

# ***3D Bilateral Filtering on the GPU***

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# Outline

What is Bilateral Filtering?

CUDA Background

GPU implementation project objectives.

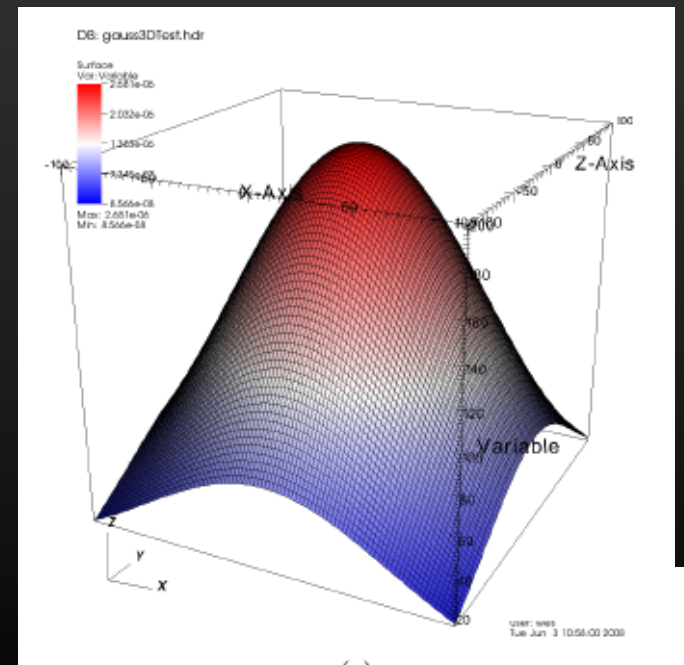
The implementation, performance evaluation,  
optimization: algorithmic design choices, tunable  
algorithm parameters.



# Gaussian Smoothing

- Convolution kernel, a *stencil-based algorithm*.
- Weights are a 2D Gaussian (right).
- Idea: nearby pixels have more influence, distant pixels have less influence.

$$G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}}$$



# Bilateral Filtering/Smoothing

- Dest pixel  $i$  is the sum of:
- Gaussian weight of nearby pixel  $\bar{i}$
- “Photometric difference” between pixel  $i$  and pixel  $\bar{i}$
- Normalization constant  $k$  –  $c$  weights are data dependent.

$$d(i) = \frac{1}{k(i)} \sum g(i, \bar{i}) c(i, \bar{i})$$

$$g(i, \bar{i}) = e^{-\frac{1}{2} \left( \frac{d(i, \bar{i})}{\sigma_d} \right)^2}$$

$$k(i) = \frac{1}{\sum g(i, \bar{i}) c(i, \bar{i})}$$

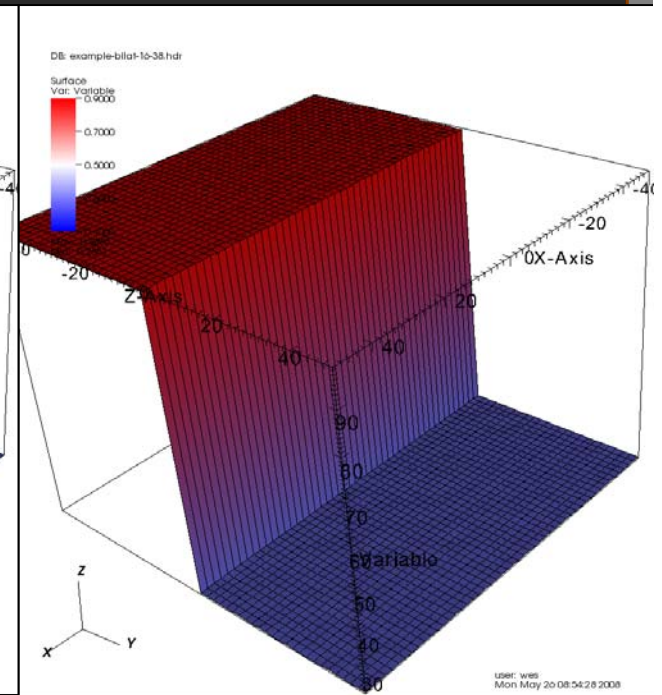
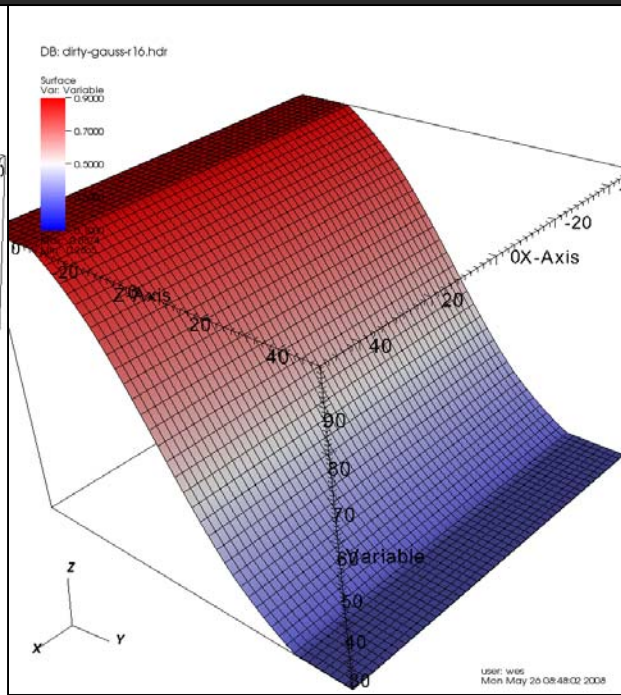
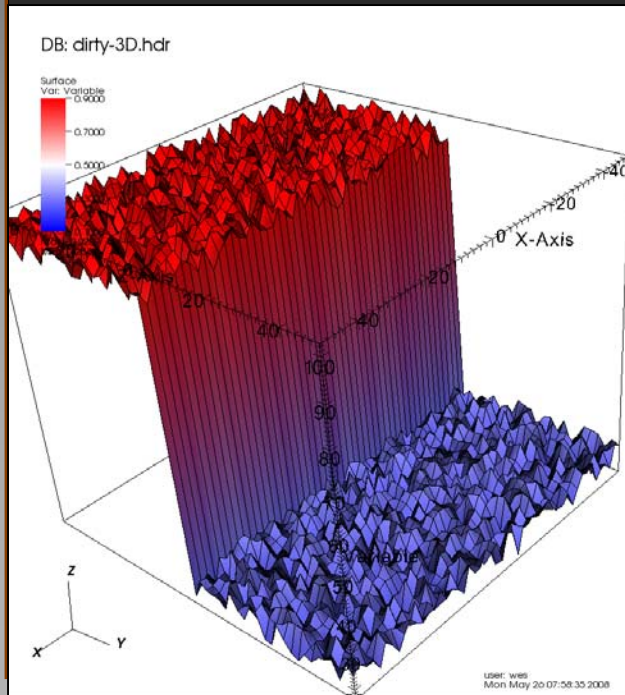


# Comparison of Bilateral and Gaussian Smoothing

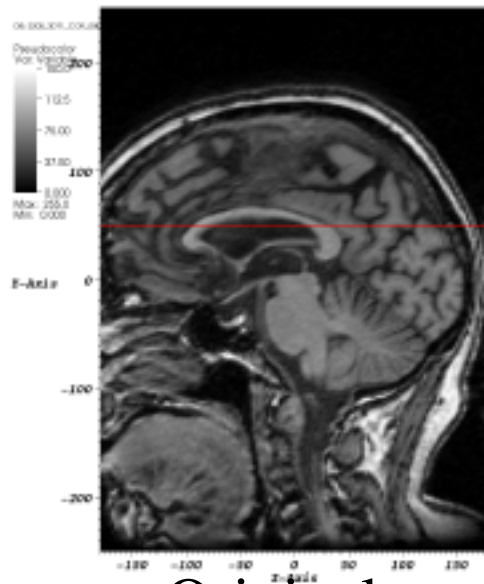
Synthetic data with  
gaussian noise

Gaussian  
smoothing

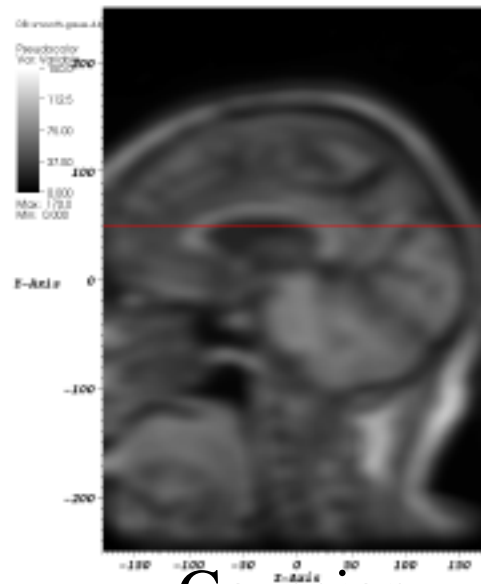
Bilateral  
smoothing



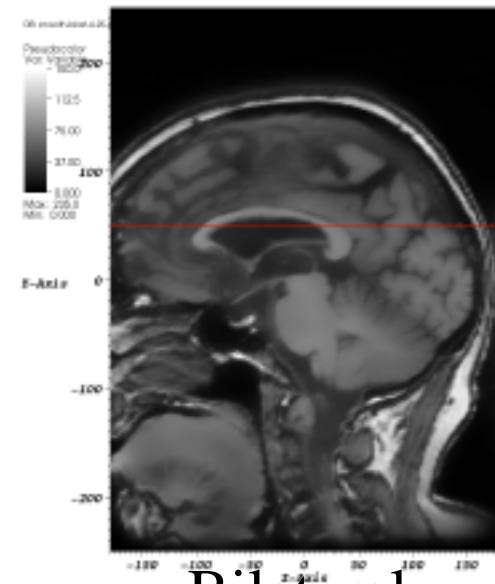
# Comparison of Bilateral and Gaussian Smoothing



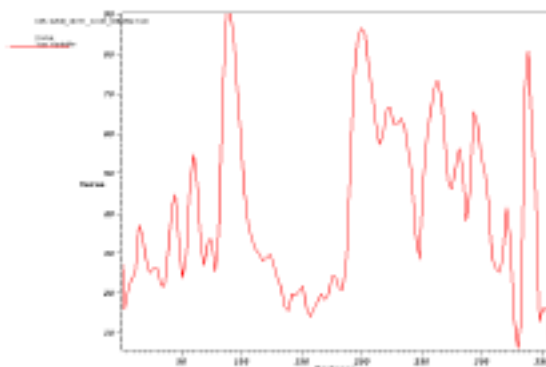
Original



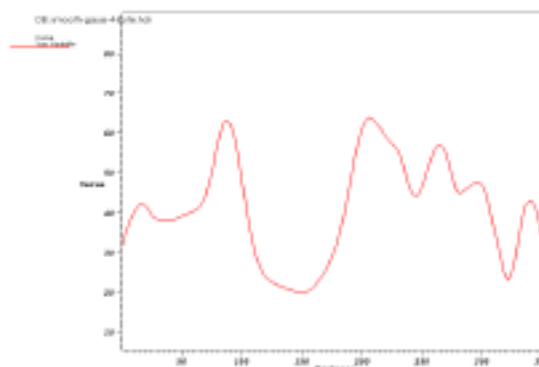
Gaussian



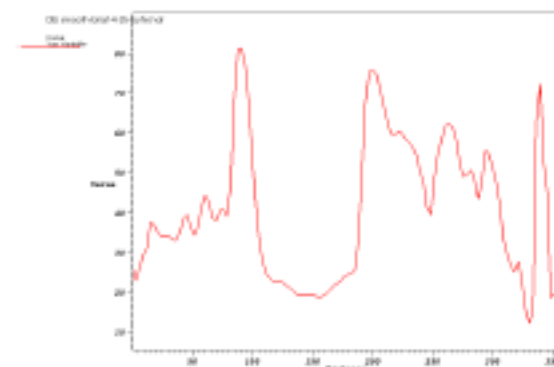
Bilateral



100% 1400  
Thu Apr 5 17:06:04 2006



100% 1400  
Thu Apr 5 18:23:23 2006



100% 1400  
Thu Apr 5 18:21:14 2006

# Why Bother with GPU Implementation?

- This algorithm is compute-bound for large filter radii.
- Long run-times:
  - $R=8$ , ~8min,  $R=16$ , ~60min.
- Data parallel algorithm, non-iterative.



# GPU Implementation Objectives

- **Gain experience developing in CUDA**
- **Performance optimization**
  - Algorithmic design choices: device memories and access patterns.
  - Tunable parameters: thread block size/shape





# CUDA Background

- **Data parallel programming language:**
  - Eg.,  $A[I] = B[I] + C[I]$
  - Runs in parallel on all cores on the GPU.
    - GeForce GTX 280: 30 “multi-processors”, 8 cores/MP, 240 cores total.
- **Requires GPU code and host code (next slides)**





## Example: Vector Addition Kernel

```
// Pair-wise addition of vector elements
// One thread per addition

__global__ void
vectorAdd(float* iA, float* iB, float* oC)
{
    int idx = threadIdx.x
              + blockDim.x * blockIdx.x;
    oC[idx] = iA[idx] + iB[idx];
}
```

# Example: Vector Addition Host Code



```
float* h_A = (float*) malloc(N * sizeof(float));
float* h_B = (float*) malloc(N * sizeof(float));
// ... initialize h_A and h_B

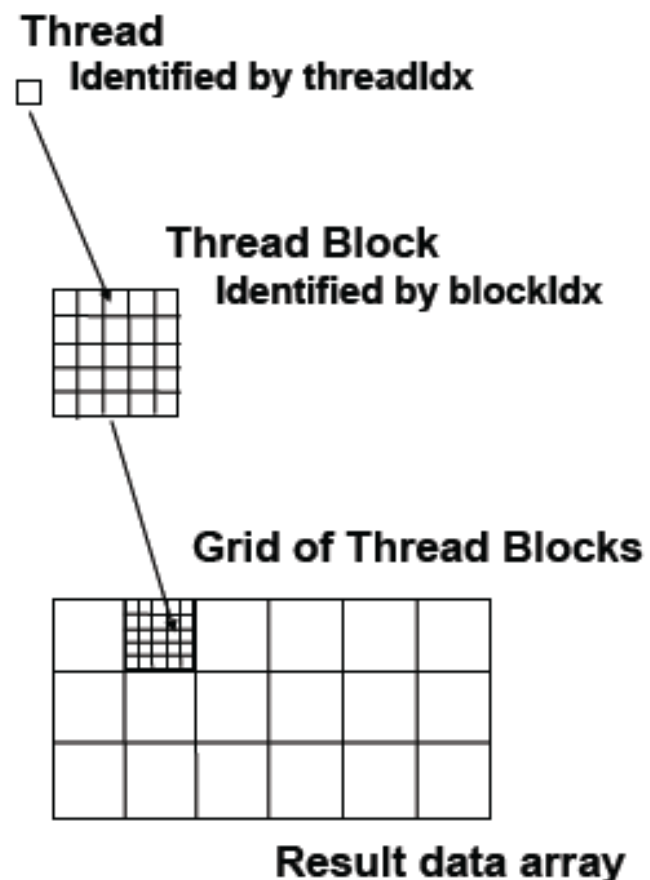
// allocate device memory
float* d_A, d_B, d_C;
cudaMalloc( (void**) &d_A, N * sizeof(float));
cudaMalloc( (void**) &d_B, N * sizeof(float));
cudaMalloc( (void**) &d_C, N * sizeof(float));

// copy host memory to device
cudaMemcpy( d_A, h_A, N * sizeof(float),
             cudaMemcpyHostToDevice) );
cudaMemcpy( d_B, h_B, N * sizeof(float),
             cudaMemcpyHostToDevice) );

// execute the kernel on N/256 blocks of 256 threads each
vectorAdd<<< N/256, 256>>>( d_A, d_B, d_C);
```

© NVIDIA Corporation 2006<<<nblocks, nthreads>>>

# Execution Model



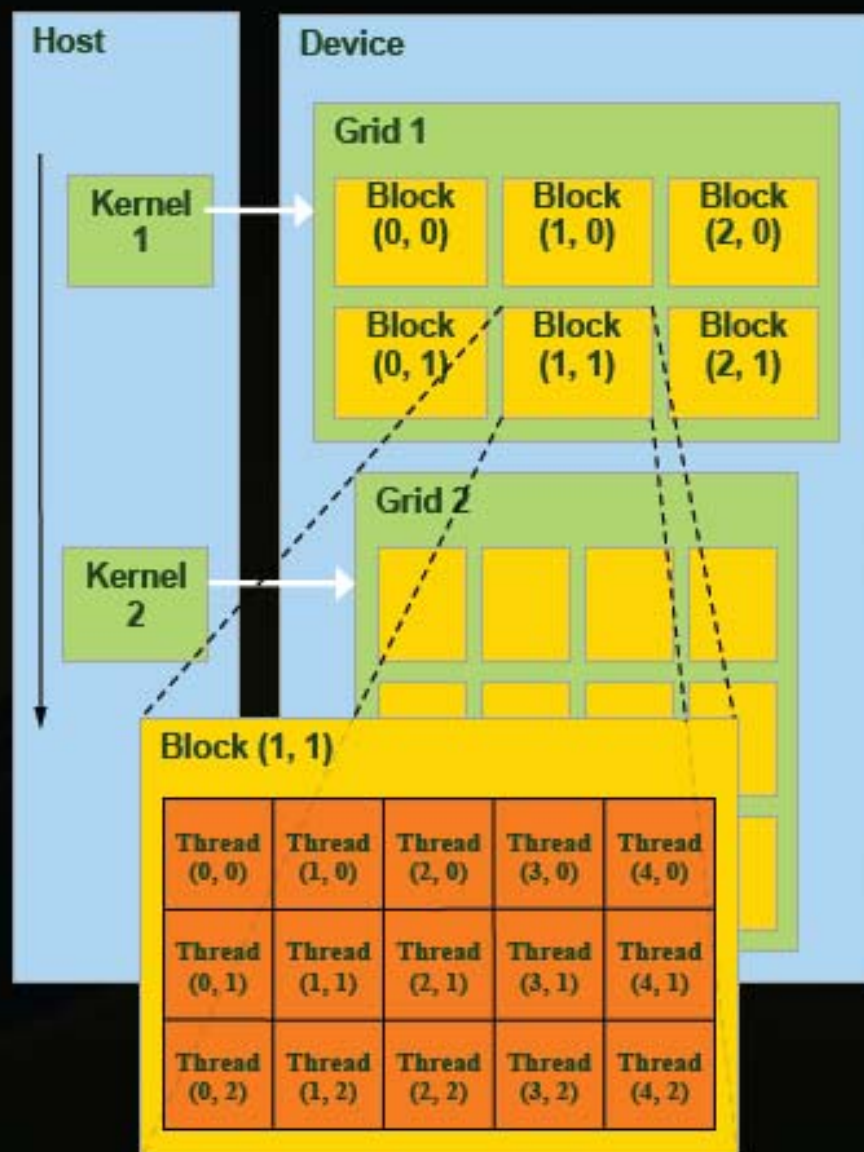
## Multiple levels of parallelism

- **Thread block**
  - Up to 512 threads per block
  - Communicate through shared memory
  - Threads guaranteed to be resident
  - `threadIdx`, `blockIdx`
  - `__syncthreads()`
- **Grid of thread blocks**
  - `f<<<nblocks, nthreads>>>(a,b,c)`



# Programming Model (SPMD + SIMD): Thread Batching

- A kernel is executed as a **grid of thread blocks**
- A **thread block** is a batch of threads that can **cooperate** with each other by:
  - Efficiently sharing data through **shared memory**
  - Synchronizing their execution
    - For hazard-free shared memory accesses
- Two threads from two different blocks cannot cooperate



# 3D Bilateral Filtering on the GPU

- **Algorithm design choices**
  - How do threads access memory?
  - Choices about use of high-speed local caches.
    - Global memory (shared), constant memory, shared memory, texture memory, etc.
- **Tunable algorithm parameters**
  - Thread block size, number of threads per block.



# Other Speed Bumps Influencing Design

- **Limit on number of thread blocks.**
  - 1D and 2D grids of thread blocks.
  - No 3D grid of thread blocks.
  - Max dim size = 64K.
- **Limit on number of threads per thread block.**
  - Max of 512 threads per block.
  - Max dims (512,512,64) threads/block.



# Design Constraints

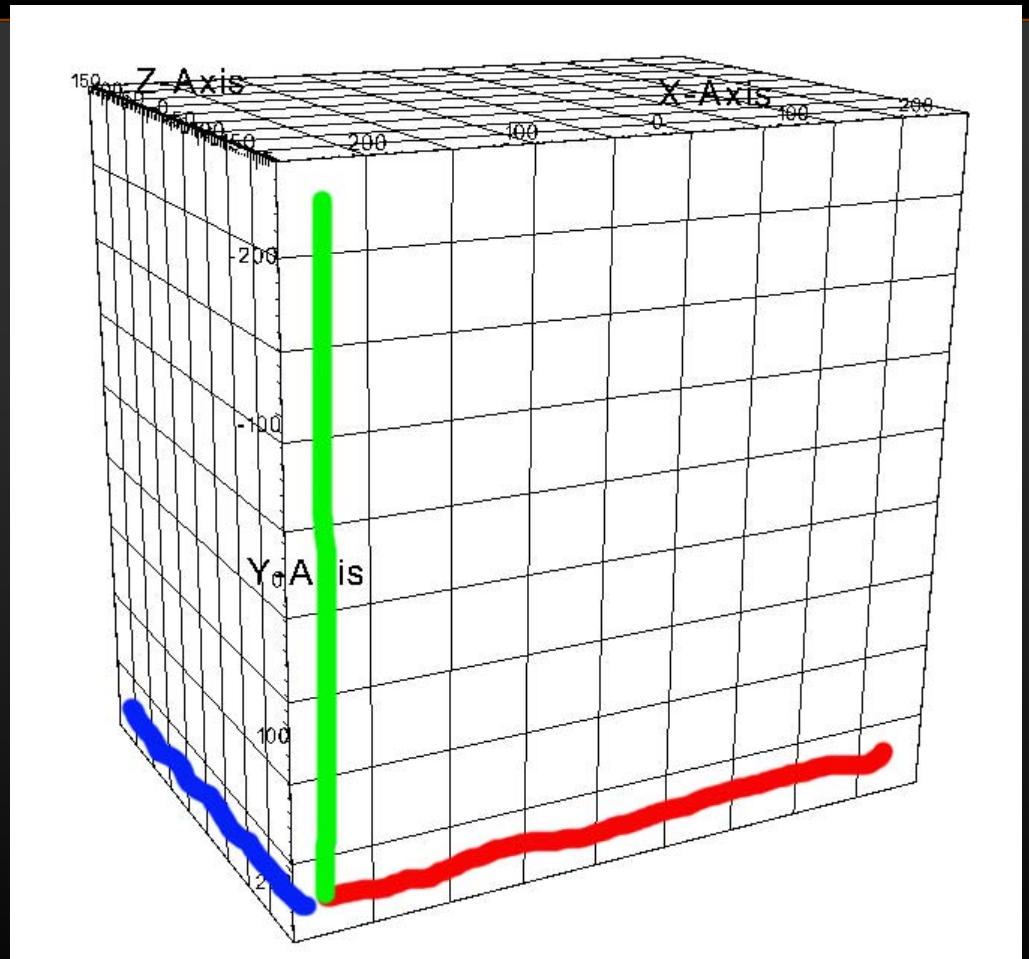
- **No 3D grid of thread blocks:**
  - Our thread kernel must process a row of voxels in width, height or depth.
    - Which works best?
  - Thread block array is 2D of some number of threads.
    - Which size/shape works best?



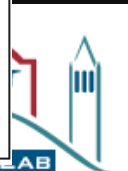
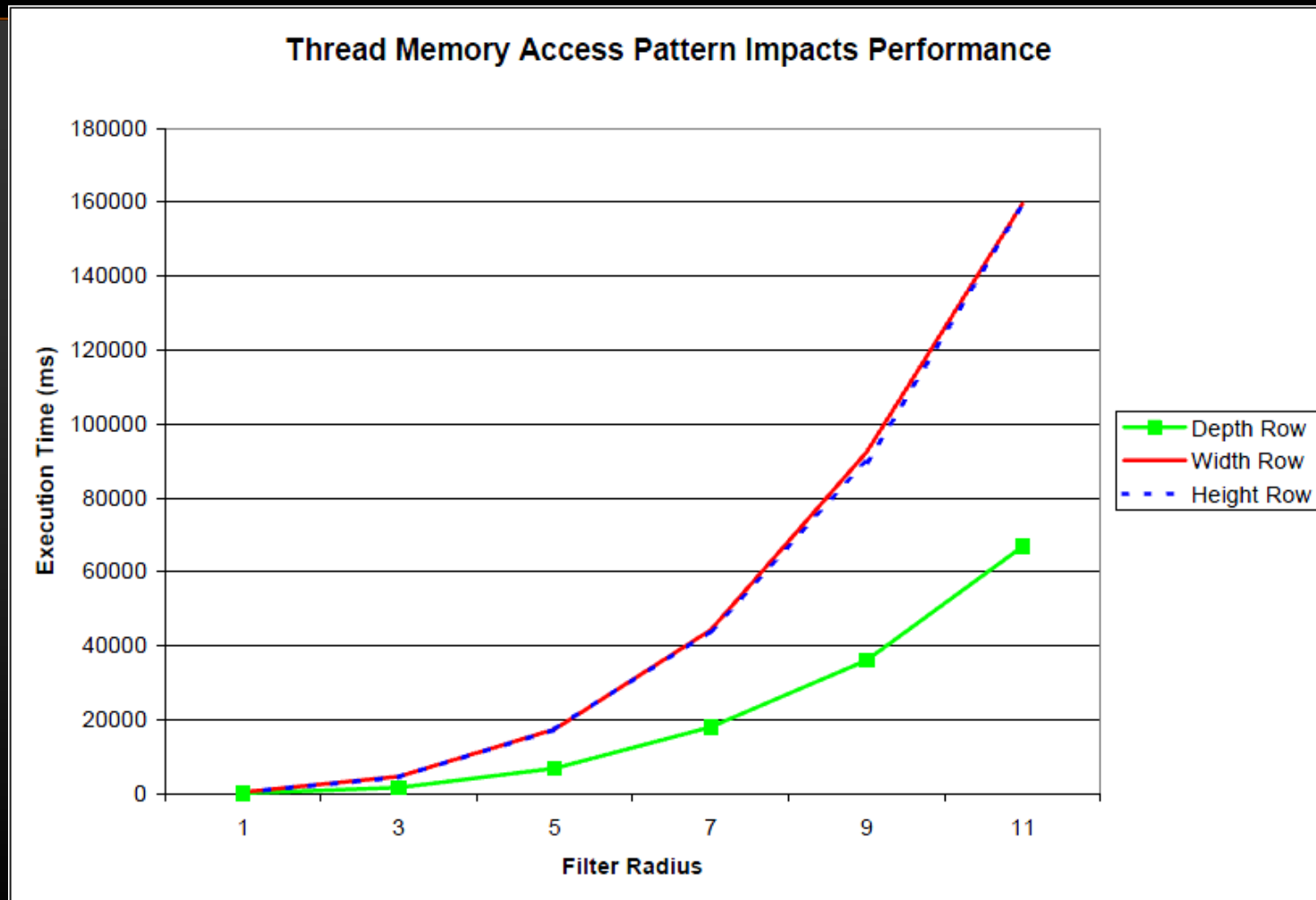


# Memory Access Patterns

- Depth-row (blue)
- Height-row (green)
- Width-row (red)
- Question: which access pattern results in best performance?



# Memory Access Pattern Test Results

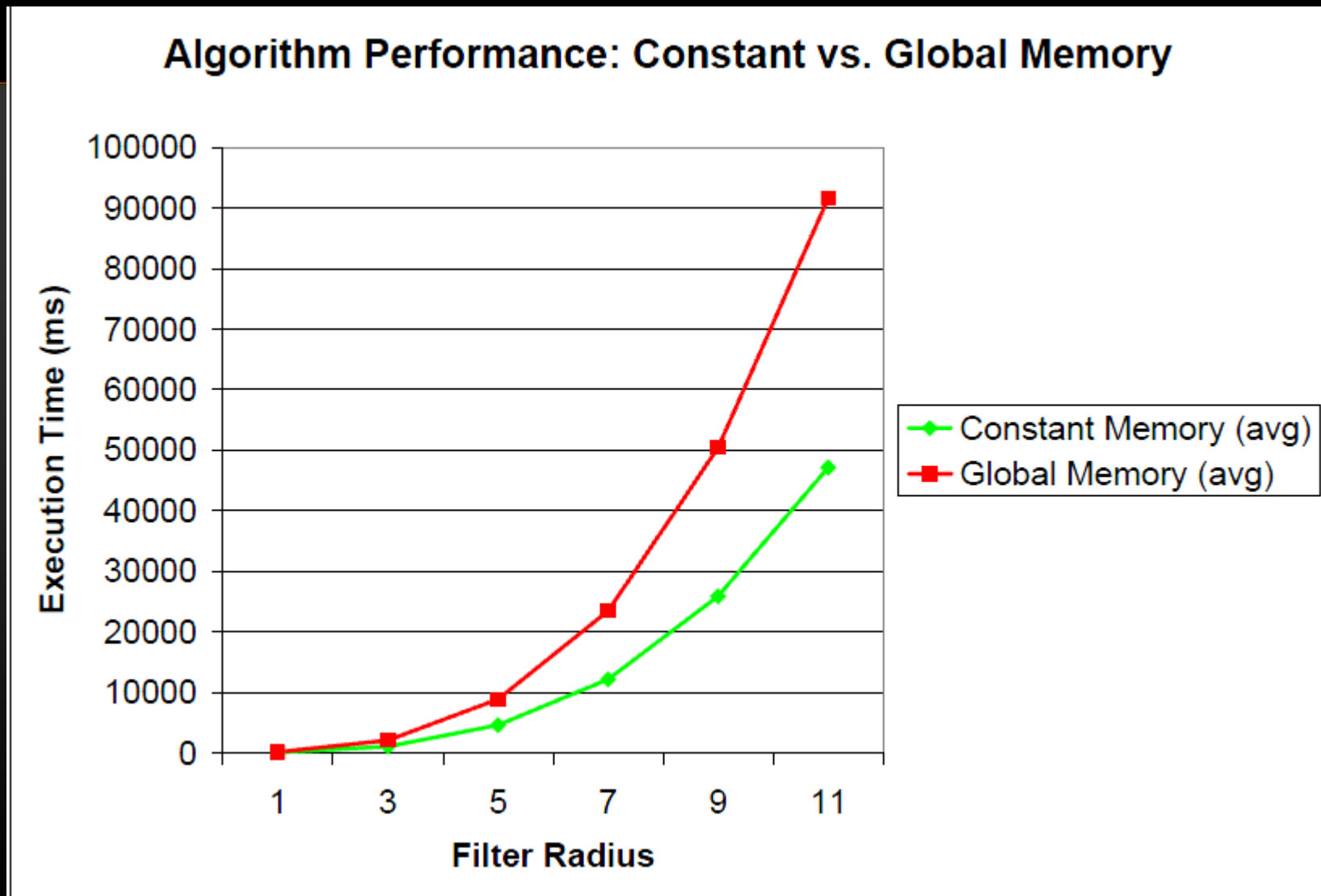


# Device Memories

- **Global – large, high latency, low bandwidth**
- **Constant – small, low-latency, high bandwidth.**
  - 64KB not large enough for src, dst volumes
  - 64KB large enough for 1D&3D filter weights up to  $r=12$ .
- **Shared memory – small, 16KB, split into banks across multiprocessors (too small for this project).**
- **Question: how is performance affected if we use global vs. constant memory for the filter weights?**



# Device Memories Test Results

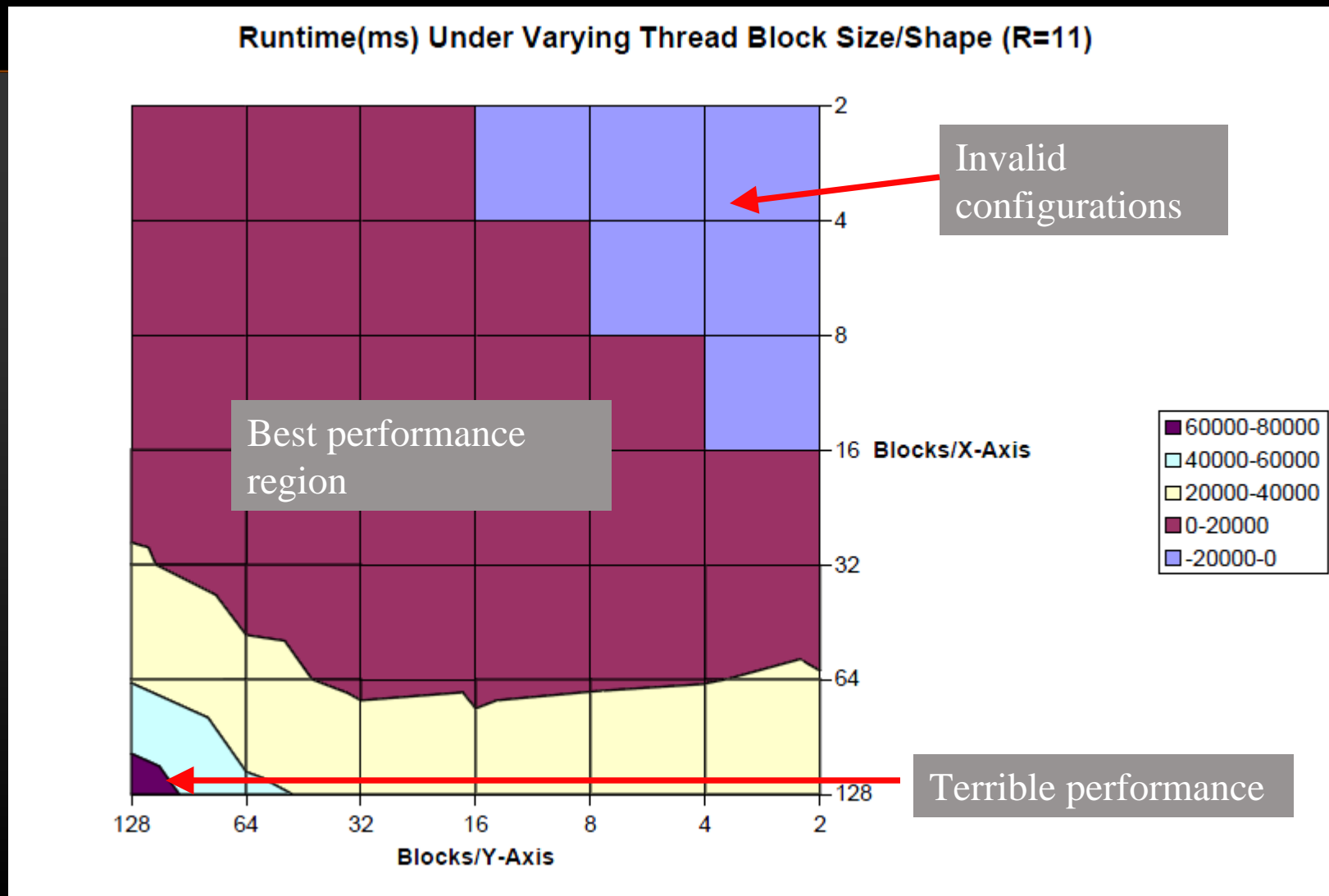


# Tunable Parameters: Thread Block Size and Shape

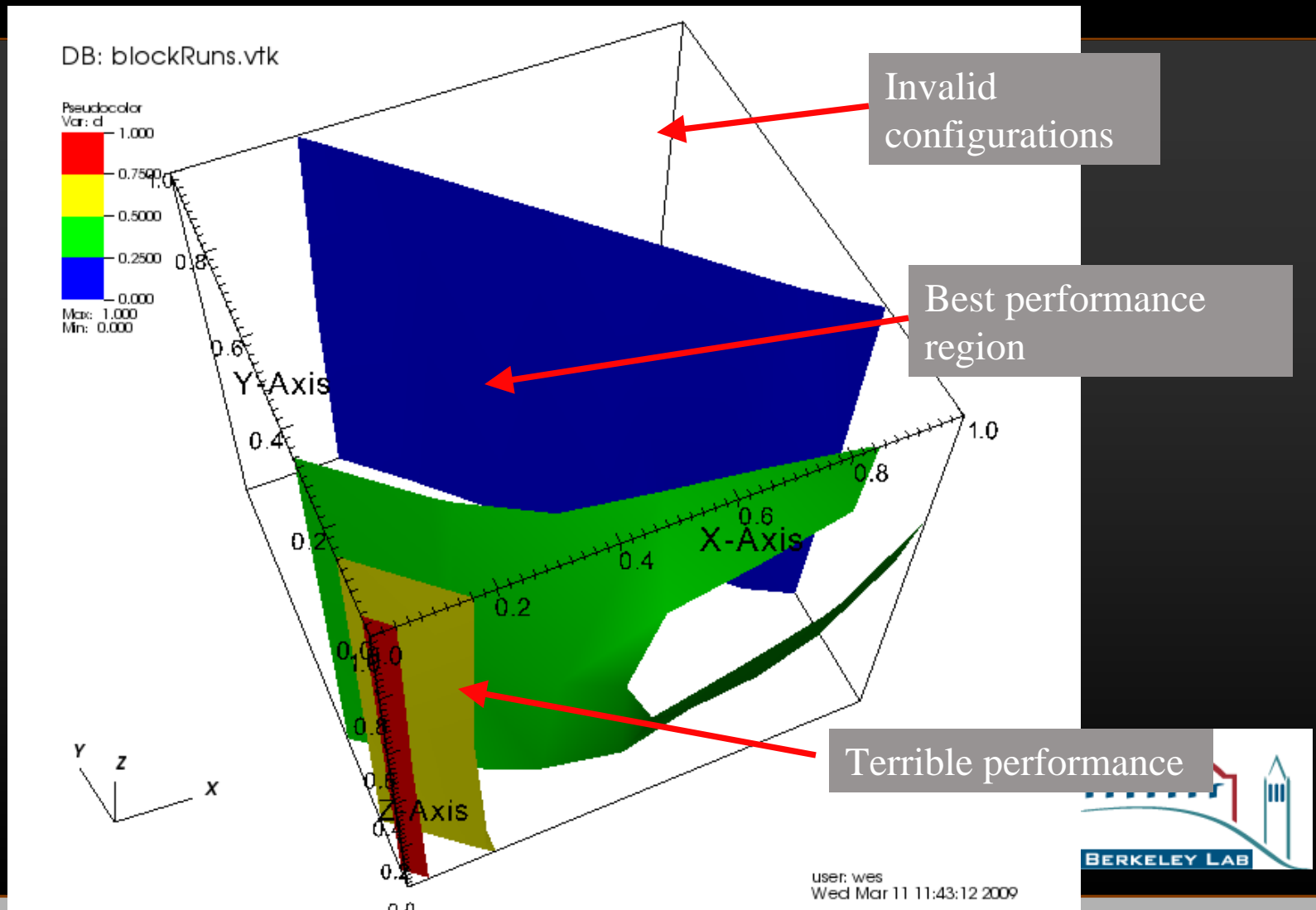
- **Basic ideas:**
  - More vs. fewer thread blocks.
    - Fewer thread blocks means more threads per block.
  - Shape of thread blocks.
    - Square-shaped vs. oblong.
- **Question: which combination of thread block size and shape results in best performance?**
  - Note: this is the domain of autotuning.



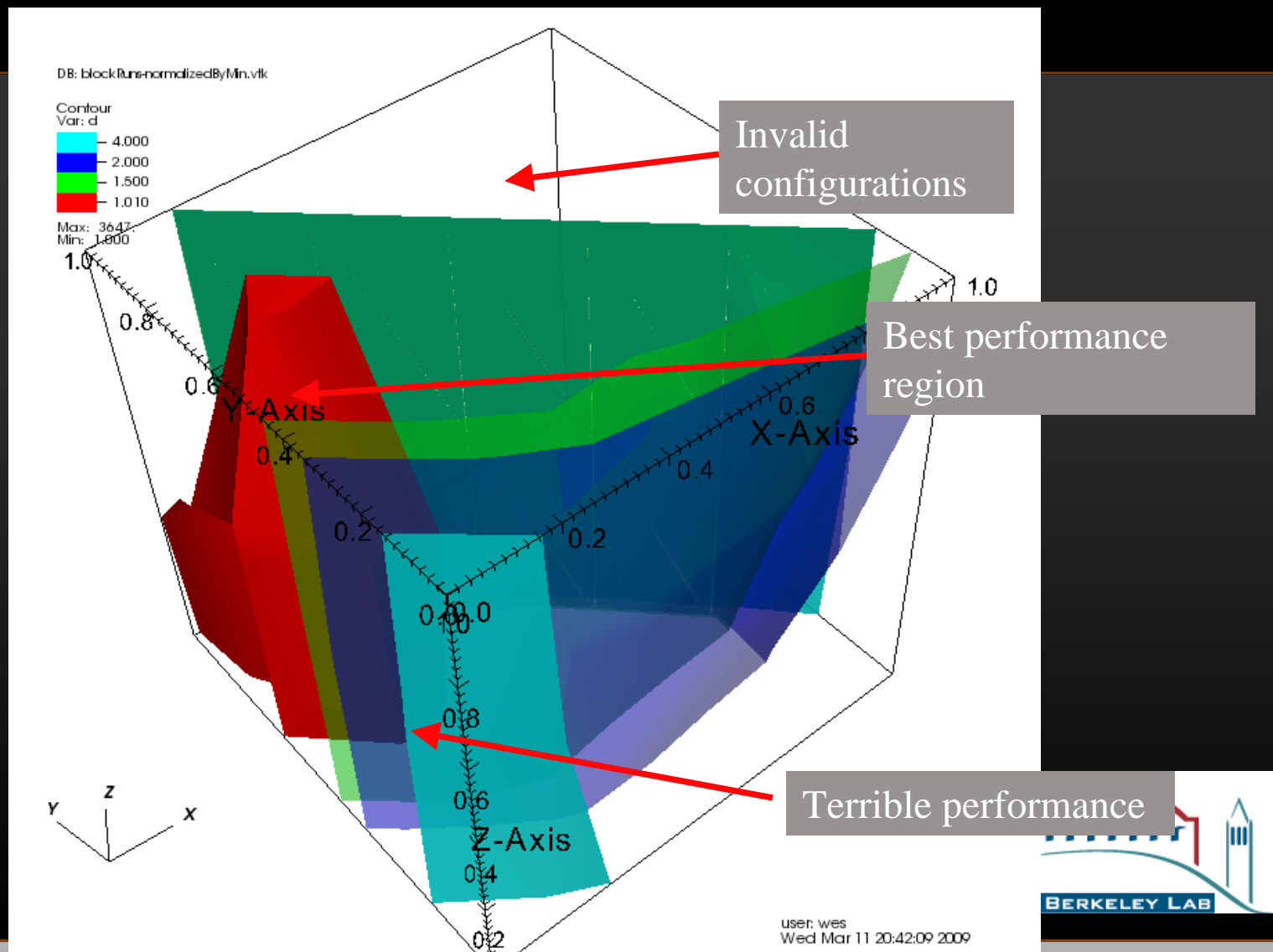
# Thread Size/Shape Test Results (1/3)



# Thread Size/Shape Test Results (2/3)

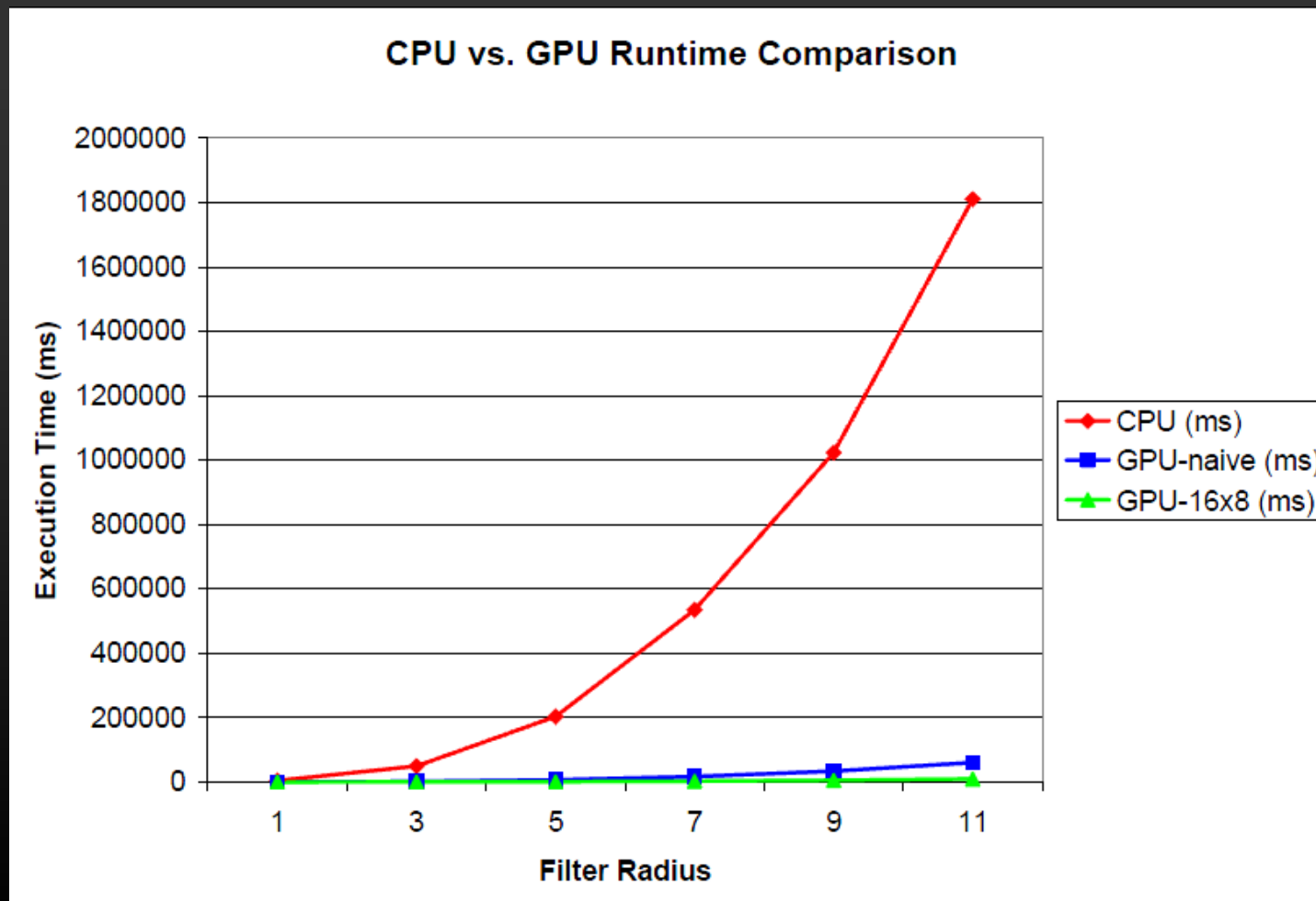


# Thread Size/Shape Test Results (3/3)

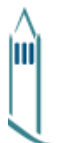
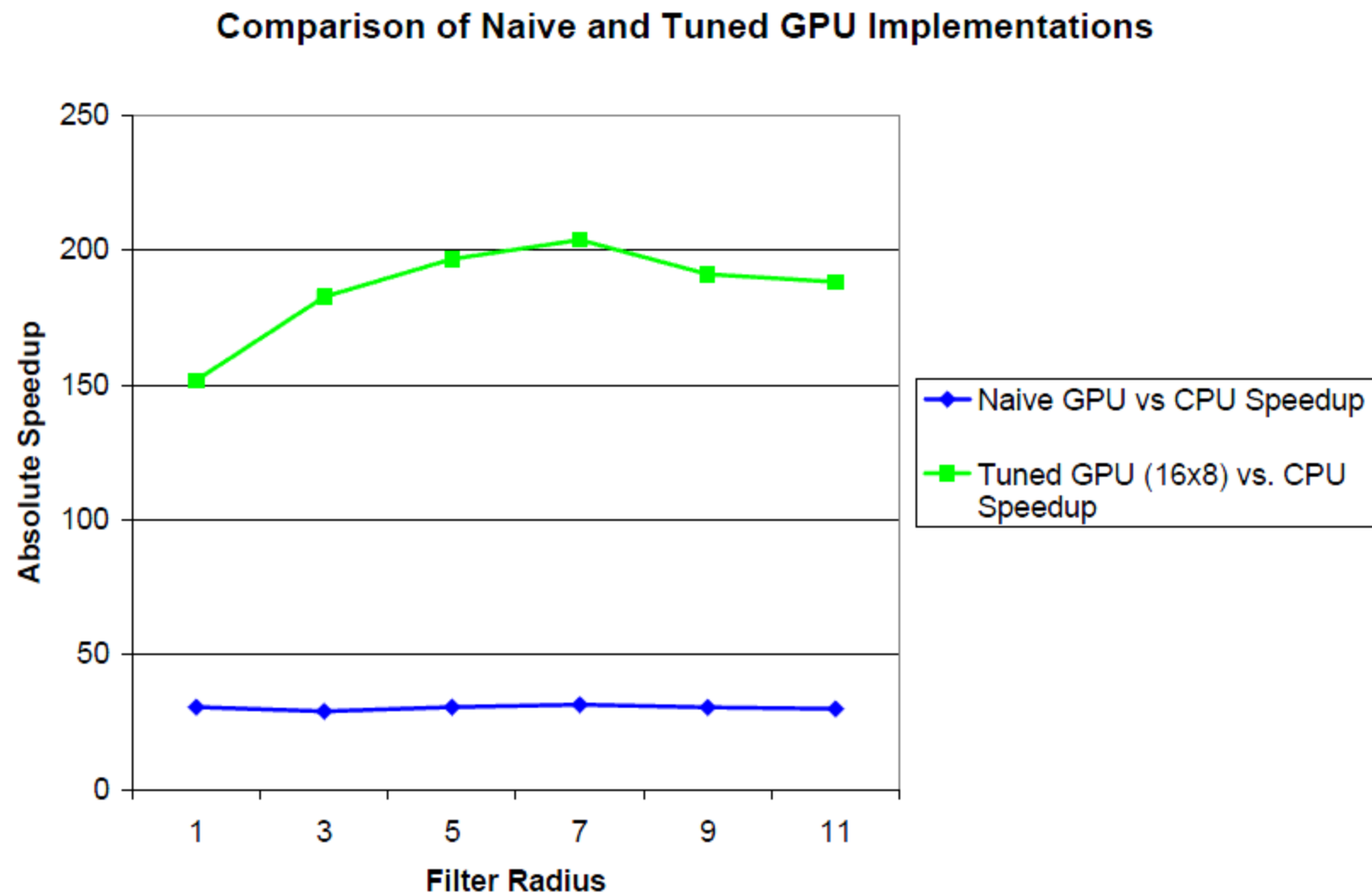




# CPU vs. GPU Performance Comparison (1/2)



# CPU vs. GPU Performance Comparison (2/2)



# Conclusions/Discussion

- **GPU configurations with best performance:**
  - Threads access voxels along depth: coalesced memory access!
  - Use Constant memory rather than global memory to hold filter weights
  - Thread block size/shape: 16x8
- **GPU version outperforms CPU implementation**
  - 30x for naïve implementation.
  - 150x-200x for tuned implementation.
  - Why? Memory bandwidth (142GB/s vs. ~10GB/s) and keeping the memory pipeline full.

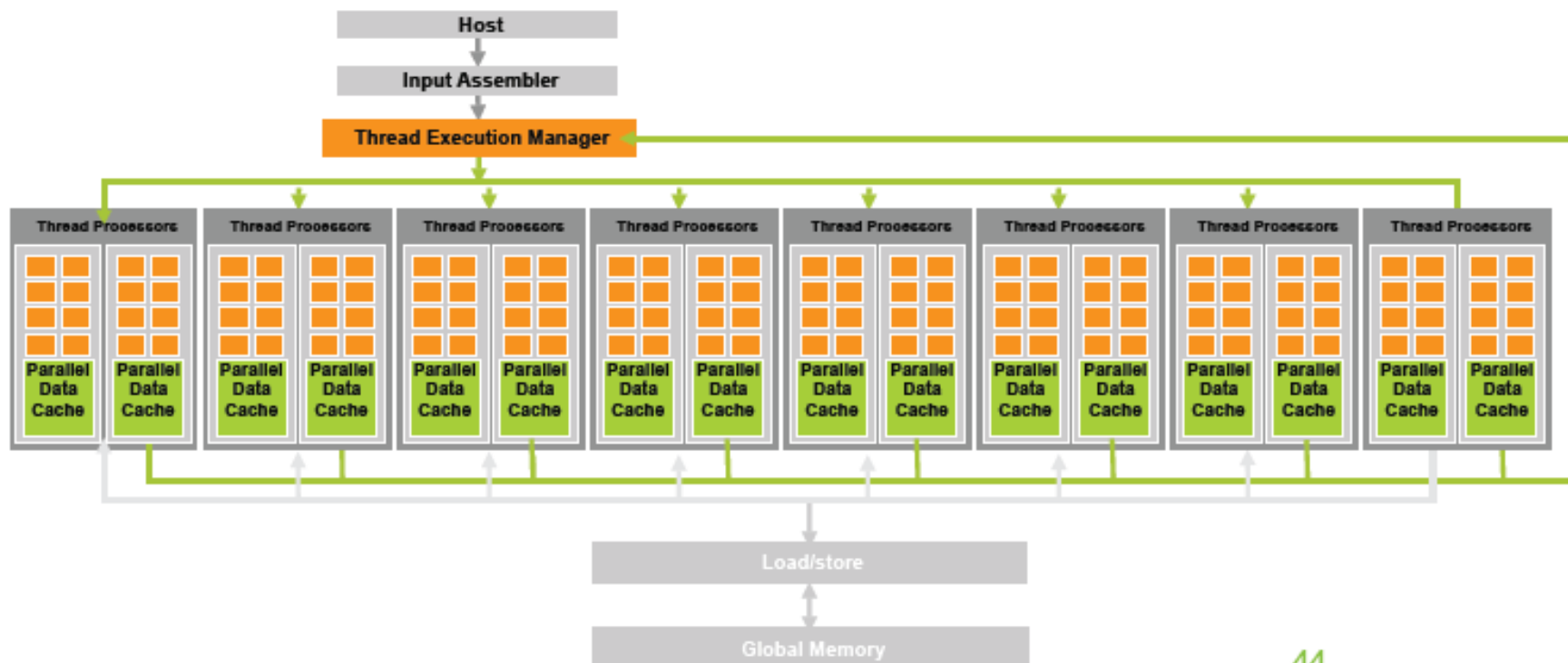




# GPU Computing

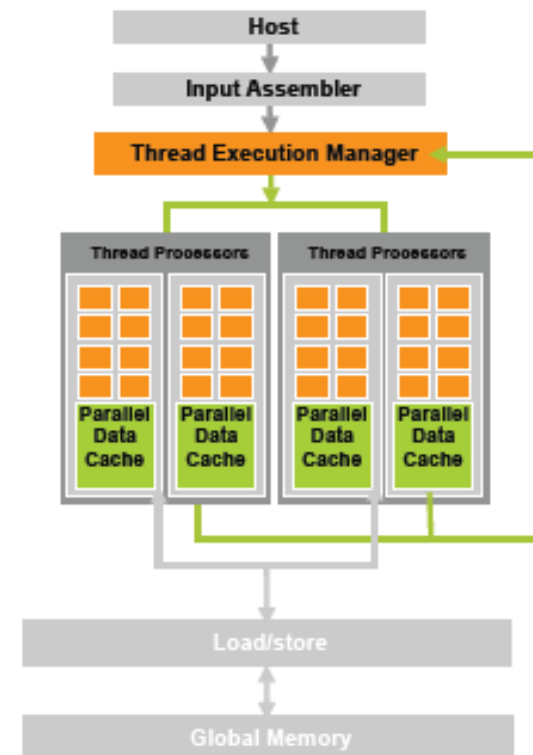
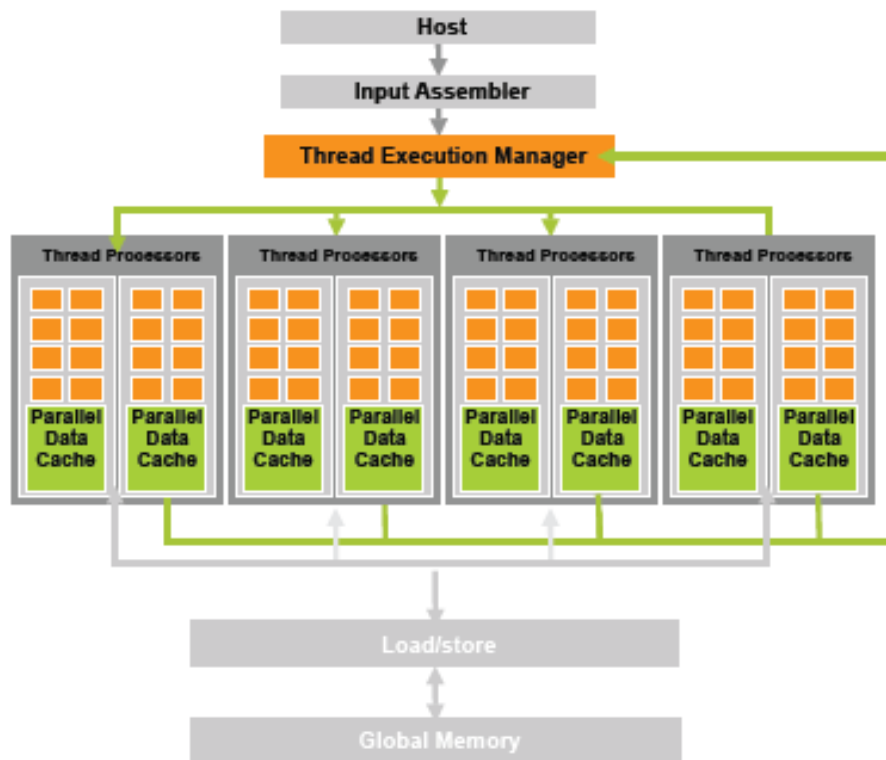


- Processors execute computing threads
- Thread Execution Manager issues threads
- 128 Thread Processors
- Parallel Data Cache accelerates processing



# Scaling the Architecture

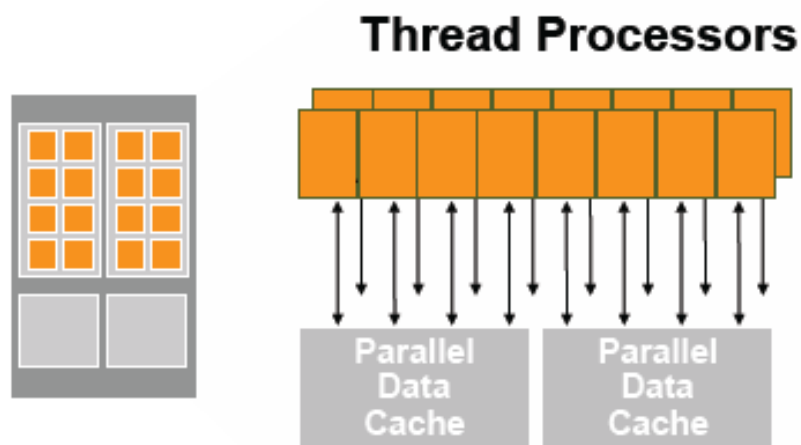
- Same program
- Scalable performance



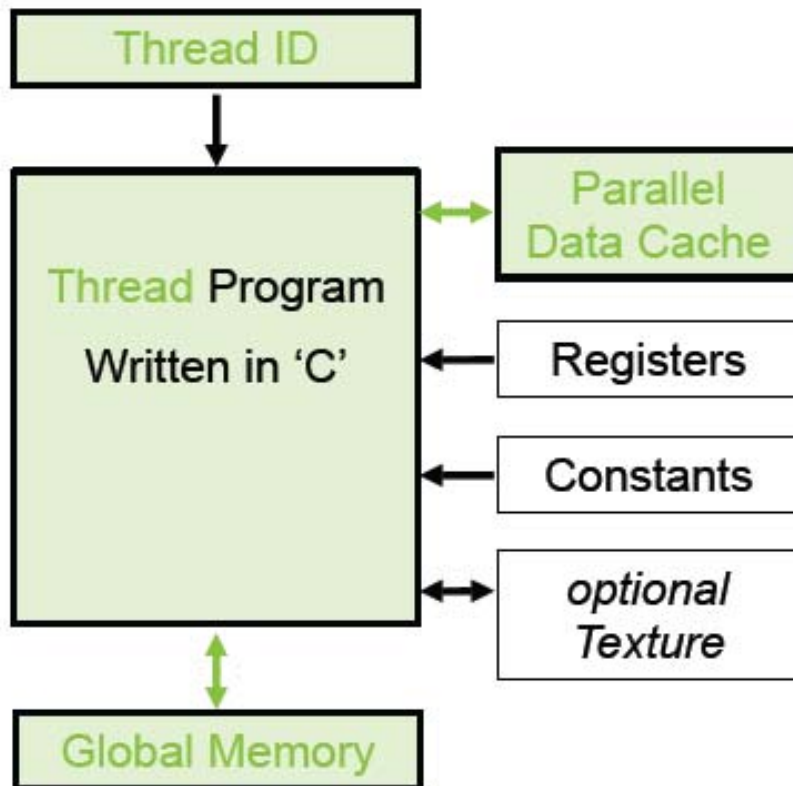
# Thread Processor Group



- 128, 1.35 GHz processors
- 16KB Parallel Data Cache per group
- Scalar architecture
- IEEE 754 Precision



# GPU Computing Model



## Parallel Data Cache

- Dedicated on-chip memory
- Shared between threads for inter-thread communication
- Explicitly managed – software managed cache
- As Fast as Registers