CUDA, Parallel Programming Language
CUDA Memories

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Latency & Throughput

- **Latency** is the delay caused by the physical speed of the hardware
- CPU = low latency, low throughput
  - CPU clock = 3 GHz (3 clocks/ns)
  - CPU main memory latency: ~100+ ns
  - CPU arithmetic instruction latency: ~1+ ns
- GPU = high latency, high throughput
  - GPU clock = 1.5 GHz (1.5 clock/ns)
  - GPU main memory latency: ~300+ ns
  - GPU arithmetic instruction latency: ~10+ ns

Compute & I/O Throughput

GeForce GTX 1080 TI

Compute throughput	11.3 TFLOPS (single precision)
Global memory bandwidth	484 GB/s (121 Gfloat/s)

- GPU is very IO limited! IO is very often the throughput bottleneck, so its important to be smart about IO.
- If you want to get beyond ~900 GFLOPS, need to do multiple FLOPs per float data load.

GPU Memory Breakdown

- Registers
- Local Memory
- Global Memory
- Shared Memory
- L1/L2/L3 Cache
- Constant Memory
- Texture Memory
- Read-only Cache

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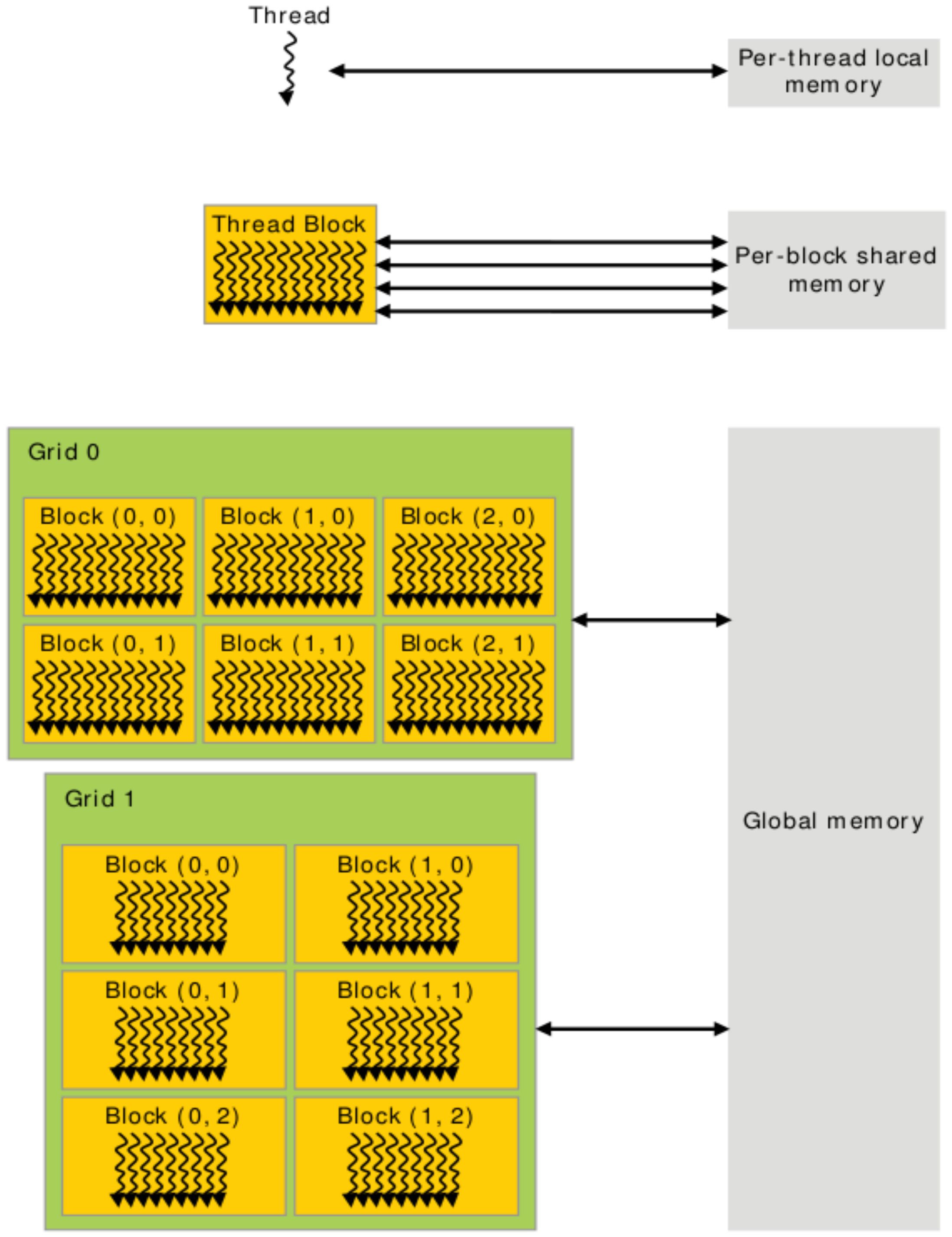
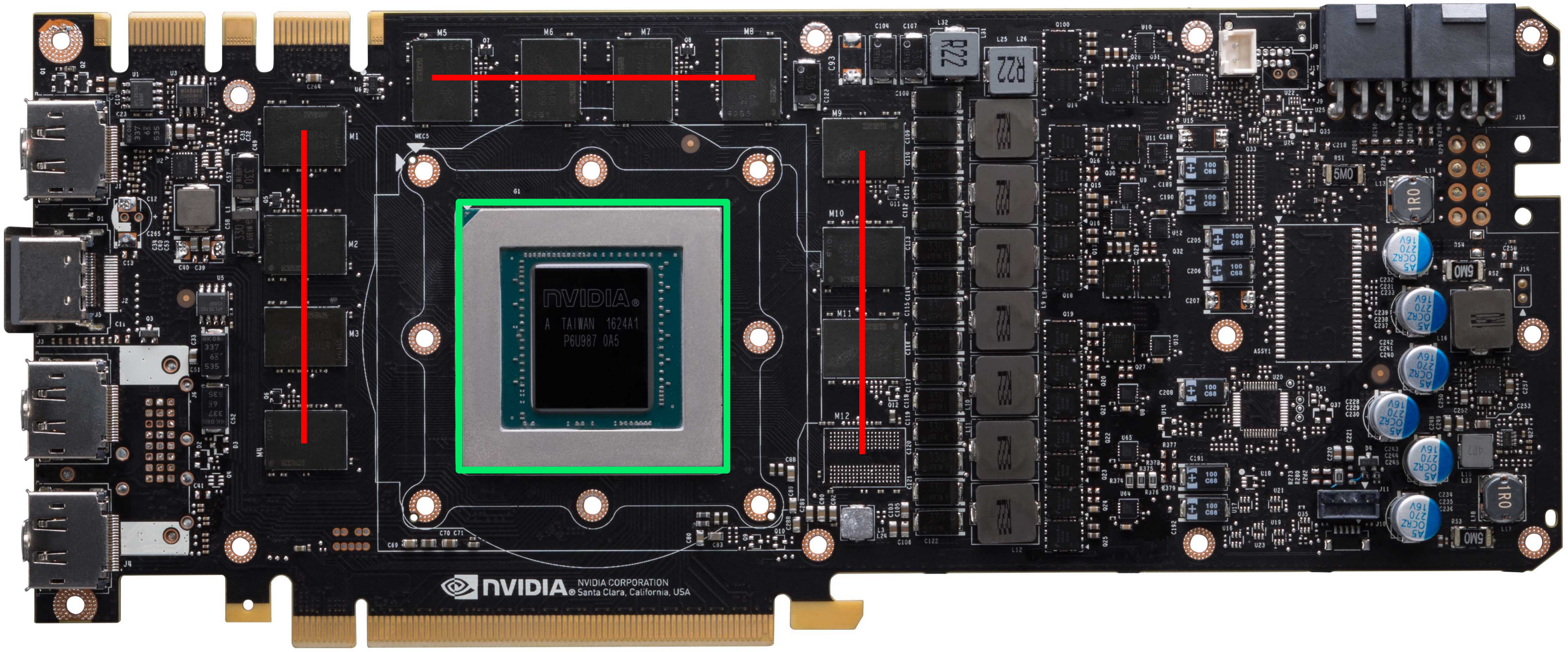
Memory Scope



Global Memory

- **Global memory** is separate hardware from GPU SMs
  - The vast majority of memory on a GPU is global memory
  - If data doesn’t fit in global memory, process it in chunks that fit
  - GPUs have 1~32GB of global memory, with most having ~10GB
- Global memory latency is ~300ns on Kepler and ~600ns on Fermi

Global Memory



Green box is 1080 TI, Red lines are global memory

NVIDIA GTX 1080 TI

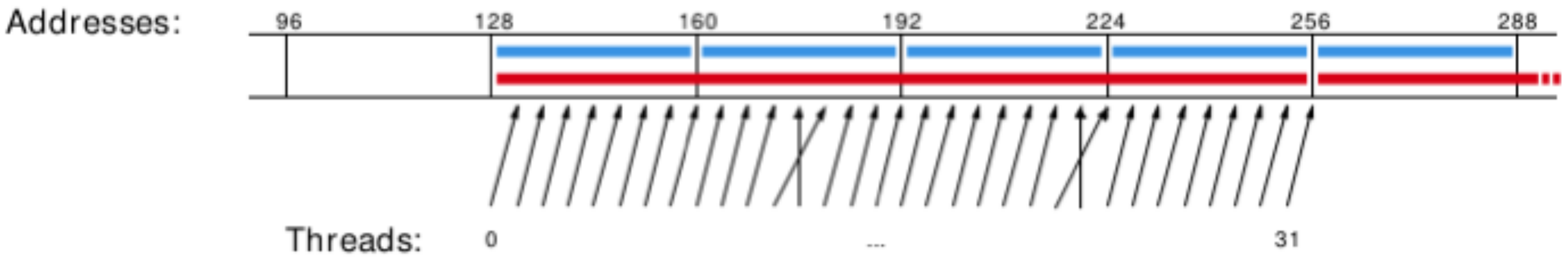
Accessing Global Memory Efficiently

- Global memory IO is the slowest form of IO on GPU
- Because of this, we want to access global memory as little as possible
- Access patterns that play nicely with GPU hardware are called **coalesced memory accesses.**

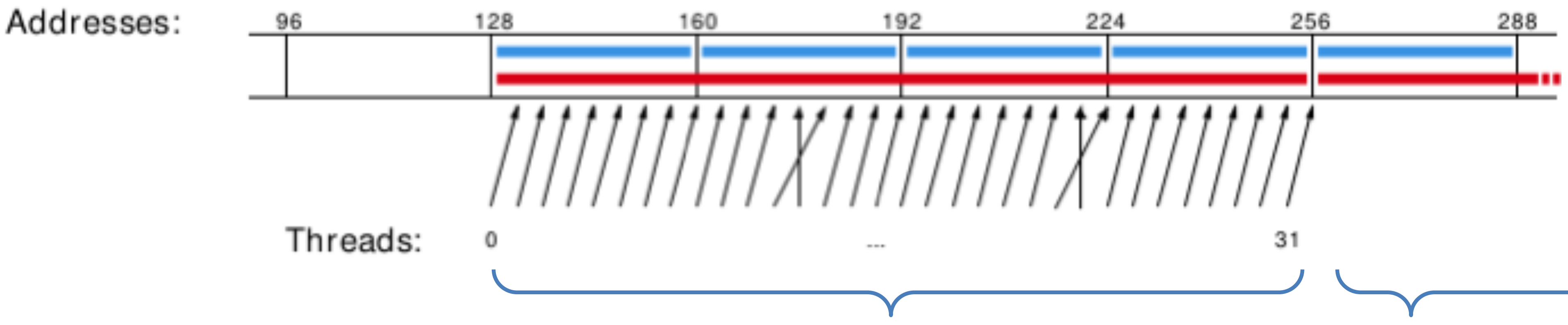
Memory Coalescing

- Memory accesses done in large groups of **Memory Transactions**
  - Done per warp
  - Fully utilizes the way IO is setup at the hardware level
- Coalesced memory accesses minimize the number of cache lines read
  - GPU cache lines are 128 bytes and are aligned

Mis-aligned Accesses



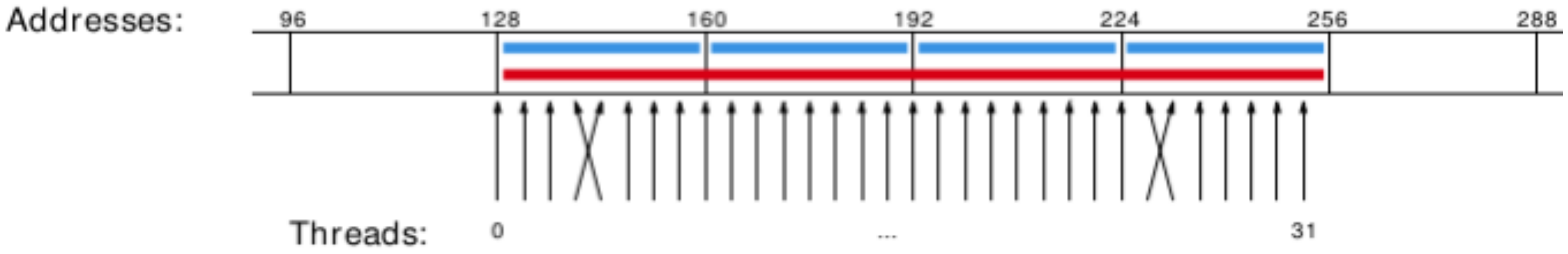
Mis-aligned Accesses



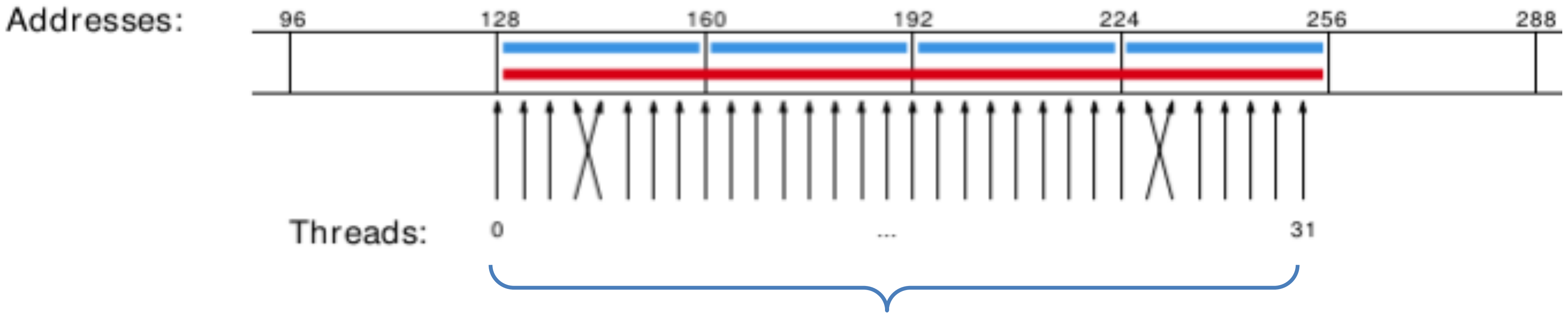
Loading Cacheline Addr: 128~255

Addr: 256~385

Aligned Accesses



Aligned Accesses



Loading Cacheline Addr: 128~255

Shared Memory

- Fast memory located in the SM
- Same hardware as L1 cache
  - ~5ns of latency
- Maximum size of ~48KB (varies per GPU)
- Scope of shared memory == thread block

Shared Memory Syntax

- Can allocate shared memory statically or dynamically
- Static allocation:
  - `__shared__ float data[1024];`
  - Declared in the kernel, nothing in host code
- Dynamic allocation:
  - Host:
    - `kernel<<<grid_dim, block_dim, numBytesShMem>>>(args);`
  - Device (in kernel):
    - `extern __shared__ float s[];`

For reference: https://devblogs.nvidia.com/using-shared-memory-cuda-cc/

CUDA Kernel w/ Shared Memory

Task: Compute histogram of color usages
Input: array of bytes of length `N`
Output: 256 element array of integers

Naive: build output in global memory, `N` global stores
Smart: build output in shared memory, copy to global memory at end, 256 global stores

Histogram (Naïve)

```
// Determine frequency of colors in a picture
// Each thread looks at one pixel and increments
// a counter atomically
__global__ void histogram(int* color,
                          int* buckets){
  int i = threadIdx.x
        + blockDim.x * blockIdx.x;
  int c = colors[i];
  atomicAdd(&buckets[c], 1);
}
```

Example: Histogram

```
__global__ void histogram(int* color,
                          int* buckets){
  __shared__ int hist[256];
  int i = threadIdx.x + blockDim.x * blockIdx.x;
  int c = colors[i];
  atomicAdd(&hist[c], 1);
  __syncthreads();
  if (threadIdx.x < 256) {
    atomicAdd(&buckets[i], hist[i]);
  }
}
```

Example: Histogram

```
__global__ void histogram(int* color, int* buckets){
  __shared__ int hist[256];
  __shared__ int _color[blockDim.x];
  int i = threadIdx.x + blockDim.x * blockIdx.x;
  _color[threadIdx.x] = colors[i];
  __syncthreads();
  atomicAdd(&hist[_color[threadIdx.x]], 1);
  __syncthreads();
  if (threadIdx.x < 256) {
    atomicAdd(&buckets[i], hist[i]);
  }}
```

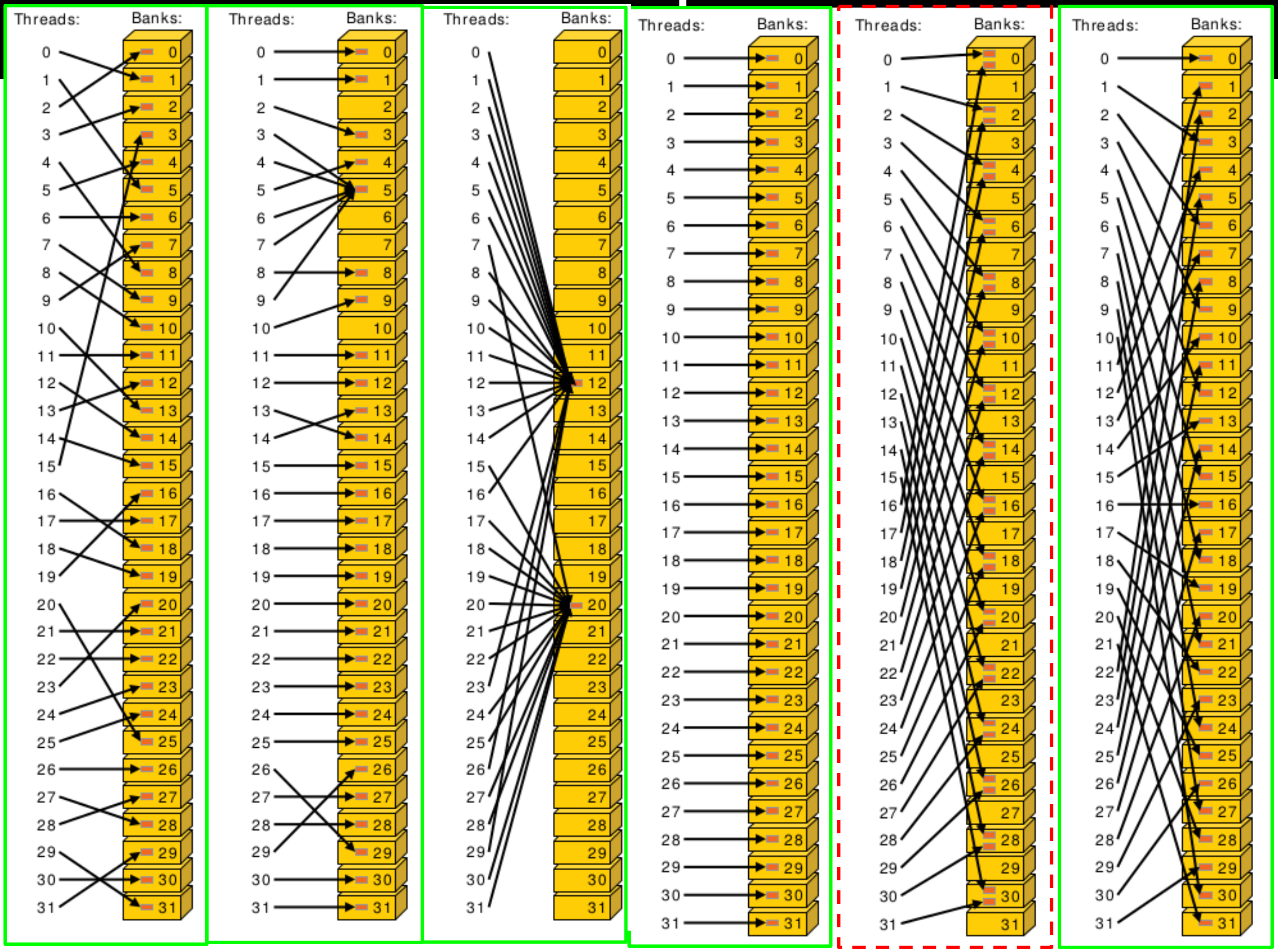
A Common Pattern in Kernels

(1) copy from global memory to shared memory
(2) __syncthreads()
(3) perform computation, incrementally storing output in shared memory, __syncthreads() as necessary
(4) copy output from shared memory to output array in global memory

Bank Conflict for Shared Memory

- Shared memory is setup as 32 **banks**
  - If an element is 4 byte-long, element`[i]` in bank `i % 32`
- A **bank conflict** occurs when 2 threads in a warp access different elements in the same bank.
  - Bank conflicts cause serial memory accesses rather than parallel
    - Serial *anything* in GPU programming = bad for performance

Bank Conflict Example



Bank Conflict and Strides

Stride 1 ⇒ 32 x 1-way “bank conflicts” (so conflict-free)

Stride 2 ⇒ 16 x 2-way bank conflicts

Stride 3 ⇒ 32 x 1-way “bank conflicts” (so conflict-free)

Stride 4 ⇒ 8 x 4-way bank conflicts

…

Stride 32 ⇒ 1 x 32-way bank conflict :(

Padding to avoid Bank Conflict

To fix the stride 32 case, we'll waste a byte on padding and make the stride 33 :)

Don't store any data in slots 32, 65, 98, ...

Now we have

thread 0 ⇒ index 0 (bank 0)

thread 1 ⇒ index 33 (bank 1)

thread `i` ⇒ index `33 * i` (bank `i`)

Registers

- Fastest “memory”, ~10x faster than shared memory
- There are tens of thousands of registers in each SM
  - Generally works out to a maximum of 32 or 64 32-bit registers per thread
- Most stack variables declared in kernels are stored in registers
  - example: `float x;`
- Statically indexed arrays stored on the stack are sometimes put in registers

Local Memory

- **Local memory** is everything on the stack that can’t fit in registers
- The scope of local memory is just the thread.
- Local memory is stored in global memory
    - much slower than registers

CUDA Variable Type Qualifiers

Variable declaration	Memory	Scope	Lifetime
`int var;`	register	thread	thread
`int array_var[10];`	local	thread	thread
`__shared__ int shared_var;`	shared	block	block
`__device__ int global_var;`	global	grid	application
`__constant__ int constant_var;`	constant	grid	application

- "automatic" scalar variables without qualifier reside in a register
  - compiler will spill to thread local memory
- "automatic" array variables without qualifier reside in thread-local memory

CUDA Variable Type Performance

Variable declaration	Memory	Penalty
`int var;`	register	1x
`int array_var[10];`	local	100x
`__shared__ int shared_var;`	shared	1x
`__device__ int global_var;`	global	100x
`__constant__ int constant_var;`	constant	1x

- scalar variables reside in fast, on-chip registers
- shared variables reside in fast, on-chip memories
- thread-local arrays & global variables reside in uncached off-chip memory
- constant variables reside in cached off-chip memory

CUDA Variable Type Scale

Variable declaration	Instances	Visibility
`int var;`	100,000s	1
`int array_var[10];`	100,000s	1
`__shared__ int shared_var;`	100s	100s
`__device__ int global_var;`	1	100,000s
`__constant__ int constant_var;`	1	100,000s

- 100Ks per-thread variables, R/W by 1 thread
- 100s shared variables, each R/W by 100s of threads
- 1 global variable is R/W by 100Ks threads
- 1 constant variable is readable by 100Ks threads

GPU Memory Breakdown

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L1 Cache

- Caches local and/or global memory
- Same hardware as shared memory
- For some GPU architectures, configurable (16, 32, 48KB)
- Each SM has its own L1 cache

L2 Cache

- Caches all global & local memory accesses
- ~1MB in size
- Shared by all SM’s

Constant Memory

Constant memory is global memory with a special cache

- Used for constants that cannot be compiled into program
- Constants must be set from host before running kernel.

~64KB for user, ~64KB for compiler

- kernel arguments are passed through constant memory

Constant Cache

- 8KB cache on each SM
- Special instruction (LDU, load uniform)
- Go to http://www.nvidia.com/object/sc10_cuda_tutorial.html for more details

Constant Memory Syntax

- In global scope (outside of kernel, at top level of program):
    - __constant__ int foo[1024];

- In host code:
    - cudaMemcpyToSymbol(foo, h_src, sizeof(int) * 1024);

Texture Memory

Complicated and not very useful for general purpose computation

Useful characteristics:

- 2D or 3D data locality for caching purposes through “CUDA arrays”. Goes into special texture cache.
- fast interpolation on 1D, 2D, or 3D array
- converting integers to “unitized” floating point numbers

Read-Only Cache

- Many CUDA programs don't use textures, but we should take advantage of the texture cache hardware
- CC (compute capability) ≥ 3.5 makes it easier to use texture cache
  - Many `const` variables will automatically load through texture cache
  - Can also force loading through cache with `__ldg` intrinsic function
- Differs from constant memory because doesn't require static indexing

Example – shared variables

```
// Adjacent Difference application:
// compute result[i] = input[i] – input[i-1]
__global__ void adj_diff_naive(int *result, int *input){
  // compute this thread's global index
  unsigned int i = blockDim.x * blockIdx.x + threadIdx.x;
  if(i > 0)
  {
    // each thread loads two elements from global memory
    int x_i = input[i];
    int x_i_minus_one = input[i-1];

    result[i] = x_i – x_i_minus_one;
  }
}
```

Example – shared variables

```
// Adjacent Difference application:
// compute result[i] = input[i] – input[i-1]
__global__ void adj_diff_naive(int *result, int *input){
  // compute this thread's global index
  unsigned int i = blockDim.x * blockIdx.x + threadIdx.x;

  if(i > 0)  {
    // what are the bandwidth requirements of this kernel?
    int x_i = input[i];
    int x_i_minus_one = input[i-1];

    result[i] = x_i – x_i_minus_one;
  }
}
```

Two loads

Example – shared variables

```
// Adjacent Difference application:
// compute result[i] = input[i] – input[i-1]
__global__ void adj_diff_naive(int *result, int *input){
  // compute this thread's global index
  unsigned int i = blockDim.x * blockIdx.x + threadIdx.x;
  if(i > 0)  {
    // How many times does this kernel load input[i]?
    int x_i = input[i]; // once by thread i
    int x_i_minus_one = input[i-1]; // again by thread i+1

    result[i] = x_i – x_i_minus_one;
  }
}
```

Example – shared variables

```
// Adjacent Difference application:
// compute result[i] = input[i] – input[i-1]
__global__ void adj_diff_naive(int *result, int *input){
  // compute this thread’s global index
  unsigned int i = blockDim.x * blockIdx.x + threadIdx.x;
  if(i > 0) {
    // Idea: eliminate redundancy by sharing data
    int x_i = input[i];
    int x_i_minus_one = input[i-1];

    result[i] = x_i – x_i_minus_one;
  }
}
```

Example – shared variables

```
// optimized version of adjacent difference
__global__ void adj_diff(int *result, int *input){
  int tx = threadIdx.x;
  // allocate a __shared__ array, one element per thread
  __shared__ int s_data[BLOCK_SIZE];
  // each thread reads one element to s_data
  unsigned int i = blockDim.x * blockIdx.x + tx;
  s_data[tx] = input[i];

  // avoid race condition: ensure all loads
  // complete before continuing
  __syncthreads();
  ...
}
```

Example – shared variables

```
// optimized version of adjacent difference
__global__ void adj_diff(int *result, int *input){

   ...

   if(tx > 0)
     result[i] = s_data[tx] - s_data[tx-1];
   else if(i > 0)
   {
     // handle thread block boundary
     result[i] = s_data[tx] - input[i-1];
   }
}
```

Optimization Analysis

Implementation	Original	Improved
Global Loads	2N	N + N/BLOCK_SIZE
Global Stores	N	N
Throughput	36.8 GB/s	57.5 GB/s
SLOCs	18	35
Relative Improvement	1x	1.57x
Improvement/SLOC	1x	0.81x

- Experiment performed on a GT200 chip
  - Improvement likely better on an older architecture
  - Improvement likely worse on a newer architecture
- Optimizations tend to come with a development cost

About Pointers

- You can point at any memory space per se:

```
__device__ int my_global_variable;
__constant__ int my_constant_variable = 13;

__global__ void foo(void){
  __shared__ int my_shared_variable;

  int *ptr_to_global = &my_global_variable;
  const int *ptr_to_constant = &my_constant_variable;
  int *ptr_to_shared = &my_shared_variable;
  ...
  *ptr_to_global = *ptr_to_shared;
}
```

About Pointers

- Pointers aren't typed on memory space
  - `__shared__ int *ptr;`
  - Where does `ptr` point?
  - `ptr` is a `__shared__` pointer variable, not a pointer to a `__shared__` variable!

Don’t confuse the compiler!

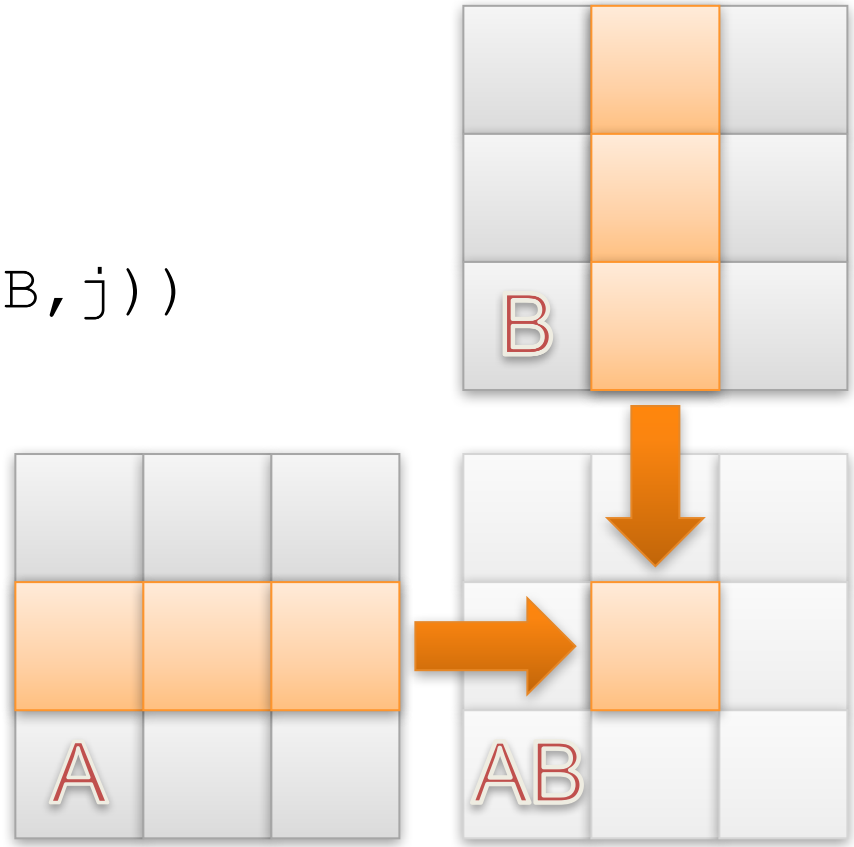
```
__device__ int my_global_variable;
__global__ void foo(int *input)
{
  __shared__ int my_shared_variable;

  int *ptr = 0;
  if(input[threadIdx.x] % 2)
    ptr = &my_global_variable;
  else
    ptr = &my_shared_variable;
  // where does ptr point?
}
```

Advice

- Prefer dereferencing pointers in simple, regular access patterns
- Avoid propagating pointers
- Avoid pointers to pointers
  - The GPU would rather not pointer chase
  - Linked lists will not perform well
- Pay attention to compiler warning messages
  - `Warning: Cannot tell what pointer points to, assuming global memory space`
  - Crash waiting to happen

Matrix Multiplication Example

- Generalize `adjacent_difference` example
- AB = A * B
  - Each element AB_{ij}
  - = `dot(row(A,i),col(B,j))`
- Parallelization strategy
  - Thread → AB_{ij}
  - 2D kernel



First Implementation

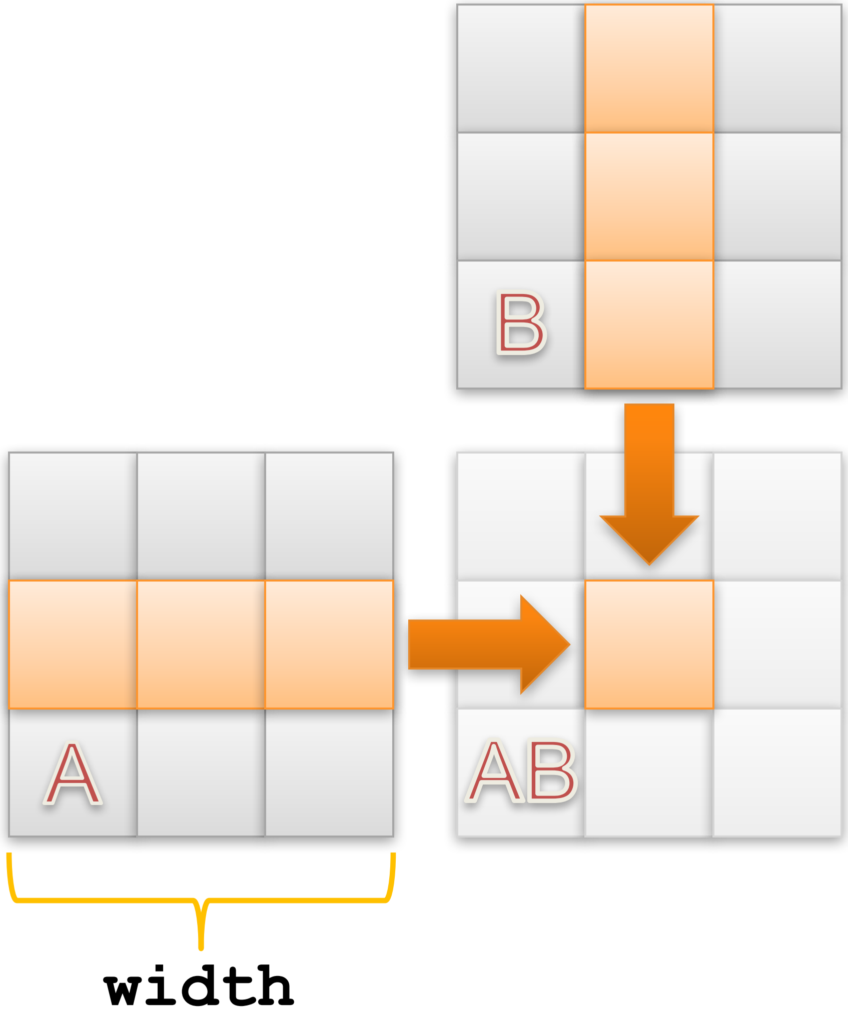
```
__global__ void mat_mul(float *a, float *b,
                        float *ab, int width){
  // calculate the row & col index of the element
  int row = blockIdx.y*blockDim.y + threadIdx.y;
  int col = blockIdx.x*blockDim.x + threadIdx.x;

  float result = 0;
  // do dot product between row of a and col of b
  for(int k = 0; k < width; ++k)
    result += a[row*width+k] * b[k*width+col];

  ab[row*width+col] = result;
}
```

How will this perform?

How many loads per term of dot product?	2 (a & b) = 8 Bytes
How many floating point operations?	2 (multiply & addition)
Global memory access to flop ratio (GMAC)	8 Bytes / 2 ops = 4 B/op
What is the peak fp performance of GeForce GTX 260?	805 GFLOPS
Lower bound on bandwidth required to reach peak fp performance	GMAC * Peak FLOPS = 4 * 805 = 3.2 TB/s
What is the actual memory bandwidth of GeForce GTX 260?	112 GB/s
Then what is an upper bound on performance of our implementation?	Actual BW / GMAC = 112 / 4 = 28 GFLOPS

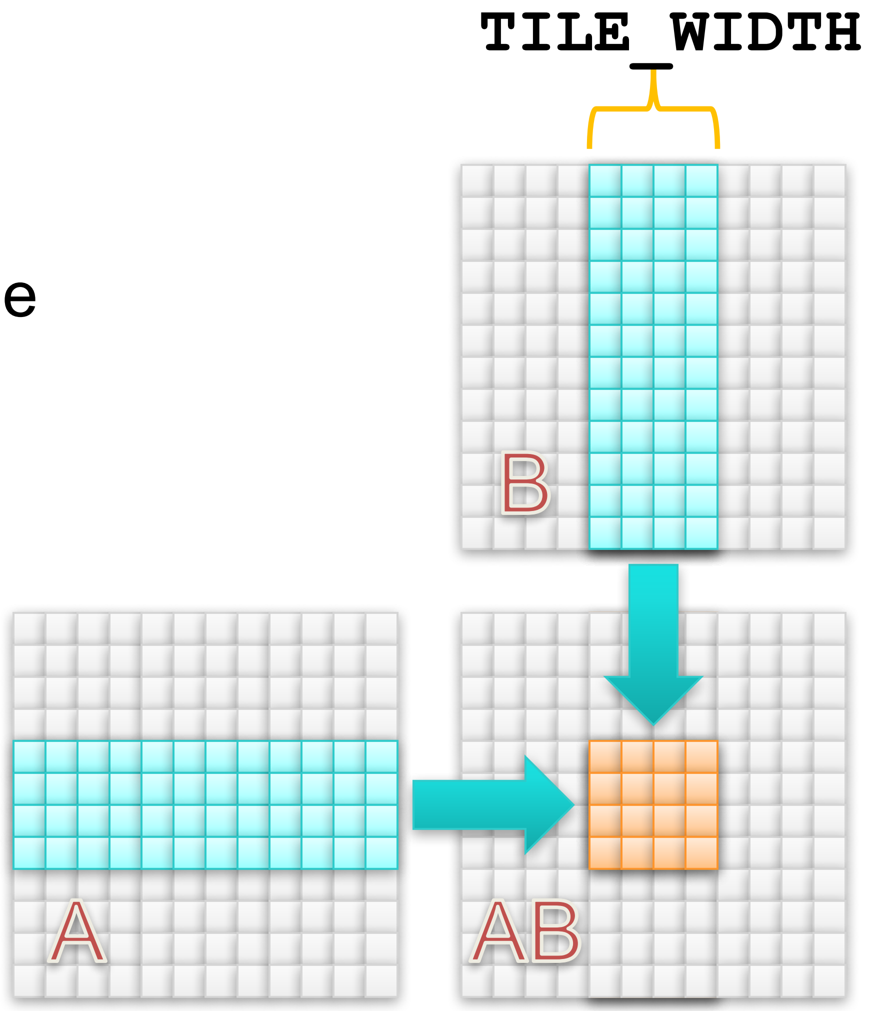
Idea: Use `__shared__` memory to reuse global data

- Each input element is read by `width` threads
- Load each element into `__shared__` memory and have several threads use the local version to reduce the memory bandwidth



Tiled Multiply

- Partition kernel loop into phases
- Load a tile of both matrices into `__shared__` each phase
- Each phase, each thread computes a partial result



Use of Barriers in `mat_mul`

- Two barriers per phase:
  - `__syncthreads` after all data is loaded into `__shared__` memory
  - `__syncthreads` after all data is read from `__shared__` memory
  - Note that second `__syncthreads` in phase `p` guards the load in phase `p+1`

- Use barriers to guard data
  - Guard against using uninitialized data
  - Guard against bashing live data

First Order Size Considerations

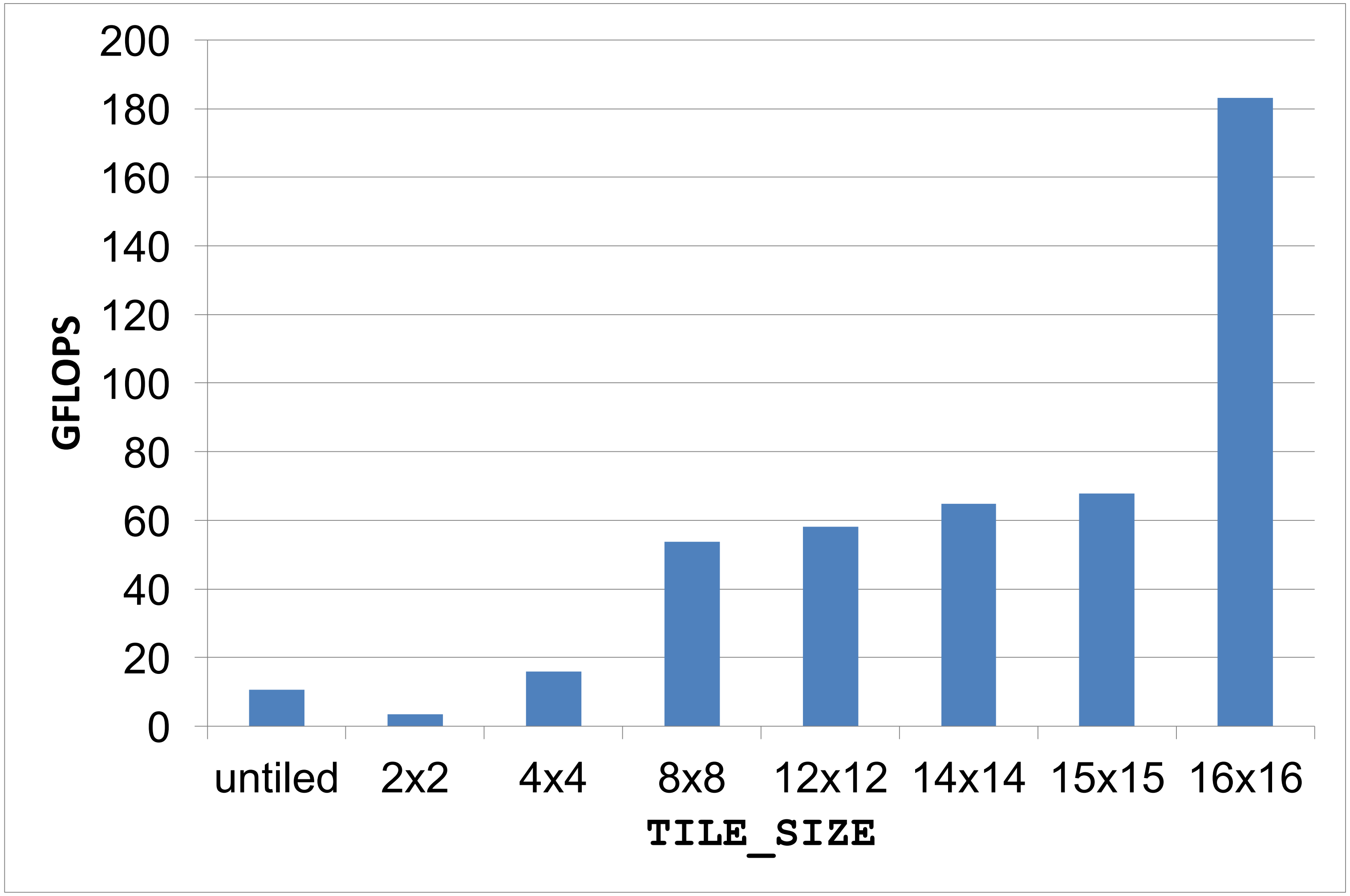
- Each thread block should have many threads
  - `TILE_WIDTH` = 16 → 16*16 = 256 threads
- There should be many thread blocks
  - 1024*1024 matrices → 64*64 = 4096 thread blocks
  - `TILE_WIDTH` = 16 → gives each SM 3 blocks, 768 threads
  - Full occupancy
- Each thread block performs 2 * 256 = 512 32b loads for 256 * (2 * 16) = 8,192 fp ops
  - Memory bandwidth no longer limiting factor

Optimization Analysis

Implementation	Original	Improved
Global Loads	$2N^3$	$2N^2$ *(N/`TILE_WIDTH`)
Throughput	10.7 GFLOPS	183.9 GFLOPS
SLOCs	20	44
Relative Improvement	1x	17.2x
Improvement/SLOC	1x	7.8x

- Experiment performed on a GT200
- This optimization was clearly worth the effort
- Better performance still possible in theory

TILE_SIZE Effects



Memory Resources as Limit to Parallelism

Resource	Per GT200 SM	Full Occupancy on GT200
Registers	16384	<= 16384 / 768 threads = 21 per thread
`__shared__` Memory	16KB	<= 16KB / 8 blocks = 2KB per block

- Effective use of different memory resources reduces the number of accesses to global memory
- These resources are finite!
- The more memory locations each thread requires → the fewer threads an SM can accommodate

Final Thoughts

- Effective use of CUDA memory hierarchy decreases bandwidth consumption to increase throughput
- Use `__shared__` memory to eliminate redundant loads from global memory
  - Use `__syncthreads` barriers to protect `__shared__` data
  - Use atomics if access patterns are sparse or unpredictable
- Optimization comes with a development cost
- Memory resources ultimately limit parallelism