SIMD and GPUs

CS/COE 1541 (Fall 2020)
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SIMD Architectures

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ISA not optimized for data parallel workloads

- This loop does multiply accumulate (MAC):

```
for (int i = 0; i < 64; i++) {
  y[i] = a * x[i] + y[i]
}
```

  - A common operation in digital signal processing

- Note how we apply the **same** MAC **operation on each data item**
  - This is how many data parallel workloads look like

- A conventional ISA (likes MIPS) is not optimal for encoding this
  - Results in wasted work and suboptimal performance
  - Let's look at the actual MIPS translation

MIPS code for $y(i) = a * x(i) + y(i)$

```
       l.d    $f0,0($sp)        ;$f0 = a
       addi   $s2,$s0,512       ;64 elements (64*8=512 bytes)
loop:  l.d    $f2,0($s0)        ;$f2 = x(i)
       mul.d  $f2,$f2,$f0       ;$f2 = a * x(i)
       l.d    $f4,0($s1)        ;$f4 = y(i)
       add.d  $f4,$f4,$f2       ;$f4 = a * x(i) + y(i)
       s.d    $f4,0($s1)        ;y(i) = $f4
       addi   $s0,$s0,8         ;increment index to x
       addi   $s1,$s1,8         ;increment index to y
       subu   $t0,$s2,$s0       ;evaluate i < 64 loop condition
       bne    $t0,$zero,loop    ;loop if not done
```

- Blue instructions don't do actual computation. There for indexing and loop control.
  - Is there a way to avoid? Loop unrolling yes. But that causes code bloat!
- Red instructions do computation. But why decode them over and over again?
  - Is there a way to fetch and decode once and apply to all data items?

SIMD (Single Instruction Multiple Data)

- **SIMD (Single Instruction Multiple Data)**
  - An architecture for applying one instruction on multiple data items
  - ISA includes **vector instructions** for doing just that
    - Along with **vector registers** to hold multiple data items

- Using MIPS vector instruction extensions:

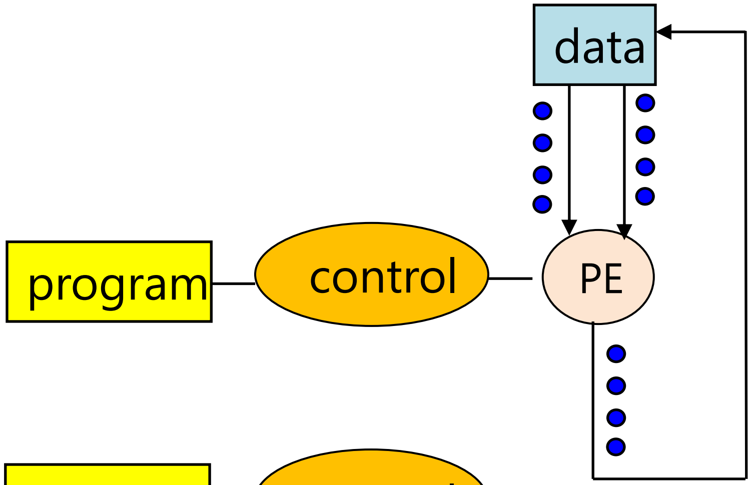
```
l.d     $f0,0($sp)     ;$f0 = scalar a
lv      $v1,0($s0)     ;$v1 = vector x (64 values)
mulvs.d $v2,$v1,$f0    ;$v2 = a * vector x
lv      $v3,0($s1)     ;$v3 = vector y (64 values)
addv.d  $v4,$v2,$v3    ;$v4 = a * vector x + vector y
sv      $v4,0($s1)     ;vector y = $v4
```

  - Note: no indexing and loop control overhead
  - Note: each instruction is fetched and decoded only once

SIMD Processor Design

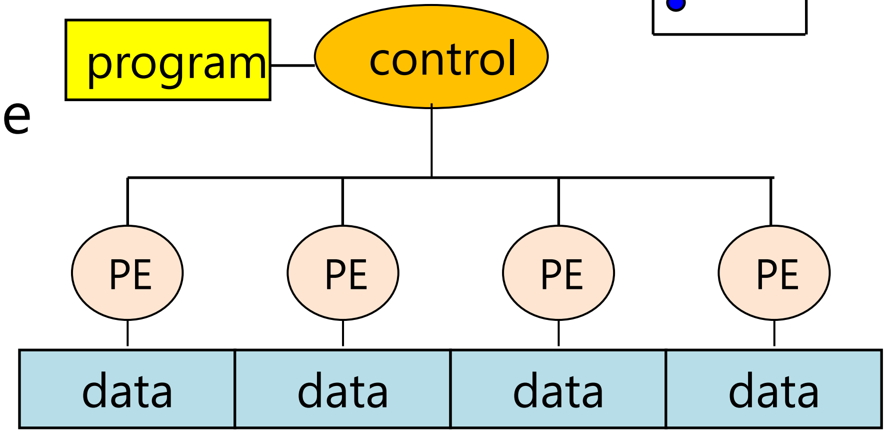
- How would you design a processor for the vector instructions?

1. One processing element (PE)
    - Fetch and decode instruction once
    - PE applies op on each data item
        - Item may be in vector register
        - Item may be in data memory



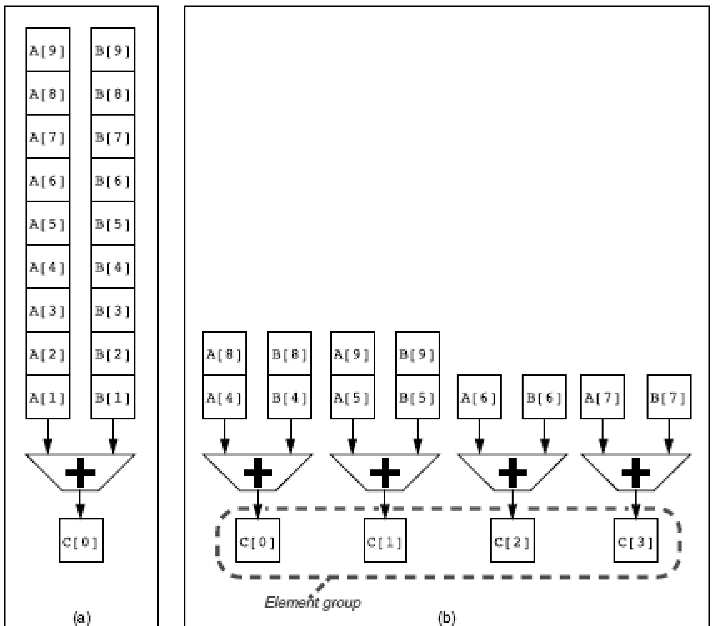
2. Multiple PEs in parallel
    - Fetch and decode instruction once
    - PEs apply op in parallel
        - In synchronous lockstep

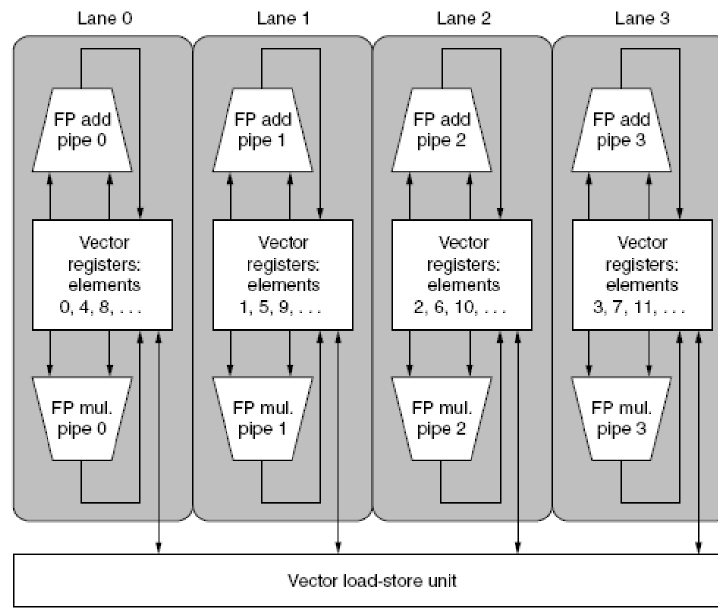
→ The more PEs, the faster!



Example: Adding Two Vectors

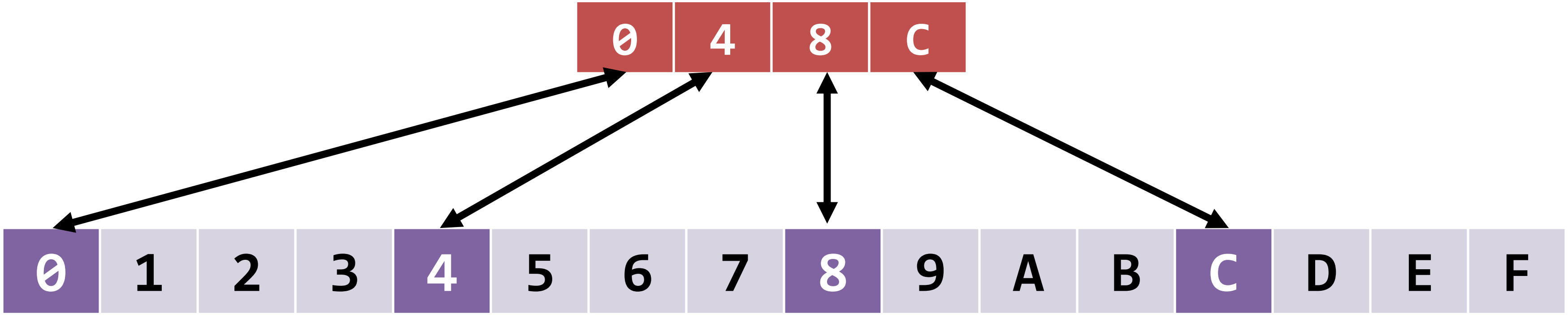
- Instead of having a single FP adder work on each item (a)
- Have four FP adders work on items in parallel (b)
- Each pipelined FP unit is in charge of pre-designated items in vector
  - For full parallelization, put as many FP units as there are items



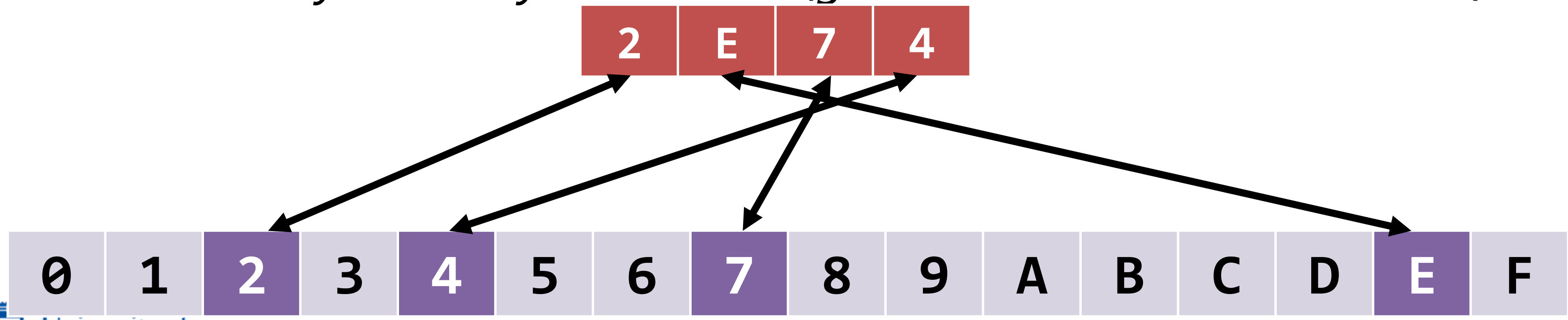


Vector Load-Store Unit

- *Striding* lets you load/store *non-contiguous* data from memory at regular offsets. (e.g. the first member of each struct in an array)



- *Gather-scatter* lets you put pointers in a vector, then load/store from *arbitrary memory addresses. (gather = load, scatter = store)*



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Vector Load-Store Unit

- Contiguous data items is still the best for performance
  - Means processor needs to access only one or a few cache blocks

- Strided or scattered accesses are possible but bad for performance
  - If any of the multiple cache blocks accessed miss, long latency
  - Accessing multiple blocks also consumes a lot of bandwidth

- If your vector program is slow, often it is due to memory issues
  - Same goes for GPUs which, as we will learn, is a type of SIMD

SIMD instructions in real processors

- x86 vector extensions
  - MMX, SSE, AVX, AVX-2
  - Current: AVX-512 (512-bit vector instructions)

- ARM vector extensions
  - VFP (Vector Floating Point)
  - Current: Neon (128-bit vector instructions)

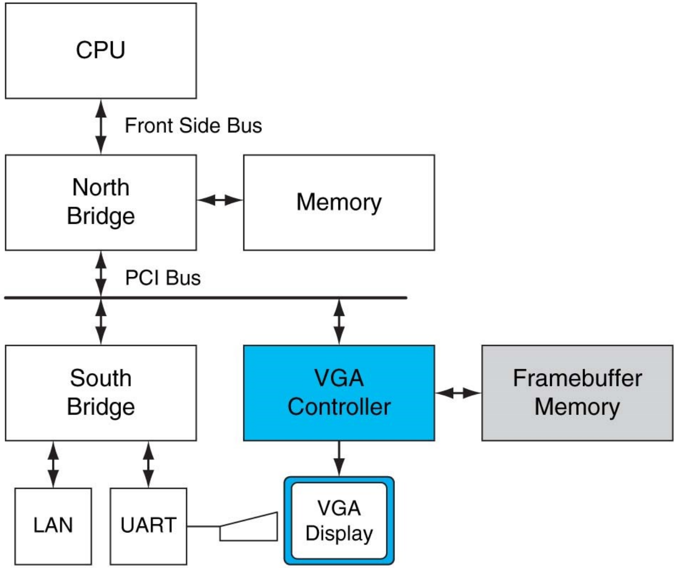
- Vector instructions have progressively become wider historically
  - Due to increase of data parallel applications
  - Good way to increase FLOPS while staying within TDP limit

- Enter GPUs for general computing (circa 2001)

GPUs:
Graphical Processing Units

History of GPUs

- VGA (Video graphic array) has been around since the early 90's
  - A display generator connected to some (video) RAM
- By 2000, VGA controllers were handling almost all graphics computation
  - Programmable through OpenGL, Direct 3D API
  - APIs allowed accelerated vertex/pixel processing:
    - Shading
    - Texture mapping
    - Rasterization
  - Gained moniker Graphical Processing Unit
- 2007: First general purpose use of GPUs
  - 2007: Release of CUDA language
  - 2011: Release of OpenCL language



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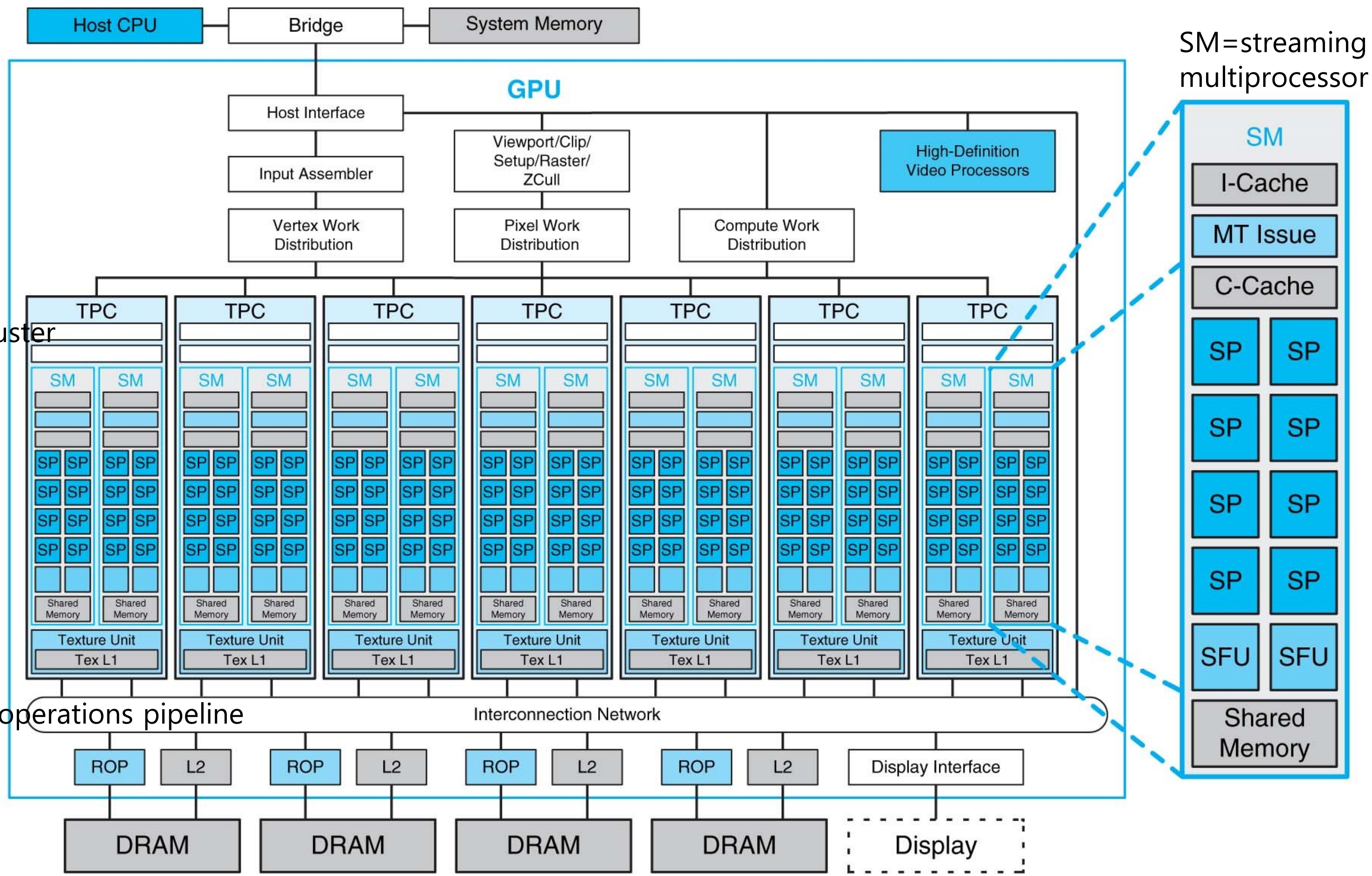
Modern GPU architecture

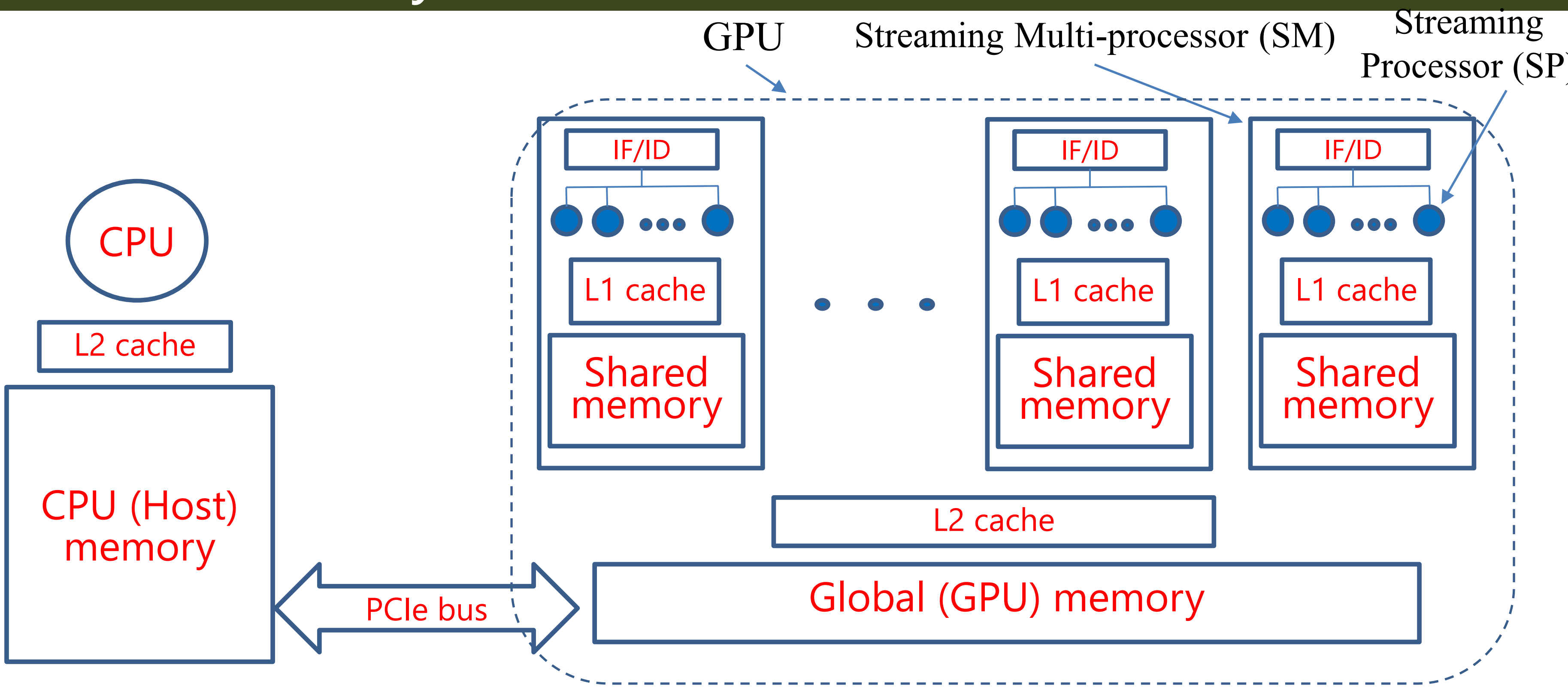
TPC = texture processing cluster

ROP = raster operations pipeline

SM=streaming multiprocessor



GPU is Really a SIMD Processor



- Logically, a GPU is composed of **SM**s (Streaming Multi-processors)
  - An SM is a **vector** unit that can process multiple pixels (or data items)
- Each SM is composed of **SPs** which work on each pixel or data item

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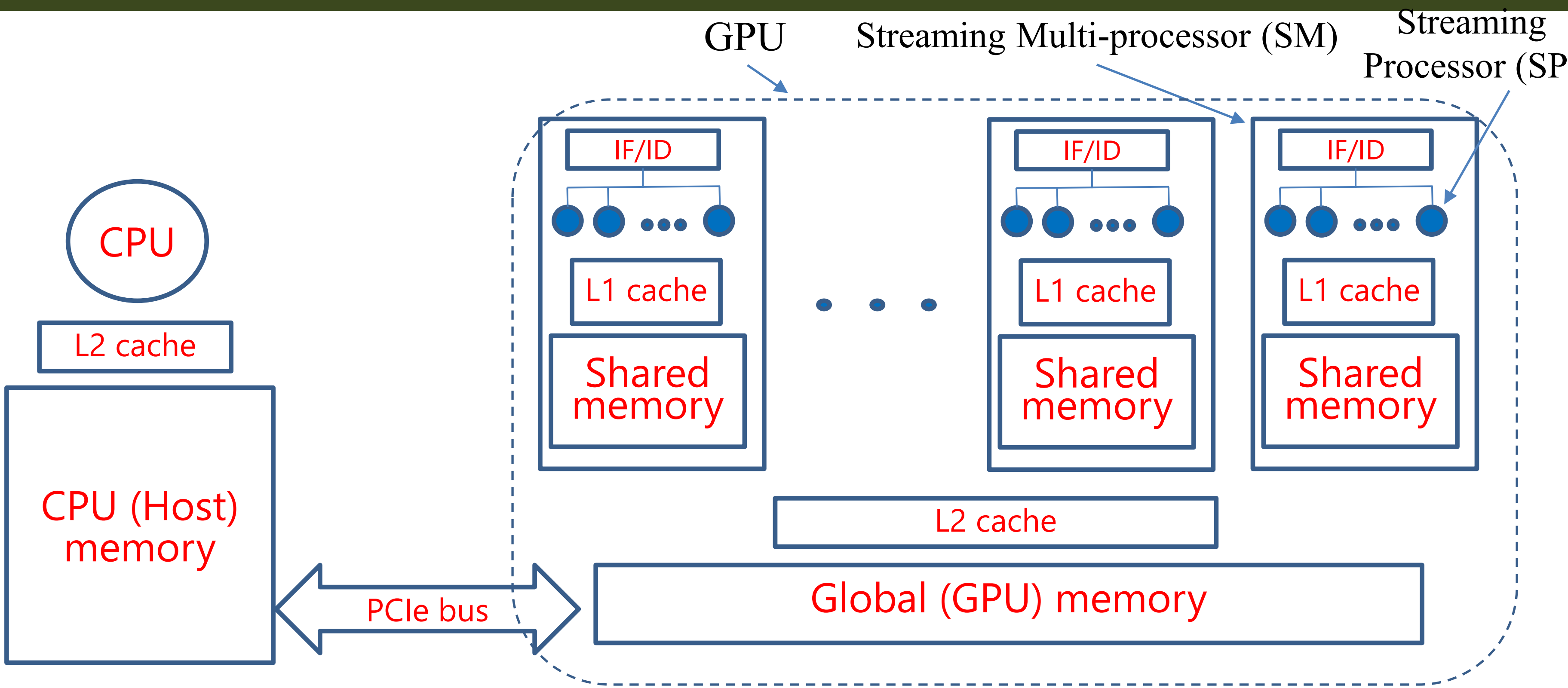
CPU-GPU architecture



- Dedicated GPU memory separate from system memory
- Code and data must be transferred to GPU memory for it to work on it
  - Through PCI-Express bus connecting GPU to CPU

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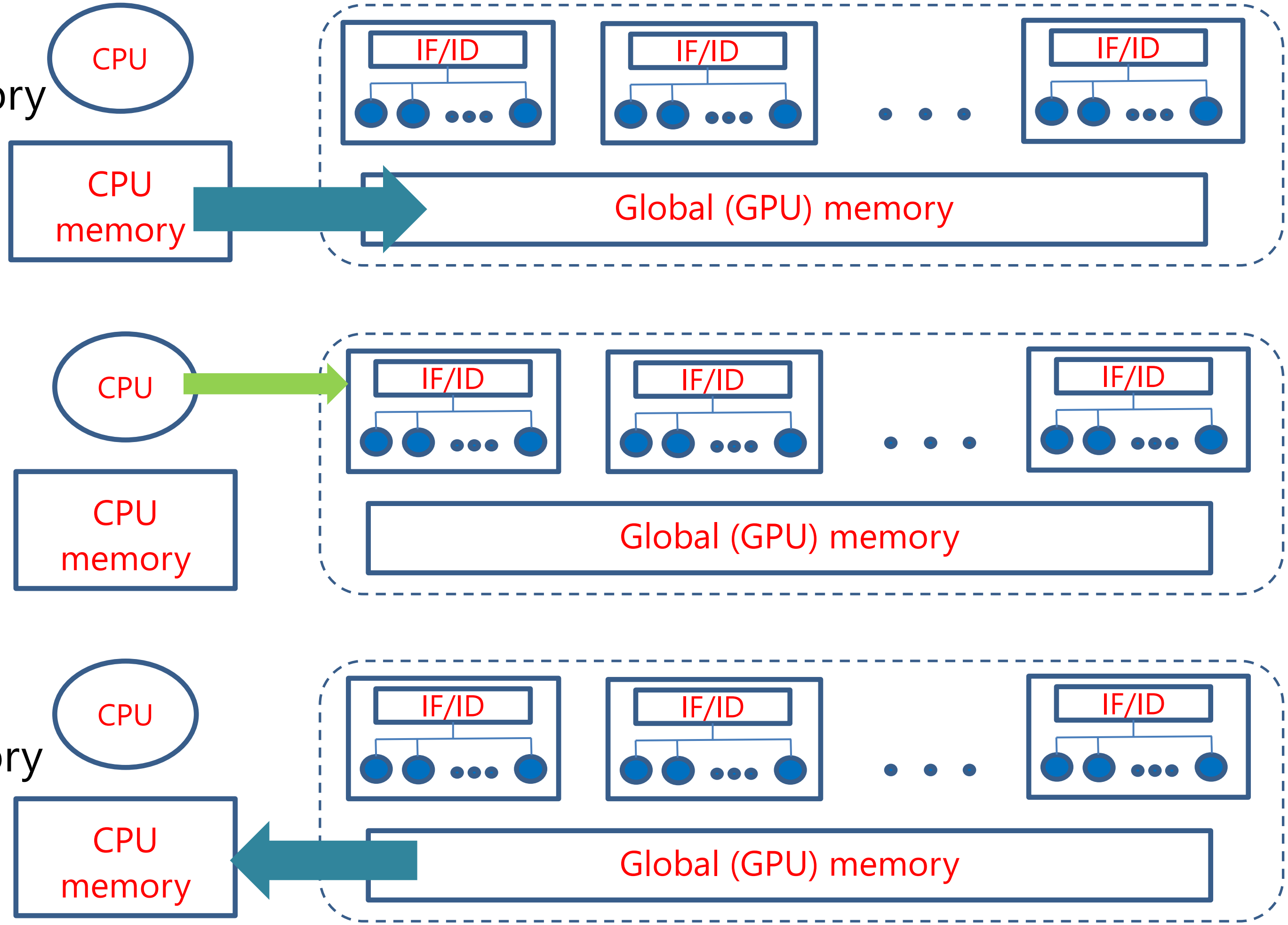
GPU Programming Model

Copy data from CPU memory to GPU memory

Launch the **kernel**

Copy data from GPU memory to CPU memory



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GPU Programming Model

CPU program
(serial code)

cudaMemcpy (…) — Copy data from CPU memory to GPU memory

Function <<<nb,nt >>> — Launch kernel on GPU

cudaMemcpy (…) — Copy results from GPU memory to CPU memory

__global_ Function (…) — Implementation of GPU kernel

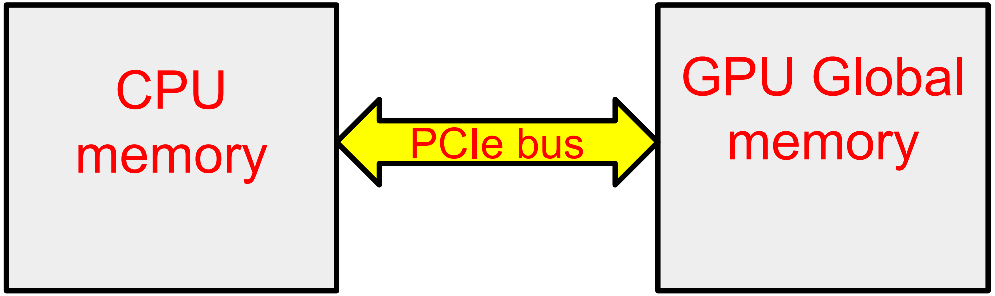
kernel: Function executed on the GPU

GPU Programming Model: Copying Data

```
/* malloc in GPU global memory */
cudaMalloc (void **pointer, size_t nbytes);
/* free malloced GPU global memory */
cudaFree(void **pointer) ;
/* initialize GPU global memory with value */
cudaMemset (void **pointer, int value, size_t count);
/* copy to and from between CPU and GPU memory */
cudaMemcpy(void *dest, void *src, size_t nbytes, enum cudaMemcopyKind dir);
```

enum cudaMemcpyKind

- cudaMemcpyHostToDevice
- cudaMemcpyDeviceToHost
- cudaMemcpyDeviceToDevice



Example: Copying array a to array b using the GPU

Data Movement Example

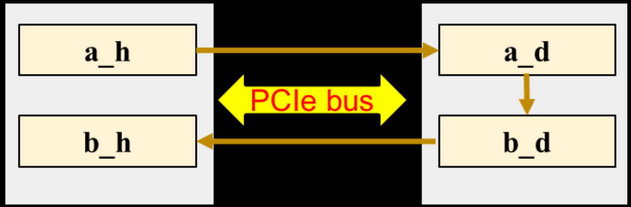
```
int main(void)
{
    float *a_h, *b_h;  // host data
    float *a_d, *b_d;  // device data
    int N = 14, nBytes, i ;

    nBytes = N*sizeof(float);
    a_h = (float *)malloc(nBytes);
    b_h = (float *)malloc(nBytes);
    cudaMalloc((void **) &a_d, nBytes);
    cudaMalloc((void **) &b_d, nBytes);

    for (i=0, i<N; i++) a_h[i] = 100.f + i;

    cudaMemcpy(a_d, a_h, nBytes, cudaMemcpyHostToDevice);
   GPUcomp<<<1, 14>>>(a_d, b_d, N) ;
    cudaMemcpy(b_h, b_d, nBytes, cudaMemcpyDeviceToHost);

    for (i=0; i< N; i++) assert( a_h[i] == b_h[i] );
    free(a_h); free(b_h); cudaFree(a_d); cudaFree(b_d);
    return 0;
}
```




```
_global_ void GPUcomp(*a,*b,N)
{
  int i = threadIdx.x ;
  if( i < N) b(i) = a(i) ;
}
```

GPU Programming Model: Launching the Kernel

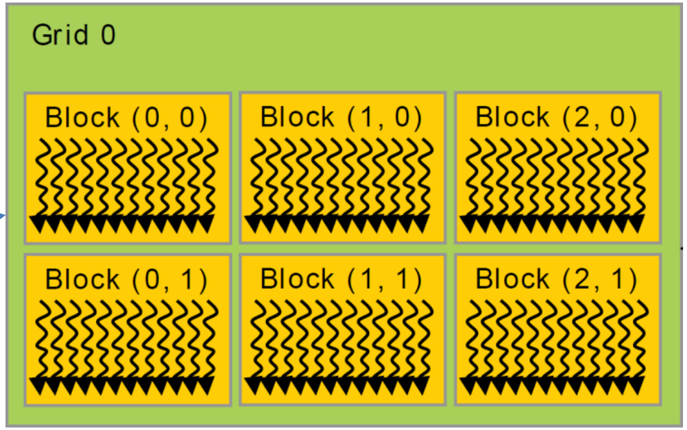
CPU program
(serial code)

cudaMemcpy (...)

Copy data from CPU memory to GPU memory

Function <<<nb,nt >>>

Launch a kernel with *nb* blocks, each with *nt* threads

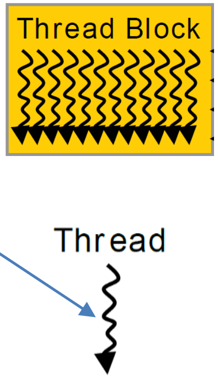


cudaMemcpy (...)

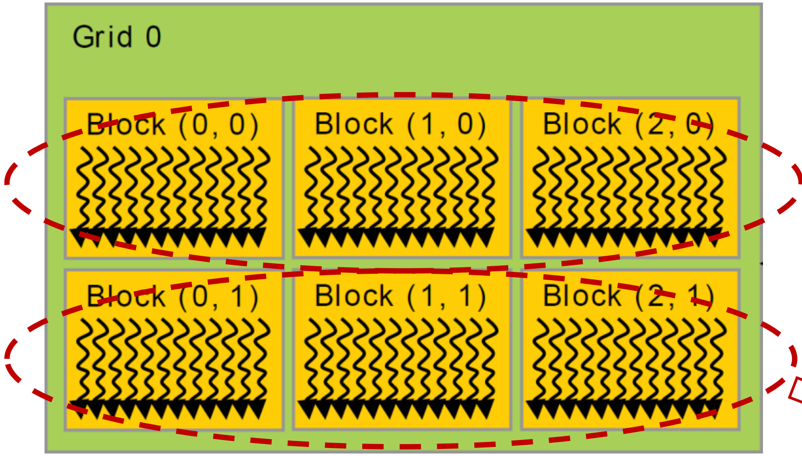
Copy results from GPU memory to CPU memory

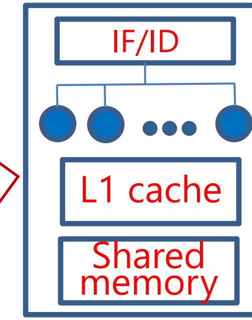
global Function (...)

Implementation of kernel (the function run by each GPU thread)



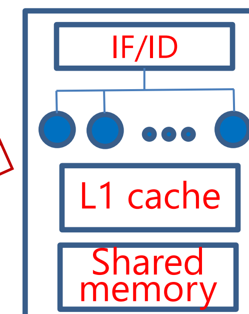
The Execution Model

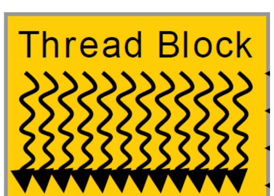




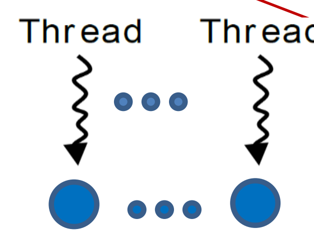
- The **thread blocks** are dispatched to **SM**s
- The number of blocks dispatched to an SM depends on the SM's resources (registers, shared memory, …).

Blocks not dispatched initially are dispatched when an SM frees up after finishing a block

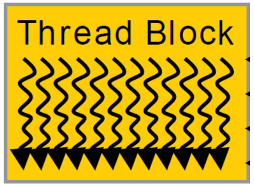




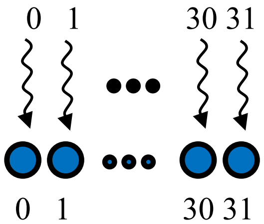
- When a block is dispatched to an SM, each of its threads executes on an SP in the SM.



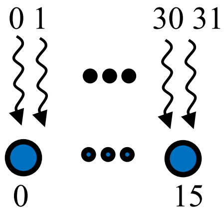
The Execution Model



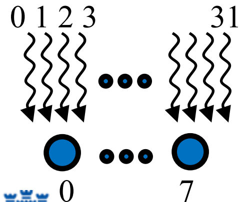
- Each block (up to 1K threads) is divided into groups of 32 threads (called **warps**) – empty threads are used as fillers.
- A warp executes as a SIMD **vector instruction** on the SM.
- Depending on the number of SPs per SM:



  - If 32 SP per SM → 1 thread of a warp executes on 1 SP (32 lanes of execution, one thread per lane)



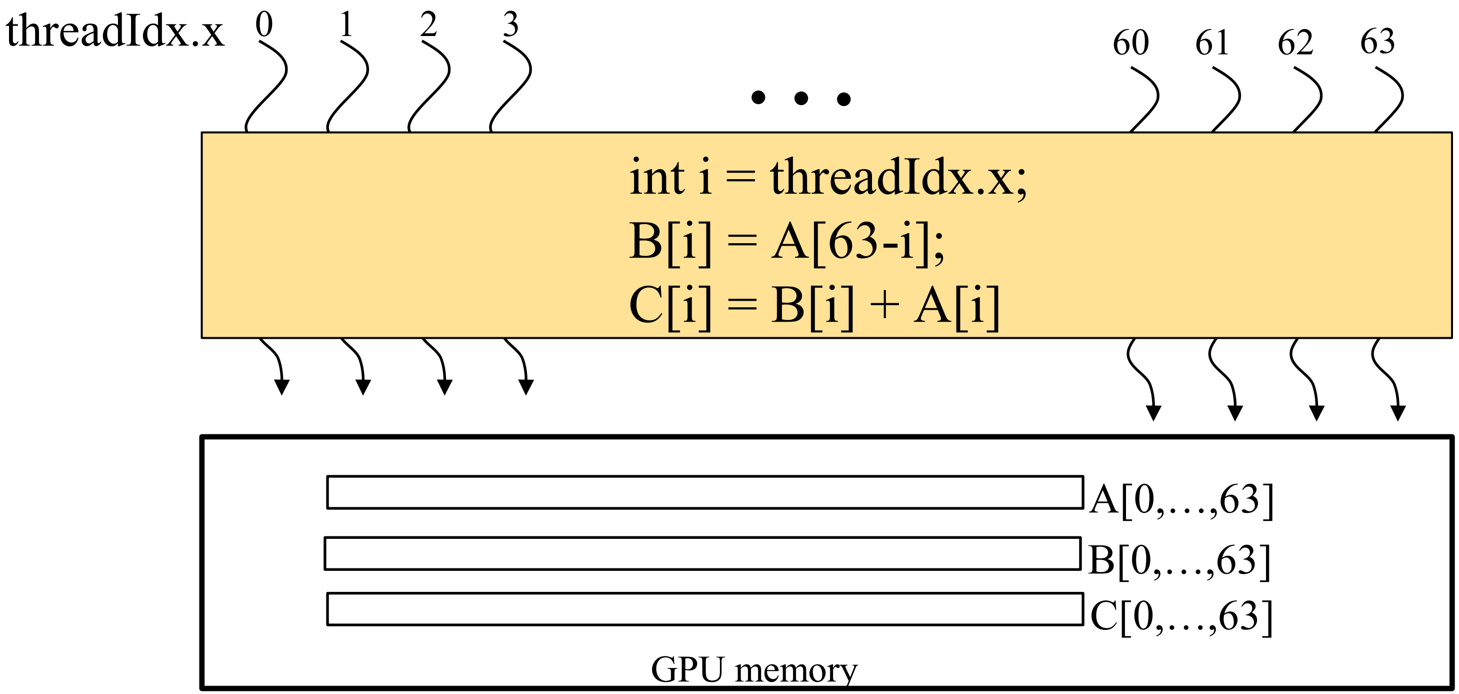
  - If 16 SP per SM → 2 threads are time multiplexed on 1 SP (16 lanes of execution, 2 threads per lane)



  - If 8 SP per SM → 4 threads are time multiplexed on 1 SP (8 lanes of execution, 4 threads per lane)

All threads execute the same code

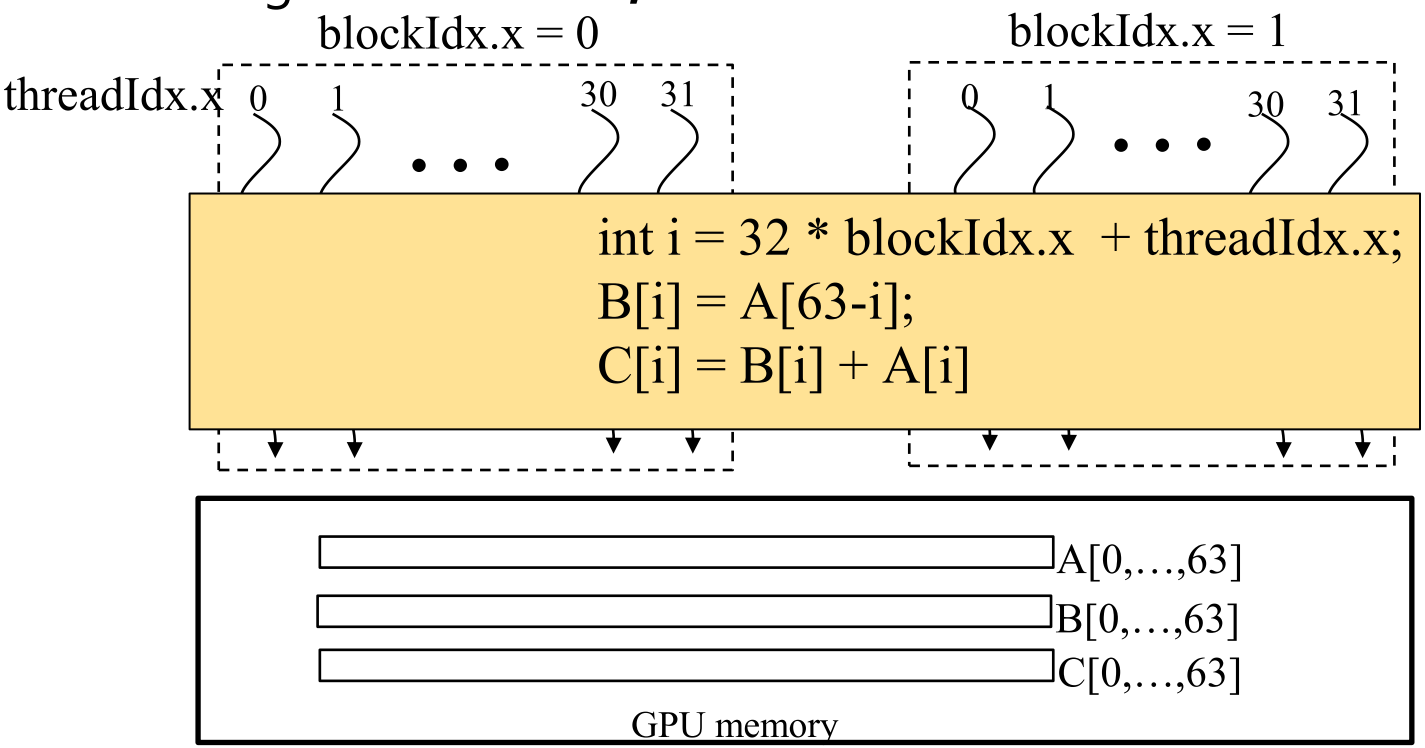
- Launched using **Kernel <<<1, 64>>>** : 1 block with 64 threads



- Each thread in a thread block has a unique "thread index" → **threadIdx.x**
- The same sequence of instructions can apply to different data items.

Blocks of Threads

- Launched using **Kernel <<<2, 32>>>** : 2 blocks of 32 threads



- Each thread block has a unique "block index" → **blockIdx.x**
- Each thread has a unique **threadIdx.x** within its own block
- Can compute a global index from the blockIdx.x and threadIdx.x

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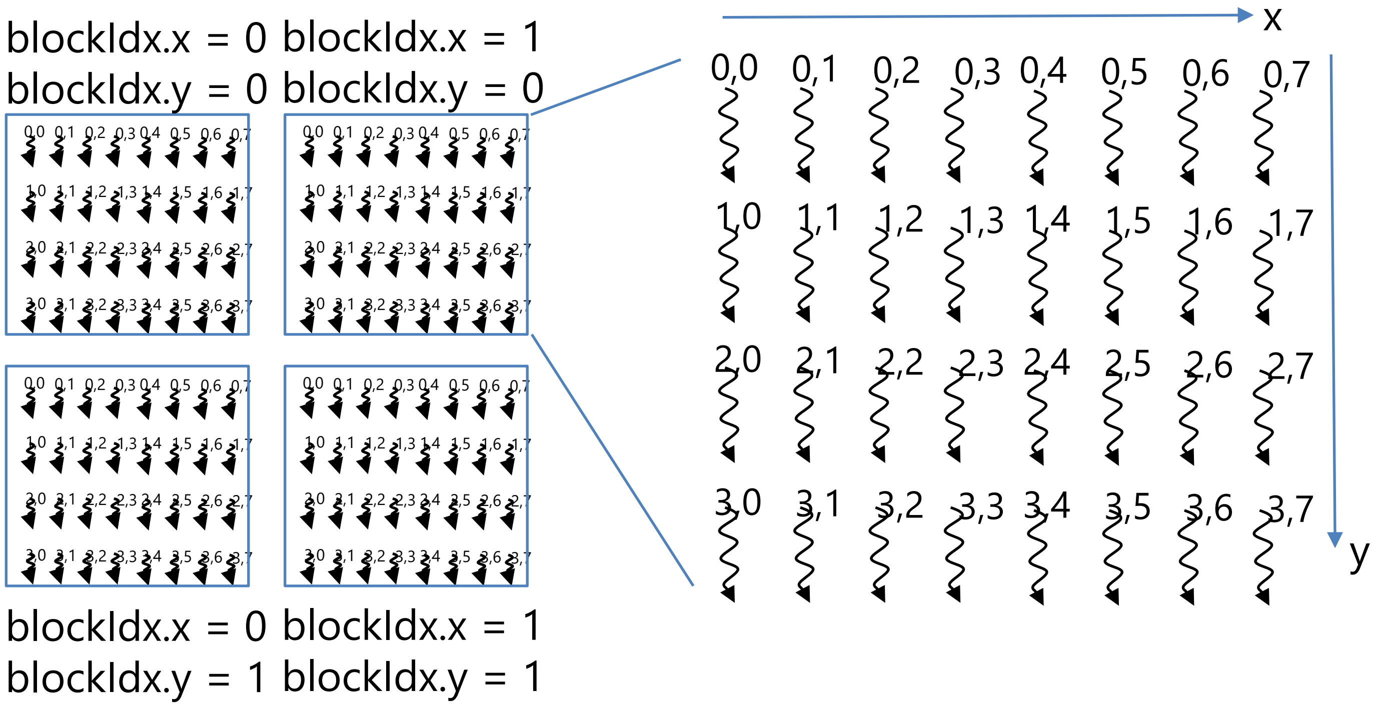
Two-dimensions grids and blocks

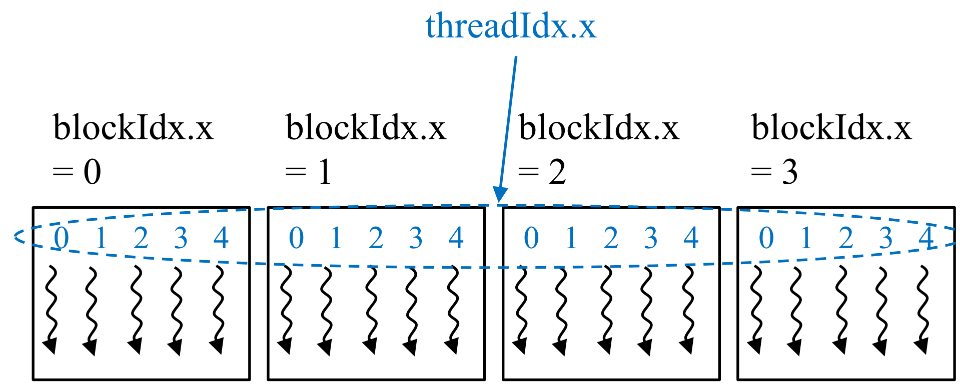
- Launched using **Kernel <<<(2, 2), (4, 8)>>>** : 2X2 blocks of 4X8 threads



- Each block has two indices **(blockIdx.x, blockIdx.y)**
- Each thread in a thread block has two indices **(threadIdx.x, threadIdx.y)**

Example: Computing the global index

```
void main ()
{  cudaMalloc (int* &a, 20*sizeof(int));
   cudaMalloc (int* &b, 20*sizeof(int));
   cudaMalloc (int* &c, 20*sizeof(int));
   …
   kernel<<<4,5>>>(a, b, c) ;
   …
}
_global_ void kernel(int *a, *b, *c)
{ int i = blockIdx.x * blockDim.x + threadIdx.x ;
  a[i] = i ;
  b[i] = blockIdx.x;
  c[i] = threadIdx.x;
}
```



NOTE: Each block will consist of one warp – only 5 threads in warp will do useful work. (Other 27 threads will execute no-ops.)

Global Memory

a[]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
b[]	0	0	0	0	0	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
c[]	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4

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Example: Computing $y(i) = a * x(i) + y(i)$

C program (on CPU)

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

```
void main ()
{
  …
  saxpy_serial(n, 2.0, x, y);
  …
}
```

CUDA program (on CPU+GPU)

```
_global_ void saxpy_gpu(int n, float a, float *x,
float *y)
{
  int i = blockIdx.x*blockDim.x +
          threadIdx.x;
  if (i < n ) y[i] = a * x[i] + y[i];
}
```

```
void main ()
{ …
  // cudaMalloc arrays X and Y
  // cudaMemcpy data to X and Y
  int NB = (n + 255) / 256;
  saxpy_gpu<<<NB, 256>>>(n, 2.0, X, Y);
  // cudaMemcpy data from Y
}
```

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Example: Computing $y(i) = a * x(i) + y(i)$

- What happens when n = 1?

```
_global_void saxpy_gpu(int n, float a, float *X, float *Y)
{
  int i = blockIdx.x*blockDim.x +  threadIdx.x;
  if (i < n ) Y[i] = a * X[i] + Y[i];
}
…..
saxpy_gpu<<<1, 256>>>(1, 2.0, X, Y); /* X and Y are both sized 1! */
```

- "if (i < n)" condition prevents writing beyond bounds of array.
- But that requires some threads within a **warp** not performing the write.
  - But a warp is a single vector instruction. How can you branch?
  - "if (i < n)" creates a **predicate** "mask" vector to use for the write
  - Only thread 0 has predicate turned on, rest has predicate turned off

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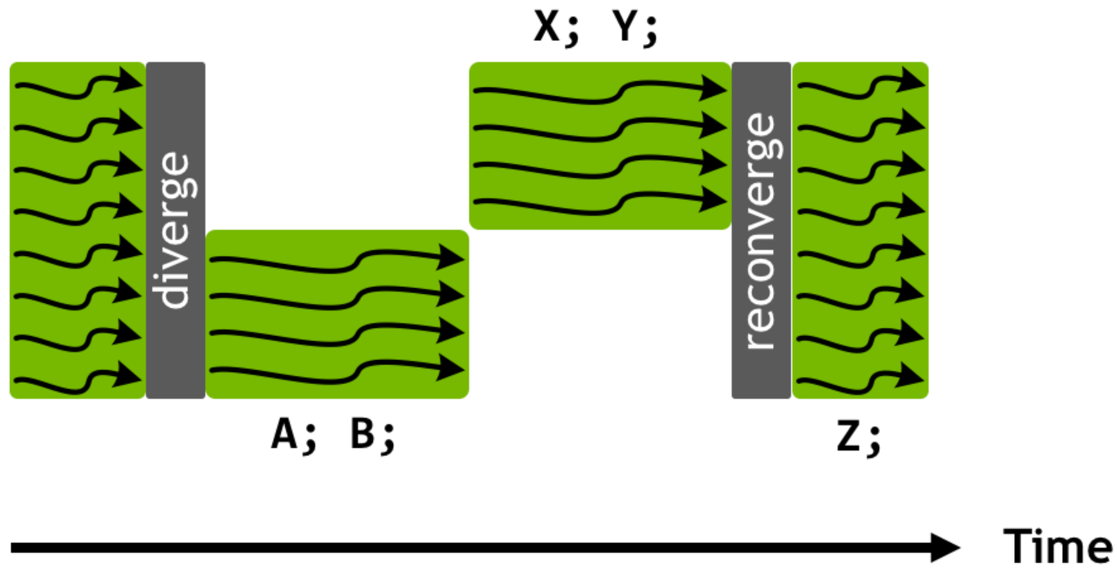
GPUs Use Predication for Branches

```
if (threadIdx.x < 4) {
    A;
    B;
} else {
    X;
    Y;
}
Z;
```



- Each thread computes own predicate for condition threadIdx.x < 4
- Taken together, 32 threads of a warp create a 32-bit predicate mask
- Mask is applied to warps for A, B, X, and Y.
- Just like for VLIW processors, this can lead to **low utilization**.

GPU Performance

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Lesson 1:
Parallelism is Important

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Thread Level Parallelism

- Superscalars and VLIWs are useful only if…
  - Program exhibits ILP (Instruction Level Parallelism) in the code

- GPUs are useful only if…
  - Program has **TLP (Thread Level Parallelism)** in the code
  - TLP can be expressed as the number of threads in the code

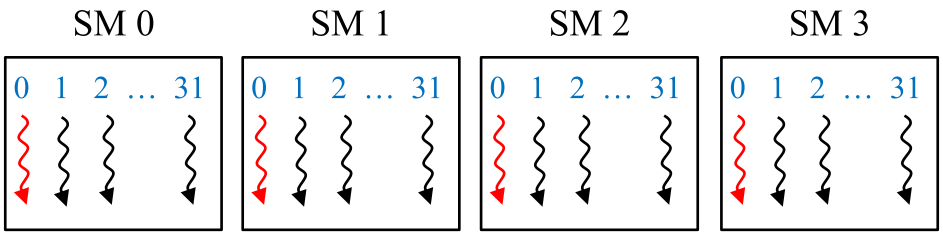
- As well as TLP, thread **layout** of the kernel is also important
  - How many **threads** are in a thread block
    - If less than threads in warp, some **SPs** may get unused
  - How many **thread blocks** are in the grid
    - If less than number of SMs, some **SM**s may get unused

→ If not careful, your GPU may get **underutilized**

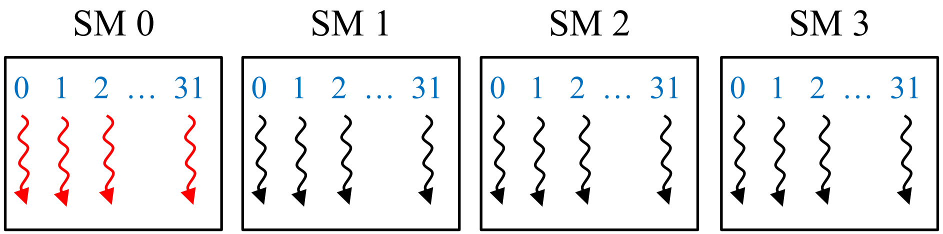
Example: Kernels with Wrong Layout

- Suppose there are 4 SMs in GPU with 32 SPs in each SM.
  - Case 1, 2 below have enough TLP (1024 threads) but bad layout
  - Utilized threads are marked in red. Rest are unused.

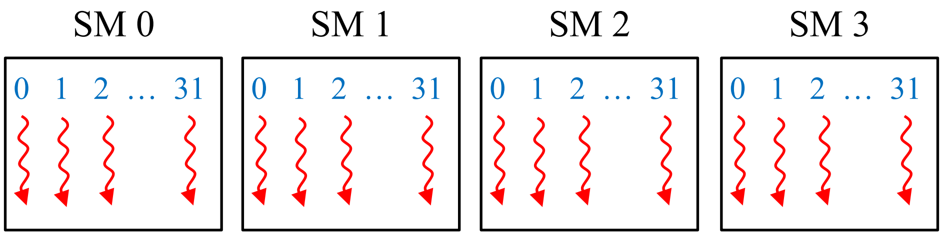
- Case 1: Not enough threads
  `kernel<<<1024, 1>>>(…) ;`



- Case 2: Not enough blocks
  `kernel<<<1, 1024>>>(…) ;`



- Balanced threads and blocks
  `kernel<<<32, 32>>>(…) ;`



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Lesson 2:
Bandwidth is Important

Example: Computing $y(i) = A(i,j) * x(j)$

C program (on CPU)

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

```
void main ()
{
  …
  mv_cpu(y, A, x, n);
  …
}
```

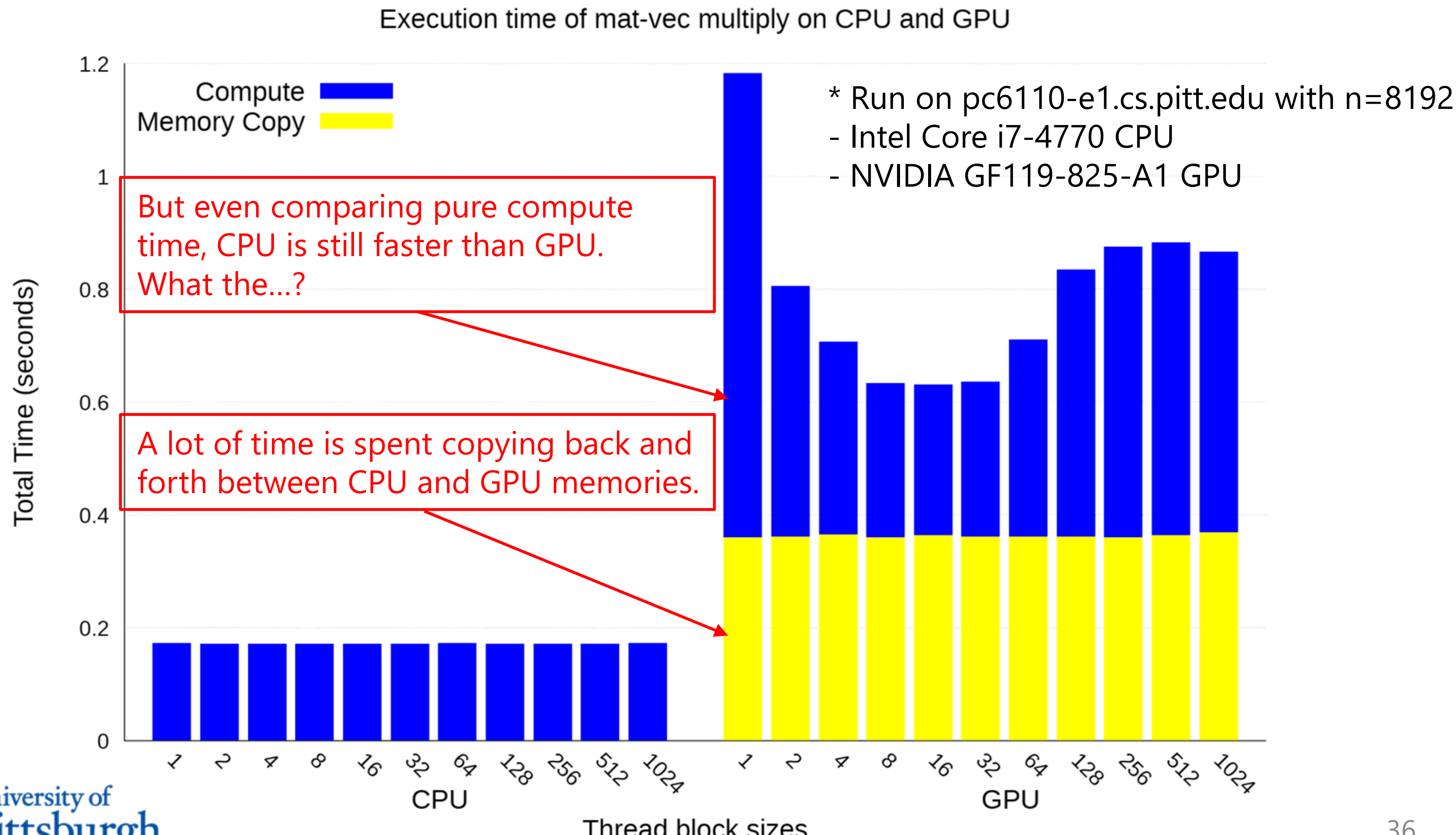
CUDA program (on CPU+GPU)

```
void mv_gpu(float* y, float* A, float* x, int n) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  if (i < n) {
    for (int j = 0; j < n; j++)
      y[i] += A[i*n + j] * x[j];
  }
}
```

```
void main ()
{
  …
  int nblocks = (n + block_size - 1) / block_size;
  mv_gpu <<<nblocks, block_size>>> (y, A, x, n);
  …
}
```

Performance Results for $y(i) = A(i,j) * x(j)$

- Guess what? CPU is faster than GPU!



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Performance Results for $y(i) = A(i,j) * x(j)$

- Was it because the GPU can't do enough **FLOPS**?

- NVIDIA GF119-825-A1 is a Fermi GPU Capability 2.1
  - Clock rate: 1046 MHz (X 2 for warp execution)
  - Number of SMs: 1
  - Number of SPs per SM: 48
  - Max FLOPS = 1046 MHz * 2 * 1 * 48 = **100.4 GFLOPS**

- What was the FLOPS achieved?
  - y[i] += A[i*n + j] * x[j] = 2 FP ops each iteration for n * n iterations
  - n = 8192, so FP ops = 8192 * 8192 * 2 = 134 M
  - Time = 0.27 seconds (shortest at 32 thread block size)
  - FLOPS = 134 M / 0.27 = **496 MFLOPS**
  - **Not even close to the limit!**

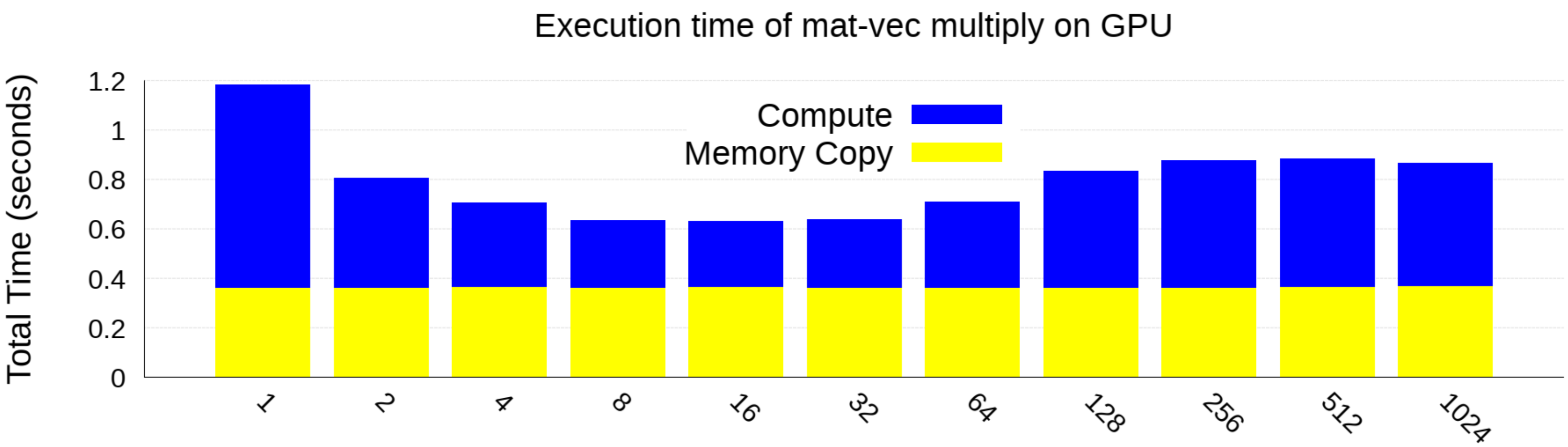
Performance Results for $y(i) = A(i, j) * x(j)$

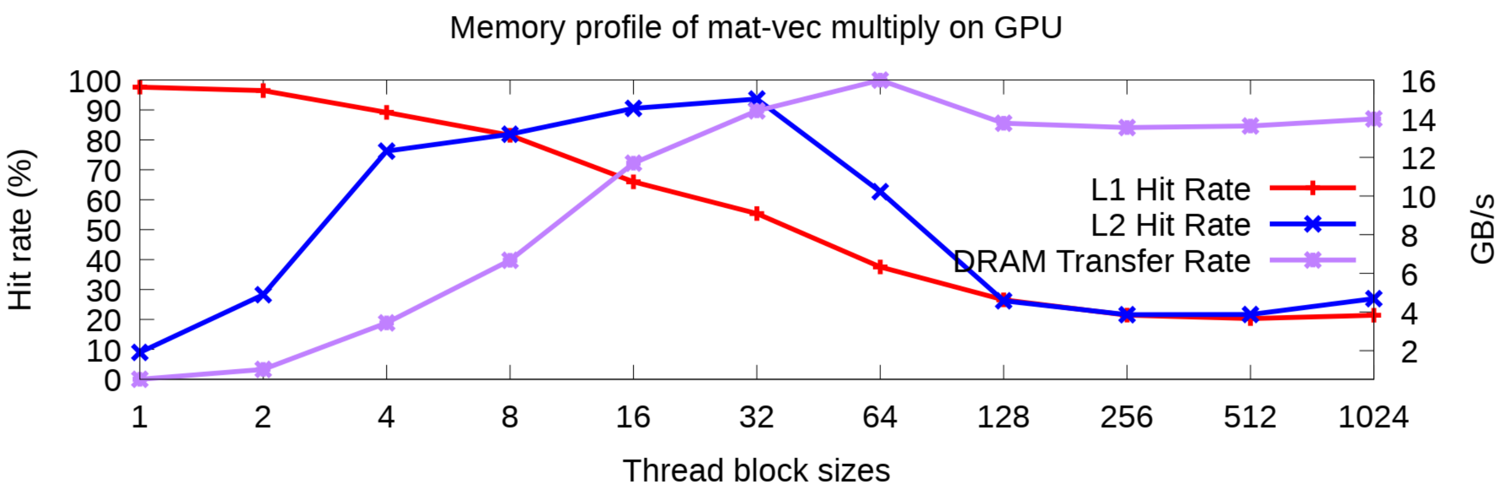
- Could it be that the GPU didn't have enough **memory bandwidth**?

- NVIDIA GF119-825-A1 is a Fermi GPU Capability 2.1
  - Memory Type: DDR3
  - Memory Bandwidth: **14.00 GB/s**

- GPUs also have Performance Monitoring Units (PMUs)
  - NVIDIA Profiler (nvprof) provides an easy way to read them: https://docs.nvidia.com/cuda/profiler-users-guide/index.html
  - Let's use the PMU to profile the following:
    - DRAM Transfer Rate (GB/s)
    - L1 Hit Rate (%)
    - L2 Hit Rate (%)

Memory Wall Hits Again





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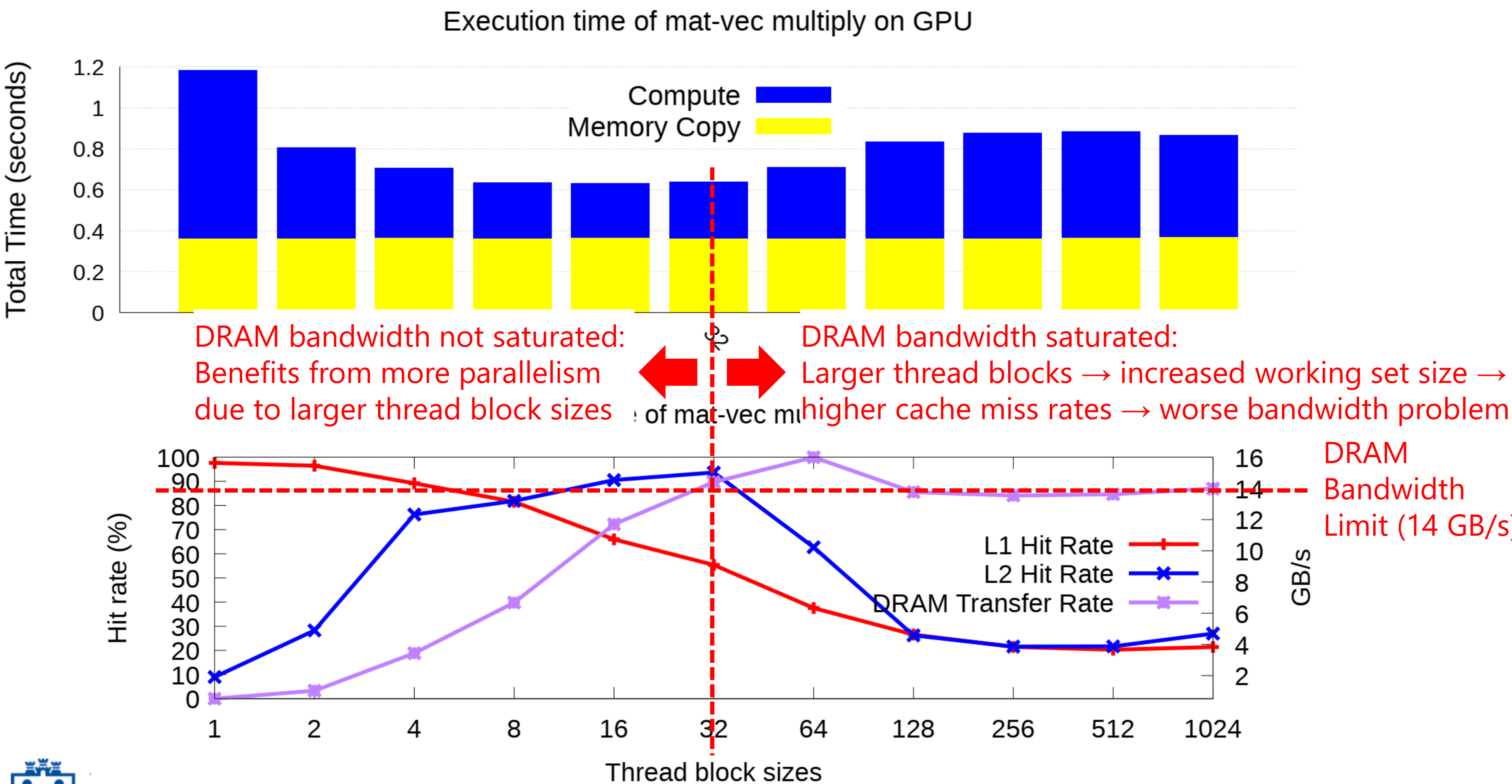
Memory Wall Hits Again



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Is there a way we can reach max FLOPS?

- Let's take a look at the GPU design metrics again:
  - Max FLOPS = 100.4 GFLOPS
  - Memory Bandwidth: 14.00 GB/s

- To sustain max FLOPS, you need to do a lot of work per byte
  - 100.4 GFLOPS / 14.00 GB/s = 7.17 FP ops / byte
  - Or, about **28 FP ops / float** (4 bytes) fetched from memory
  - Otherwise, the memory bandwidth cannot sustain the FLOPS

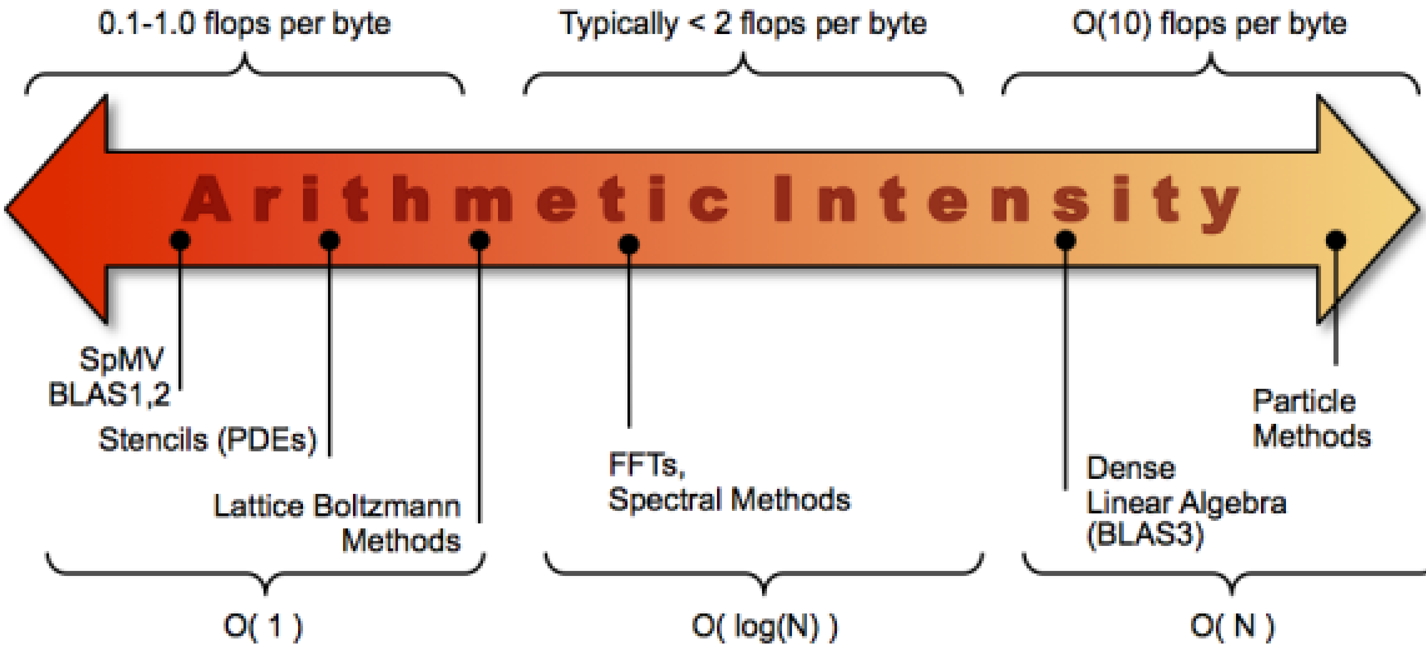
- All GPUs have this problem with **memory bandwidth**:
  - It's easy to put in more SMs using transistors for Moore's Law
  - Your memory bandwidth is limited due to your DDR interface

Arithmetic Intensity: A property of the program

- How many **FP ops / float** for our mat-vec multiplication?
  - y[i] += A[i*n + j] * x[j] each iteration with n * n iterations
  - FP ops = **2 * n * n** (one multiply and one add)
  - Float accesses = **n * n + 2n** (1 matrix and 2 vector accesses)
    - That's counting only cold misses but could be even more
  - So approx. **2 FP ops / float** (a far cry from 28 FP ops / float)
  - This metric is called **arithmetic intensity**

- Arithmetic intensity is a **property of the program** need by GPUs
  - Just like TLP (thread-level-parallelism) is needed by GPUs
  - Matrix-vector multiplication has low intensity
    → Fundamentally not suited for fast GPU computation

Arithmetic Intensity: A property of the program



* Courtesy of Lawrence Berkeley National Laboratory:
https://crd.lbl.gov/departments/computer-science/par/research/roofline/introduction/

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Matrix-Matrix Multiply: Good Arithmetic Intensity

- Matrix-multiplication:

```
for (int i=0; i<n; i++)
    for (int j=0; j<n; j++)
      for (int k=0; k<n; k++)
        C[i*n + j] += A[i*n + k] * B[k*n + j];
```

- What's the arithmetic intensity for this program?
  - FP ops = **2 * n * n * n** (one multiply and one add)
  - Float accesses = **3 * n * n** (3 matrix accesses)
    - If we only have cold misses and no capacity misses
  - Arithmetic intensity = 2 * n / 3 = **0.66 * n**
  - Implication: The larger the matrix size, the better suited for GPUs!
    - Important result for deep learning and other apps

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Example: Computing $C(i,j) = A(i,k) * B(k,j)$

C program (on CPU)

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

```
void main ()
{
  mm_cpu(C, A, B, n);
}
```

CUDA program (on CPU+GPU)

```
void mm_gpu(float* C, float* A, float* B, int n) {
  float Cvalue = 0;
  int i = blockIdx.y * blockDim.y + threadIdx.y;
  int j = blockIdx.x * blockDim.x + threadIdx.x;
  for (int k = 0; k < n; ++k)
    Cvalue += A[i * n + k] * B[k * n + j];
  C[i * n + j] = Cvalue;
}
```

```
void main ()
{
  dim3 dimBlock(block_size, block_size);
  dim3 dimGrid(n / dimBlock.x, n / dimBlock.y);
  mm_gpu <<<dimGrid, dimBlock>>> (C, A, B, n);
}
```

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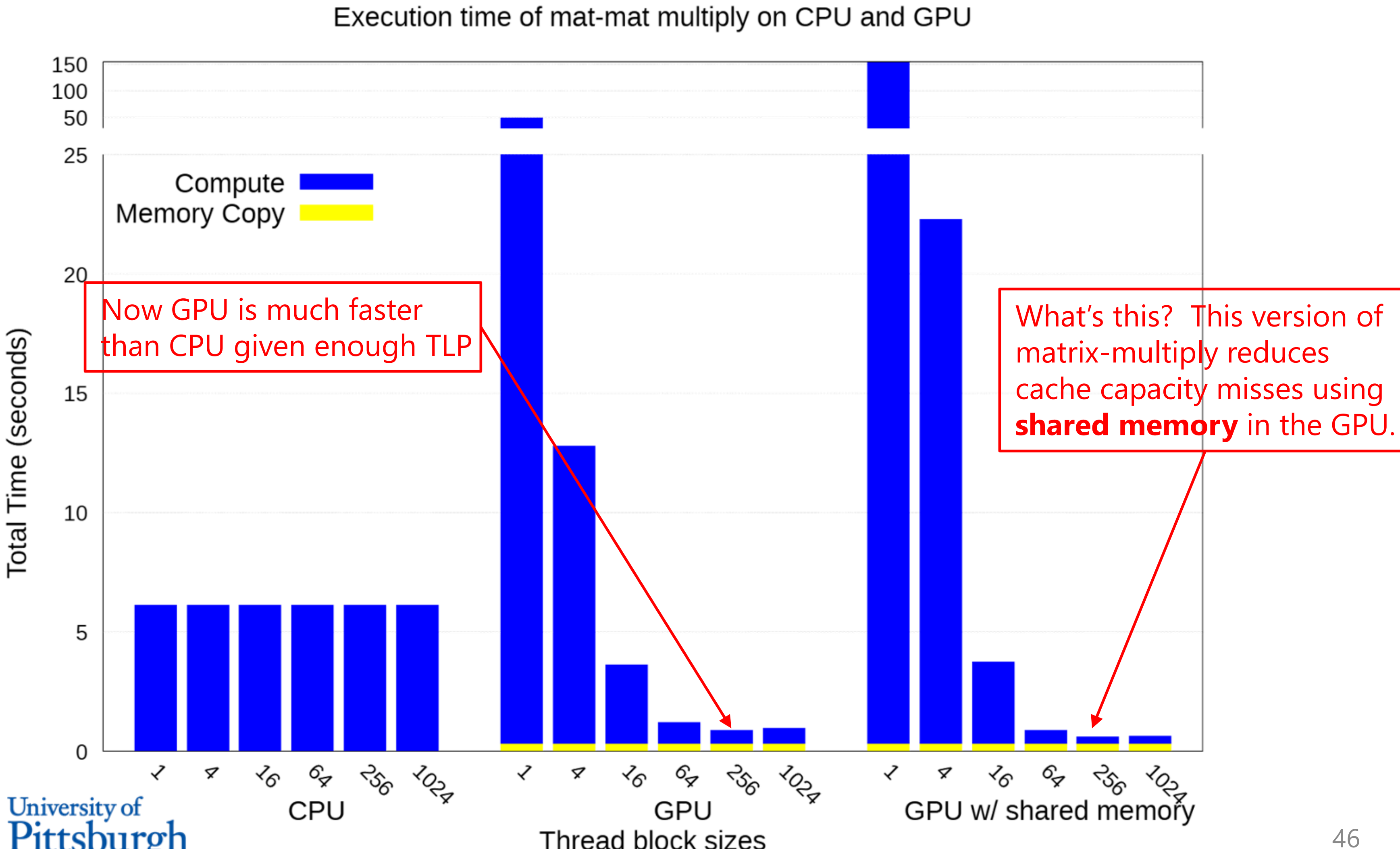
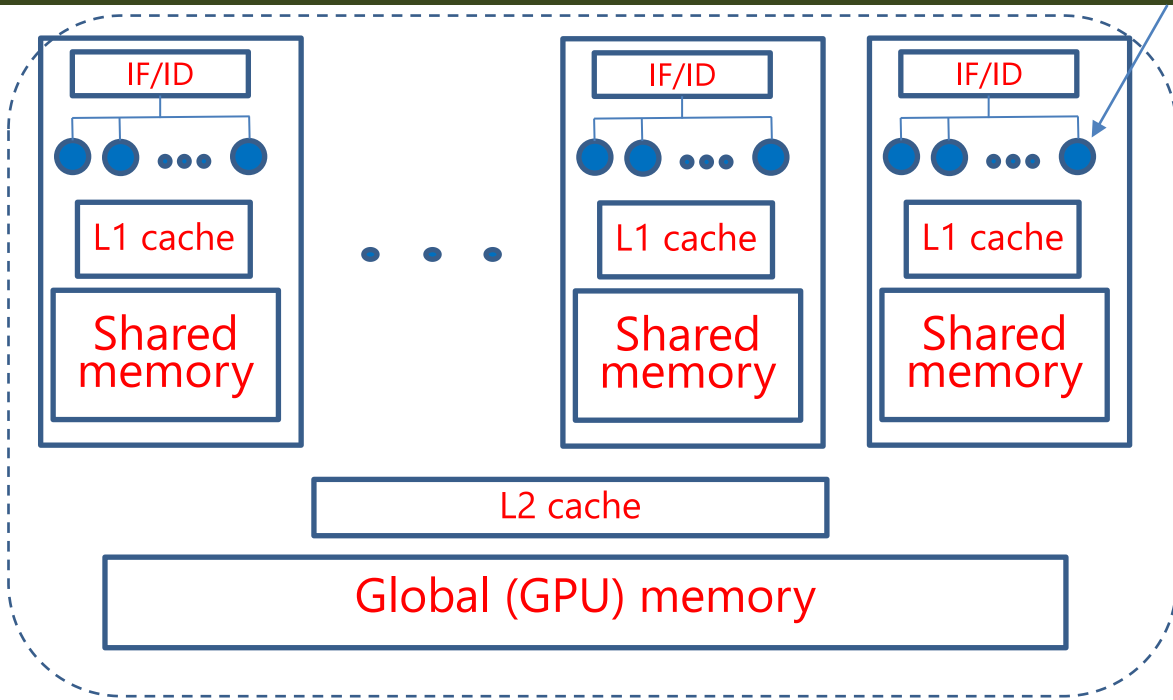
Performance Results for $C(i,j) = A(i,k) * B(k,j)$



So what is Shared Memory?



- **Shared Memory**: memory shared among threads in a thread block
  - Variables declared with __shared__ modifier live in shared memory
  - Is same as L1 cache in terms of latency and bandwidth!
  - Storing frequently used data in shared memory can save on bandwidth

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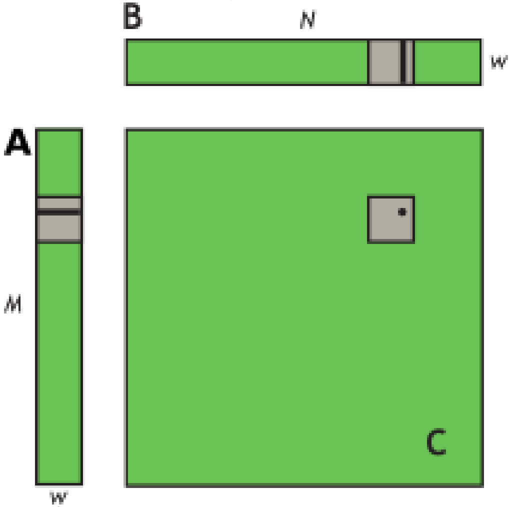
Loop Tiling with Shared Memory

- You can store a “tile” within the matrix in shared memory
  - While operating on the tile
  - Can drastically reduce the accesses to DRAM memory



- Don’t have time to cover in detail but if you are interested, visit: https://docs.nvidia.com/cuda/cuda-c-best-practices-guide/index.html#shared-memory-in-matrix-multiplication-c-ab

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