



Advanced CUDA

Abhinav Bhatele Department of Computer Science



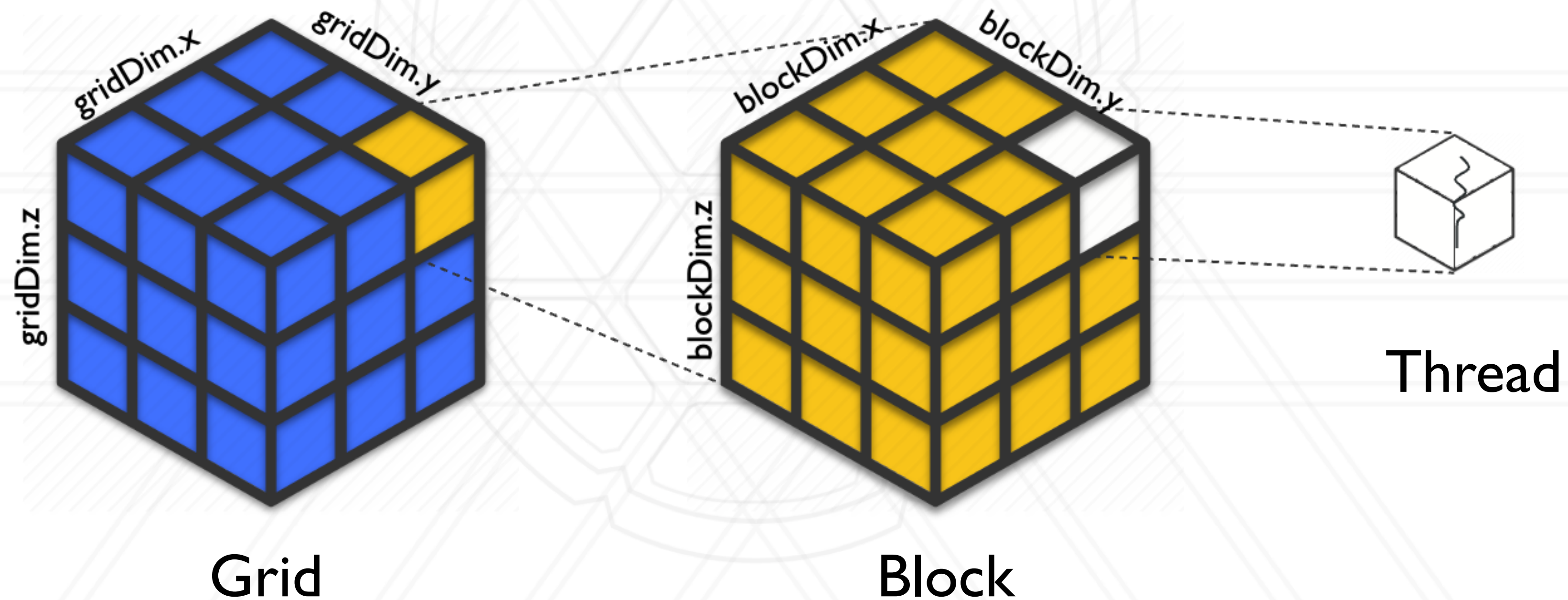
UNIVERSITY OF
MARYLAND

Striding

```
__global__ void saxpy(float *x, float *y, float alpha, int N) {  
    int i0 = blockDim.x * blockIdx.x + threadIdx.x;  
    int stride = blockDim.x * gridDim.x;  
  
    for (int i = i0; i < N; i += stride)  
        y[i] = alpha*x[i] + y[i];  
}  
  
int main() {  
    ...  
    int blockSize = 8; int gridSize = 16;  
  
    saxpy<<gridSize, blockSize>>>(x, y, alpha, N);  
    ...  
}
```

Grid and Block Dimensions

- Blocks in a grid and threads in a block can be arranged in a 3D virtual mesh
- And they can be indexed in 3D



Adding 2D matrices

```
__global__ void matrixAdd(float **X, float **Y, float alpha, int M, int
N) {
    int i = blockDim.x * blockIdx.x + threadIdx.x;
    int j = blockDim.y * blockIdx.y + threadIdx.y;

    if (i < M && j < N)
        Y[i][j] = alpha * X[i][j] + Y[i][j];
}

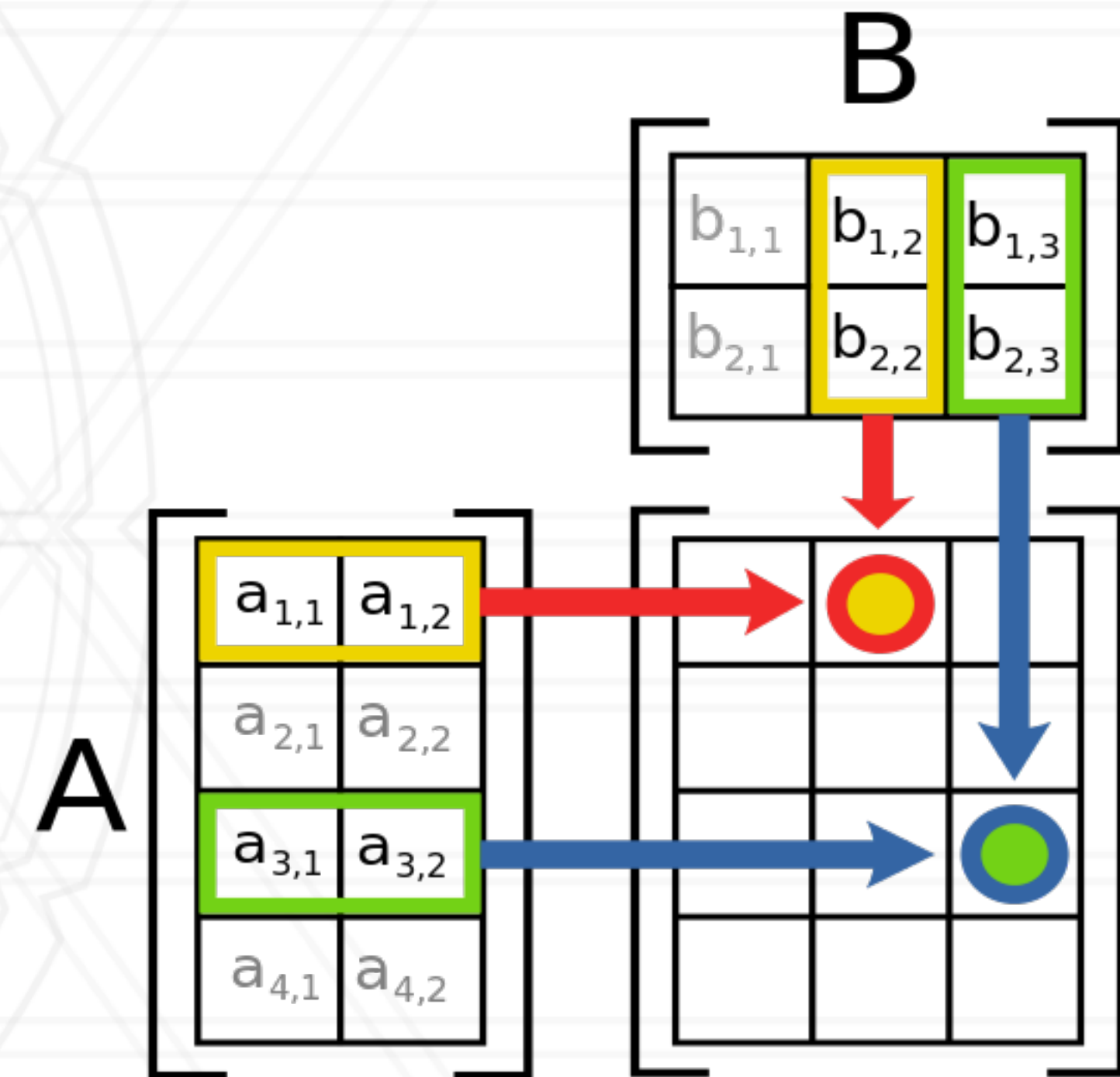
int main() {
    dim3 threadsPerBlock(16, 16);
    dim3 numBlocks(M/threadsPerBlock.x + (M % threadsPerBlock.x != 0),
        N/threadsPerBlock.y + (N % threadsPerBlock.y != 0));

    matrixAdd<<<numBlocks, threadsPerBlock>>>(X, Y, alpha, M, N);
}
```

Matrix Multiply in CUDA

- Solution: use 2D virtual mesh of threads
- Each thread computes one element of the C matrix
- Thread (i, j) computes c_{ij}

```
for (i=0; i<M; i++)  
  for (j=0; j<N; j++)  
    for (k=0; k<L; k++)  
      C[i][j] += A[i][k]*B[k][j];
```



https://en.wikipedia.org/wiki/Matrix_multiplication

Matrix Multiply in CUDA

```
int main() {  
    dim3 threadsPerBlock(BLOCK_SIZE, BLOCK_SIZE);  
    dim3 numBlocks(M/threadsPerBlock.x + (M % threadsPerBlock.x != 0),  
                  N/threadsPerBlock.y + (N % threadsPerBlock.y != 0));  
  
    matmul<<<numBlocks, threadsPerBlock>>>(C, A, B, M, L, N);  
}
```

Matrix Multiply in CUDA

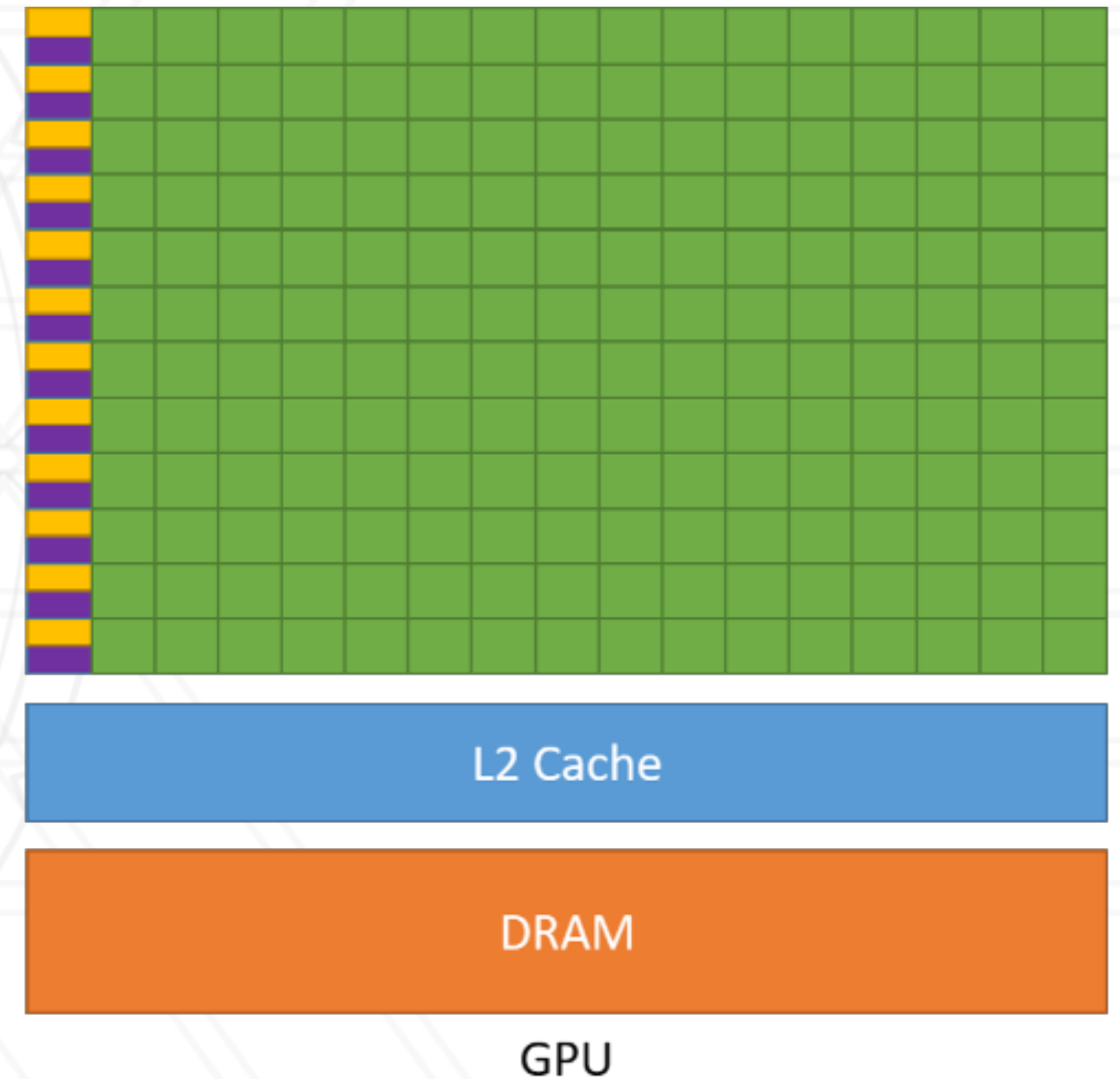
```
__global__ void matmul(double *C, double *A, double *B, size_t M,
size_t L, size_t N) {

    int i = blockDim.x*blockIdx.x + threadIdx.x;
    int j = blockDim.y*blockIdx.y + threadIdx.y;

    if (i < M && j < N) {
        for (int k = 0; k < L; k++) {
            C[i*N+j] += A[i*L+k] * B[k*N+j];
        }
    }
}
```

Any potential performance issues?

- Poor data re-use
- Every value of A & B is loaded from the global DRAM
- Both A and B are read multiple times



Different types of GPU memory

- Global memory: this is like the main memory on a CPU
 - Allocated using `cudaMalloc`
- Shared memory: very fast memory located in the SMs
 - All threads in a block can access this shared memory
 - Allocated in the kernel using `__shared__`
- Local memory: everything on the stack that can't fit in registers
 - Stored in global memory
 - Private to each thread

Different types of GPU memory

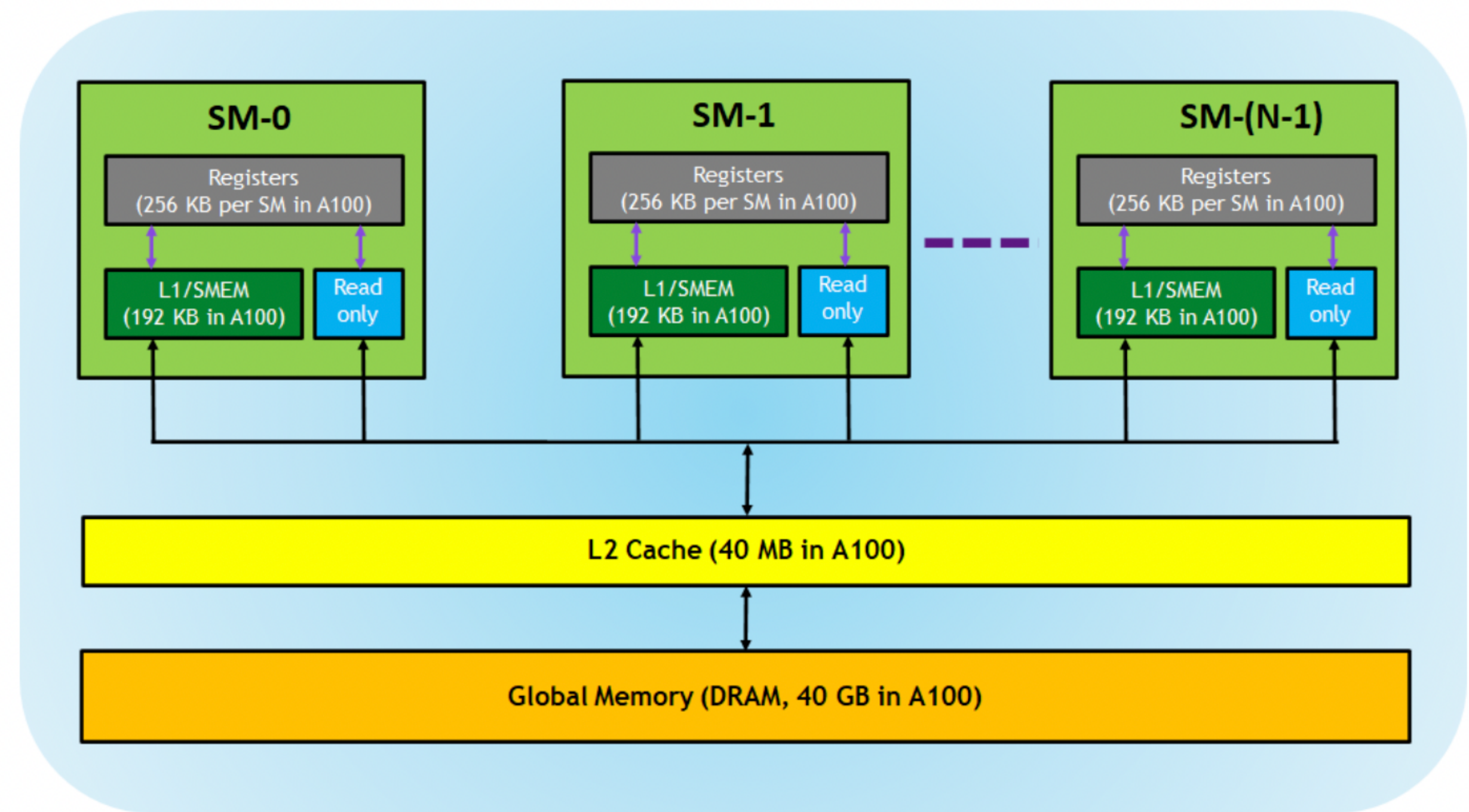
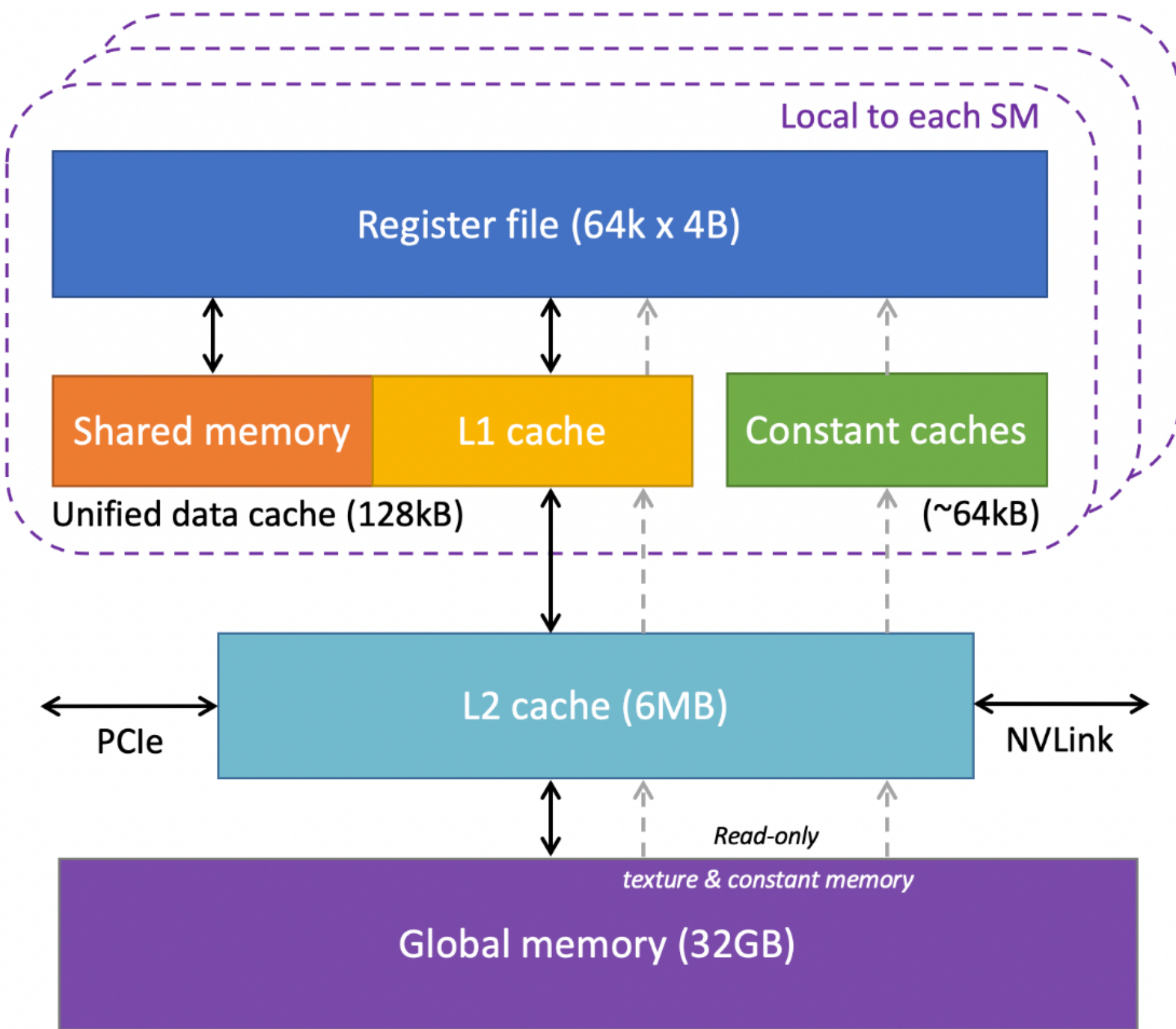


Figure 4. Memory hierarchy in GPUs.



GPU memory levels and sizes for the NVIDIA Tesla V100.
(Based on diagrams by [NVIDIA](#) and [Citadel](#) at GTC 2018)

<https://velog.io/@hansoljang/GPU-Architecture-and-Memory>

Common pattern in kernels

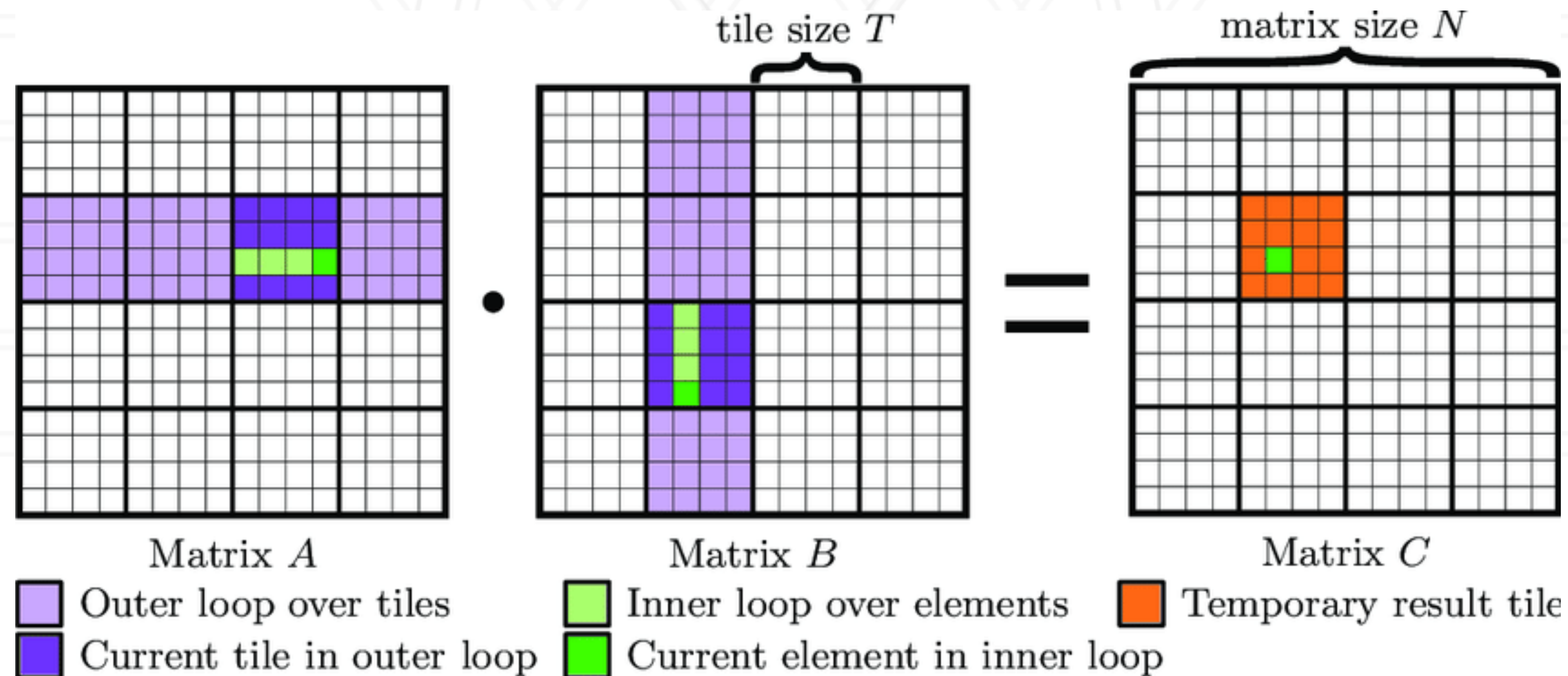
- Copy from global to shared memory
- `__syncthreads ( )`: synchronizes all threads in a block
- Perform computation in shared memory
 - `__syncthreads ( )` as needed
- Copy from shared to global memory

Reverse array contents using shared memory

```
__global__ void reverse(int *vec) {  
    __shared__ int sharedVec[N];  
  
    int idx = threadIdx.x;  
    int idxReversed = N - idx - 1;  
  
    sharedVec[idx] = vec[idx];  
    __syncthreads();  
    vec[idx] = sharedVec[idxReversed];  
}
```

Matrix multiply using shared memory

- Each block (i, j) computes a sub-block C_{ij}
- Individual threads in the block work on different elements of sub-block C_{ij}



Unified memory

- Data is allocated both on the CPU and GPU
- GPU takes care of the synchronization

```
void sortfile(FILE *fp, int N) {  
    char *data;  
    cudaMallocManaged(&data, N);  
  
    fread(data, 1, N, fp);  
    qsort<<<...>>>(data, N, 1, compare);  
    cudaDeviceSynchronize();  
  
    ... use data on CPU ...  
    cudaFree(data);  
}
```

CUDA libraries

- Linear algebra
 - cuBLAS, CUTLASS, cuSPARSE
- Deep Learning
 - cuDNN
- Graphics
 - OpenCV, OpenGL, FFmpeg

Profiling GPUs

- HPCToolkit + Hatchet
 - Add `-e gpu=nvidia` to the `hpcrun` command line
- Nsight Systems
 - Whole application tracing
- Nsight Compute
 - Kernel-level profiling

<https://docs.nvidia.com/nsight-systems/UserGuide/index.html>

Nsight Systems

- Outputs a .qdrep file that can be visualized in the Nsight GUI

```
nsys profile -t {cuda, nvtx, openmp, mpi, ...}
```



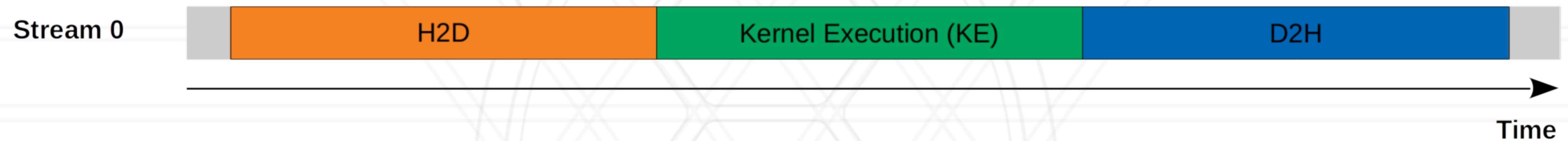
CUDA streams

- Streams can be used to perform multiple CUDA operations simultaneously
 - CUDA Kernel <<<>>>
 - cudaMemcpyAsync()
 - Operations on the CPU

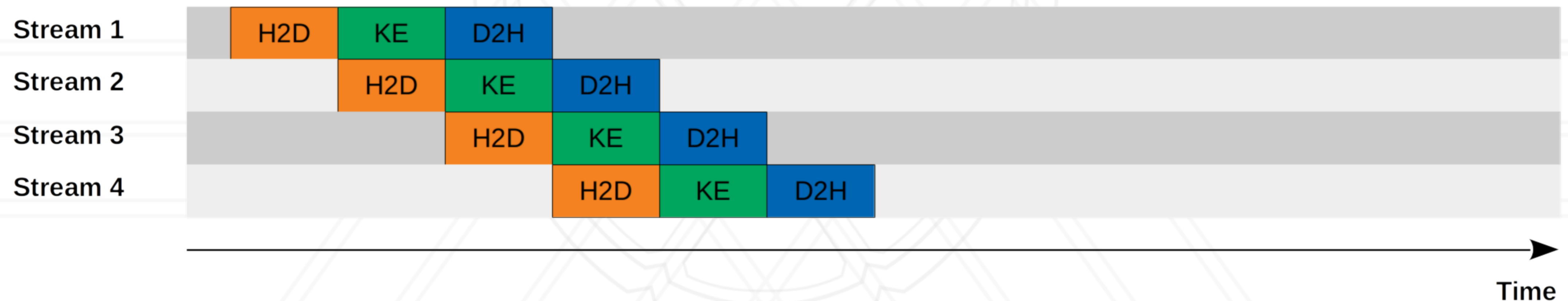
```
int main() {  
    cudaStream_t stream;  
    cudaStreamCreate(&stream);  
    ...  
  
    kernel<<<grid, block, 0, stream>>>(x, b);  
}
```

Serial vs. concurrent execution in streams

Serial Model



Concurrent Model



Launching all streams at once

```
cudaStream_t stream[nStreams];
for (int i = 0; i < nStreams; i++) {
    cudaStreamCreate(&stream[i]);
}

for (int i = 0; i < nStreams; i++){
    int offset = i * streamSize;
    cudaMemcpyAsync(&d_a[offset], &a[offset], streamBytes,
                                                            cudaMemcpyHostToDevice, stream[i]);

    kernel<<<streamSize/blockSize, blockSize, 0, stream[i]>>>(d_a,
offset);

    cudaMemcpyAsync(&a[offset], &d_a[offset], streamBytes,
                                                            cudaMemcpyDeviceToHost, stream[i]);
}
```



UNIVERSITY OF MARYLAND

Abhinav Bhatele

5218 Brendan Iribe Center (IRB) / College Park, MD 20742

phone: 301.405.4507 / e-mail: bhatele@cs.umd.edu