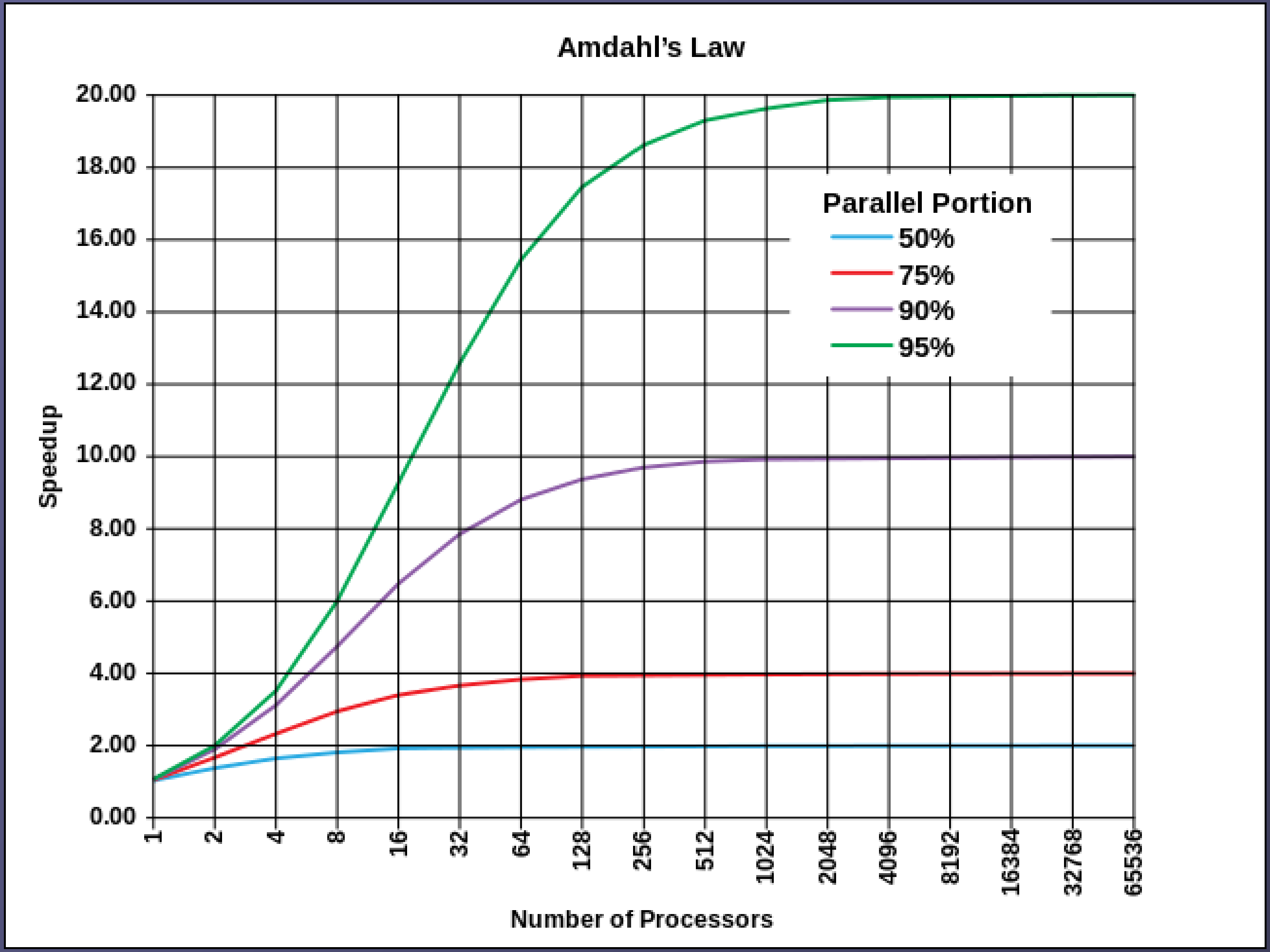
Parallel Computing

Some basic ideas

Amdahl's Law (Gene Amdahl 1967)



Evolution according to Amdahl's law of the theoretical speedup of the execution of a program in function of the number of processors executing it, for different values of p. The speedup is limited by the serial part of the program. For example, if 95% of the program can be parallelized, the theoretical maximum speedup using parallel computing would be 20 times.

By Daniels220 at English Wikipedia - Own work based on: File:AmdahlsLaw.png, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=6678551

Calculate Amdahl's Law:

Let X be the part of my program (in terms of computing time) which can be parallelised. The sequential computing time Tseq is normalized to unity (1), and can be expressed as:

$\mathrm{Tseq} = 1 = X + (1-X)$

The parallel computing time Tpar under ideal conditions (ideal load balancing, ultrafast communication):

$\mathrm{Tpar} = X/p + (1-X)$ with processor number (core number) p

Then the speed-up of the program $S = \mathrm{Tseq} / \mathrm{Tpar}$:

$S = 1 / (1-X+X/p)$; Note: $\mathrm{Tpar}/\mathrm{Tseq} = 1/S$ (sometimes also plotted)

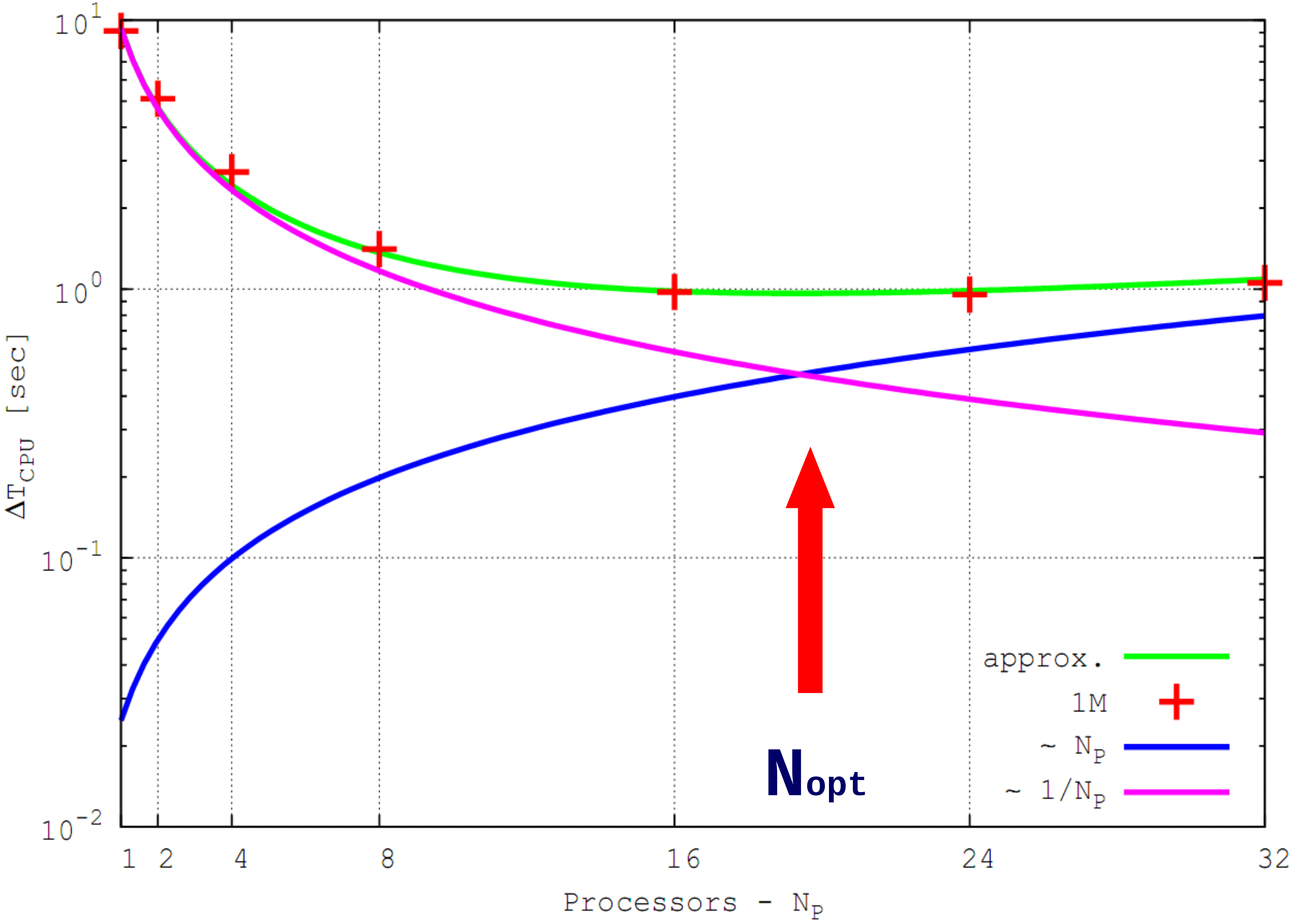
Note the limit if p is very large: $S = 1/(1-X)$. And if $X \sim 1$: $S \sim p$

With communication overhead:

$\mathrm{Tpar} = X/p + (1-X) + \mathrm{Tcomm}$ → $S = 1 / (1-X+X/p+\mathrm{Tcomm})$

If Tcomm independent of p we have for large p: $S = 1 / (1-X + \mathrm{Tcomm}) = \mathrm{const.}$

Parallel code on cluster



Strong and Soft Scaling

- ➔ Strong Scaling: Fixed Problem size, increase p
- ➔ Soft Scaling: Increase Problem size, increase p (constant amount of work per processing element)

Ansatz for Soft Scaling:

- ➔ **Tseq = p = p (X + (1-X))**
- ➔ **Tpar = X + p (1-X)**
- ➔ **S = Tseq/Tpar = p / (X+p (1-X))**

If X~1: S = p ; Tpar = X = const.

ΦGPU – NBODY Code

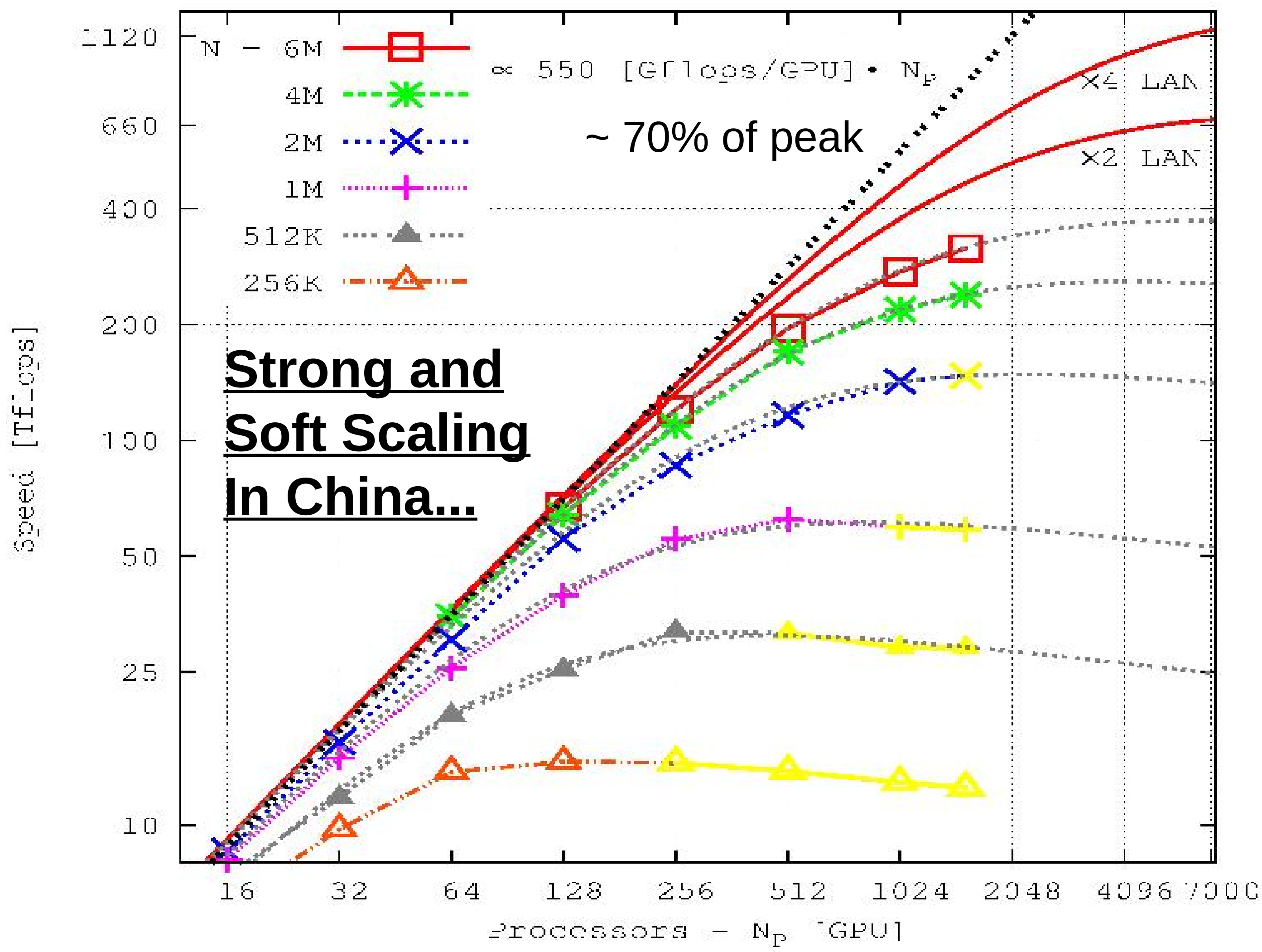
中国科学院国家天文台

National Astronomical Observatories, CAS

350 Teraflop/s
1600 GPUs .
440 cores
= 704.000
GPU-Cores

Using
Mole-8.5
of
IPE/CAS
Beijing

Berczik et al.
2013



~ 70% of peak

Strong and Soft Scaling In China...

中国科学院过程工程研究所

Institute Of Process Engineering, Chinese Academy Of Sciences

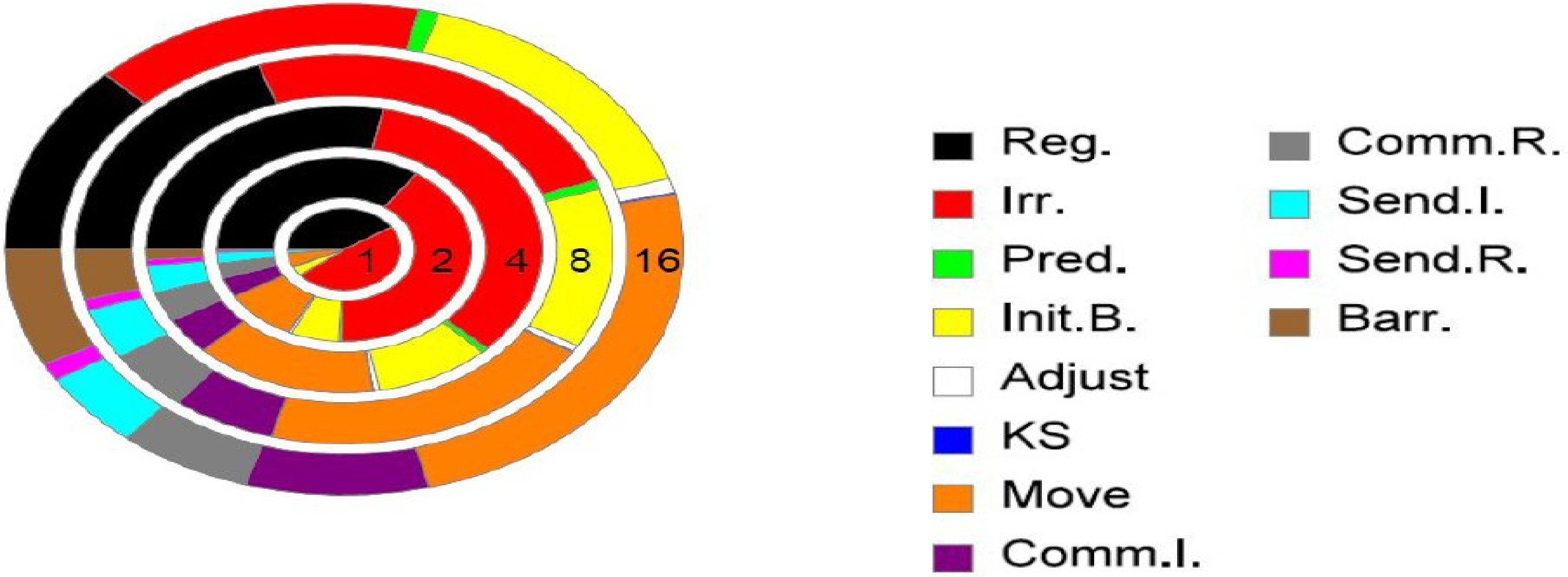
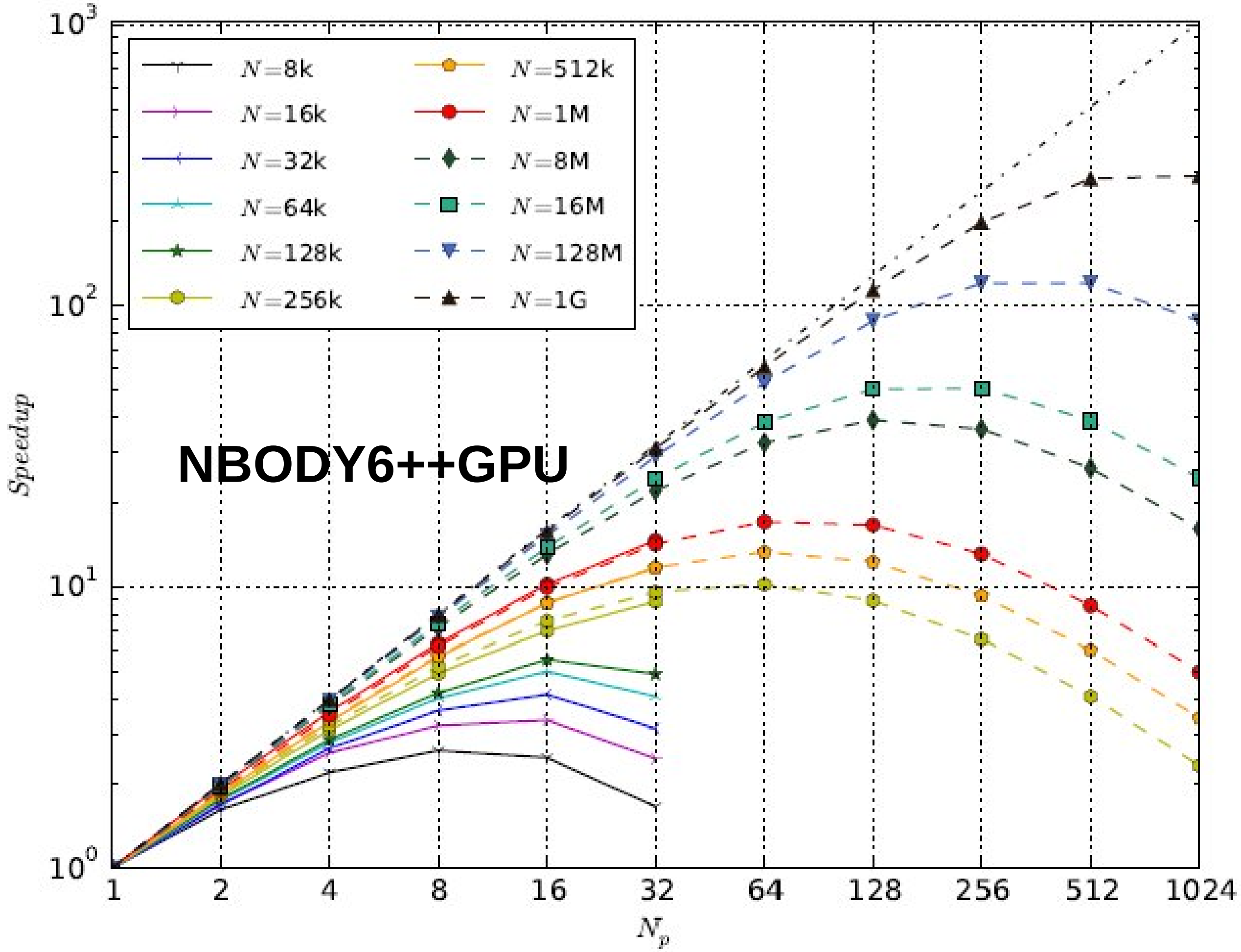


Table 1 Main components of NBODY6++

Description	Timing variable	Expected scaling		Fitting value [sec]
		N	N_p	
Regular force computation	T_{reg}	$\mathcal{O}(N_{\mathrm{reg}} \cdot N)$	$\mathcal{O}(N_p^{-1})$	$(2.2 \cdot 10^{-9} \cdot N^{2.11} + 10.43) \cdot N_p^{-1}$
Irregular force computation	T_{irr}	$\mathcal{O}(N_{\mathrm{irr}} \cdot \langle N_{nb} \rangle)$	$\mathcal{O}(N_p^{-1})$	$(3.9 \cdot 10^{-7} \cdot N^{1.76} - 16.47) \cdot N_p^{-1}$
Prediction	T_{pre}	$\mathcal{O}(N^{kn_p})$	$\mathcal{O}(N_p^{-kp_p})$	$(1.2 \cdot 10^{-6} \cdot N^{1.51} - 3.58) \cdot N_p^{-0.5}$
Data moving	T_{mov}	$\mathcal{O}(N^{kn_{m1}})$	$\mathcal{O}(1)$	$2.5 \cdot 10^{-6} \cdot N^{1.29} - 0.28$
MPI communication (regular)	T_{mcr}	$\mathcal{O}(N^{kn_{cr}})$	$\mathcal{O}(kp_{cr} \cdot \frac{N_p - 1}{N_p})$	$(3.3 \cdot 10^{-6} \cdot N^{1.18} + 0.12)(1.5 \cdot \frac{N_p - 1}{N_p})$
MPI communication (irregular)	T_{mci}	$\mathcal{O}(N^{kn_{ci}})$	$\mathcal{O}(kp_{ci} \cdot \frac{N_p - 1}{N_p})$	$(3.6 \cdot 10^{-7} \cdot N^{1.40} + 0.56)(1.5 \cdot \frac{N_p - 1}{N_p})$
Synchronization	T_{syn}	$\mathcal{O}(N^{kn_s})$	$\mathcal{O}(N_p^{kp_s})$	$(4.1 \cdot 10^{-8} \cdot N^{1.34} + 0.07) \cdot N_p$
Sequential parts on host	T_{host}	$\mathcal{O}(N^{kn_h})$	$\mathcal{O}(1)$	$4.4 \cdot 10^{-7} \cdot N^{1.49} + 1.23$



NBODY6++GPU

Huang, Berczik, Spurzem, Res. Astron. Astroph. 2016, 16, 11.

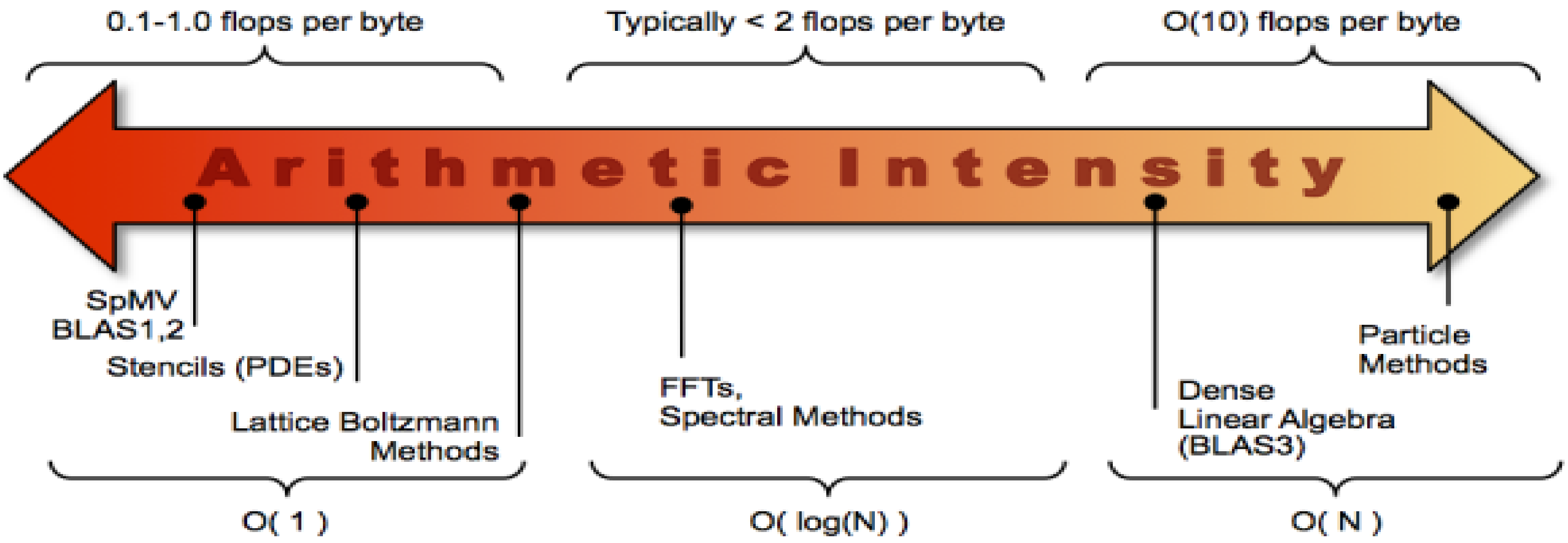
Fig. 2 The speed-up (S) of NBODY6++ as a function of particle number (N) and processor number (N_p). Solid points are the measured speed-up ratio between sequential and parallel wall-clock time, dash lines predict the performance of larger scale simulations further. The symbols used in figure have the magnitudes: $1k = 1,024$, $1M = 1k^2$ and $1G = 1k^3$.

Roofline Performance Model (LBL)

http://crd.lbl.gov/departments/computer-science/PAR/research/roofline

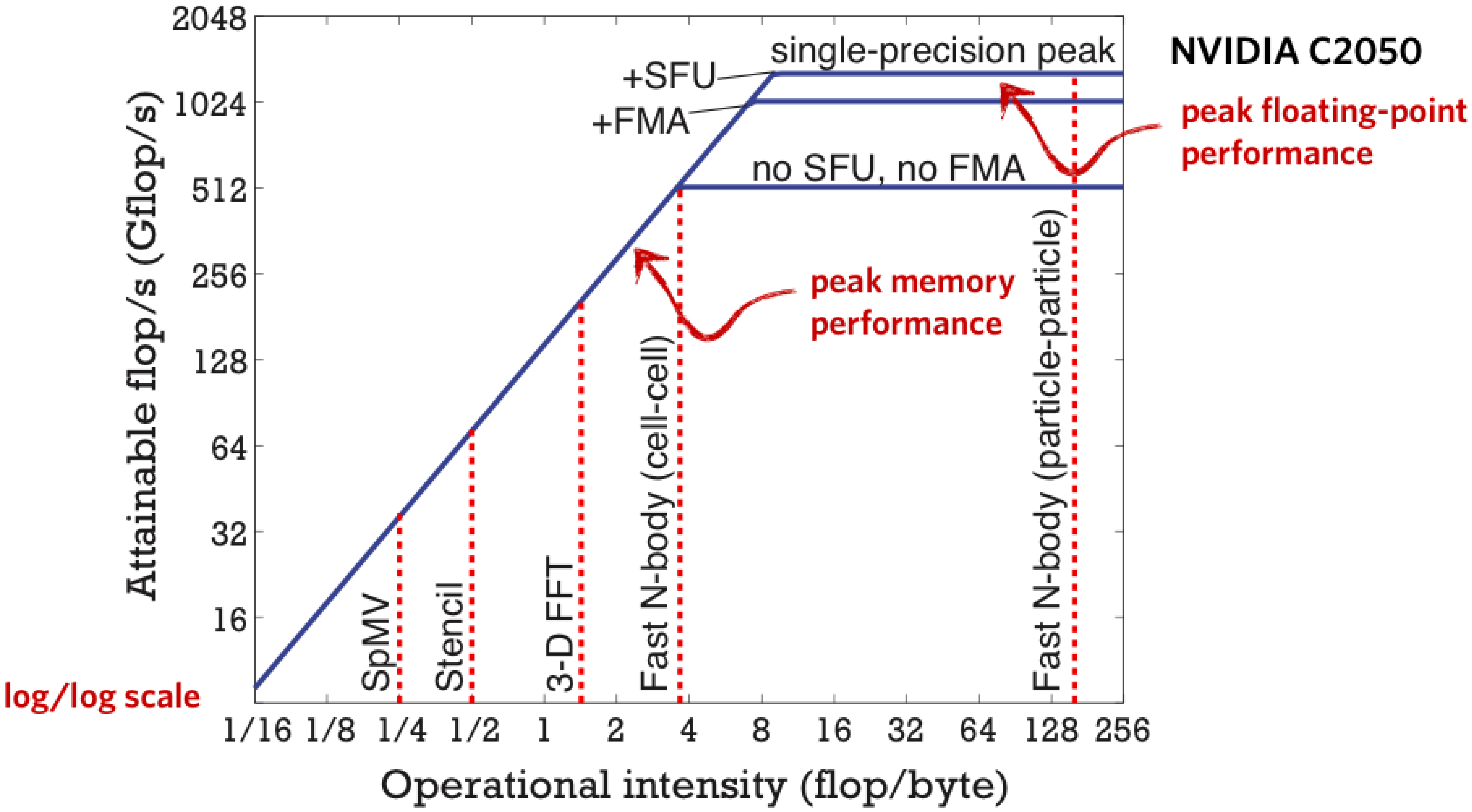
Arithmetic Intensity

The core parameter behind the Roofline model is Arithmetic Intensity. Arithmetic Intensity is the ratio of total floating-point operations to total data movement (bytes).



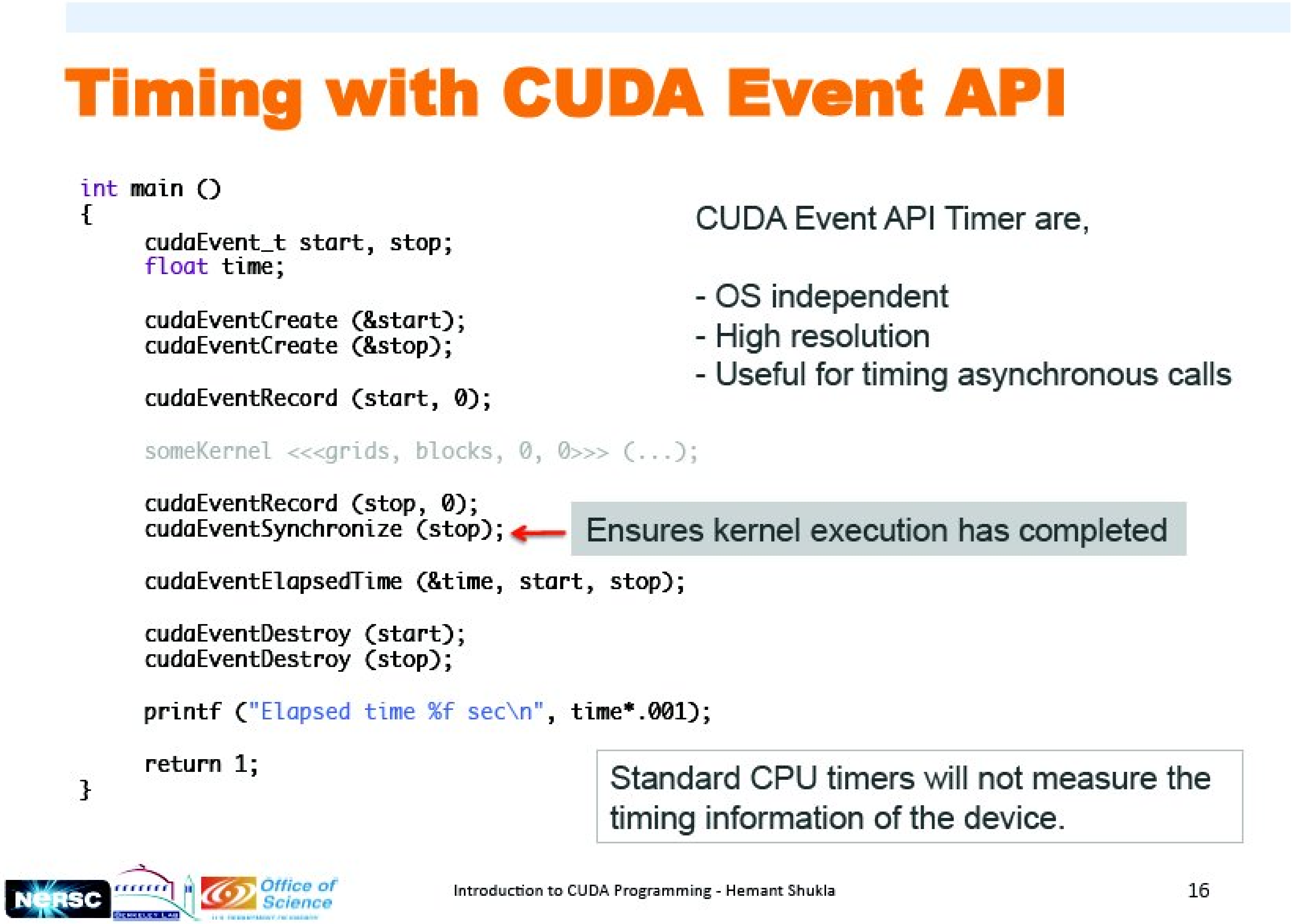
Roofline Performance Model (LBL)

http://lorenabarba.com/wp-content/uploads/2012/01/roofline_slide.png



Parallel Computing

Matrix Multiply and Debugging



Timing with CUDA Event API

```
int main ()
{
        cudaEvent_t start, stop;
        float time;

        cudaEventCreate (&start);
        cudaEventCreate (&stop);

        cudaEventRecord (start, 0);

        someKernel <<<grids, blocks, 0, 0>>> (...);

        cudaEventRecord (stop, 0);
        cudaEventSynchronize (stop);

        cudaEventElapsedTime (&time, start, stop);

        cudaEventDestroy (start);
        cudaEventDestroy (stop);

        printf ("Elapsed time %f sec\n", time*.001);

        return 1;
}
```

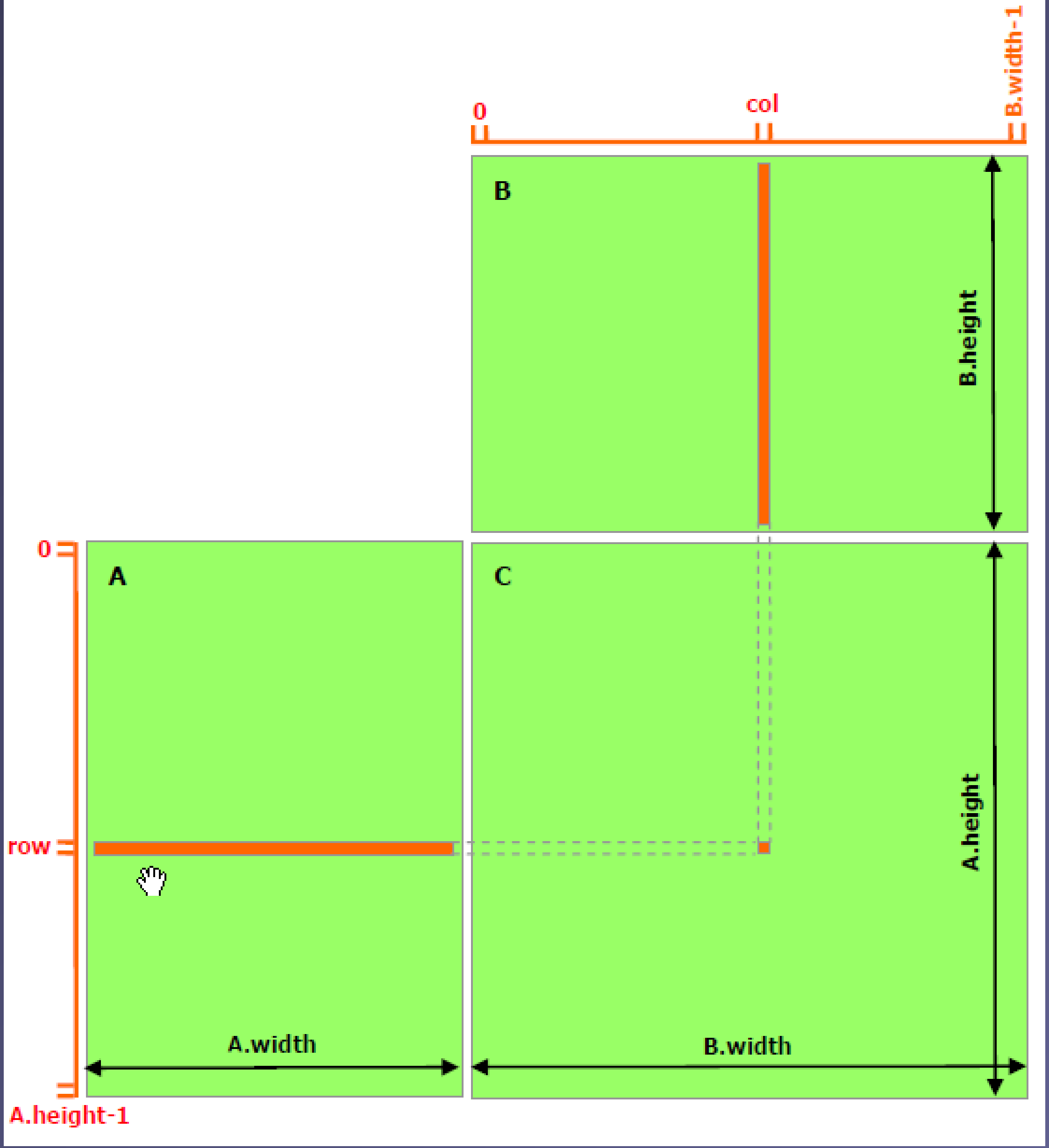
Ensures kernel execution has completed

CUDA Event API Timer are,

- OS independent
- High resolution
- Useful for timing asynchronous calls

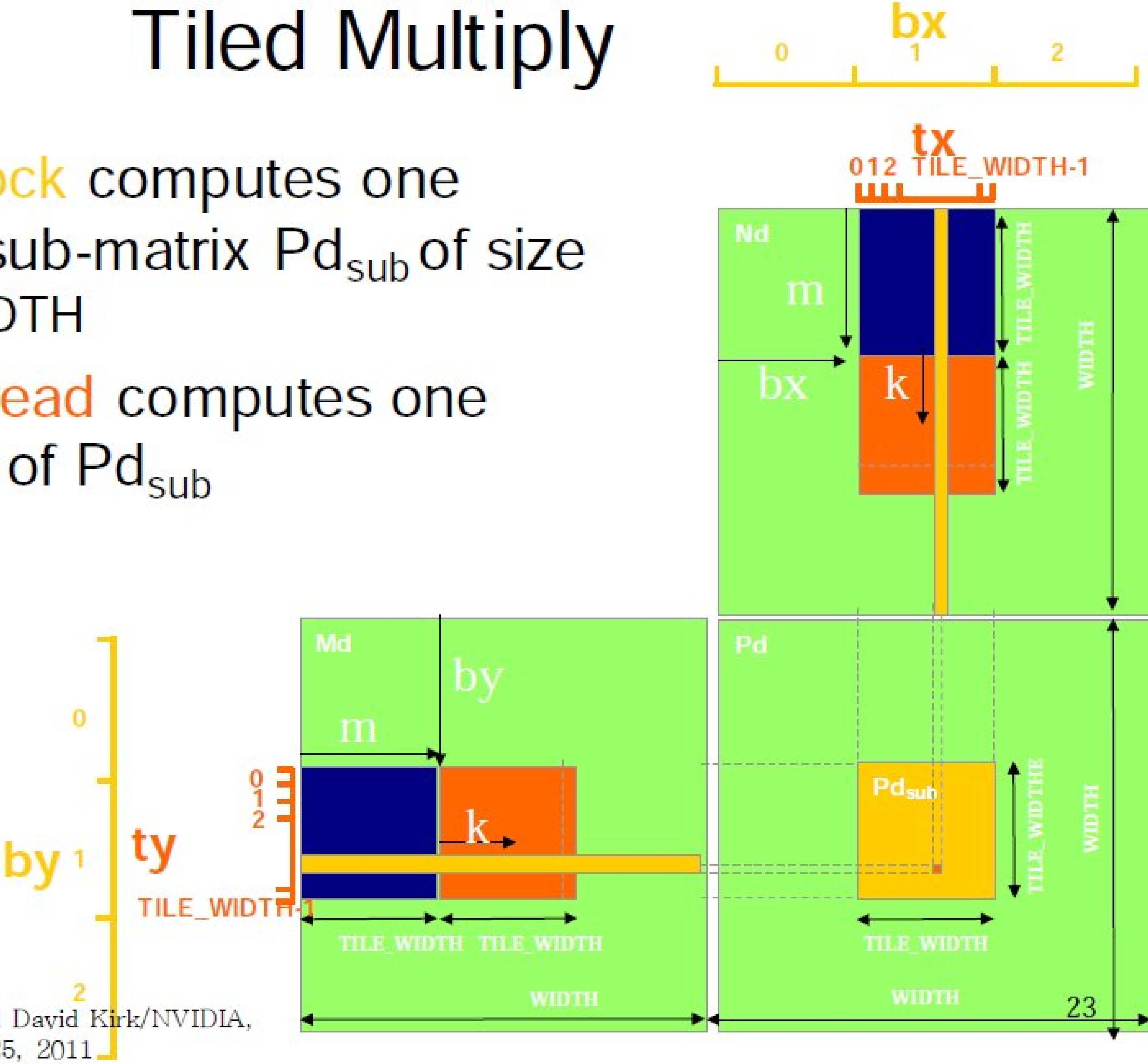
Standard CPU timers will not measure the timing information of the device.

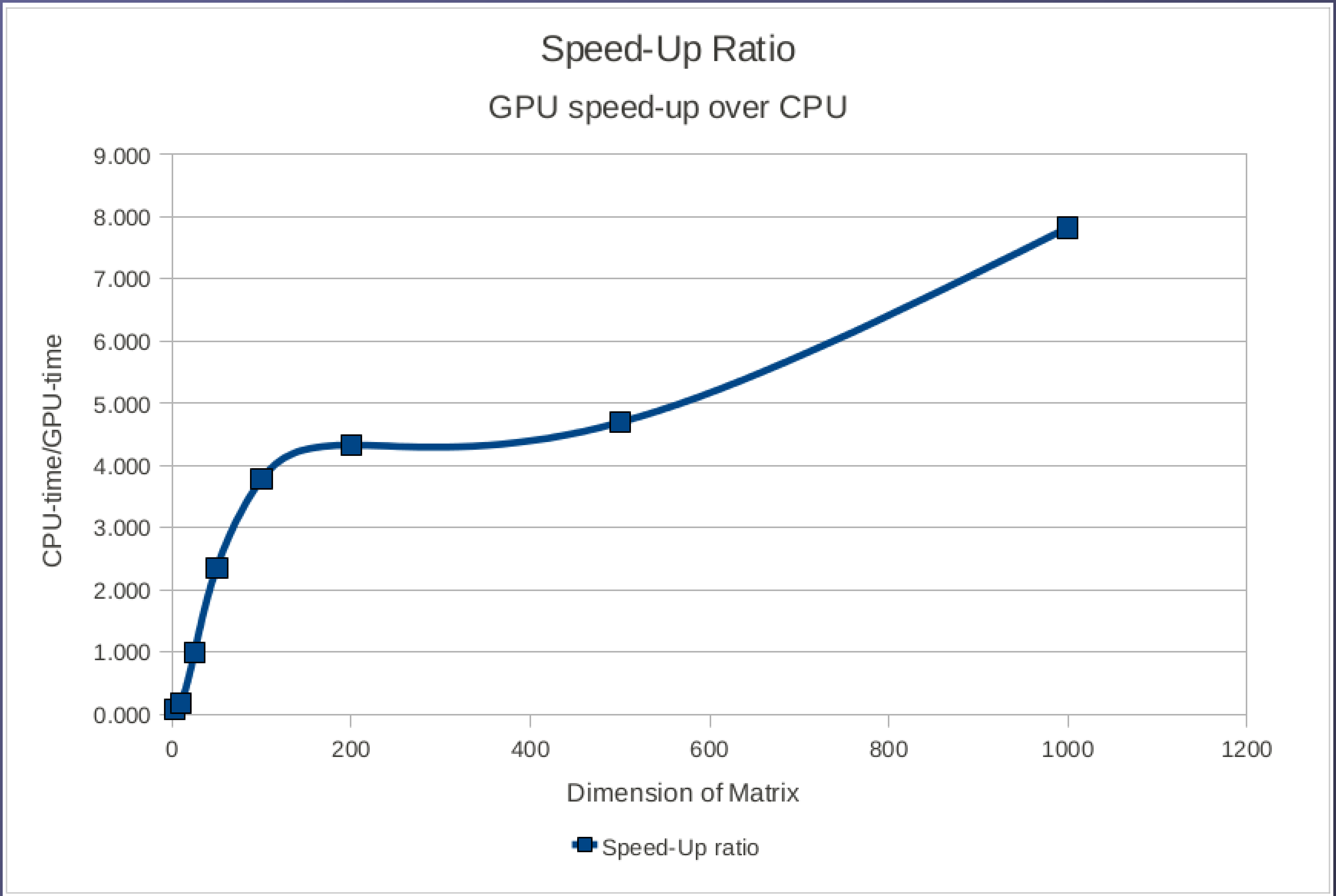
Intuitive multiply



Tiled Multiply

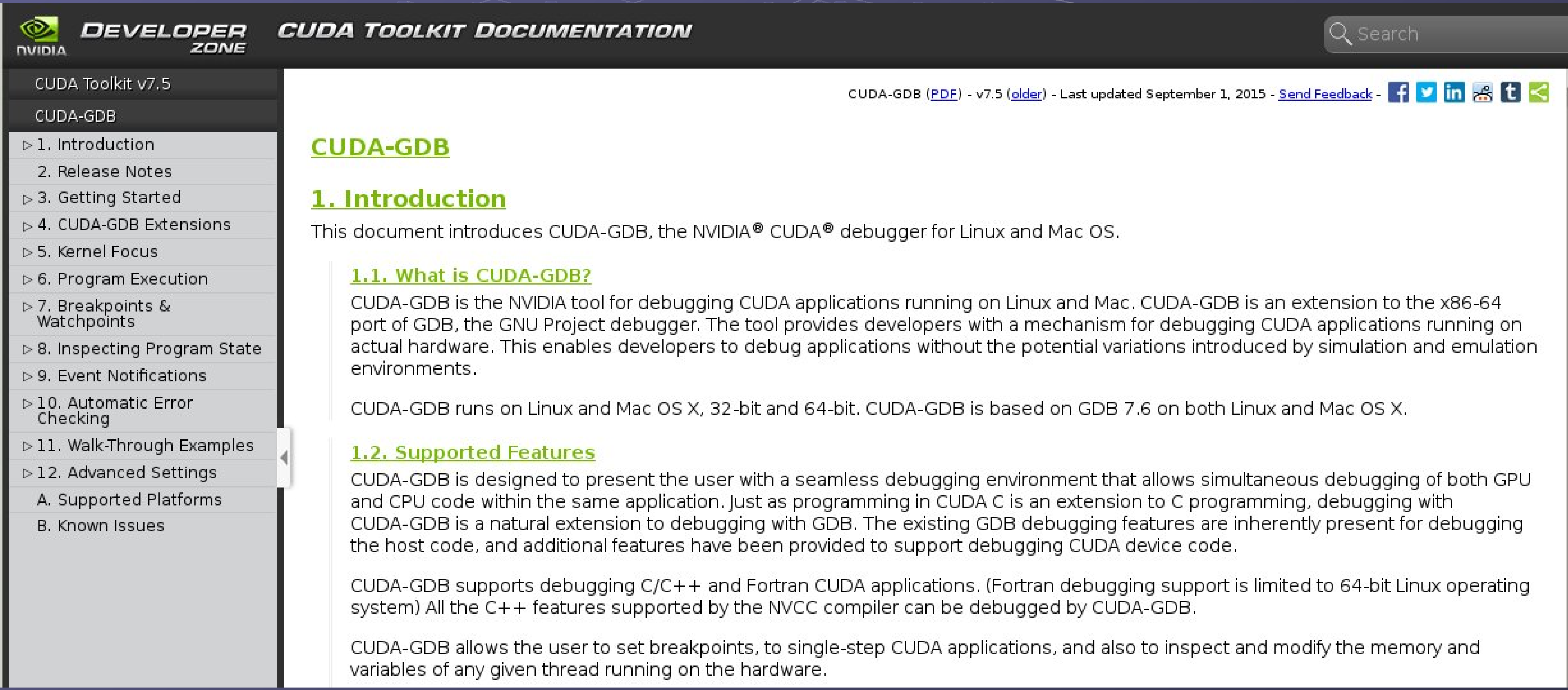
- Each block computes one square sub-matrix Pd_{sub} of size TILE_WIDTH
- Each thread computes one element of Pd_{sub}




Speed-Up Ratio
GPU speed-up over CPU
CPU-time/GPU-time
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
0
200
400
600
800
1000
1200
Dimension of Matrix
Speed-Up ratio

CUDA – GNU Debugger – CUDA-gdb

http://docs.nvidia.com/cuda/cuda-gdb/index.html



CUDA-GDB (PDF) - v7.5 (older) - Last updated September 1, 2015 - Send Feedback -

CUDA-GDB

1. Introduction

This document introduces CUDA-GDB, the NVIDIA® CUDA® debugger for Linux and Mac OS.

1.1. What is CUDA-GDB?

CUDA-GDB is the NVIDIA tool for debugging CUDA applications running on Linux and Mac. CUDA-GDB is an extension to the x86-64 port of GDB, the GNU Project debugger. The tool provides developers with a mechanism for debugging CUDA applications running on actual hardware. This enables developers to debug applications without the potential variations introduced by simulation and emulation environments.

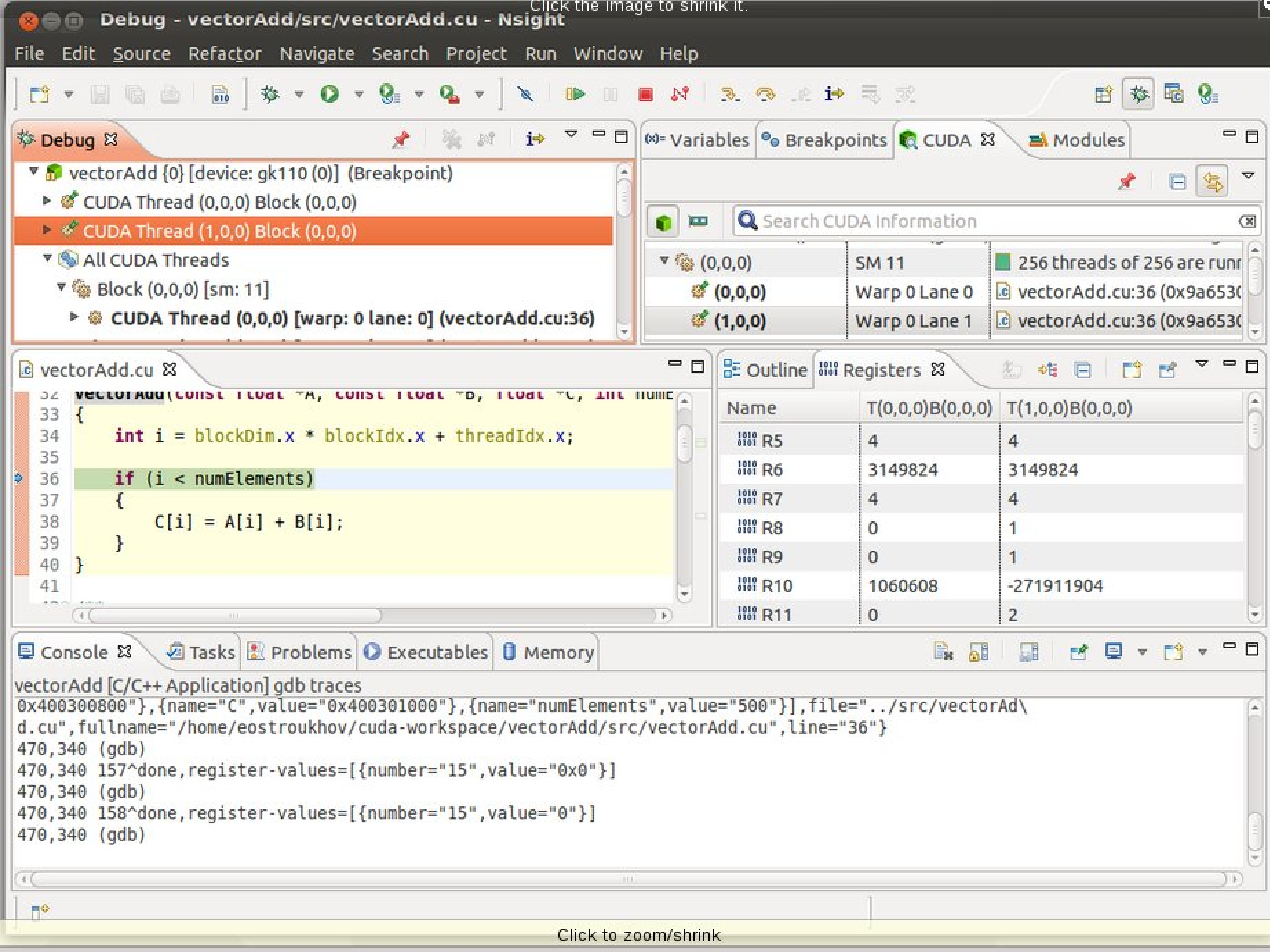
CUDA-GDB runs on Linux and Mac OS X, 32-bit and 64-bit. CUDA-GDB is based on GDB 7.6 on both Linux and Mac OS X.

1.2. Supported Features

CUDA-GDB is designed to present the user with a seamless debugging environment that allows simultaneous debugging of both GPU and CPU code within the same application. Just as programming in CUDA C is an extension to C programming, debugging with CUDA-GDB is a natural extension to debugging with GDB. The existing GDB debugging features are inherently present for debugging the host code, and additional features have been provided to support debugging CUDA device code.

CUDA-GDB supports debugging C/C++ and Fortran CUDA applications. (Fortran debugging support is limited to 64-bit Linux operating system) All the C++ features supported by the NVCC compiler can be debugged by CUDA-GDB.

CUDA-GDB allows the user to set breakpoints, to single-step CUDA applications, and also to inspect and modify the memory and variables of any given thread running on the hardware.



Click the image to shrink it.
Debug - vectorAdd/src/vectorAdd.cu - Nsight
File Edit Source Refactor Navigate Search Project Run Window Help
Debug
Variables Breakpoints CUDA Modules
Search CUDA Information
vectorAdd.cu
Outline Registers
Console Tasks Problems Executables Memory
Click to zoom/shrink

- vectorAdd {0} [device: gk110 (0)] (Breakpoint)
  - CUDA Thread (0,0,0) Block (0,0,0)
  - CUDA Thread (1,0,0) Block (0,0,0)
  - All CUDA Threads
    - Block (0,0,0) [sm: 11]
      - CUDA Thread (0,0,0) [warp: 0 lane: 0] (vectorAdd.cu:36)

(0,0,0)	SM 11	🟩 256 threads of 256 are runn
(0,0,0)	Warp 0 Lane 0	vectorAdd.cu:36 (0x9a653(
(1,0,0)	Warp 0 Lane 1	vectorAdd.cu:36 (0x9a653(

```
vectorAdd(const float *A, const float *B, float *C, int nume
{
    int i = blockDim.x * blockIdx.x + threadIdx.x;

    if (i < numElements)
    {
        C[i] = A[i] + B[i];
    }
}
```

Name	T(0,0,0)B(0,0,0)	T(1,0,0)B(0,0,0)
R5	4	4
R6	3149824	3149824
R7	4	4
R8	0	1
R9	0	1
R10	1060608	-271911904
R11	0	2

vectorAdd [C/C++ Application] gdb traces

```
0x400300800"},{name="C",value="0x400301000"},{name="numElements",value="500"}],file="../src/vectorAd\
d.cu",fullname="/home/eostroukhov/cuda-workspace/vectorAdd/src/vectorAdd.cu",line="36"}
470,340 (gdb)
470,340 157^done,register-values=[{number="15",value="0x0"}]
470,340 (gdb)
470,340 158^done,register-values=[{number="15",value="0"}]
470,340 (gdb)
```

Wrapping Up 1

Exercises (CUDA Lectures in afternoon)

1. hello, device- first kernel call, hello world, GPU properties
2. add - vector addition using one thread in one block only
3. add-index - vector addition using blocks in parallel,
   one thread per block only.
4. add-parallel - vector addition using all blocks and threads in parallel
5. dot - scalar product using shared memory of one block
   only for reduction
6. dot-full - scalar product using shared memory and
   atomic add across blocks
7. histo - histogram using fat threads and atomic add
   on shared and global memory, timing
8. dot-perfect - scalar product using fat threads, shared memory,
   final reduction on host.
9. matmul - matrix multiplication with tiled access shared memory

Wrapping Up 2

Elements of CUDA C learnt:

threadId.x , blockId.x, blockDim.x, gridDim.x	Threads, Blocks
(threadId.y, blockId.y, blockdim.y, gridDim.y	work with 2D grids)
kernel<<<n,m>>> (...)	kernel calls
__device__ __global__	device code
__shared__	shared memory on GPU
cudaMalloc / cudaFree	manage global memory of GPU
cudaMemcpy / cudaMemset	copy/set to or from memory
cudaGetDeviceProperties	get device properties in program
cudaEventCreate, cudaEventRecord, cudaEventSynchronize, cudaEventElapsedTime, cudaEventDestroy	CUDA profiling
AtomicAdd	atomic functions

Wrapping Up 3

What we have not yet learnt...

__constant__	constant memory on GPU
cudaBindTexture	using texture memory
fat threads for 2D and 3D stencils	thread coalescence opt.
cudaStreamCreate, cudaStreamDestroy	working with CUDA streams