# An Introduction to CUDA/OpenCL and Graphics Processors

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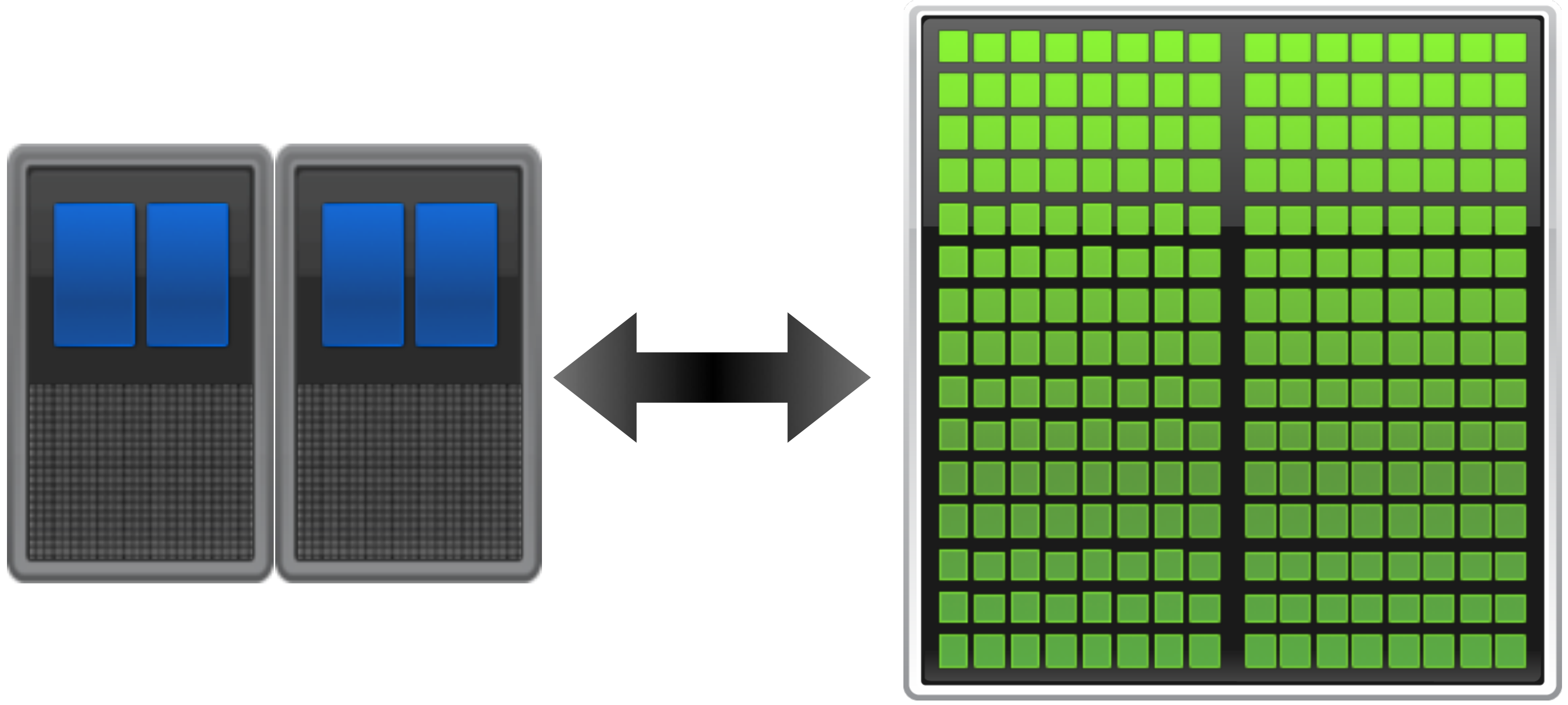
## Overview

- Terminology
- The CUDA and OpenCL programming models
- Understanding how CUDA maps to NVIDIA GPUs
- Thrust & Libraries

# Heterogeneous Parallel Computing



**Latency Optimized CPU**

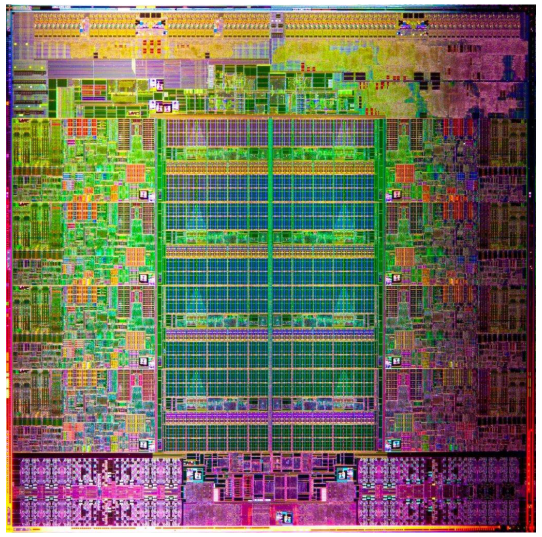
Fast Serial Processing

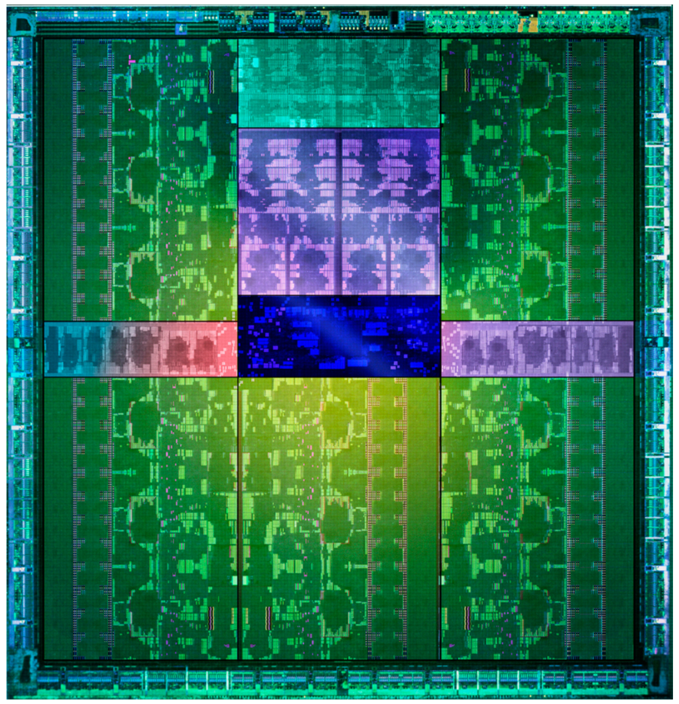
**Throughput Optimized GPU**

Scalable Parallel Processing

# Latency vs. Throughput

| Specifications | Sandy Bridge-EP | Kepler (Tesla K20) |
|---|---|---|
| Processing Elements | 8 cores, 2 issue, 8 way SIMD @**3.1** GHz | 14 SMs, 6 issue, 32 way SIMD @**730** MHz |
| Resident Strands/ Threads (max) | 8 cores, 2 threads, 8 way SIMD: **96** strands | 14 SMs, 64 SIMD vectors, 32 way SIMD: **28672** threads |
| SP GFLOP/s | 396 | 3924 |
| Memory Bandwidth | 51 GB/s | 250 GB/s |
| Register File | 128 kB (?) | 3.5 MB |
| Local Store/L1 Cache | 256 kB | 896 kB |
| L2 Cache | 2 MB | 1.5 MB |
| L3 Cache | 20 MB | - |


Sandy Bridge-EP (32nm)


Kepler GK110 (28nm)

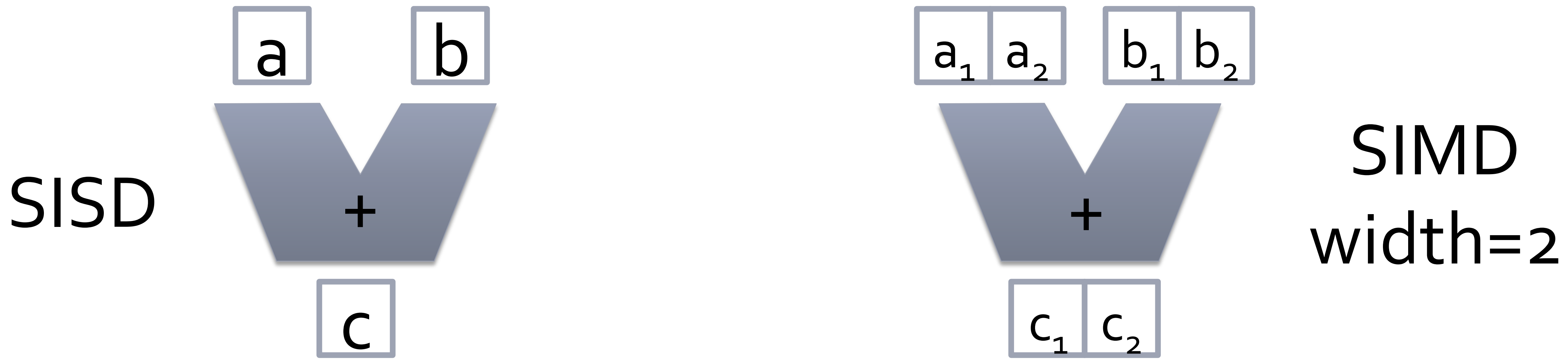
## Why Heterogeneity?

- Different goals produce different designs
  - Throughput cores: assume work load is highly parallel
  - Latency cores: assume workload is mostly sequential

- Latency goal: minimize latency experienced by 1 thread
  - lots of big on-chip caches
  - extremely sophisticated control

- Throughput goal: maximize throughput of all threads
  - lots of big ALUs
  - multithreading can hide latency … so skip the big caches
  - simpler control, cost amortized over ALUs via SIMD

# SIMD



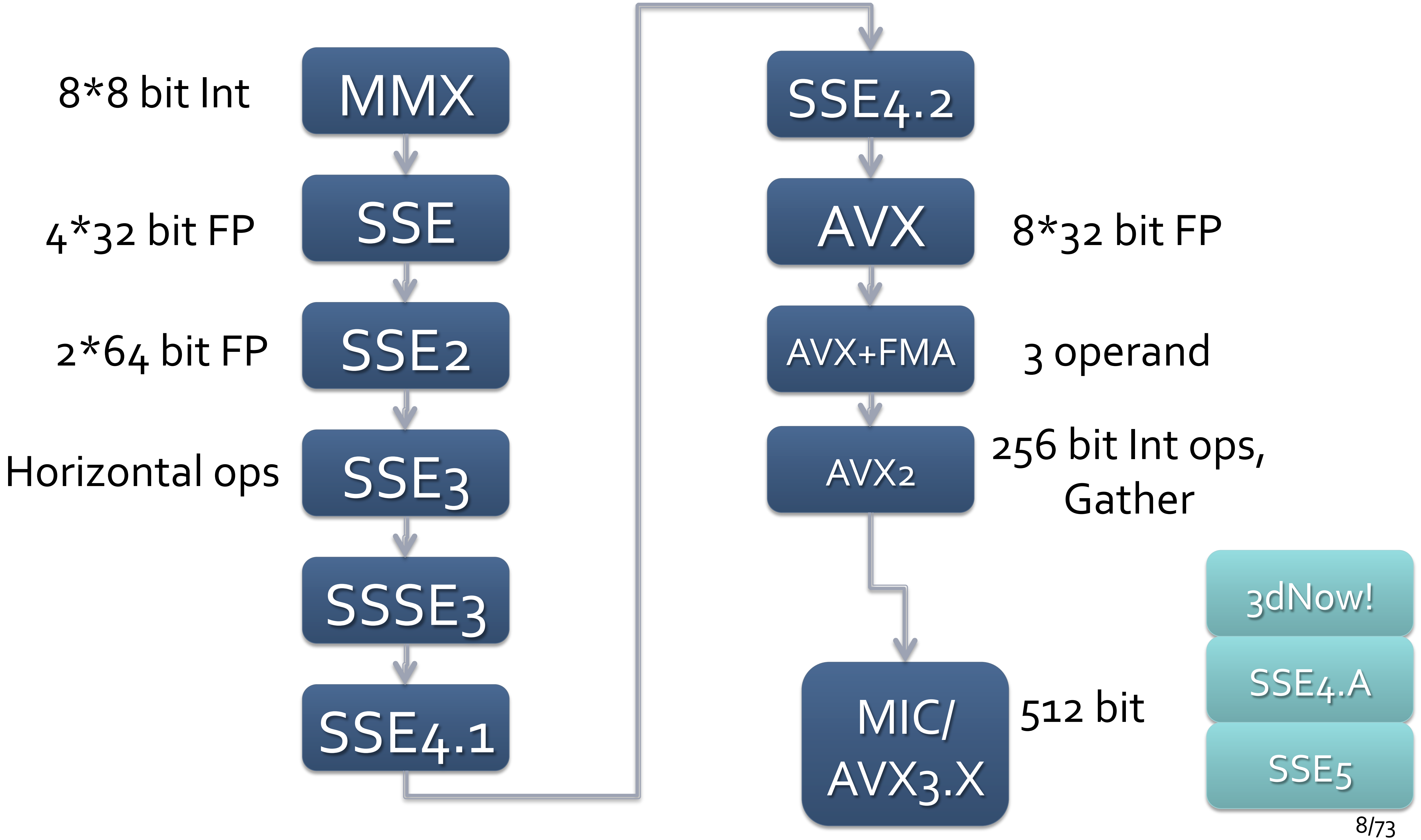
- Single Instruction Multiple Data architectures make use of data parallelism
- We care about SIMD because of area and power efficiency concerns
  - Amortize control overhead over SIMD width
- Parallelism exposed to programmer & compiler

# SIMD: Neglected Parallelism

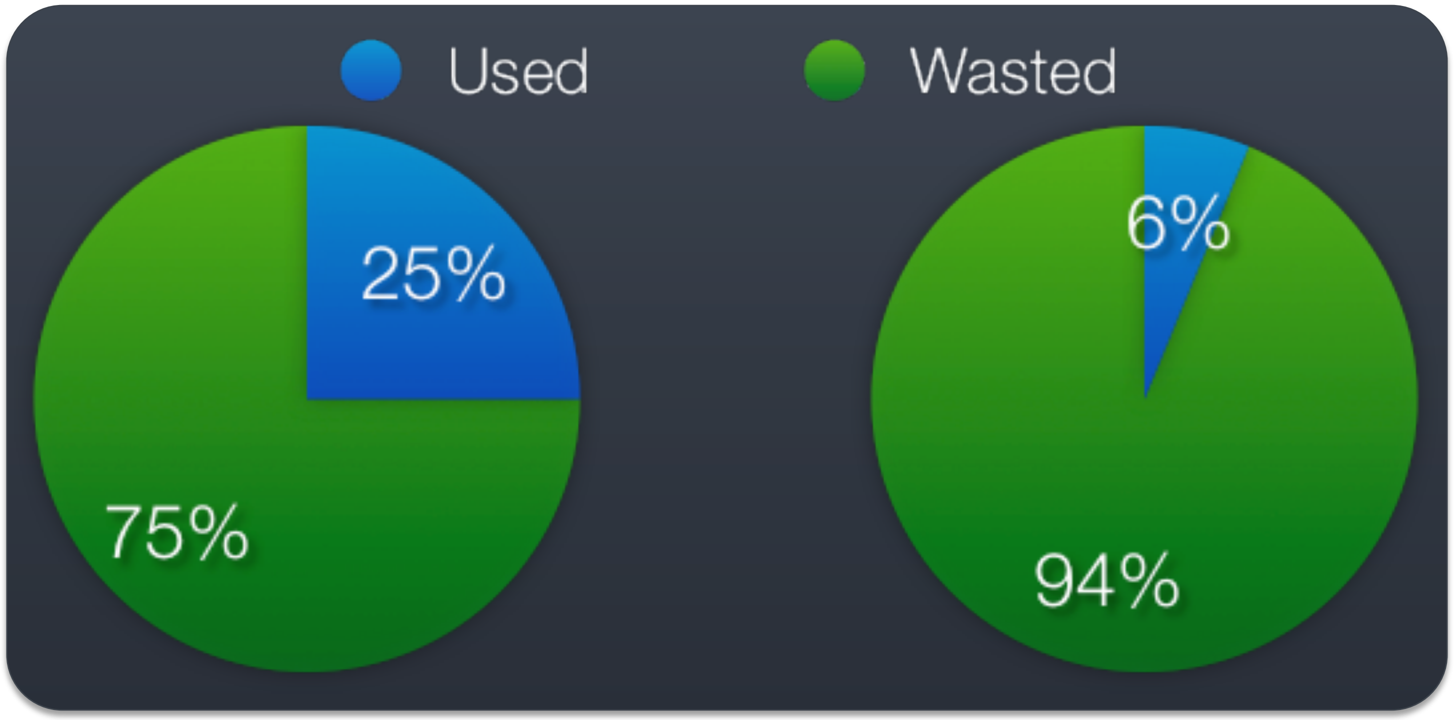
- OpenMP / Pthreads / MPI all neglect SIMD parallelism
- Because it is difficult for a compiler to exploit SIMD
- How do you deal with sparse data & branches?
  - Many languages (like C) are difficult to vectorize

- Most common solution:
  - Either forget about SIMD
    - Pray the autovectorizer likes you
  - Or instantiate intrinsics (assembly language)
  - Requires a new code version for every SIMD extension

# A Brief History of x86 SIMD Extensions



# Many-Lane Parallelism is Proliferating



4 way SIMD (SSE)      16 way SIMD (Phi, AVX 3.x)

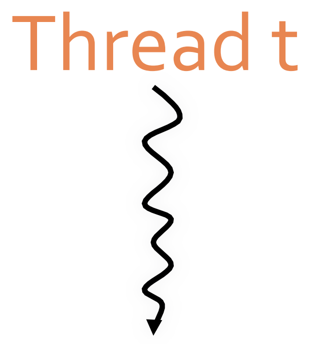
- Neglecting SIMD is becoming more expensive
  - AVX: 8 way SIMD, Xeon Phi: 16 way SIMD,
    Nvidia: 32 way SIMD, AMD: 64 way SIMD
- This problem composes with thread level parallelism
- We need a programming model which addresses both problems

## The CUDA Programming Model

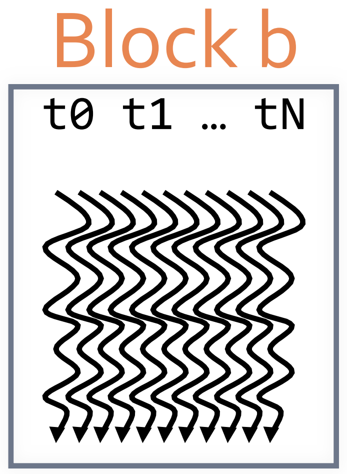
- CUDA is a programming model designed for:
  - Heterogeneous architectures
  - Many SIMD lane parallelism
  - Scalability
- CUDA provides:
  - A thread abstraction to deal with SIMD
  - Synchronization & data sharing between small thread groups
- CUDA programs are written in C++ with minimal extensions
- OpenCL is inspired by CUDA, but HW & SW vendor neutral

# Hierarchy of Concurrent Threads

- Parallel kernels composed of many threads
  - all threads execute the same sequential program



- Threads are grouped into thread blocks
  - threads in the same block can cooperate



- Threads/blocks have unique IDs

## What is a CUDA Thread?

- Independent thread of execution
  - has its own program counter, variables (registers), processor state, etc.
  - no implication about how threads are scheduled

- CUDA threads might be physical threads
  - as mapped onto NVIDIA GPUs

- CUDA threads might be virtual threads
  - might pick 1 block = 1 physical thread on multicore CPU

# What is a CUDA Thread Block?

- Thread block = a (data) parallel task
  - all blocks in kernel have the same entry point
  - but may execute any code they want

- Thread blocks of kernel must be independent tasks
  - program valid for ***any interleaving*** of block executions

## CUDA Supports:

- Thread parallelism
  - each thread is an independent thread of execution
- Data parallelism
  - across threads in a block
  - across blocks in a kernel
- Task parallelism
  - different blocks are independent
  - independent kernels executing in separate streams

## Synchronization

- Threads within a block may synchronize with barriers

```
… Step 1 …
__syncthreads();
… Step 2 …
```

- Blocks coordinate via atomic memory operations
  - e.g., increment shared queue pointer with `atomicInc()`

- Implicit barrier between dependent kernels

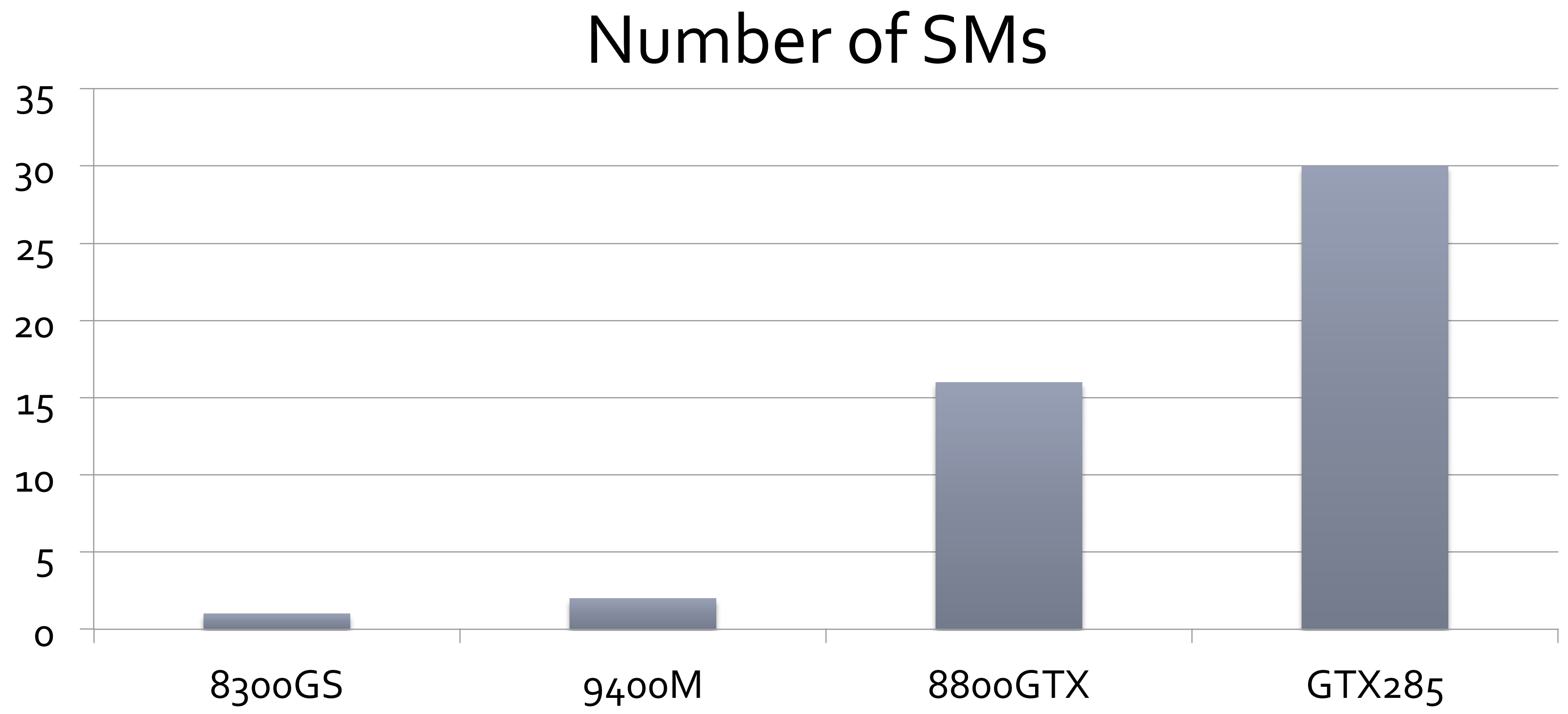
```
vec_minus<<<nblocks, blksize>>>(a, b, c);
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
vec_dot<<<nblocks, blksize>>>(c, c);
```

# Blocks must be independent

- Any possible interleaving of blocks should be valid
  - presumed to run to completion without pre-emption
  - can run in any order
  - can run concurrently OR sequentially
- Blocks may coordinate but not synchronize
  - shared queue pointer: OK
  - shared lock: BAD … can easily deadlock
- Independence requirement gives scalability

# Scalability

- Manycore chips exist in a diverse set of configurations

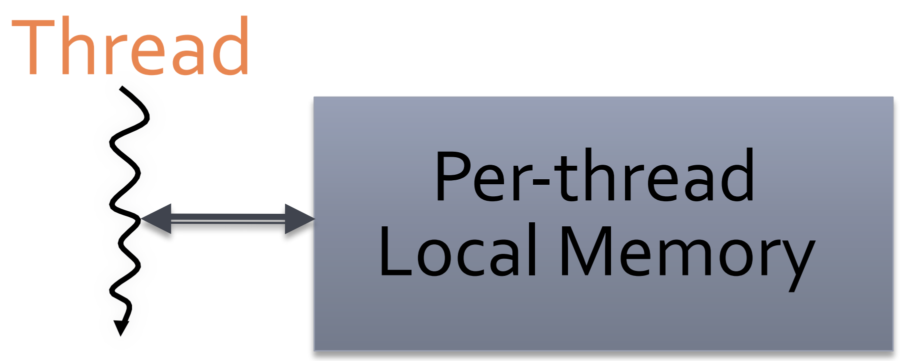


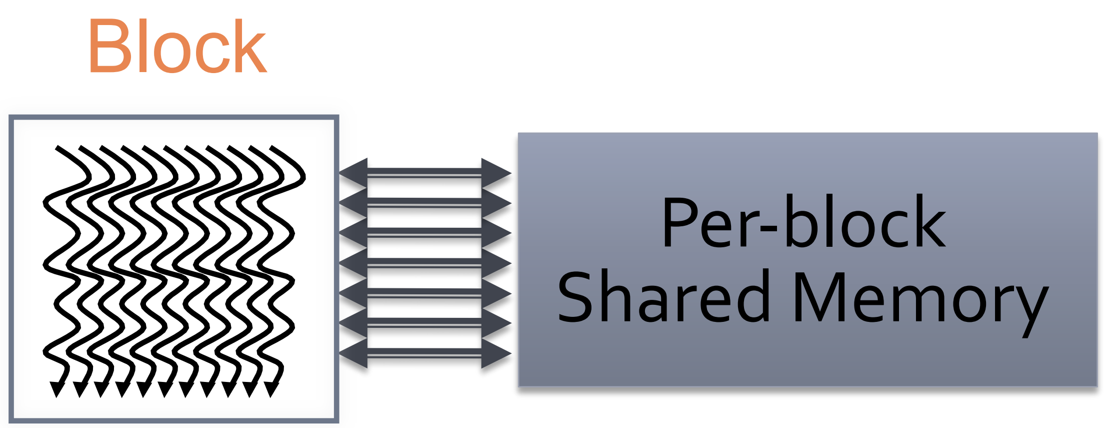
- CUDA allows one binary to target all these chips
- Thread blocks bring scalability!

## Hello World: Vector Addition

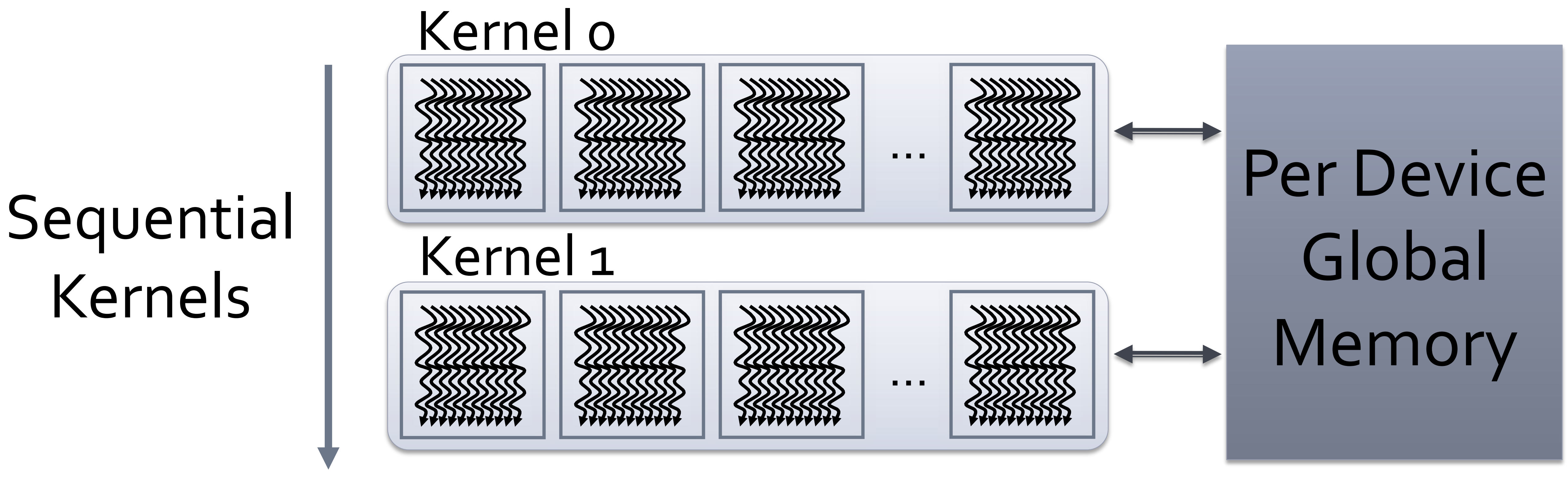
```
//Compute vector sum C=A+B
//Each thread performs one pairwise addition
__global__ void vecAdd(float* a, float* b, float* c) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  c[i] = a[i] + b[i];
}

int main() {
  //Run N/256 blocks of 256 threads each
  vecAdd<<<N/256, 256>>>(d_a, d_b, d_c);
}
```

# Memory model

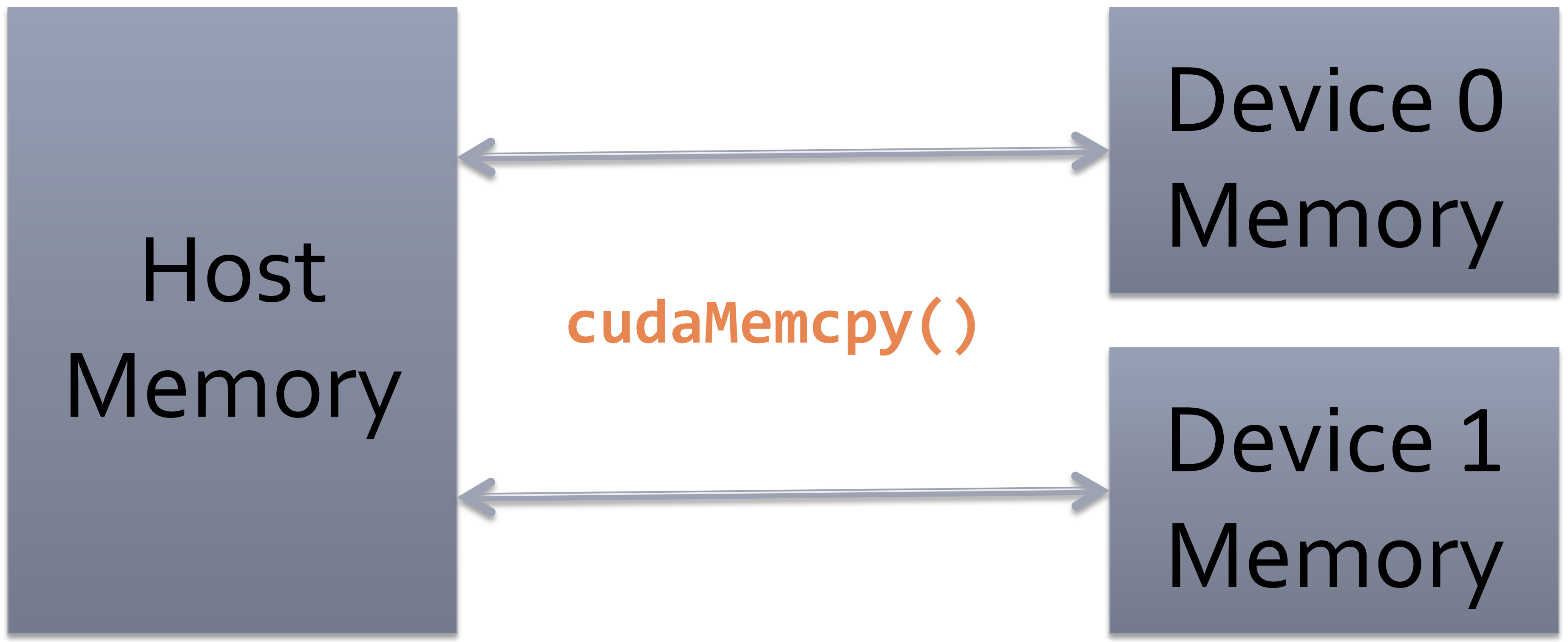




## Memory model



## Memory model



## Hello World: Managing Data

```
int main() {
   int N = 256 * 1024;
   float* h_a = malloc(sizeof(float) * N);
   //Similarly for h_b, h_c. Initialize h_a, h_b

   float *d_a, *d_b, *d_c;
   cudaMalloc(&d_a, sizeof(float) * N);
   //Similarly for d_b, d_c

   cudaMemcpy(d_a, h_a, sizeof(float) * N, cudaMemcpyHostToDevice);
   //Similarly for d_b

   //Run N/256 blocks of 256 threads each
   vecAdd<<<N/256, 256>>>(d_a, d_b, d_c);

   cudaMemcpy(h_c, d_c, sizeof(float) * N, cudaMemcpyDeviceToHost);
}
```

# CUDA: Minimal extensions to C/C++

- Declaration specifiers to indicate where things live

```
__global__ void KernelFunc(...);   // kernel callable from host
__device__ void DeviceFunc(...);   // function callable on device
__device__ int  GlobalVar;         // variable in device memory
__shared__ int  SharedVar;         // in per-block shared memory
```

- Extend function invocation syntax for parallel kernel launch

```
KernelFunc<<<500, 128>>>(...);     // 500 blocks, 128 threads each
```

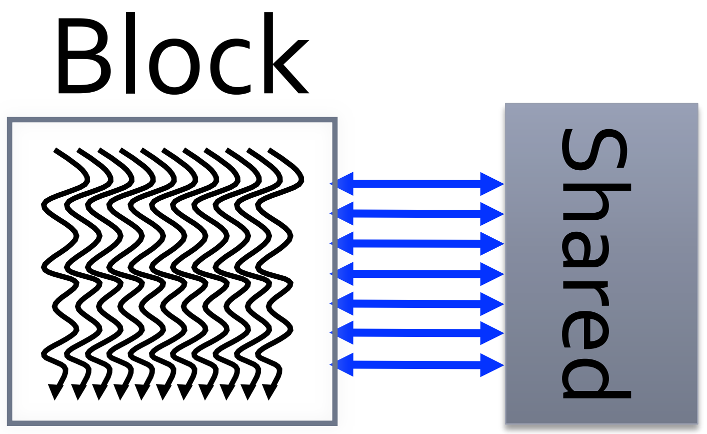
- Special variables for thread identification in kernels

```
dim3 threadIdx;  dim3 blockIdx;  dim3 blockDim;
```

- Intrinsics that expose specific operations in kernel code

```
__syncthreads();                   // barrier synchronization
```

# Using per-block shared memory



- Variables shared across block

```
    __shared__ int *begin, *end;
```

- Scratchpad memory

```
    __shared__ int scratch[BLOCKSIZE];
    scratch[threadIdx.x] = begin[threadIdx.x];
    // … compute on scratch values …
    begin[threadIdx.x] = scratch[threadIdx.x];
```

- Communicating values between threads

```
    scratch[threadIdx.x] = begin[threadIdx.x];
    __syncthreads();
    int left = scratch[threadIdx.x - 1];
```

- Per-block shared memory is faster than L1 cache, slower than register file
- It is relatively small: register file is 2-4x larger

## CUDA: Features available on GPU

- Double and single precision (IEEE compliant)

- Standard mathematical functions
  - `sinf`, `powf`, `atanf`, `ceil`, `min`, `sqrtf`, etc.

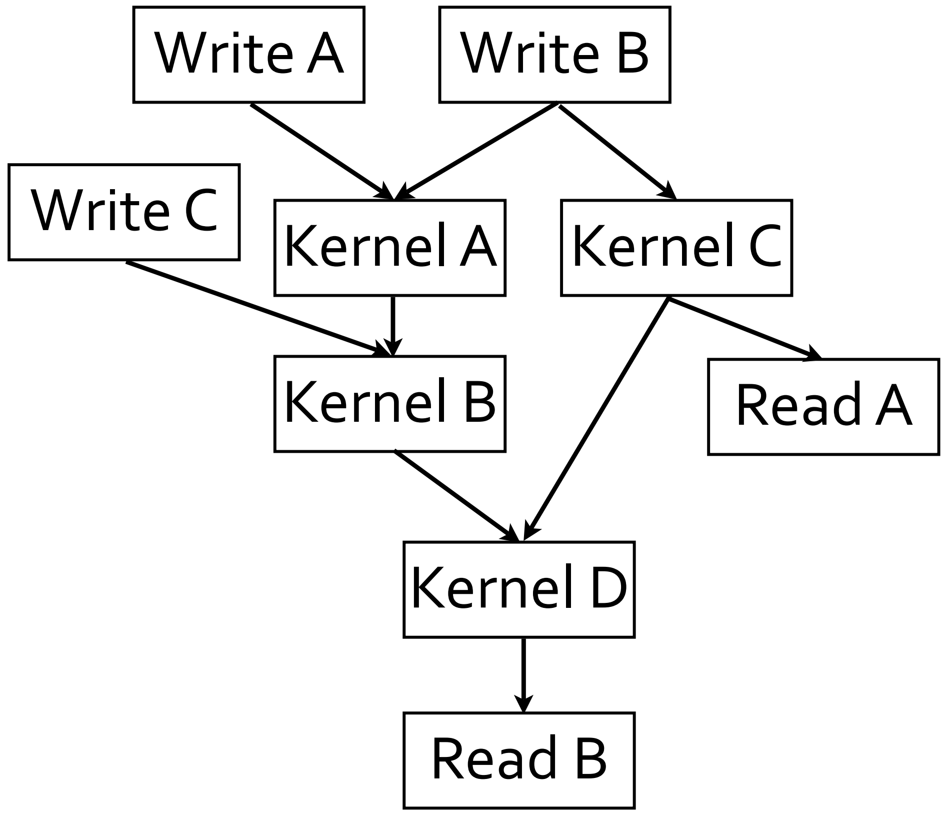
- Atomic memory operations
  - `atomicAdd`, `atomicMin`, `atomicAnd`, `atomicCAS`, etc.
- These work on both global and shared memory

# CUDA: Runtime support

- Explicit memory allocation returns pointers to GPU memory
  - `cudaMalloc()`, `cudaFree()`
- Explicit memory copy for host ↔ device, device ↔ device
  - `cudaMemcpy()`, `cudaMemcpy2D()`, ...
- Texture management
  - `cudaBindTexture()`, `cudaBindTextureToArray()`, ...
- OpenGL & DirectX interoperability
  - `cudaGLMapBufferObject()`, `cudaD3D9MapVertexBuffer()`, ...

# OpenCL

- OpenCL is supported by AMD {CPUs, GPUs} and Nvidia
  - Intel, Imagination Technologies (purveyor of GPUs for iPhone/etc.) are also on board
- OpenCL's data parallel execution model mirrors CUDA, but with different terminology
- OpenCL has rich task parallelism model
  - Runtime walks a dependence DAG of kernels/memory transfers



# CUDA and OpenCL correspondence

| | |
|---|---|
| Thread | Work-item |
| Thread-block | Work-group |
| Global memory | Global memory |
| Constant memory | Constant memory |
| Shared memory | Local memory |
| Local memory | Private memory |
| __global__ function | __kernel function |
| __device__ function | no qualification needed |
| __constant__ variable | __constant variable |
| __device__ variable | __global variable |
| __shared__ variable | __local variable |

# OpenCL and SIMD

- SIMD issues are handled separately by each runtime
- AMD GPU Runtime
  - Vectorizes over 64-way SIMD
    - Prefers scalar code per work-item (on newer AMD GPUs)
- AMD CPU Runtime
  - No vectorization
    - Use float4 vectors in your code (float8 when AVX appears?)
- Intel CPU Runtime
  - Vectorization optional, using float4/float8 vectors still good idea
- Nvidia GPU Runtime
  - Full vectorization, like CUDA
    - Prefers scalar code per work-item

## Imperatives for Efficient CUDA Code

- Expose abundant fine-grained parallelism
  - need 1000's of threads for full utilization
- Maximize on-chip work
  - on-chip memory orders of magnitude faster
- Minimize execution divergence
  - SIMT execution of threads in 32-thread warps
- Minimize memory divergence
  - warp loads and consumes complete 128-byte cache line

# Mapping CUDA to Nvidia GPUs

- CUDA is designed to be functionally forgiving
  - First priority: make things work. Second: get performance.
- However, to get good performance, one must understand how CUDA is mapped to Nvidia GPUs
- Threads: each thread is a SIMD vector lane
- Warps: A SIMD instruction acts on a "warp"
  - Warp width is 32 elements: ***LOGICAL*** SIMD width
- Thread blocks: Each thread block is scheduled onto an SM
  - Peak efficiency requires multiple thread blocks per SM

## Mapping CUDA to a GPU, *continued*

- The GPU is very deeply pipelined to maximize throughput

- This means that performance depends on the number of thread blocks which can be allocated on a processor

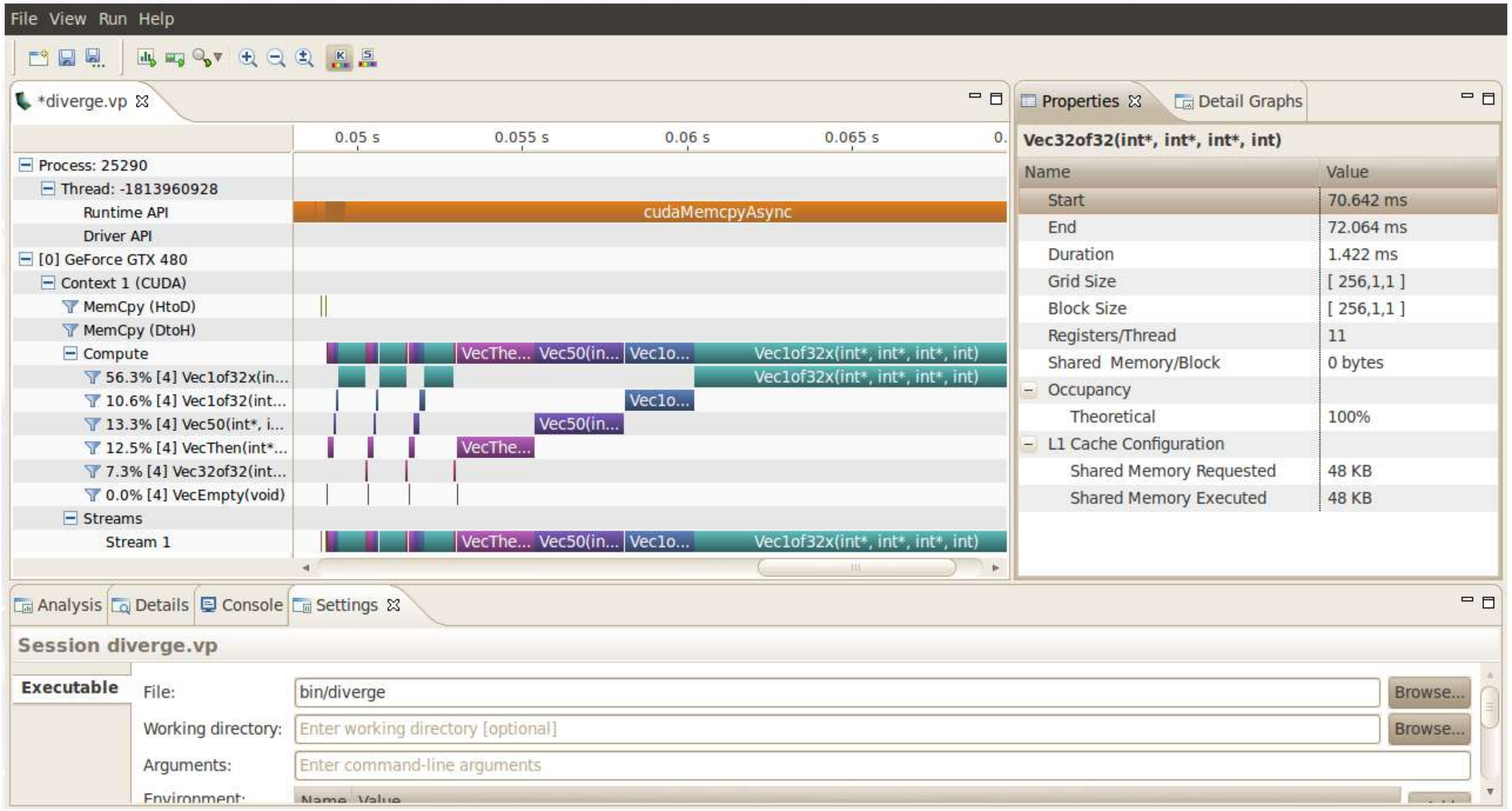
- Therefore, resource usage costs performance:
  - More registers => Fewer thread blocks
  - More shared memory usage => Fewer thread blocks

- It is often worth trying to reduce register count in order to get more thread blocks to fit on the chip
  - For Kepler, target 32 registers or less per thread for full occupancy

## Occupancy (Constants for Kepler)

- The Runtime tries to fit as many thread blocks simultaneously as possible on to an SM
  - The number of simultaneous thread blocks (B) is ≤ 8
- The number of warps per thread block (T) ≤ 32
- Each SM has scheduler space for 64 warps (W)
  - B * T ≤ W=64
- The number of threads per warp (V) is 32
- B * T * V * Registers per thread ≤ 65536
- B * Shared memory (bytes) per block ≤ 49152/16384
  - Depending on Shared memory/L1 cache configuration
- Occupancy is reported as B * T / W

# Profiling



Vec32of32(int*, int*, int*, int)

| Name | Value |
|---|---|
| Start | 70.642 ms |
| End | 72.064 ms |
| Duration | 1.422 ms |
| Grid Size | [ 256,1,1 ] |
| Block Size | [ 256,1,1 ] |
| Registers/Thread | 11 |
| Shared Memory/Block | 0 bytes |
| Occupancy | |
| Theoretical | 100% |
| L1 Cache Configuration | |
| Shared Memory Requested | 48 KB |
| Shared Memory Executed | 48 KB |

Session diverge.vp

Executable

File: bin/diverge

Working directory: Enter working directory [optional]

Arguments: Enter command-line arguments

Environment: Name Value

- nvvp (nvidia visual profiler) useful for interactive profiling
- `export CUDA_PROFILE=1` in shell for simple profiler
  - Then examine cuda_profile_*.log for kernel times & occupancies

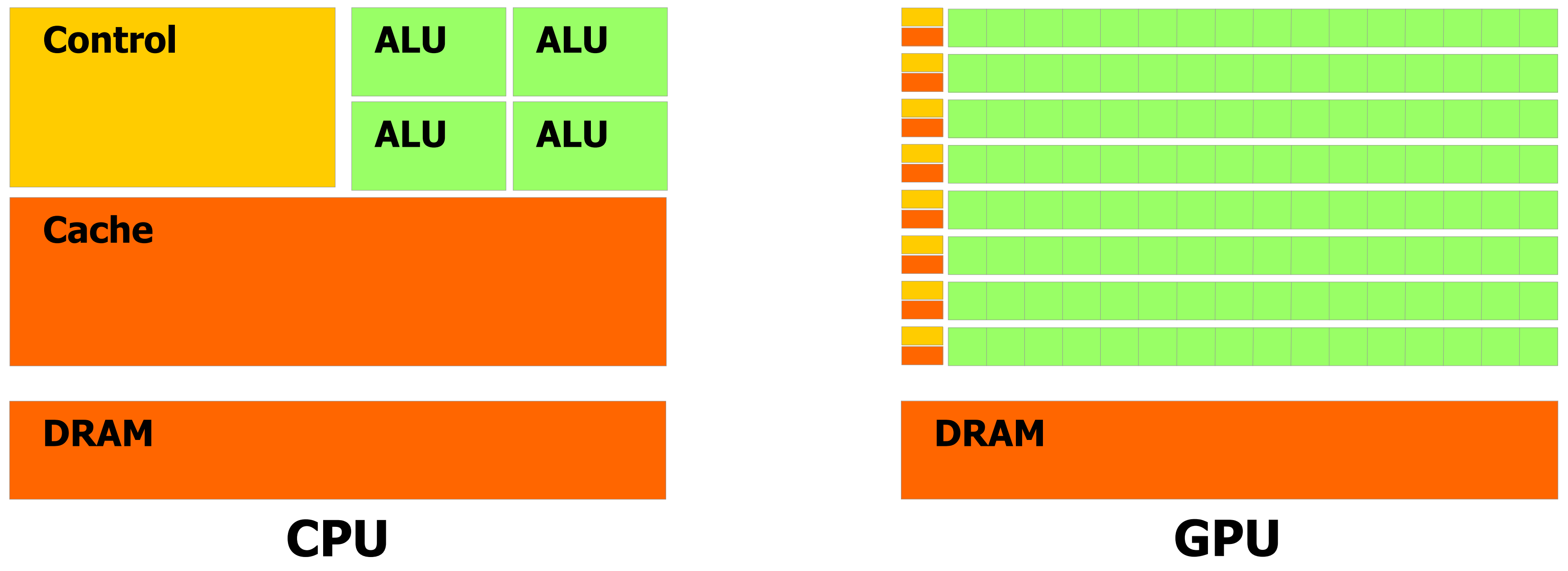
# SIMD & Control Flow

- Nvidia GPU hardware handles control flow divergence and reconvergence
  - Write scalar SIMD code, the hardware schedules the SIMD execution
  - One caveat: __syncthreads() can't appear in a divergent path
    - This may cause programs to hang
  - Good performing code will try to keep the execution convergent within a warp
    - Warp divergence only costs because of a finite instruction cache

# Memory, Memory, Memory

- A many core processor ≡ A device for turning a compute bound problem into a memory bound problem

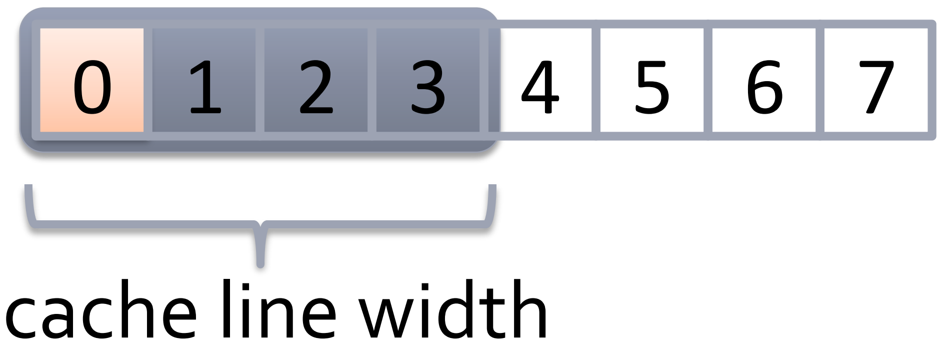
  *Kathy Yelick, Berkeley*



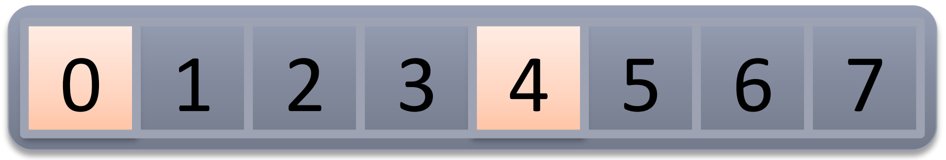
- Lots of processors, only one socket
- Memory concerns dominate performance tuning

## Memory is SIMD too

- Virtually all processors have SIMD memory subsystems

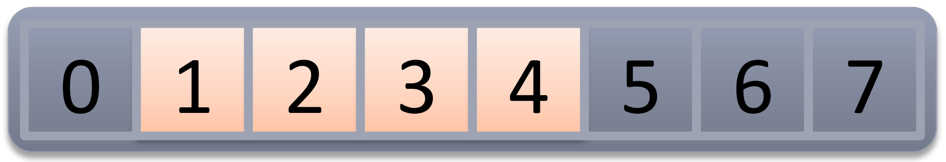


- This has two effects:
  - Sparse access wastes bandwidth



2 words used, 8 words loaded:
¼ effective bandwidth

  - Unaligned access wastes bandwidth

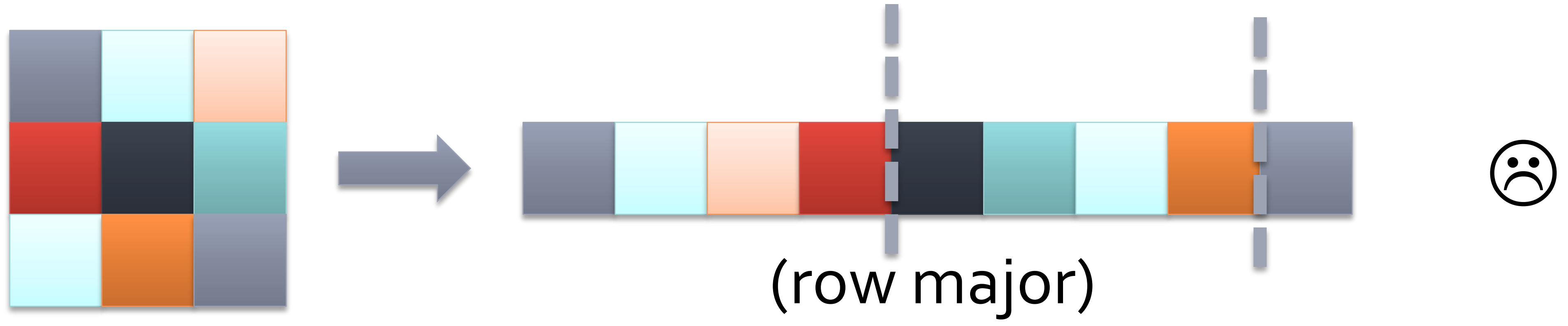


4 words used, 8 words loaded:
½ effective bandwidth

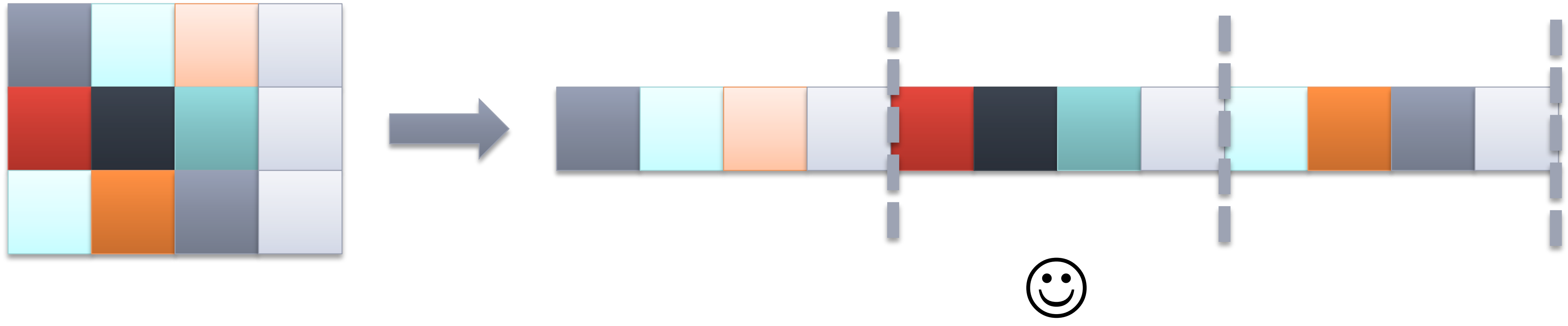
## Coalescing

- GPUs and CPUs both perform memory transactions at a larger granularity than the program requests ("cache line")
- GPUs have a "coalescer", which examines memory requests dynamically from different SIMD lanes and coalesces them
- To use bandwidth effectively, when threads load, they should:
  - Present a set of unit strided loads (dense accesses)
  - Keep sets of loads aligned to vector boundaries

## Data Structure Padding

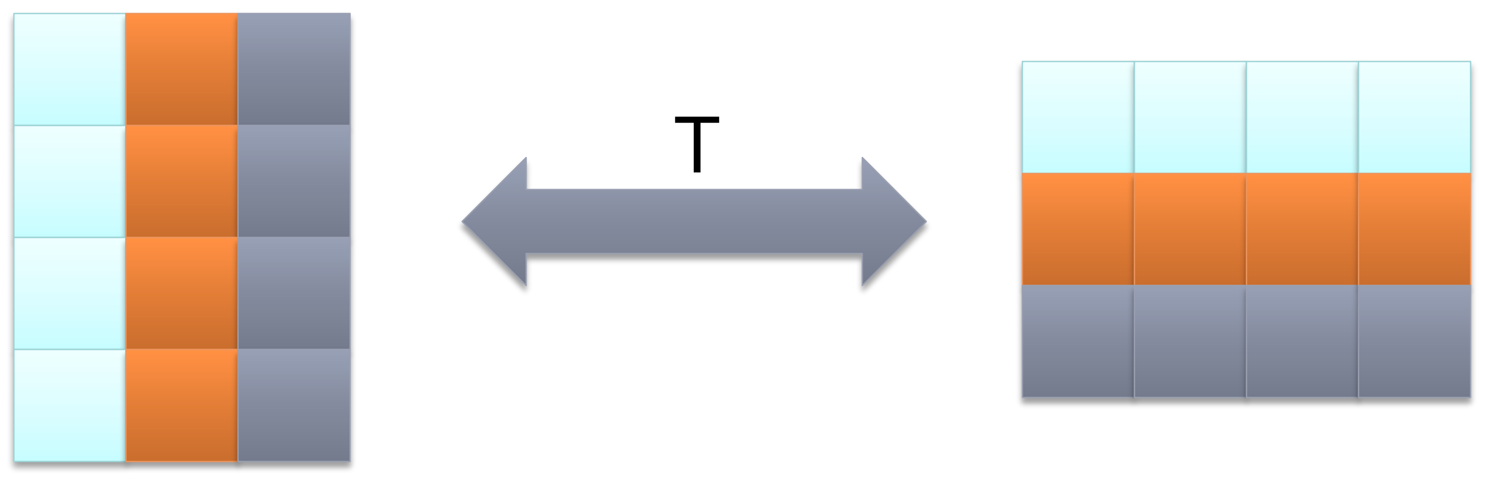


- Multidimensional arrays are usually stored as monolithic vectors in memory
- Care should be taken to assure aligned memory accesses for the necessary access pattern



## SoA, AoS

- Different data access patterns may also require transposing data structures



Array of Structs

Structure of Arrays

- The cost of a transpose on the data structure is often much less than the cost of uncoalesced memory accesses
- Use shared memory to handle block transposes

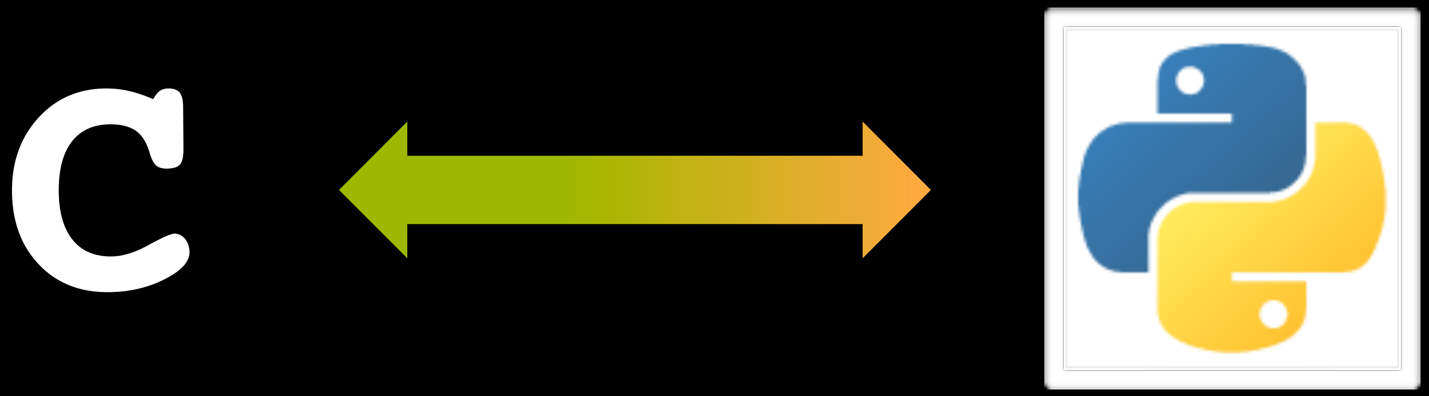
## Efficiency vs Productivity

- Productivity is often in tension with efficiency
  - This is often called the “abstraction tax”

Efficiency Language

Productivity Language

Low level



High level

Less Productive

Fast

Slow

More Productive

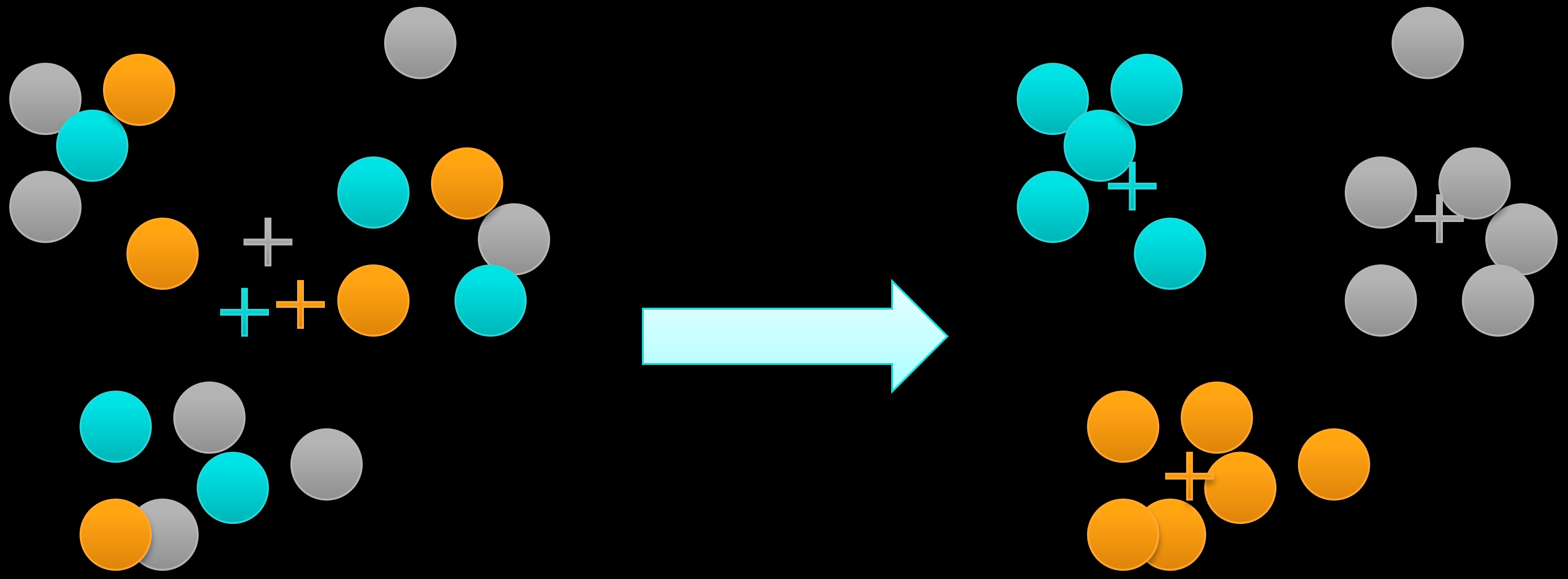
# Efficiency *and* Productivity

- Parallel programming also gives us a "concrete tax"
  - How many of you have tried to write … which is faster than a vendor supplied library?

FFT SGEMM Sort Scan Reduce

- Divergent Parallel Architectures means performance portability is increasingly elusive
- Low-level programming models tie you to a particular piece of hardware
- And if you're like me, often make your code slow
  - My SGEMM isn't as good as NVIDIA's

## The Concrete Tax: A Case Study



- K-means clustering
- Someone came to me complaining of slow code
  - Multi-thousands of lines of OpenCL
  - Hybrid reduction between CPU and GPU
- I rewrote it using Thrust and CUBLAS
- Very simple, unoptimized kernels
- 60 times faster
- http://github.com/BryanCatanzaro/kmeans

## Abstraction, *cont.*

- Reduction is one of the simplest parallel computations
- Performance differentials are even starker as complexity increases
- There's a need for abstractions at many levels
  - Primitive computations (BLAS, Data-parallel primitives)
  - Domain-specific languages
- These abstractions make parallel programming more efficient *and* more productive

- Use libraries whenever possible!
  - CUBLAS, CUFFT, Thrust

## Thrust

- A C++ template library for CUDA
  - Mimics the C++ STL
- Containers
  - On host and device
- Algorithms
  - Sorting, reduction, scan, etc.

## Diving In

```
#include <thrust/host_vector.h>
#include <thrust/device_vector.h>
#include <thrust/sort.h>
#include <cstdlib>

int main(void)
{
    // generate 32M random numbers on the host
    thrust::host_vector<int> h_vec(32 << 20);
    thrust::generate(h_vec.begin(), h_vec.end(), rand);

    // transfer data to the device
    thrust::device_vector<int> d_vec = h_vec;

    // sort data on the device (846M keys per sec on GeForce GTX 480)
    thrust::sort(d_vec.begin(), d_vec.end());

    // transfer data back to host
    thrust::copy(d_vec.begin(), d_vec.end(), h_vec.begin());

    return 0;
}
```

## Objectives

- Programmer productivity
  - Build complex applications quickly
- Encourage generic programming
  - Leverage parallel primitives
- High performance
  - Efficient mapping to hardware

## Containers

- Concise and readable code
  - Avoids common memory management errors

```
// allocate host vector with two elements
thrust::host_vector<int> h_vec(2);

// copy host vector to device
thrust::device_vector<int> d_vec = h_vec;

// write device values from the host
d_vec[0] = 13;
d_vec[1] = 27;

// read device values from the host
std::cout << "sum: " << d_vec[0] + d_vec[1] <<
std::endl;
```

## Iterators

- Pair of iterators defines a *range*

```
// allocate device memory
device_vector<int> d_vec(10);

// declare iterator variables
device_vector<int>::iterator begin  =
d_vec.begin();
device_vector<int>::iterator end    = d_vec.end();
device_vector<int>::iterator middle = begin + 5;

// sum first and second halves
int sum_half1 = reduce(begin, middle);
int sum_half2 = reduce(middle, end);

// empty range
int empty = reduce(begin, begin);
```

# Iterators

- Iterators act like pointers

```
// declare iterator variables
device_vector<int>::iterator begin = d_vec.begin();
device_vector<int>::iterator end   = d_vec.end();

// pointer arithmetic
begin++;

// dereference device iterators from the host
int a = *begin;
int b = begin[3];

// compute size of range [begin,end)
int size = end - begin;
```

## Iterators

- Encode memory location
    - Automatic algorithm selection

```
// initialize random values on host
host_vector<int> h_vec(100);
generate(h_vec.begin(), h_vec.end(), rand);

// copy values to device
device_vector<int> d_vec = h_vec;

// compute sum on host
int h_sum = reduce(h_vec.begin(), h_vec.end());

// compute sum on device
int d_sum = reduce(d_vec.begin(), d_vec.end());
```

## Algorithms

- Elementwise operations
  - `for_each`, `transform`, `gather`, `scatter` …
- Reductions
  - `reduce`, `inner_product`, `reduce_by_key` …
- Prefix-Sums
  - `inclusive_scan`, `inclusive_scan_by_key` …
- Sorting
  - `sort`, `stable_sort`, `sort_by_key` …

## Algorithms

- Standard operators

```
// allocate memory
device_vector<int>  A(10);
device_vector<int>  B(10);
device_vector<int>  C(10);

// transform A + B -> C
transform(A.begin(), A.end(), B.begin(), C.begin(), plus<int>());

// transform A - B -> C
transform(A.begin(), A.end(), B.begin(), C.begin(), minus<int>());

// multiply reduction
int product = reduce(A.begin(), A.end(), 1, multiplies<int>());
```

## Algorithms

- Standard data types

```
// allocate device memory
device_vector<int>   i_vec = ...
device_vector<float> f_vec = ...

// sum of integers
int i_sum = reduce(i_vec.begin(), i_vec.end());

// sum of floats
float f_sum = reduce(f_vec.begin(),
f_vec.end());
```

# Custom Types & Operators

```
struct negate_float2
{
    __host__ __device__
    float2 operator()(float2 a)
    {
        return make_float2(-a.x, -a.y);
    }
};

// declare storage
device_vector<float2> input  = ...
device_vector<float2> output = ...

// create function object or 'functor'
negate_float2 func;

// negate vectors
transform(input.begin(), input.end(), output.begin(), func);
```

# Custom Types & Operators

```
// compare x component of two float2 structures
struct compare_float2
{
    __host__ __device__
    bool operator()(float2 a, float2 b)
    {
        return a.x < b.x;
    }
};

// declare storage
device_vector<float2> vec = ...

// create comparison functor
compare_float2 comp;

// sort elements by x component
sort(vec.begin(), vec.end(), comp);
```

## Interoperability

- Convert iterators to raw pointers

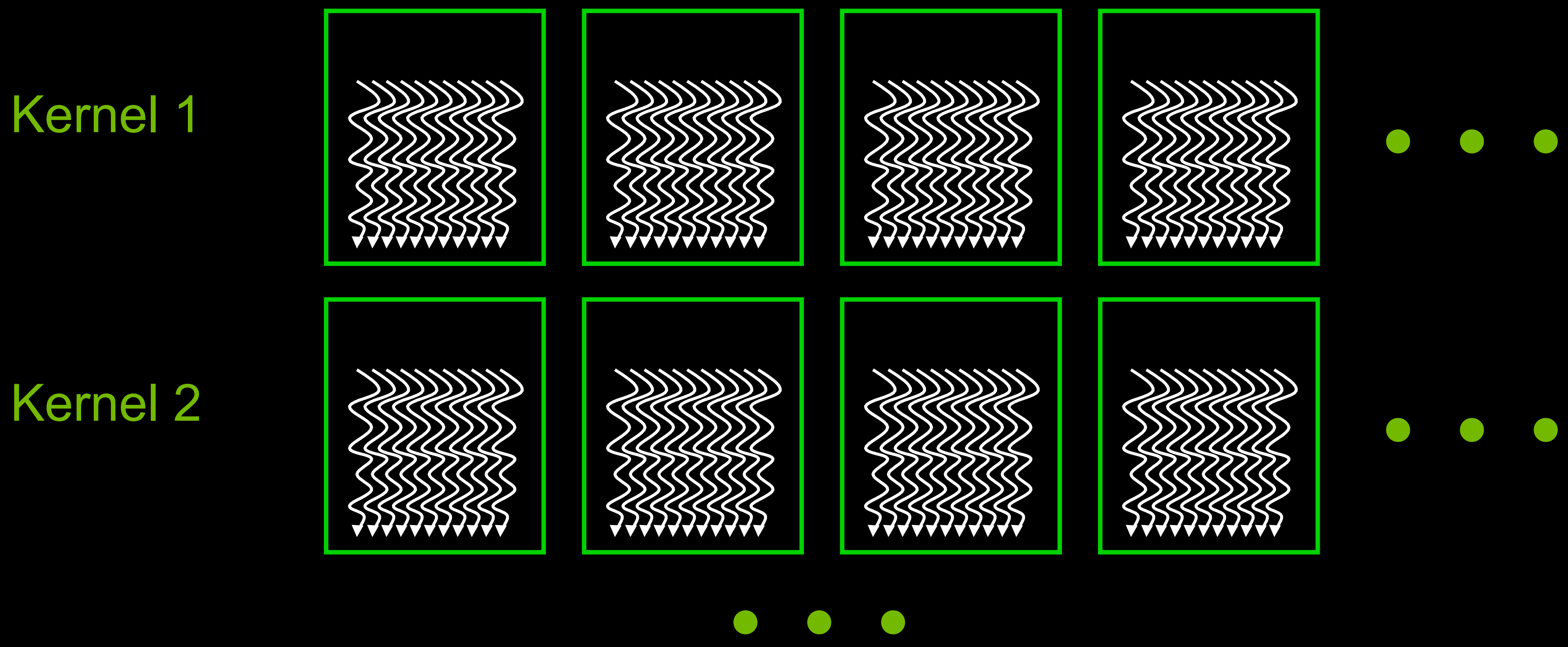
```
// allocate device vector
thrust::device_vector<int> d_vec(4);

// obtain raw pointer to device vector's memory
int * ptr = thrust::raw_pointer_cast(&d_vec[0]);

// use ptr in a CUDA C kernel
my_kernel<<< N / 256, 256 >>>(N, ptr);

// Note: ptr cannot be dereferenced on the host!
```

## Recap

- Containers manage memory
  - Help avoid common errors
- Iterators define ranges
  - Know where data lives
- Algorithms act on ranges
  - Support general types and operators

# Explicit versus implicit parallelism

- CUDA is explicit
  - Programmer's responsibility to schedule resources
  - Decompose algorithm into kernels
  - Decompose kernels into blocks
  - Decompose blocks into threads



## Explicit versus implicit parallelism

- SAXPY in CUDA

```
__global__
void SAXPY(int n, float a, float * x, float * y)
{
    int i = blockDim.x * blockIdx.x + threadIdx.x;

    if (i < n)
        y[i] = a * x[i] + y[i];
}

SAXPY <<< n/256, 256 >>>(n, a, x, y);
```

## Explicit versus implicit parallelism

- SAXPY in CUDA

```
__global__
void SAXPY(int n, float a, float * x, float * y)
{
    int i = blockDim.x * blockIdx.x + threadIdx.x;

    if (i < n)
        y[i] = a * x[i] + y[i];
}

SAXPY <<< n/256, 256 >>>(n, a, x, y);
```

Decomposition

## Explicit versus implicit parallelism

- SAXPY in Thrust

```
// C++ functor replaces __global__ function
struct saxpy {
    float a;
    saxpy(float _a) : a(_a) {}

    __host__ __device__
    float operator()(float x, float y) {
        return a * x + y;
    }
};

transform(x.begin(), x.end(), y.begin(), y.begin(),
  saxpy(a));
```

## Implicitly Parallel

- Algorithms expose lots of *fine-grained* parallelism
  - Generally expose O(N) independent threads of execution
  - Minimal constraints on implementation details
- Programmer identifies opportunities for parallelism
  - Thrust determines explicit decomposition onto hardware
- Finding parallelism in sequential code is hard
  - Mapping parallel computations onto hardware is easier

## Productivity Implications

- Consider a serial reduction

```
// sum reduction
int sum = 0;
for(i = 0; i < n; ++i)
   sum += v[i];
```

## Productivity Implications

- Consider a serial reduction

```
// product reduction
int product = 1;
for(i = 0; i < n; ++i)
  product *= v[i];
```

## Productivity Implications

- Consider a serial reduction

```
// max reduction
int max = 0;
for(i = 0; i < n; ++i)
  max = std::max(max,v[i]);
```

## Productivity Implications

- Compare to low-level CUDA

```
int sum = 0;
for(i = 0; i < n; ++i)
  sum += v[i];
```

```
__global__
void block_sum(const float *input,
               float *per_block_results,
               const size_t n)
{
  extern __shared__ float sdata[];

  unsigned int i = blockIdx.x *
   blockDim.x + threadIdx.x;

  // load input into __shared__ memory
  float x = 0;
  if(i < n)
  {
    x = input[i];
                      ...
```

# Leveraging Parallel Primitives

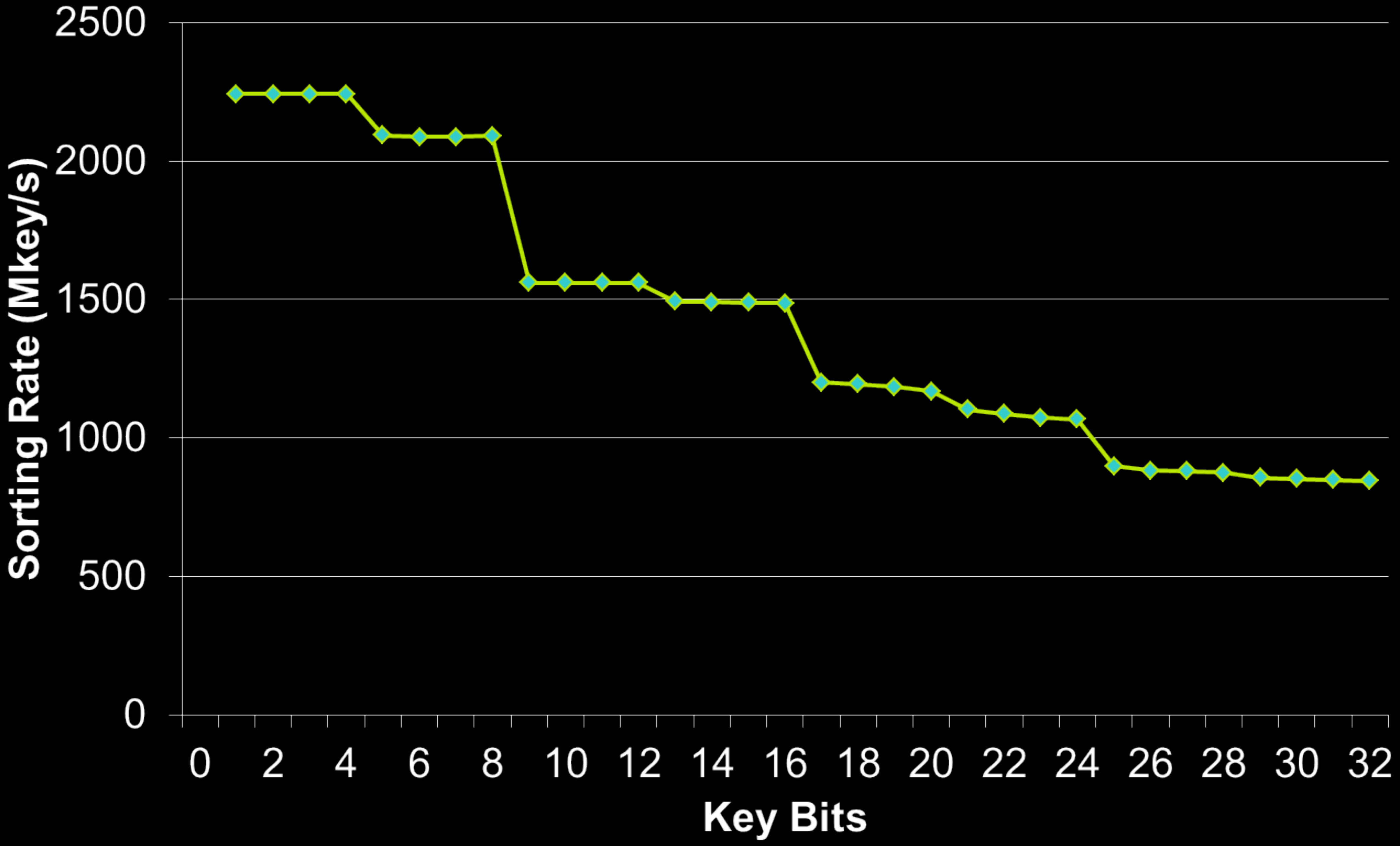
- Use `sort` liberally

| data type | std::sort | tbb::parallel_sort | thrust::sort |
|---|---|---|---|
| `char` | 25.1 | 68.3 | 3532.2 |
| `short` | 15.1 | 46.8 | 1741.6 |
| `int` | 10.6 | 35.1 | 804.8 |
| `long` | 10.3 | 34.5 | 291.4 |
| `float` | 8.7 | 28.4 | 819.8 |
| `double` | 8.5 | 28.2 | 358.9 |

Intel Core i7 950

NVIDIA GeForce 480

# Input-Sensitive Optimizations

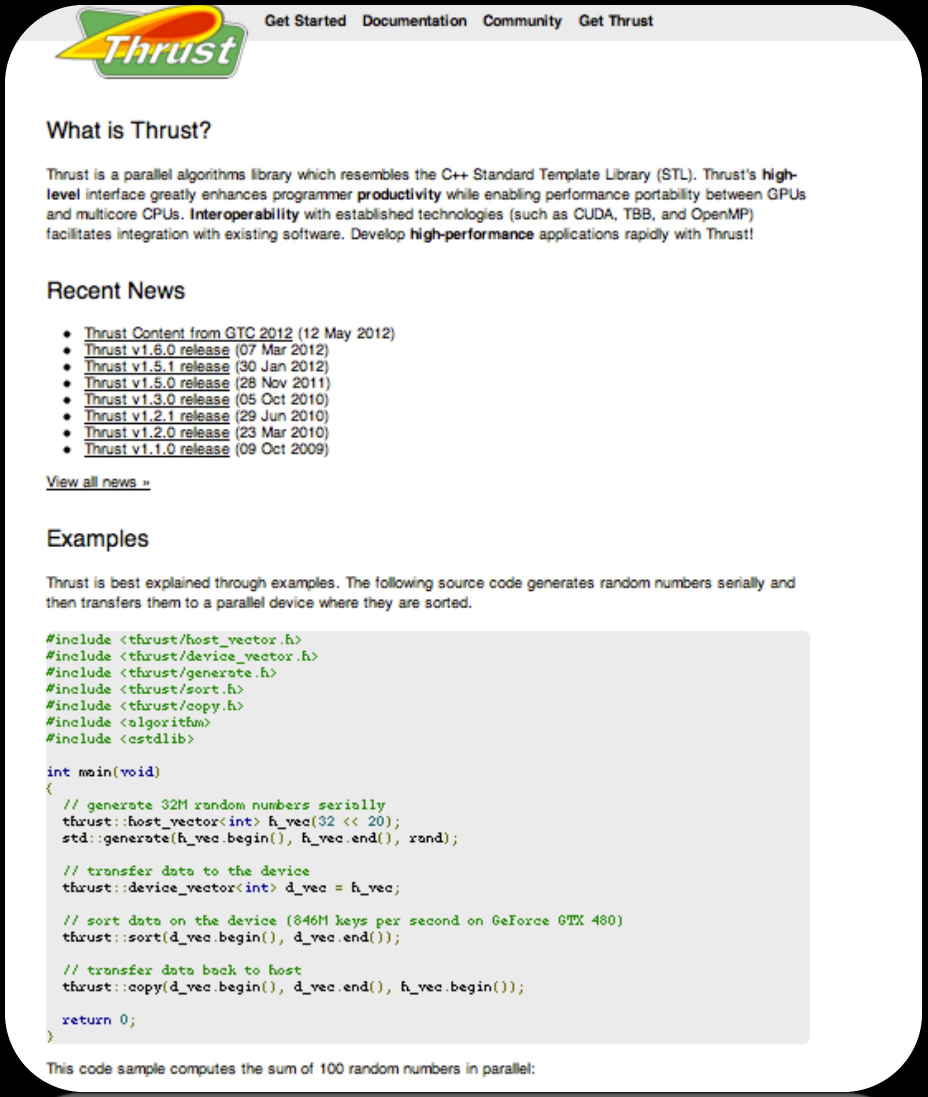


## Leveraging Parallel Primitives

- Combine `sort` with `reduce_by_key`
  - Keyed reduction
  - Bring like items together, collapse
  - Poor man's MapReduce
- Can often be faster than custom solutions
  - I wrote an image histogram routine in CUDA
  - Bit-level optimizations and shared memory atomics
  - Was 2x slower than `thrust::sort` + `thrust::reduce_by_key`

## Thrust on github

- Quick Start Guide
- Examples
- Documentation
- Mailing list (thrust-users)



Get Started Documentation Community Get Thrust

What is Thrust?

Thrust is a parallel algorithms library which resembles the C++ Standard Template Library (STL). Thrust's **high-level** interface greatly enhances programmer **productivity** while enabling performance portability between GPUs and multicore CPUs. **Interoperability** with established technologies (such as CUDA, TBB, and OpenMP) facilitates integration with existing software. Develop **high-performance** applications rapidly with Thrust!

Recent News

- Thrust Content from GTC 2012 (12 May 2012)
- Thrust v1.6.0 release (07 Mar 2012)
- Thrust v1.5.1 release (30 Jan 2012)
- Thrust v1.5.0 release (28 Nov 2011)
- Thrust v1.3.0 release (05 Oct 2010)
- Thrust v1.2.1 release (29 Jun 2010)
- Thrust v1.2.0 release (23 Mar 2010)
- Thrust v1.1.0 release (09 Oct 2009)

View all news »

Examples

Thrust is best explained through examples. The following source code generates random numbers serially and then transfers them to a parallel device where they are sorted.

```
#include <thrust/host_vector.h>
#include <thrust/device_vector.h>
#include <thrust/generate.h>
#include <thrust/sort.h>
#include <thrust/copy.h>
#include <algorithm>
#include <cstdlib>

int main(void)
{
  // generate 32M random numbers serially
  thrust::host_vector<int> h_vec(32 << 20);
  std::generate(h_vec.begin(), h_vec.end(), rand);

  // transfer data to the device
  thrust::device_vector<int> d_vec = h_vec;

  // sort data on the device (846M keys per second on GeForce GTX 480)
  thrust::sort(d_vec.begin(), d_vec.end());

  // transfer data back to host
  thrust::copy(d_vec.begin(), d_vec.end(), h_vec.begin());

  return 0;
}
```

This code sample computes the sum of 100 random numbers in parallel:

## Summary

- Throughput optimized processors complement latency optimized processors
- Programming models like CUDA and OpenCL enable heterogeneous parallel programming
- They abstract SIMD, making it easy to use wide SIMD vectors
- CUDA and OpenCL encourages SIMD friendly, highly scalable algorithm design and implementation
- Thrust is a productive C++ library for parallel programming
- Start with libraries when doing parallel programming!

## Questions?

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