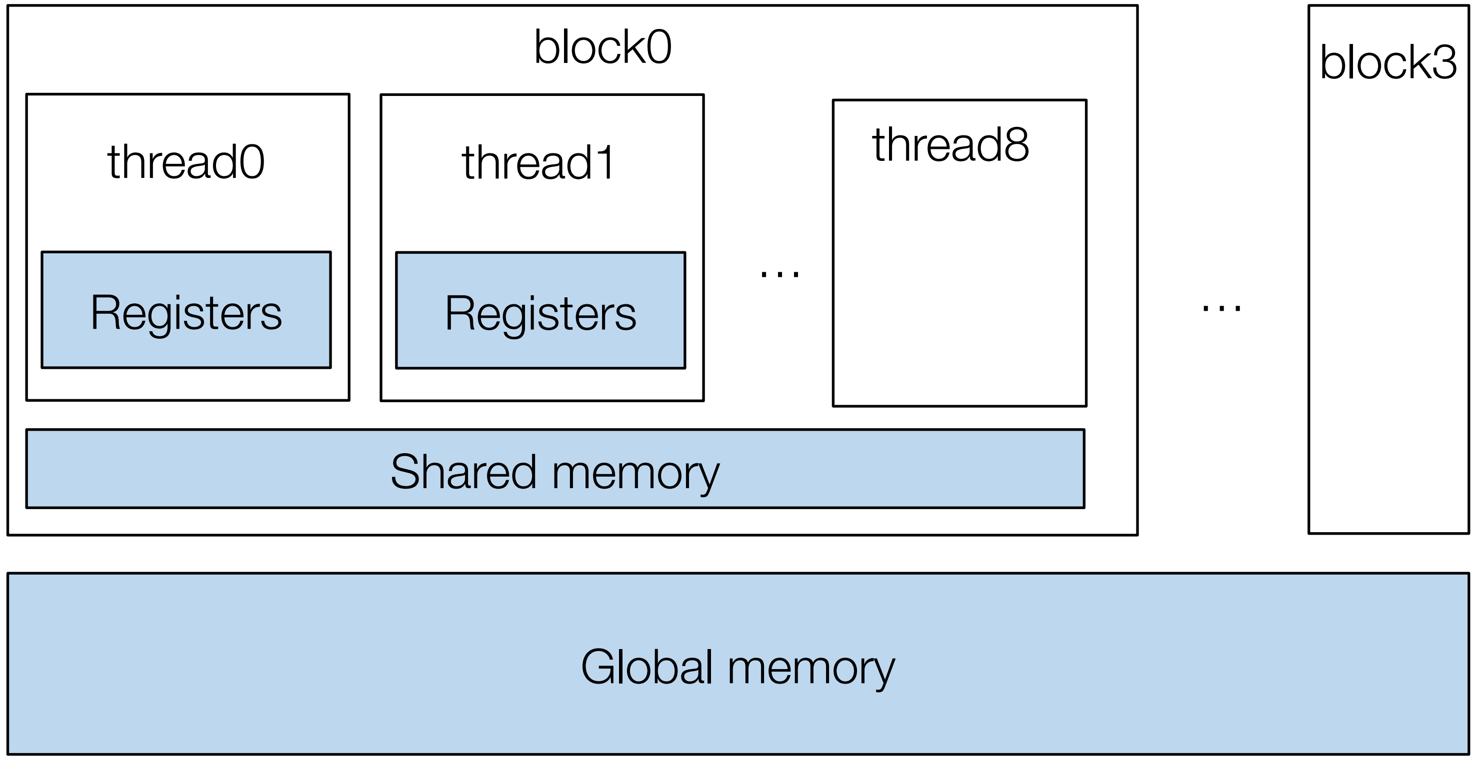
```
__kernel void VecAdd(__global float *a,
                     __global float* b,
                     __global float* c,
                     int n) {
  int gid = get_global_id(0)
  if (gid < n) {
    c[gid] = a[gid] + b[gid];
  }
}
```

Metal (Apple devices)

```
kernel void VecAdd(float* a [[buffer(0)]],
                   float* b [[buffer(1)]],
                   float* c [[buffer(1)]],
                   uint gid [[thread_position_in_grid]]
                   int n) {
  if (gid < n) {
    c[gid] = a[gid] + b[gid];
  }
}
```

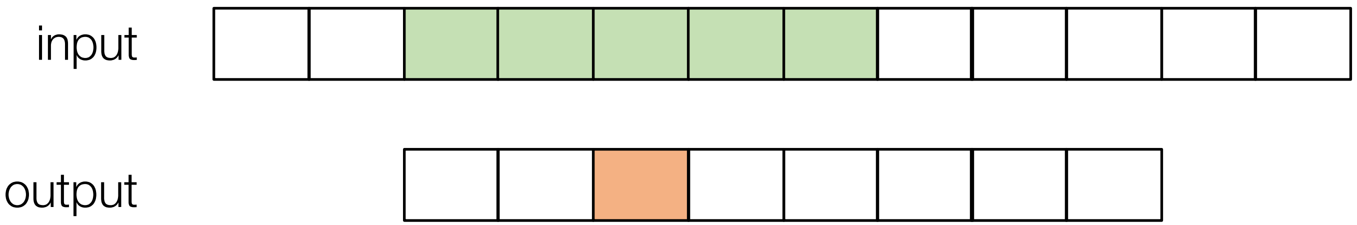
GPU memory hierarchy





Example: window sum

Compute the sums over a sliding window of radius=2

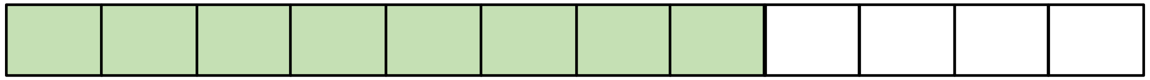



```
#define RADIUS 2
__global__ void WindowSumSimpleKernel(float* A, float *B, int n) {
  int out_idx = blockDim.x * blockIdx.x + threadIdx.x;
  if (out_idx < n) {
    float sum = 0;
    for (int dx = -RADIUS; dx <= RADIUS; ++dx) {
      sum += A[dx + out_idx + RADIUS];
    }
    B[out_idx] = sum;
}
```

Example: window sum with shared memory

Use thread block of size 4 to cooperatively fetch the data to shared memory

input



output

```
__global__ void WindowSumSharedKernel(float* A, float *B, int n) {
  __shared__ float temp[THREADS_PER_BLOCK + 2 * RADIUS];
  int base = blockDim.x * blockIdx.x;
  int out_idx = base + threadIdx.x;
  if (base + threadIdx.x < n) {
     temp[threadIdx.x] = A[base + threadIdx.x];
  }
  if (threadIdx.x < 2 * RADIUS && base + THREADS_PER_BLOCK + threadIdx.x < n) {
    temp[threadIdx.x + THREADS_PER_BLOCK] = A[base + THREADS_PER_BLOCK + threadIdx.x];
  }
  __syncthreads();
  if (out_idx < n) {
     float sum = 0;
     for (int dx = -RADIUS; dx <= RADIUS; ++dx) {
    sum += temp[threadIdx.x + dx + RADIUS];
   }
   B[out_idx] = sum;
}
```

High level takeaways

Launch thread grid and blocks

Cooperatively fetch common to shared memory to increase reuse

Outline

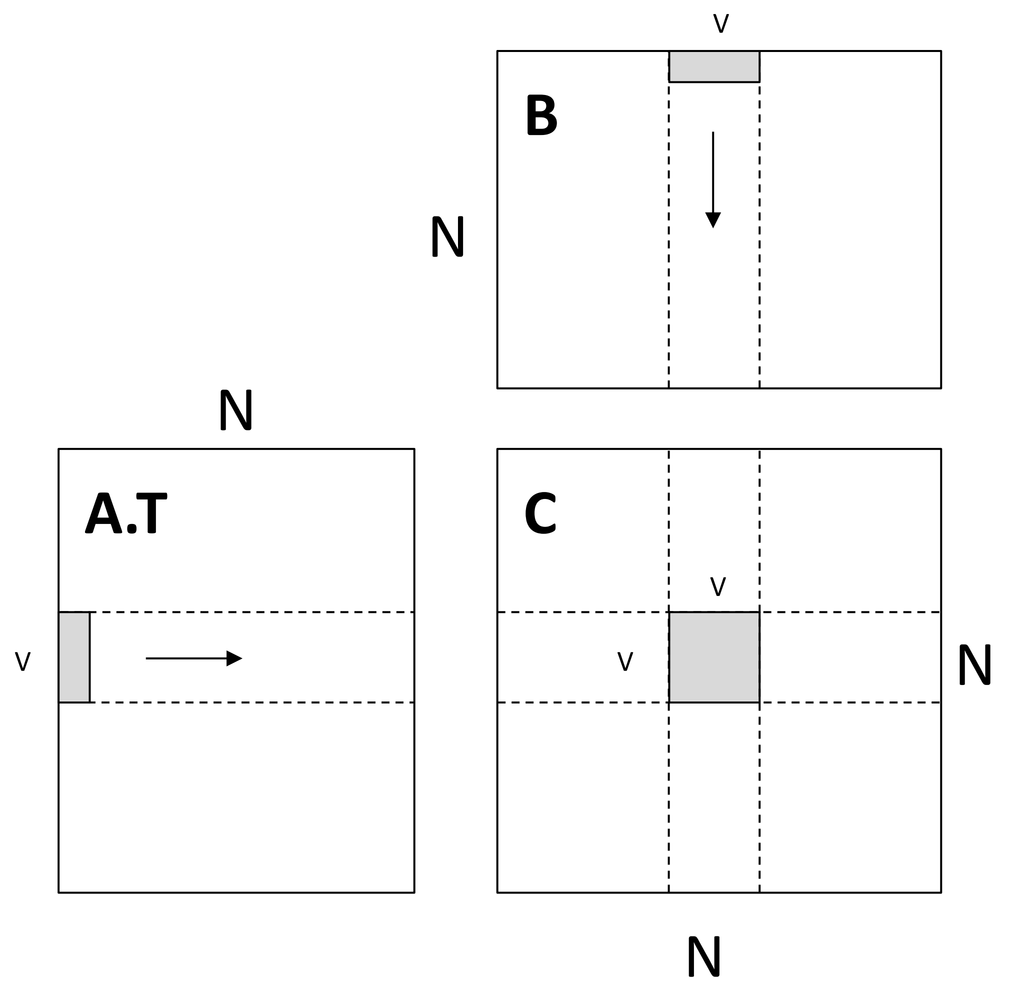
General acceleration techniques

Case study: matrix multiplication on GPU

Thread-level: register tiling

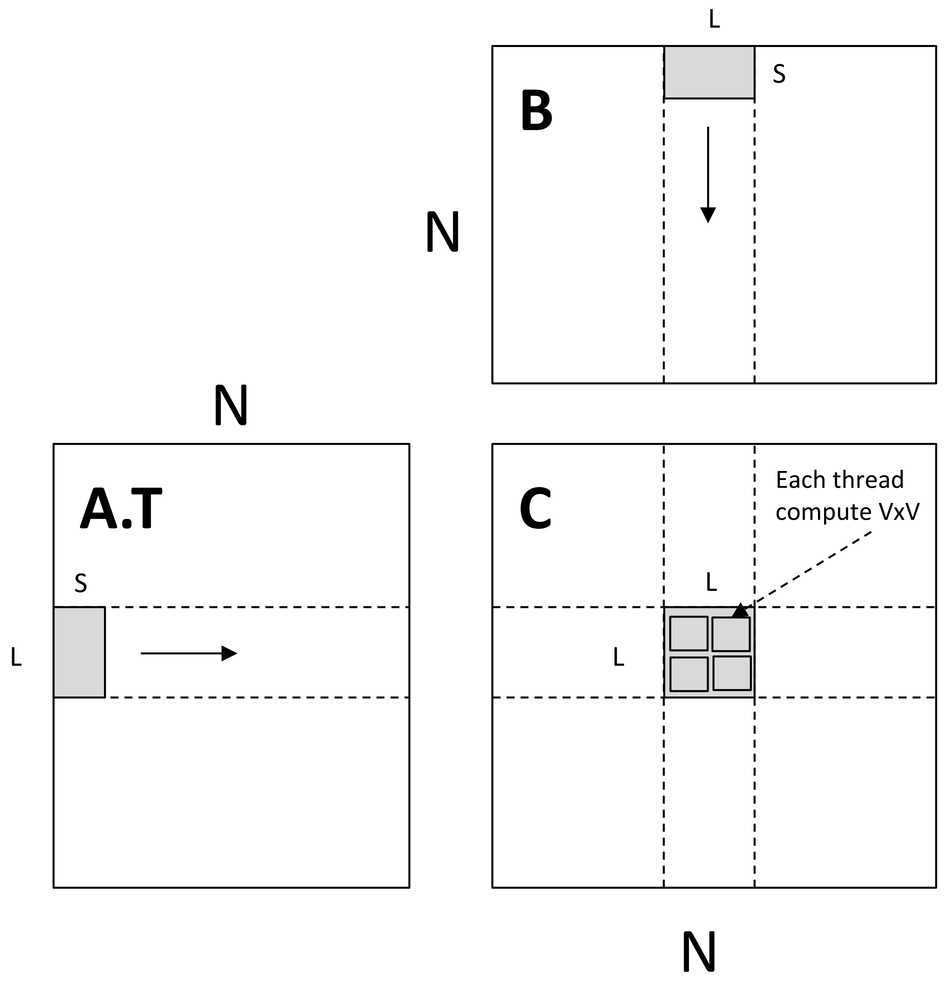
Compute C = dot(A.T, B)

```
__global__ void mm(float A[N][N], float B[N][N], float C[N][N]) {
  int ybase = blockIdx.y * blockDim.y + threadIdx.y;
  int xbase = blockIdx.x * blockDim.x + threadIdx.x;

  float c[V][V] = {0};
  float a[V], b[V];
  for (int k = 0; k < N; ++k) {
    a[:] = A[k, ybase*V : ybase*V + V];
    b[:] = B[k, xbase*V : xbase*V + V];
    for (int y = 0; y < V; ++y) {
      for (int x = 0; x < V; ++x) {
        c[y][x] += a[y] * b[x];
      }
    }
  }
  C[ybase * V : ybase*V + V, xbase*V : xbase*V + V] = c[:];
}
```



Block-level: shared memory tiling

```
__global__ void mm(float A[N][N], float B[N][N], float C[N][N]) {
  __shared__ float sA[S][L], sB[S][L];
  float c[V][V] = {0};
  float a[V], b[V];
  int yblock = blockIdx.y;
  int xblock = blockIdx.x;

  for (int ko = 0; ko < N; ko += S) {
    __syncthreads();
    // needs to be implemented by thread cooperative fetching
    sA[:, :] = A[k : k + S, yblock * L : yblock * L + L];
    sB[:, :] = B[k : k + S, xblock * L : xblock * L + L];
    __syncthreads();
    for (int ki = 0; ki < S; ++ ki) {
      a[:] = sA[ki, threadIdx.y * V : threadIdx.y * V + V];
      b[:] = sA[ki, threadIdx.x * V : threadIdx.x * V + V];
      for (int y = 0; y < V; ++y) {
        for (int x = 0; x < V; ++x) {
          c[y][x] += a[y] * b[x];
        }
      }
    }
  }
  int ybase = blockIdx.y * blockDim.y + threadIdx.y;
  int xbase = blockIdx.x * blockDim.x + threadIdx.x;
  C[ybase * V : ybase*V + V, xbase*V : xbase*V + V] = c[:];
}
```



Analysis of memory reuse

```
__global__ void mm(float A[N][N], float B[N][N], float C[N][N]) {
  __shared__ float sA[S][L], sB[S][L];
  float c[V][V] = {0};
  float a[V], b[V];
  int yblock = blockIdx.y;
  int xblock = blockIdx.x;

  for (int ko = 0; ko < N; ko += S) {
    __syncthreads();
    // needs to be implemented by thread cooperative fetching
    sA[:, :] = A[k : k + S, yblock * L : yblock * L + L];
    sB[:, :] = B[k : k + S, xblock * L : xblock * L + L];
    __syncthreads();
    for (int ki = 0; ki < S; ++ ki) {
      a[:] = sA[ki, threadIdx.y * V : threadIdx.y * V + V];
      b[:] = sA[ki, threadIdx.x * V : threadIdx.x * V + V];
      for (int y = 0; y < V; ++y) {
        for (int x = 0; x < V; ++x) {
          c[y][x] += a[y] * b[x];
        }
      }
    }
  }
  int ybase = blockIdx.y * blockDim.y + threadIdx.y;
  int xbase = blockIdx.x * blockDim.x + threadIdx.x;
  C[ybase * V : ybase*V + V, xbase*V : xbase*V + V] = c[:];
}
```

```
global->shared copy: 2 * N^3 / L
shared->register:    2 * N^3 / V
```

Expand Cooperative Fetching

```
sA[:, :] = A[k : k + S, yblock * L : yblock * L + L];
```

```
int nthreads = blockDim.y * blockDim.x;
int tid = threadIdx.y * blockDim.x + threadIdx.x;

for(int j = 0; j < L * S / nthreads; ++j) {
  int y = (j * nthreads + tid) / L;
  int x = (j * nthreads + tid) % L;
  s[y, x] = A[k + y, yblock * L + x];
}
```

More GPU optimization techniques

Global memory continuous read

Shared memory bank conflict

Software pipelining

Warp level optimizations

Tensor Core

Checkout CUDA Programming guide

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