

**NVIDIA**®

## Optimizing CUDA

# Outline



- **Overview**
- **Hardware**
- **Memory Optimizations**
- **Execution Configuration Optimizations**
- **Instruction Optimizations**
- **Summary**

# Optimize Algorithms for the GPU



- Maximize independent parallelism
- Maximize arithmetic intensity (math/bandwidth)
- Sometimes it's better to recompute than to cache
  - GPU spends its transistors on ALUs, not memory
- Do more computation on the GPU to avoid costly data transfers
  - Even low parallelism computations can sometimes be faster than transferring back and forth to host

# Optimize Memory Access



- Coalesced vs. Non-coalesced = order of magnitude
  - Global/Local device memory
- Optimize for spatial locality in cached texture memory
- In shared memory, avoid high-degree bank conflicts
- Partition camping
  - When global memory access not evenly distributed amongst partitions
  - Problem-size dependent

# Take Advantage of Shared Memory



- Hundreds of times faster than global memory
- Threads can cooperate via shared memory
- Use one / a few threads to load / compute data shared by all threads
- Use it to avoid non-coalesced access
  - Stage loads and stores in shared memory to re-order non-coalesceable addressing

# Use Parallelism Efficiently



- Partition your computation to keep the GPU multiprocessors equally busy
  - Many threads, many thread blocks
- Keep resource usage low enough to support multiple active thread blocks per multiprocessor
  - Registers, shared memory

# Outline

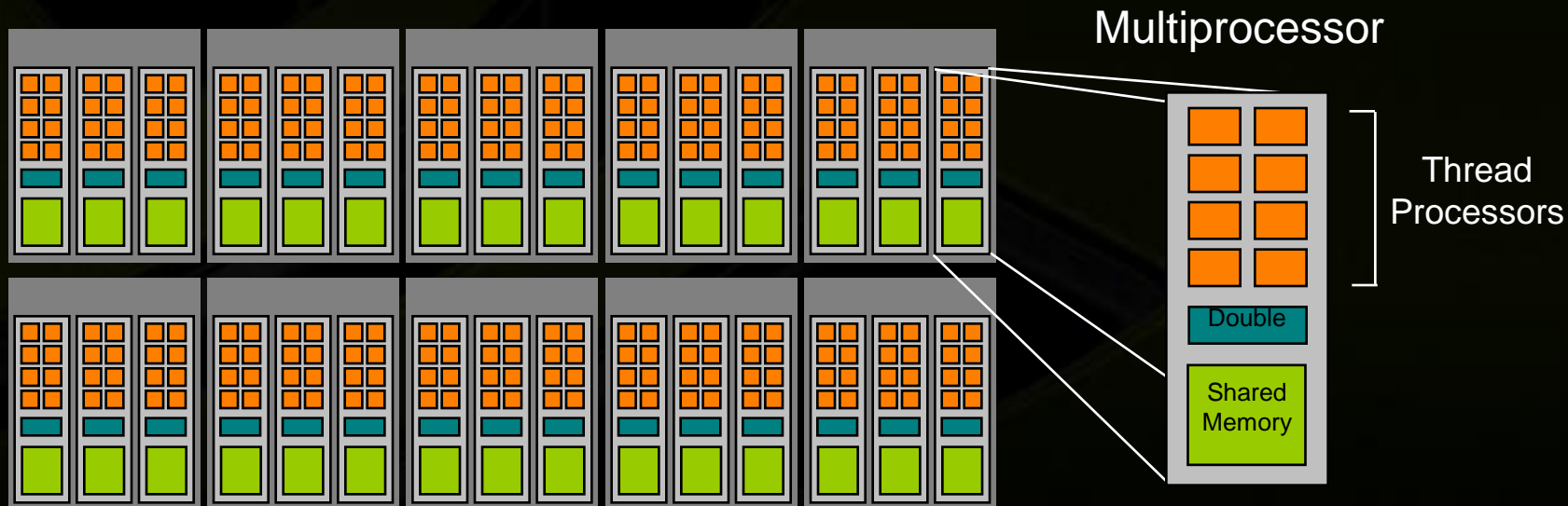


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# 10-Series Architecture



- 240 **thread processors** execute kernel threads
- 30 multiprocessors, each contains
  - 8 thread processors
  - One double-precision unit
  - **Shared memory** enables thread cooperation



# Execution Model



## Software

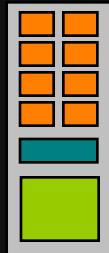
## Hardware



Threads are executed by thread processors



Thread Block

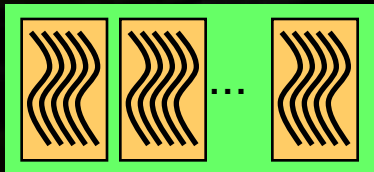


Multiprocessor

Thread blocks are executed on multiprocessors

Thread blocks do not migrate

Several concurrent thread blocks can reside on one multiprocessor - limited by multiprocessor resources (shared memory and register file)



Grid



Device

A kernel is launched as a grid of thread blocks

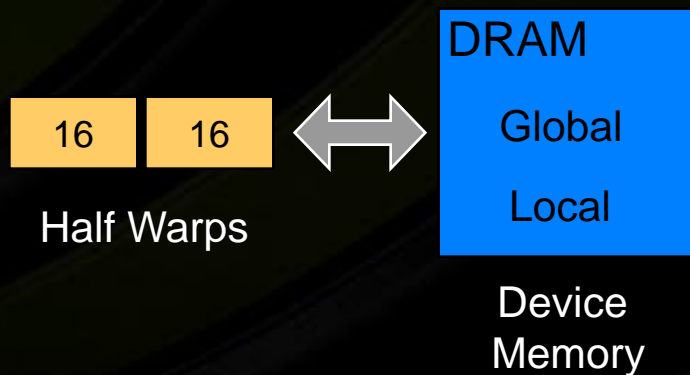
Only one kernel can execute on a device at one time

# Warps and Half Warps



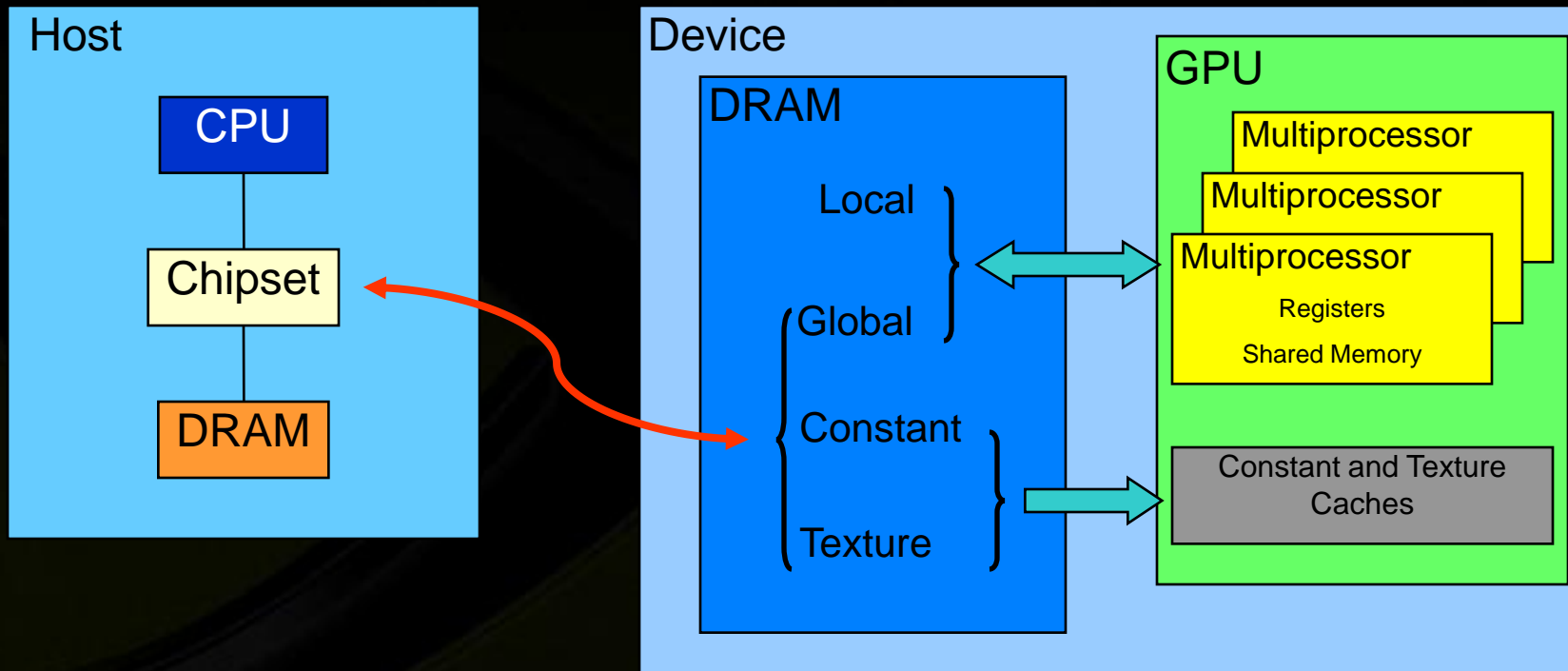
A thread block consists of 32-thread warps

A warp is executed physically in parallel (SIMD) on a multiprocessor



A half-warp of 16 threads can coordinate global memory accesses into a single transaction

# Memory Architecture



# Memory Architecture



Memory	Location	Cached	Access	Scope	Lifetime
Register	On-chip	N/A	R/W	One thread	Thread
Local	Off-chip	No	R/W	One thread	Thread
Shared	On-chip	N/A	R/W	All threads in a block	Block
Global	Off-chip	No	R/W	All threads + host	Application
Constant	Off-chip	Yes	R	All threads + host	Application
Texture	Off-chip	Yes	R	All threads + host	Application

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# Host-Device Data Transfers



- **Device to host memory bandwidth much lower than device to device bandwidth**
  - 4GB/s peak (PCI-e x16 Gen 1) vs. 102 GB/s peak (Tesla C1060)
- **Minimize transfers**
  - Intermediate data can be allocated, operated on, and deallocated without ever copying them to host memory
- **Group transfers**
  - One large transfer much better than many small ones

# Page-Locked Data Transfers



- `cudaMallocHost()` allows allocation of page-locked (“pinned”) host memory
- Enables highest `cudaMemcpy` performance
  - 3.2 GB/s on PCI-e x16 Gen1
  - 5.2 GB/s on PCI-e x16 Gen2
- See the “bandwidthTest” CUDA SDK sample
- Use with caution!
  - Allocating too much page-locked memory can reduce overall system performance
  - Test your systems and apps to learn their limits

# Overlapping Data Transfers and Computation

- **Async and Stream APIs allow overlap of H2D or D2H data transfers with computation**
  - CPU computation can overlap data transfers on all CUDA capable devices
  - Kernel computation can overlap data transfers on devices with “Concurrent copy and execution” (roughly compute capability  $\geq 1.1$ )
- **Stream = sequence of operations that execute in order on GPU**
  - Operations from different streams can be interleaved
  - Stream ID used as argument to async calls and kernel launches

# Asynchronous Data Transfers



- Asynchronous host-device memory copy returns control immediately to CPU
  - `cudaMemcpyAsync(dst, src, size, dir, stream);`
  - requires **pinned** host memory (allocated with “`cudaMallocHost`”)
- Overlap CPU computation with data transfer
  - `0` = default stream

```
cudaMemcpyAsync(a_d, a_h, size,  
               cudaMemcpyHostToDevice, 0);  
cpuFunction();  
cudaThreadSynchronize();  
kernel<<<grid, block>>>(dst);
```

} overlapped

# GPU/CPU Synchronization



- Context based
  - `cudaThreadSynchronize()`
    - Blocks until all previously issued CUDA calls from a CPU thread complete
- Stream based
  - `cudaStreamSynchronize(stream)`
    - Blocks until all CUDA calls issued to given stream complete
  - `cudaStreamQuery(stream)`
    - Indicates whether stream is idle
    - Returns `cudaSuccess`, `cudaErrorNotReady`, ...
    - Does not block CPU thread

# GPU/CPU Synchronization



- **Stream based using events**
  - Events can be inserted into streams:  
`cudaEventRecord(event, stream)`
  - Event is recorded then GPU reaches it in a stream
    - Recorded = assigned a timestamp (GPU clocktick)
    - Useful for timing
- **`cudaEventSynchronize(event)`**
  - Blocks until given event is recorded
- **`cudaEventQuery(event)`**
  - Indicates whether event has recorded
  - Returns `cudaSuccess`, `cudaErrorNotReady`, ...
  - Does not block CPU thread

# Overlapping kernel and data transfer



- **Requires:**
  - “Concurrent copy and execute”
    - deviceOverlap field of a cudaDeviceProp variable
  - Kernel and transfer use different, **non-zero** streams
    - A CUDA call to stream-0 blocks until all previous calls complete and cannot be overlapped

- **Example:**

```
cudaStreamCreate(&stream1);  
cudaStreamCreate(&stream2);  
cudaMemcpyAsync(dst, src, size, dir, stream1);  
kernel<<<grid, block, 0, stream2>>>(...);  
cudaStreamSynchronize(stream2);
```

}  
overlapped

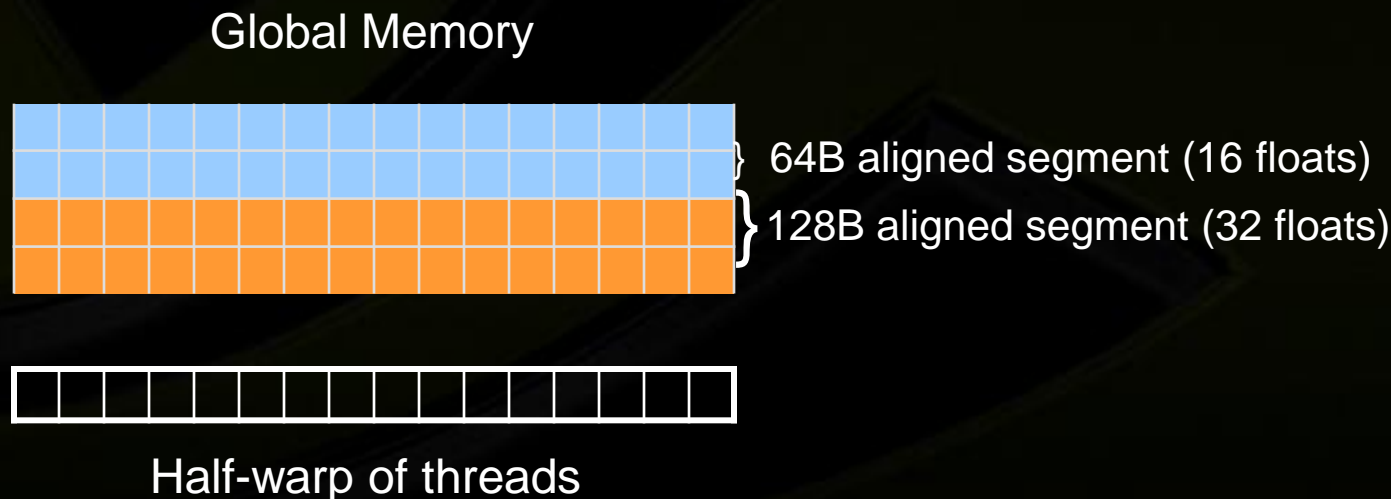
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    - Coalescing
    - Shared memory bank conflicts
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# Coalescing

- Global memory access of 32, 64, or 128-bit words by a half-warp of threads can result in as few as one (or two) transaction(s) if certain access requirements are met
- Depends on compute capability
  - 1.0 and 1.1 have stricter access requirements

Examples – float (32-bit) data

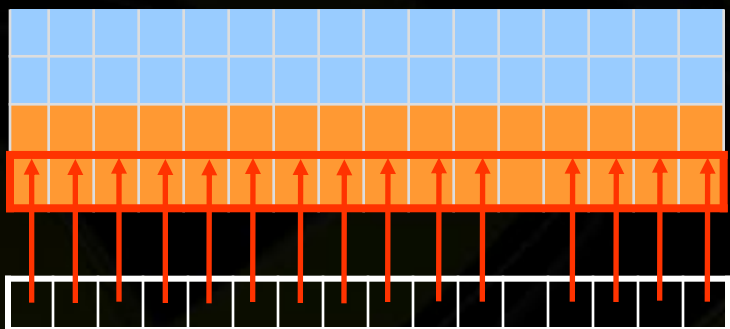


# Coalescing Constraints

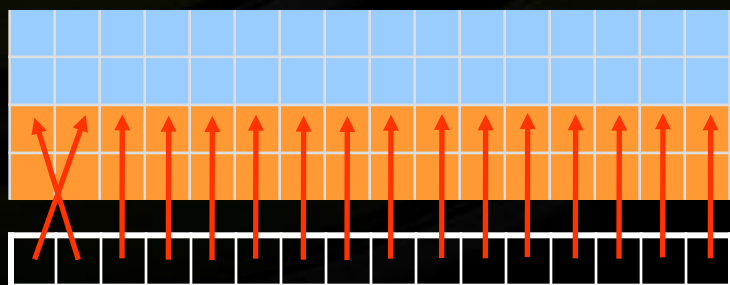
## Compute capability 1.0 and 1.1

- K-th thread must access k-th word in the segment (or k-th word in 2 contiguous 128B segments for 128-bit words), not all threads need to participate

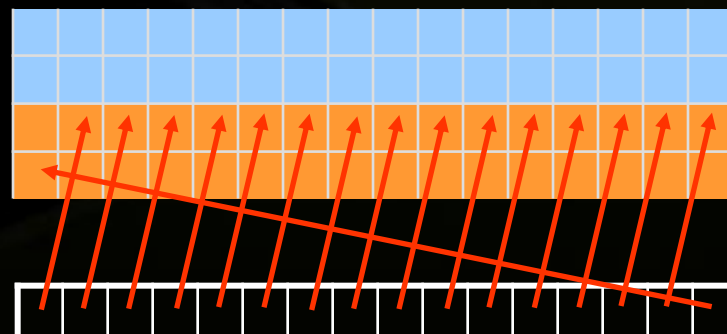
Coalesces – 1 transaction



Out of sequence – 16 transactions



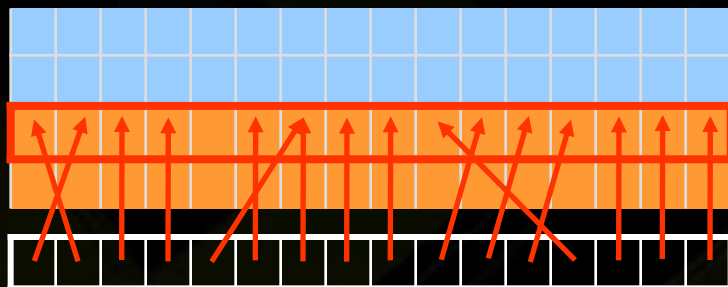
Misaligned – 16 transactions



# Coalescing Constraints

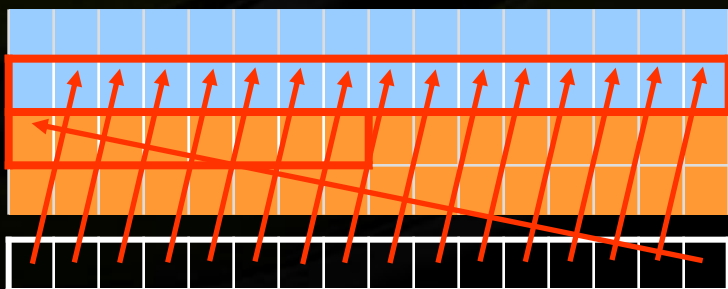
## Compute capability 1.2 and higher

- Coalescing is achieved for any pattern of addresses that fits into a segment of size: 32B for 8-bit words, 64B for 16-bit words, 128B for 32- and 64-bit words
- Smaller transactions may be issued to avoid wasted bandwidth due to unused words

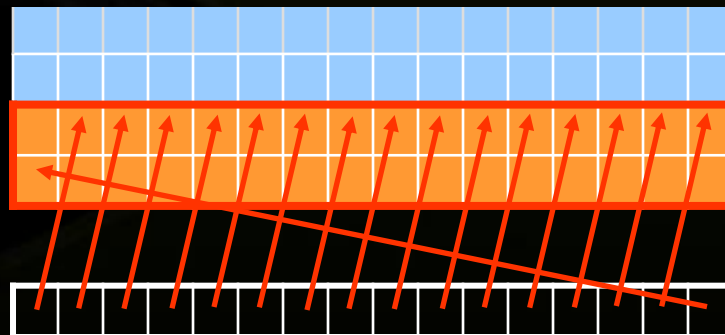


1 transaction - 64B segment

2 transactions - 64B and 32B segments



1 transaction - 128B segment



# Shared Memory



- ~Hundred times faster than global memory
- Cache data to reduce global memory accesses
- Threads can cooperate via shared memory
- Use it to avoid non-coalesced access
  - Stage loads and stores in shared memory to re-order non-coalesceable addressing

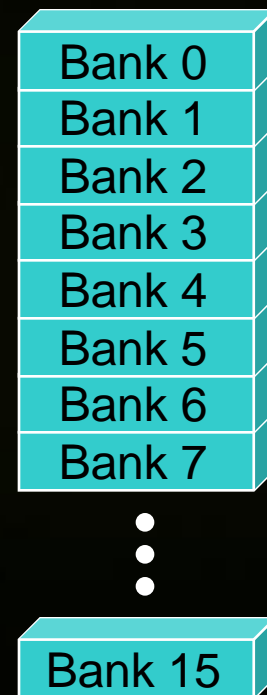
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    - **Shared memory bank conflicts**
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# Shared Memory Architecture



- **Many threads accessing memory**
  - Therefore, memory is divided into **banks**
  - Successive 32-bit words assigned to successive banks
- **Each bank can service one address per cycle**
  - A memory can service as many simultaneous accesses as it has banks
- **Multiple simultaneous accesses to a bank result in a **bank conflict****
  - Conflicting accesses are serialized

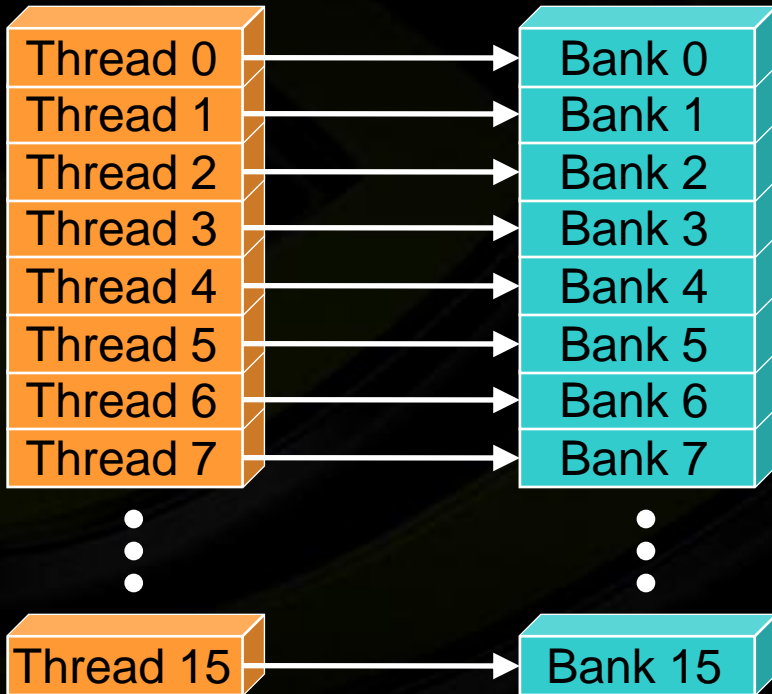


# Bank Addressing Examples



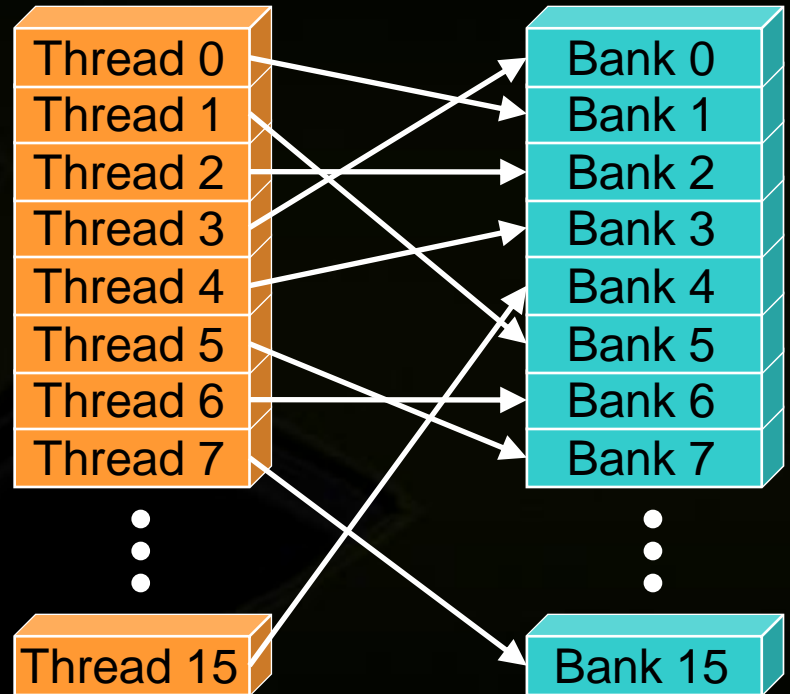
## No Bank Conflicts

- Linear addressing  
stride == 1



## No Bank Conflicts

- Random 1:1 Permutation

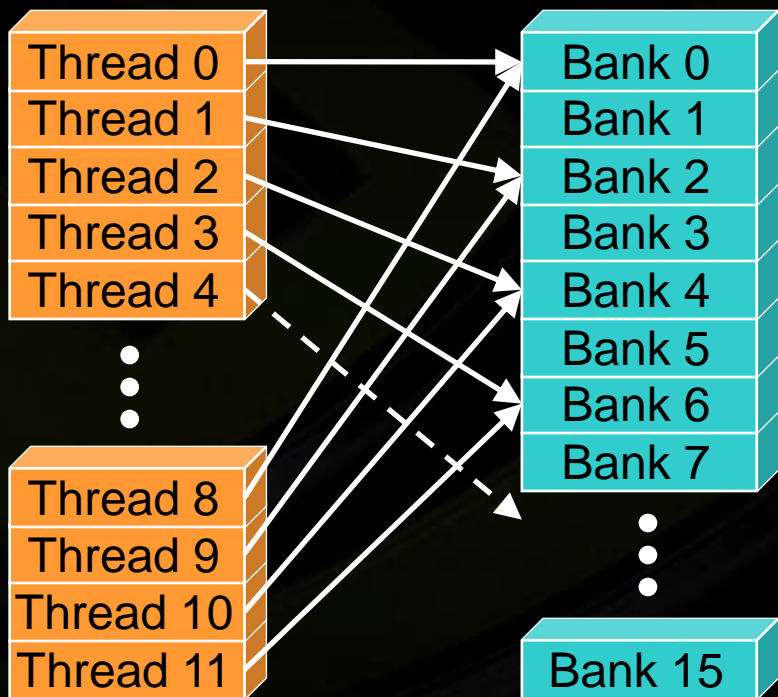


# Bank Addressing Examples



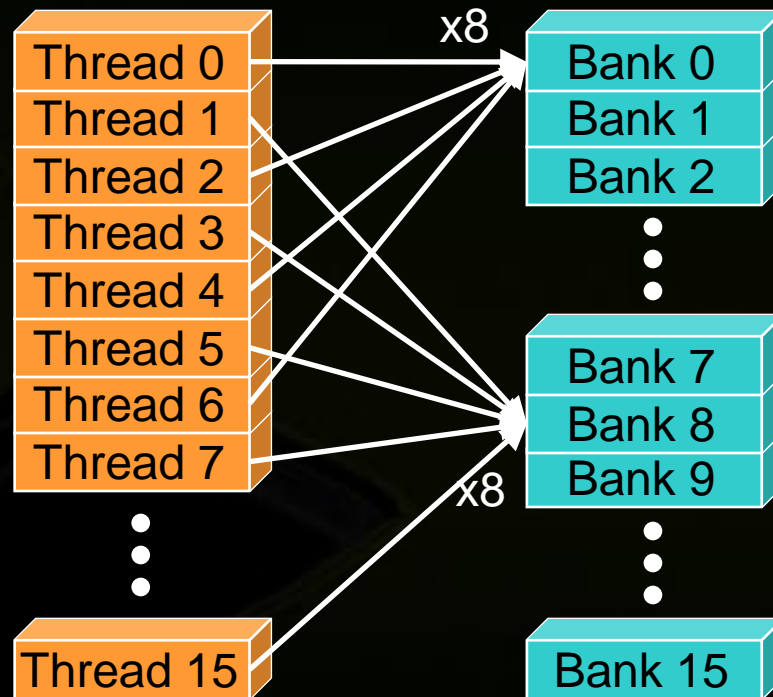
## 2-way Bank Conflicts

- Linear addressing stride == 2



## 8-way Bank Conflicts

- Linear addressing stride == 8



# Shared memory bank conflicts

- Shared memory is ~ as fast as registers if there are no bank conflicts
- `warp_serialize` profiler signal reflects conflicts
- **The fast case:**
  - If all threads of a half-warp access **different banks**, there is no bank conflict
  - If all threads of a half-warp read the **identical address**, there is no bank conflict (broadcast)
- **The slow case:**
  - Bank Conflict: multiple threads in the same half-warp access the same bank
  - Must serialize the accesses
  - **Cost = max # of simultaneous accesses to a single bank**

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  - **Data transfers between host and device**
  - **Device memory optimizations**
    - **Matrix transpose study**
      - Measuring performance - effective bandwidth
      - Coalescing
      - Shared memory bank conflicts
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# Occupancy



- Thread instructions are executed sequentially, so executing other warps is the only way to hide latencies and keep the hardware busy
- **Occupancy** = Number of warps running concurrently on a multiprocessor divided by maximum number of warps that can run concurrently
- Limited by resource usage:
  - **Registers**
  - **Shared memory**

# Grid/Block Size Heuristics



- **# of blocks > # of multiprocessors**
  - So all multiprocessors have at least one block to execute
- **# of blocks / # of multiprocessors > 2**
  - Multiple blocks can run concurrently in a multiprocessor
  - Blocks that aren't waiting at a `__syncthreads()` keep the hardware busy
  - Subject to resource availability – registers, shared memory
- **# of blocks > 100 to scale to future devices**
  - Blocks executed in pipeline fashion
  - 1000 blocks per grid will scale across multiple generations

# Register Dependency



- **Read-after-write register dependency**

- Instruction's result can be read ~11 cycles later

- Scenarios:

CUDA:

```
x = y + 5;
```

```
z = x + 3;
```

```
s_data[0] += 3;
```

PTX:

```
add.f32 $f3, $f1, $f2
```

```
add.f32 $f5, $f3, $f4
```

```
ld.shared.f32 $f3, [$r31+0]
```

```
add.f32 $f3, $f3, $f4
```

- **To completely hide the latency:**

- Run at least **192** threads (6 warps) per multiprocessor
  - At least **25%** occupancy
- Threads do not have to belong to the same thread block

# Register Pressure

- Hide latency by using more threads per SM
- Limiting Factors:
  - Number of registers per kernel
    - 8K/16K per SM, partitioned among concurrent threads
  - Amount of shared memory
    - 16KB per SM, partitioned among concurrent threadblocks
- Compile with `-ptxas-options=-v` flag
- Use `-maxrregcount=N` flag to NVCC
  - N = desired maximum registers / kernel
  - At some point “spilling” into local memory may occur
    - Reduces performance – local memory is slow

# Occupancy Calculator



Microsoft Excel - CUDA\_Occupancy\_calculator.xls

File Edit View Insert Format Tools Data Window Help

MyRegCount 20

## CUDA GPU Occupancy Calculator

click Here for detailed instructions on how to use this occupancy calculator

For more information on NVIDIA CUDA, visit <http://developer.nvidia.com/cuda>

Just follow steps 1, 2, and 3 below! (or click here for help)

Your chosen resource usage is indicated by the red triangle on the graphs.  
The other data points represent the range of possible block sizes, register counts, and shared memory allocation.

1.) Select a GPU from the list (click): **G80** (Help)

2.) Enter your resource usage:

Threads Per Block	192
Registers Per Thread	20
Shared Memory Per Block (bytes)	68

(Don't edit anything below this line)

3.) GPU Occupancy Data is displayed here and in the graphs:

Active Threads per Multiprocessor	384
Active Warps per Multiprocessor	12
Active Thread Blocks per Multiprocessor	2
Occupancy of each Multiprocessor	50%
Maximum Simultaneous Blocks per GPU	32

(Note: This assumes there are at least this many blocks)

Physical Limits for GPU: **G80**

Multiprocessors per GPU	16
Threads / Warp	32
Warps / Multiprocessor	24
Threads / Multiprocessor	768
Thread Blocks / Multiprocessor	8
Total # of 32-bit registers / Multiprocessor	8192
Shared Memory / Multiprocessor (bytes)	16384

Allocation Per Thread Block

Warps	6
Registers	3840
Shared Memory	512

These data are used in computing the occupancy data in blue

Maximum Thread Blocks Per Multiprocessor

Limited by Max Warps / Multiprocessor	4
Limited by Registers / Multiprocessor	2
Limited by Shared Memory / Multiprocessor	32

Thread Block Limit Per Multiprocessor is the minimum of these 3

CUDA Occupancy Calculator

Version: 1.1

Copyright and License

Calculator / Help / GPU Data / Copyright & License

Ready

### Varying Block Size

### Varying Register Count

### Varying Shared Memory Usage

# Optimizing threads per block

- Choose threads per block as a multiple of warp size
  - Avoid wasting computation on under-populated warps
- More threads per block == better memory latency hiding
- But, more threads per block == fewer registers per thread
  - Kernel invocations can fail if too many registers are used
- Heuristics
  - Minimum: 64 threads per block
    - Only if multiple concurrent blocks
  - 128 to 256 threads a better choice
    - Usually still enough regs to compile and invoke successfully
  - This all depends on your computation, so experiment!

# Occupancy != Performance



- Increasing occupancy does not necessarily increase performance

*BUT ...*

- Low-occupancy multiprocessors cannot adequately hide latency on memory-bound kernels
  - (It all comes down to arithmetic intensity and available parallelism)

# Parameterize Your Application



- Parameterization helps adaptation to different GPUs
- GPUs vary in many ways
  - # of multiprocessors
  - Memory bandwidth
  - Shared memory size
  - Register file size
  - Max. threads per block
- You can even make apps self-tuning (like FFTW and ATLAS)
  - “Experiment” mode discovers and saves optimal configuration

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# CUDA Instruction Performance



- **Instruction cycles (per warp) = sum of**
  - Operand read cycles
  - Instruction execution cycles
  - Result update cycles
- **Therefore instruction throughput depends on**
  - Nominal instruction throughput
  - Memory latency
  - Memory bandwidth
- **“Cycle” refers to the multiprocessor clock rate**
  - 1.3 GHz on the Tesla C1060, for example

# Maximizing Instruction Throughput



- **Maximize use of high-bandwidth memory**
  - Maximize use of shared memory
  - Minimize accesses to global memory
  - Maximize coalescing of global memory accesses
- **Optimize performance by overlapping memory accesses with HW computation**
  - High arithmetic intensity programs
    - i.e. high ratio of math to memory transactions
  - Many concurrent threads

# Arithmetic Instruction Throughput



- **int and float add, shift, min, max and float mul, mad: 4 cycles per warp**
  - int multiply (\*) is by default 32-bit
    - requires multiple cycles / warp
  - Use `__mul24()` / `__umul24()` intrinsics for 4-cycle 24-bit int multiply
- **Integer divide and modulo are more expensive**
  - Compiler will convert literal power-of-2 divides to shifts
    - But we have seen it miss some cases
  - Be explicit in cases where compiler can't tell that divisor is a power of 2!
  - Useful trick: `foo % n == foo & (n-1)` if n is a power of 2

# Arithmetic Instruction Throughput



- The intrinsics reciprocal, reciprocal square root, sin/cos, log, exp prefixed with “\_\_” 16 cycles per warp
  - Examples: `__rcp()`, `__sin()`, `__exp()`
- Other functions are combinations of the above
  - $y / x == \text{rcp}(x) * y$  takes 20 cycles per warp
  - $\text{sqrt}(x) == x * \text{rsqrt}(x)$  takes 20 cycles per warp

- There are two types of runtime math operations
  - `__func()`: direct mapping to hardware ISA
    - Fast but lower accuracy (see prog. guide for details)
    - Examples: `__sin(x)`, `__exp(x)`, `__pow(x,y)`
  - `func()` : compile to multiple instructions
    - Slower but higher accuracy (5 ulp or less)
    - Examples: `sin(x)`, `exp(x)`, `pow(x,y)`
- The `-use_fast_math` compiler option forces every `func()` to compile to `__func()`

# GPU results may not match CPU



- Many variables: hardware, compiler, optimization settings
- CPU operations aren't strictly limited to 0.5 ulp
  - Sequences of operations can be more accurate due to 80-bit extended precision ALUs
- Floating-point arithmetic is not associative!

# FP Math is Not Associative!



- In symbolic math,  $(x+y)+z == x+(y+z)$
- This is not necessarily true for floating-point addition
  - Try  $x = 10^{30}$ ,  $y = -10^{30}$  and  $z = 1$  in the above equation
- When you parallelize computations, you potentially change the order of operations
- Parallel results may not exactly match sequential results
  - This is not specific to GPU or CUDA – inherent part of parallel execution

# Control Flow Instructions



- Main performance concern with branching is divergence
  - Threads within a single warp take different paths
  - Different execution paths must be serialized
- Avoid divergence when branch condition is a function of thread ID
  - Example with divergence:
    - `if (threadIdx.x > 2) { }`
    - Branch granularity < warp size
  - Example without divergence:
    - `if (threadIdx.x / WARP_SIZE > 2) { }`
    - Branch granularity is a whole multiple of warp size

# Summary



- GPU hardware can achieve great performance on data-parallel computations if you follow a few simple guidelines:
  - Use parallelism efficiently
  - Coalesce memory accesses if possible
  - Take advantage of shared memory
  - Explore other memory spaces
    - Texture
    - Constant
  - Reduce bank conflicts
  - Avoid partition camping