GPU PROGRAMMING 101

GRIDKA SCHOOL 2018

30 August 2018 | Andreas Herten | Forschungszentrum Jülich

About, Outline

About me

- Physics: Dr. at PANDA (Particle Tracking with GPUs)
- Since then: NVIDIA Application Lab, POWER Acceleration and Design Centre
  Optimizing scientific applications for/on GPUs at Jülich Supercomputing Centre

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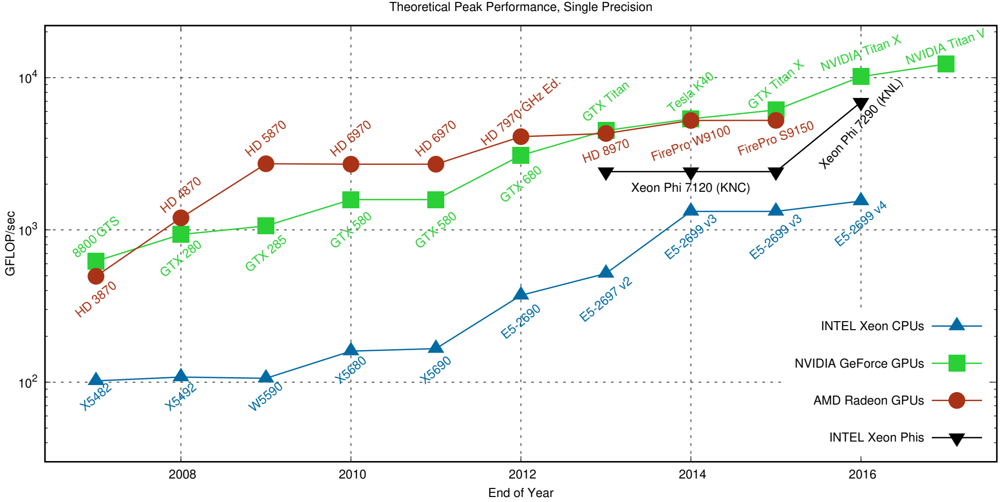
Status Quo

GPU all around

- 1999: General computations with shaders of *graphics hardware*
- 2001: NVIDIA GeForce 3 with programmable shaders [2]; 2003: DirectX 9 at ATI
- 2007: CUDA
- 2018: Top 500: 20 % with GPUs (#1, #3), Green 500: 7 of top 10 with GPUs

Status Quo

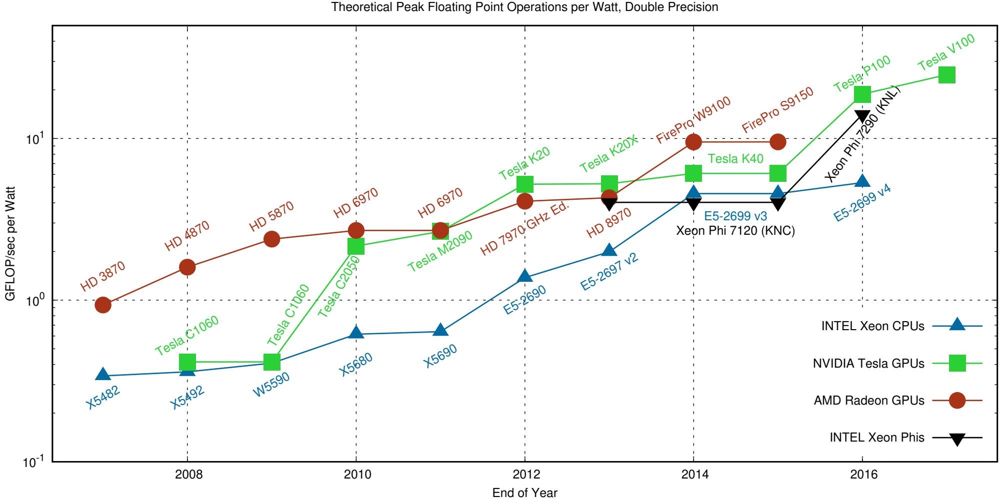
Peak performance single precision



Graphic: Rupp [3]

Status Quo

Performance per Watt



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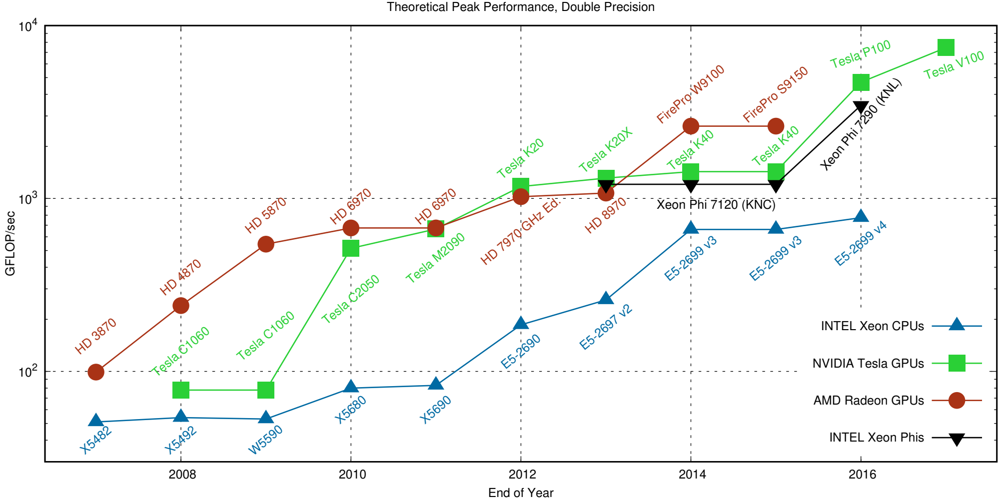

Graphic: Rupp [3]

Status Quo

JUWELS


JUWELS
But why?!

JUWELS

But why?!

Let’s find out!

Platform

CPU vs. GPU

A matter of specialties

Graphics: Lee [4] and Shearings Holidays [5]

CPU vs. GPU

A matter of specialties

Transporting one

Transporting many

Graphics: Lee [4] and Shearings Holidays [5]

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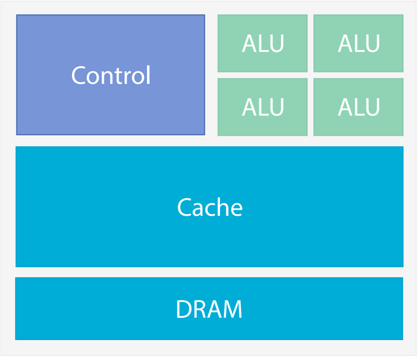
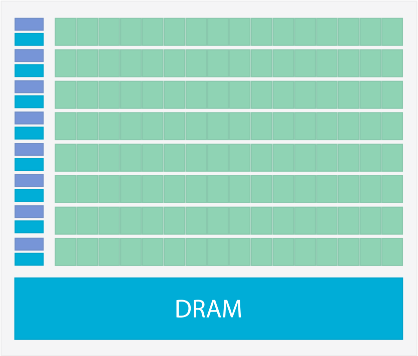
CPU vs. GPU

Chip





GPU Architecture

Overview

Aim: Hide Latency

Everything else follows

GPU Architecture

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Everything else follows

SIMT

Asynchronicity

Memory

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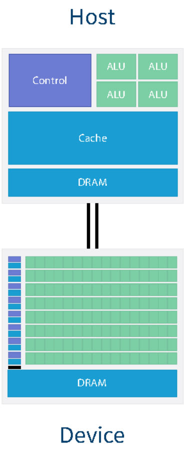
Memory

Memory

GPU memory ain't no CPU memory

- GPU: accelerator / extension card

→ Separate device from CPU



Memory

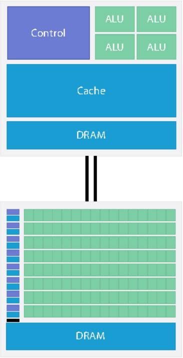
GPU memory ain't no CPU memory

Unified Virtual Addressing

- GPU: accelerator / extension card

→ Separate device from CPU
Separate memory, but UVA

Host



Device

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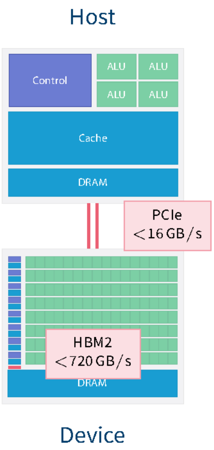

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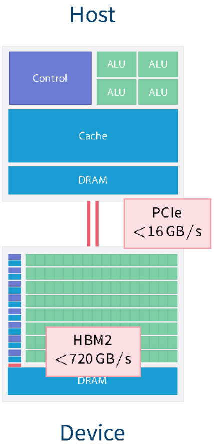
Separate memory, but UVA

- Memory transfers need special consideration!

Do as little as possible!



Memory

GPU memory ain't no CPU memory

Unified Memory

- GPU: accelerator / extension card

→ Separate device from CPU

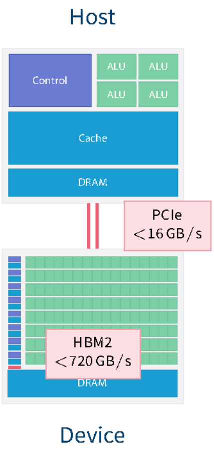
Separate memory, but UVA and UM

- Memory transfers need special consideration!

  Do as little as possible!

- Formerly: Explicitly copy data to/from GPU

  Now: Done automatically (performance…?)



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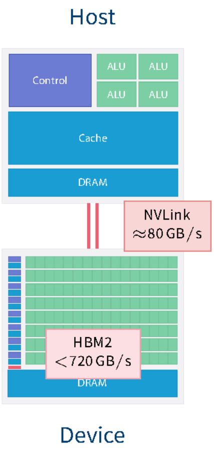

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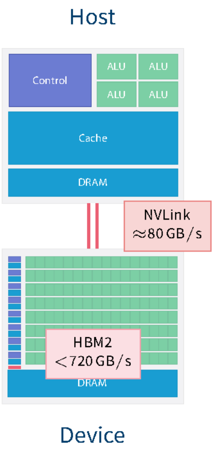
P100

16 GB RAM, 720 GB/s



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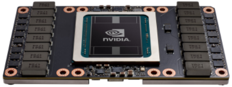
P100

16 GB RAM, 720 GB/s

V100

32 GB RAM, 900 GB/s



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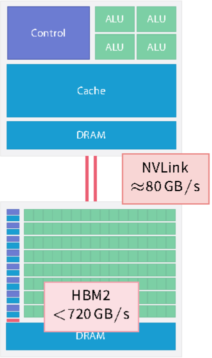

Device

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GPU Architecture

Overview

Aim: Hide Latency

Everything else follows

SIMT

Asynchronicity

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Async

Following different streams

- Problem: Memory transfer is comparably slow
  Solution: Do something else in meantime (**computation**)!

→ Overlap tasks

- Copy and compute engines run separately (*streams*)

- GPU needs to be fed: Schedule many computations
- CPU can do other work while GPU computes; synchronization
- Also: Fast switching of contexts to keep GPU busy (*KGB*)

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SIMT

Of threads and warps

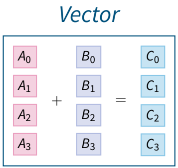
- CPU:
  - Single Instruction, Multiple Data (SIMD)

Scalar

$$A_0 + B_0 = C_0$$
$$A_1 + B_1 = C_1$$
$$A_2 + B_2 = C_2$$
$$A_3 + B_3 = C_3$$

SIMT

Of threads and warps



- CPU:
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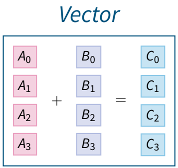
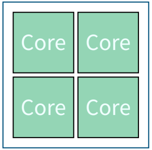
SIMT

Of threads and warps

- CPU:
  - Single Instruction, Multiple Data (SIMD)
  - Simultaneous Multithreading (SMT)





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SIMT

Of threads and warps

- CPU:
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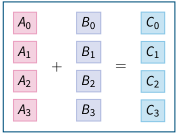
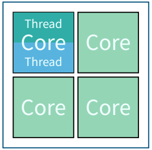
Vector



SMT

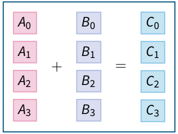


SIMT

Of threads and warps

- CPU:
  - Single Instruction, Multiple Data (SIMD)
  - Simultaneous Multithreading (SMT)
- GPU: Single Instruction, Multiple Threads (SIMT)

Vector



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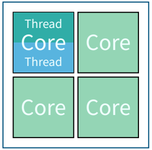

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Of threads and warps

- CPU:
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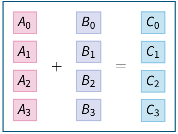
  - Simultaneous Multithreading (SMT)
- GPU: Single Instruction, Multiple Threads (SIMT)

Vector



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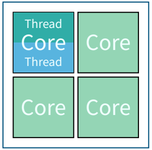

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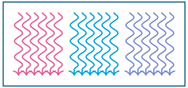
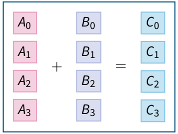


SIMT

Of threads and warps

- CPU:
  - Single Instruction, Multiple Data (SIMD)
  - Simultaneous Multithreading (SMT)
- GPU: Single Instruction, Multiple Threads (SIMT)
  - CPU core ≊ GPU multiprocessor (SM)
  - Working unit: set of threads (32, a *warp*)
  - Fast switching of threads (large register file)
  - Branching 

Vector



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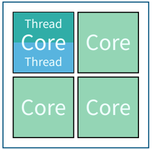

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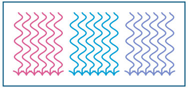

SIMT

Of t

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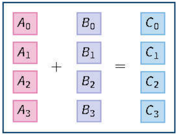

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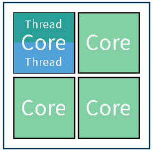
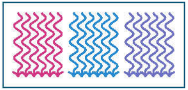


SIMT

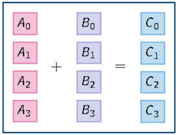


Graphics: volta-pictures

SIMT

Of t

Vector



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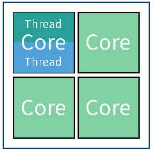

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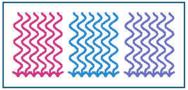

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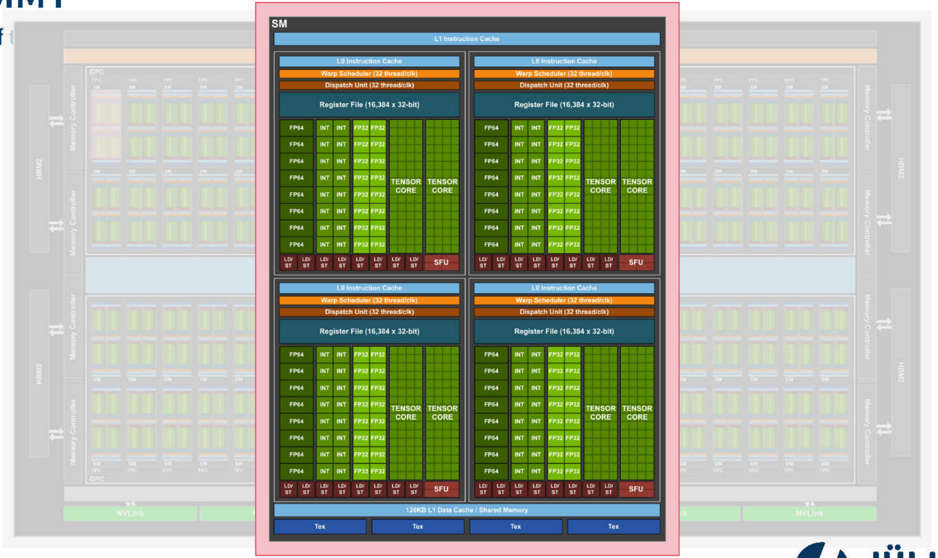
SIMT

Of t

Multiprocessor



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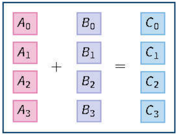

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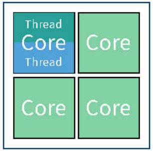

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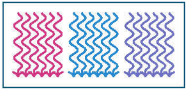

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SIMT

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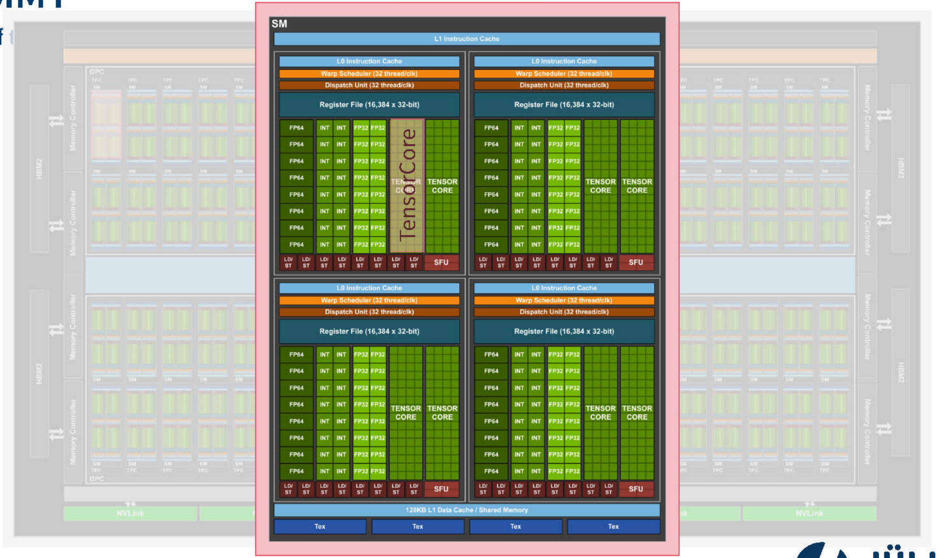
Multiprocessor



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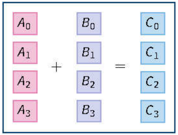

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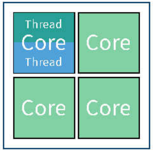

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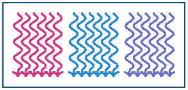

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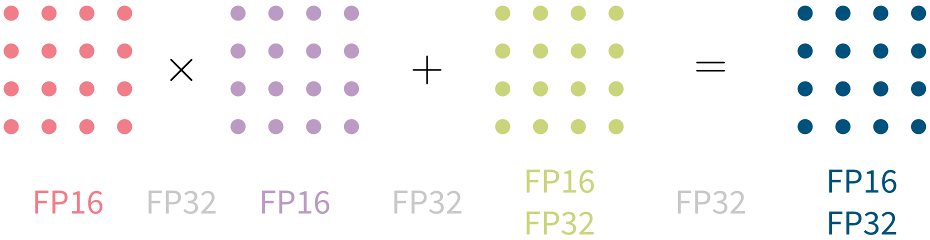
New: Tensor Cores

New in Volta

- 8 Tensor Cores per Streaming Multiprocessor (SM) (640 total for V100)
- Performance: 125 TFLOP/s (half precision)
- Calculate $\mathbf{A} \times \mathbf{B} + \mathbf{C} = \mathbf{D}$ (4×4 matrices; **A**, **B**: half precision)

→ 64 floating-point FMA operations per clock (mixed precision)



Low Latency vs. High Throughput

Maybe GPU's ultimate feature

CPU Minimizes latency within each thread

GPU Hides latency with computations from other thread warps

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Maybe GPU’s ultimate feature

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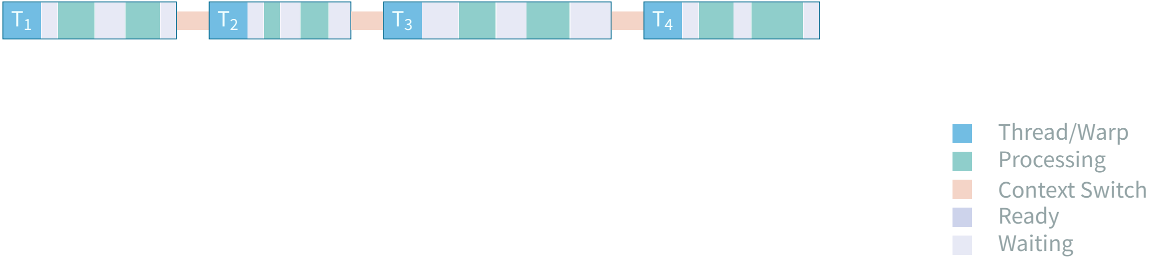
GPU Hides latency with computations from other thread warps

CPU Core: Low Latency



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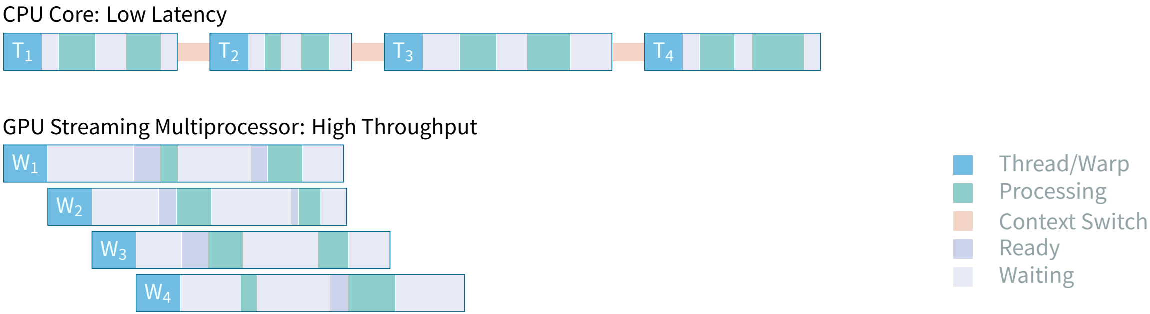

CPU vs. GPU

Let's summarize this!

Optimized for **low latency**

+ Large main memory
+ Fast clock rate
+ Large caches
+ Branch prediction
+ Powerful ALU
− Relatively low memory bandwidth
− Cache misses costly
− Low performance per watt

Optimized for **high throughput**

+ High bandwidth main memory
+ Latency tolerant (parallelism)
+ More compute resources
+ High performance per watt
− Limited memory capacity
− Low per-thread performance
− Extension card

Programming GPUs

Preface: CPU

A simple CPU program as reference!

SAXPY: $\vec{y} = a\vec{x} + \vec{y}$, with single precision

Part of LAPACK BLAS Level 1

```c
void saxpy(int n, float a, float * x, float * y) {
  for (int i = 0; i < n; i++)
    y[i] = a * x[i] + y[i];
}

int a = 42;
int n = 10;
float x[n], y[n];
// fill x, y

saxpy(n, a, x, y);
```

Libraries

Programming GPUs is easy: **Just don't!**

Libraries

Programming GPUs is easy: **Just don't!**

Use applications & libraries

Libraries

Programming GPUs is easy: **Just don't!**

Use applications & libraries

Wizard: Breazell [7]

Libraries

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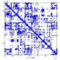
Use applications & libraries

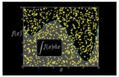
cuBLAS



cuSPARSE

cuDNN

cuFFT



cuRAND

CUDA Math

OpenCV

Thrust

ArrayFire

Numba

theano

Wizard: Breazell [7]

Libraries

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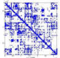
Use applications & libraries

cuBLAS



cuSPARSE

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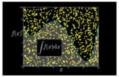

cuRAND

CUDA Math

Wizard: Breazell [7]

cuBLAS

Parallel algebra

- GPU-parallel BLAS (all 152 routines)
- Single, double, complex data types
- Constant competition with Intel's MKL
- Multi-GPU support

→ https://developer.nvidia.com/cublas
http://docs.nvidia.com/cuda/cublas

cuBLAS

Code example

```
int a = 42;  int n = 10;
float x[n], y[n];
// fill x, y

cublasHandle_t handle;
cublasCreate(&handle);

float * d_x, * d_y;
cudaMallocManaged(&d_x, n * sizeof(x[0]));
cudaMallocManaged(&d_y, n * sizeof(y[0]));
cublasSetVector(n, sizeof(x[0]), x, 1, d_x, 1);
cublasSetVector(n, sizeof(y[0]), y, 1, d_y, 1);

cublasSaxpy(n, a, d_x, 1, d_y, 1);

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cudaFree(d_x); cudaFree(d_y);
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```

cuBLAS

Code example

```
int a = 42;  int n = 10;
float x[n], y[n];
// fill x, y

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Initialize

Allocate GPU memory

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Initialize

Allocate GPU memory

Copy data to GPU

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Initialize

Allocate GPU memory

Copy data to GPU

Call BLAS routine

cuBLAS

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Copy data to GPU

Call BLAS routine

Copy result to host

cuBLAS

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```

Initialize

Allocate GPU memory

Copy data to GPU

Call BLAS routine

Copy result to host

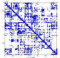
Finalize

Libraries

Programming GPUs is easy: **Just don't!**

Use applications & libraries

cuBLAS



cuSPARSE

cuDNN

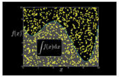
OpenCV

ArrayFire

Thrust

Numba

cuFFT



cuRAND

CUDA Math

theano

Wizard: Breazell [7]

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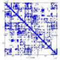

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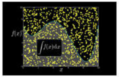

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Thrust

Iterators! Iterators everywhere! 🚀

- $\frac{\text{Thrust}}{\text{CUDA}} = \frac{\text{STL}}{\text{C++}}$
- Template library
- Based on iterators
- Data-parallel primitives (`scan()`, `sort()`, `reduce()`, …)
- Fully compatible with plain CUDA C (comes with CUDA Toolkit)
- Great with `[](){}` lambdas!

→ http://thrust.github.io/
http://docs.nvidia.com/cuda/thrust/

Thrust

Code example

```
int a = 42;
int n = 10;
thrust::host_vector<float> x(n), y(n);
// fill x, y

thrust::device_vector d_x = x, d_y = y;

using namespace thrust::placeholders;
thrust::transform(d_x.begin(), d_x.end(), d_y.begin(), d_y.begin(), a * _1 + _2);

x = d_x;
```

Thrust

Code example with lambdas

```
#include <thrust/for_each.h>
#include <thrust/execution_policy.h>
constexpr int gGpuThreshold = 10000;
void saxpy(float *x, float *y, float a, int N) {
    auto r = thrust::counting_iterator<int>(0);

    auto lambda = [=] __host__ __device__ (int i) {
      y[i] = a * x[i] + y[i];};

    if(N > gGpuThreshold)
      thrust::for_each(thrust::device, r, r+N, lambda);
    else
      thrust::for_each(thrust::host, r, r+N, lambda);}
```

Source

Programming GPUs

Directives

GPU Programming with Directives

Keepin' you portable

- Annotate usual source code by directives

```
#pragma acc loop
for (int i = 0; i < 1; i+*) {};
```

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```
acc_copy();
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- Compiler interprets directives, creates according instructions

GPU Programming with Directives

Keepin' you portable

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```
#pragma acc loop
for (int i = 0; i < 1; i++) {};
```

- Also: Generalized API functions

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acc_copy();
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Pro

- Portability
  - Other compiler? No problem! To it, it's a serial program
  - Different target architectures from same code
- Easy to program

Con

- Compilers support limited
- Raw power hidden
- Somewhat harder to debug

GPU Programming with Directives

The power of... two.

OpenMP Standard for multithread programming on CPU, GPU since 4.0, better since 4.5

```
#pragma omp target map(tofrom:y), map(to:x)
#pragma omp teams num_teams(10) num_threads(10)
#pragma omp distribute
for (   ) {
    #pragma omp parallel for
    for (   ) {
    // ...
    }
}
```

OpenACC Similar to OpenMP, but more specifically for GPUs

Might eventually be re-merged into OpenMP standard

OpenACC

Code example

```c
void saxpy_acc(int n, float a, float * x, float * y) {
  #pragma acc kernels
  for (int i = 0; i < n; i++)
    y[i] = a * x[i] + y[i];
}

int a = 42;
int n = 10;
float x[n], y[n];
// fill x, y

saxpy_acc(n, a, x, y);
```

OpenACC

Code example

```
void saxpy_acc(int n, float a, float * x, float * y) {
  #pragma acc parallel loop copy(y) copyin(x)
  for (int i = 0; i < n; i++)
    y[i] = a * x[i] + y[i];
}

int a = 42;
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GPU tutorial this afternoon!

Programming GPUs

Languages

Programming GPU Directly

Finally…

- Two solutions:

Programming GPU Directly

Finally…

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  OpenCL Open Computing Language by Khronos Group (Apple, IBM, NVIDIA, …) *2009*
    - Platform: Programming language (OpenCL C/C++), API, and compiler
    - Targets CPUs, GPUs, FPGAs, and other many-core machines
    - Fully open source
    - Different compilers available

Programming GPU Directly

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  - Platform: Drivers, programming language (CUDA C/C++), API, compiler, debuggers, profilers, …
  - Only NVIDIA GPUs
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CUDA Threading Model

Warp the kernel, it's a thread!

- Methods to exploit parallelism:

CUDA Threading Model

Warp the kernel, it’s a thread!

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CUDA Threading Model

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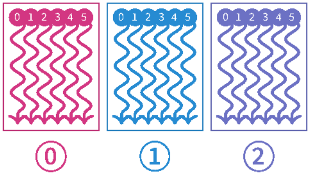

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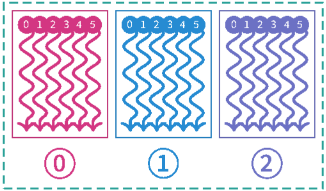

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- Methods to exploit parallelism:
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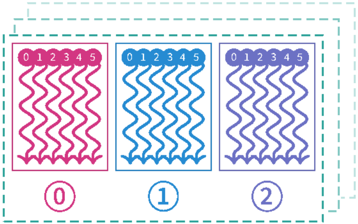
  - Blocks → Grid
  - Threads & blocks in 3D



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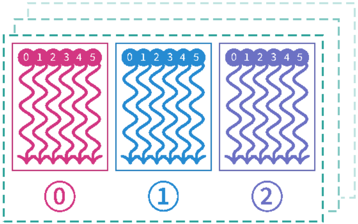

- Parallel function: **kernel**
  - `__global__ kernel(int a, float * b) { }`
  - Access own ID by global variables `threadIdx`.x, `blockIdx`.y, ...
- Execution entity: **threads**
  - Lightweight → fast switchting!
  - 1000s threads execute simultaneously → order non-deterministic!

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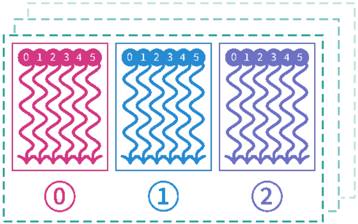

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⇒ **SAXPY!**

CUDA SAXPY

With runtime-managed data transfers

```
__global__ void saxpy_cuda(int n, float a, float * x, float * y) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  if (i < n)
    y[i] = a * x[i] + y[i];
}

int a = 42;
int n = 10;
float x[n], y[n];
// fill x, y
cudaMallocManaged(&x, n * sizeof(float));
cudaMallocManaged(&y, n * sizeof(float));

saxpy_cuda<<<2, 5>>>(n, a, x, y);

cudaDeviceSynchronize();
```

CUDA SAXPY

With runtime-managed data transfers

Specify kernel

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Call kernel 2 blocks, each 5 threads

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```

Specify kernel

ID variables

Guard against too many threads

Allocate GPU-capable memory

Call kernel 2 blocks, each 5 threads

Wait for kernel to finish

Programming GPUs

Abstraction Libraries/DSL

Abstraction Libraries & DSLs

- Libraries with ready-programmed abstractions; partly compiler/transpiler necessary
- Have different backends to choose from for targeted accelerator
- Between Thrust, OpenACC, and CUDA
- Examples: Kokkos, Alpaka, Futhark, HIP, C++AMP, …

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- Examples: **Kokkos**, Alpaka, Futhark, HIP, C++AMP, …

An Alternative: Kokkos

From Sandia National Laboratories

- C++ library for *performance* portability
- Data-parallel patterns, architecture-aware memory layouts, …

```
Kokkos::View<double*> x("X", length);
Kokkos::View<double*> y("Y", length);
double a = 2.0;

// Fill x, y

Kokkos::parallel_for(length, KOKKOS_LAMBDA (const int& i) {
    x(i) = a*x(i) + y(i);
});
```

→ https://github.com/kokkos/kokkos/

Programming GPUs

Tools

GPU Tools

The helpful helpers helping helpless (and others)

- NVIDIA

`cuda-gdb`	GDB-like command line utility for debugging
`cuda-memcheck`	Like Valgrind's `memcheck`, for checking errors in memory accesses
Nsight	IDE for GPU developing, based on Eclipse (Linux, OS X) or Visual Studio (Windows)
`nvprof`	Command line profiler, including detailed performance counters
Visual Profiler	Timeline profiling and annotated performance experiments

- OpenCL: CodeXL (Open Source, GPUOpen/AMD) – debugging, profiling.

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nvprof

Command that line

Usage: `nvprof ./app`

```
$ nvprof ./matrixMul -wA=1024 -hA=1024 -wB=1024 -hB=1024
==37064== Profiling application: ./matrixMul -wA=1024 -hA=1024 -wB=1024 -hB=1024
==37064== Profiling result:
Time(%)      Time     Calls       Avg       Min       Max  Name
 99.19%  262.43ms       301  871.86us  863.88us  882.44us  void matrixMulCUDA<int=32>(float*, float*, float*, int, int)
  0.58%  1.5428ms         2  771.39us  764.65us  778.12us  [CUDA memcpy HtoD]
  0.23%  599.40us         1  599.40us  599.40us  599.40us  [CUDA memcpy DtoH]

==37064== API calls:
Time(%)      Time     Calls       Avg       Min       Max  Name
 61.26%  258.38ms         1  258.38ms  258.38ms  258.38ms  cudaEventSynchronize
 35.68%  150.49ms         3  50.164ms  914.97us  148.65ms  cudaMalloc
  0.73%  3.0774ms         3  1.0258ms  1.0097ms  1.0565ms  cudaMemcpy
  0.62%  2.6287ms         4  657.17us  655.12us  660.56us  cuDeviceTotalMem
  0.56%  2.3408ms       301  7.7760us  7.3810us  53.103us  cudaLaunch
  0.48%  2.0111ms       364  5.5250us     235ns  201.63us  cuDeviceGetAttribute
  0.21%  872.52us         1  872.52us  872.52us  872.52us  cudaDeviceSynchronize
```

nvprof

Command that line

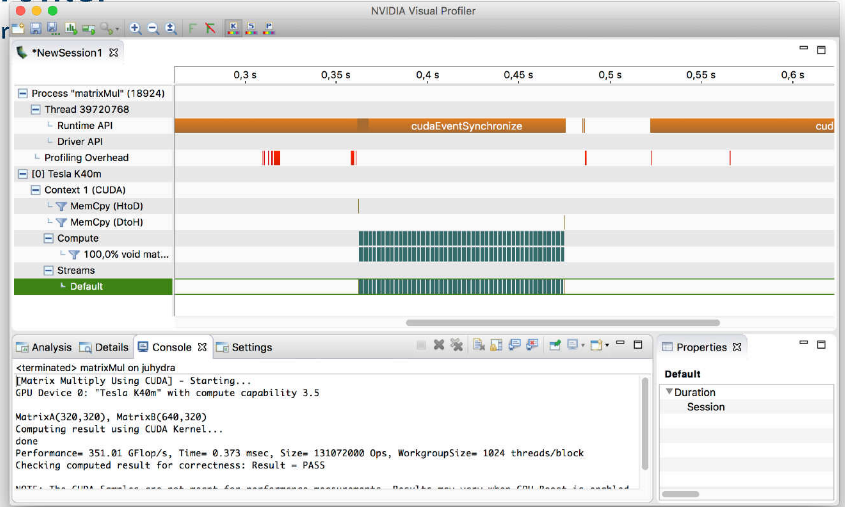
With metrics: `nvprof --metrics flop_sp_efficiency ./app`

```
$ nvprof --metrics flop_sp_efficiency ./matrixMul -wA=1024 -hA=1024 -wB=1024 -hB=1024
[Matrix Multiply Using CUDA] - Starting...
==37122== NVPROF is profiling process 37122, command: ./matrixMul -wA=1024 -hA=1024 -wB=1024 -hB=1024
GPU Device 0: "Tesla P100-SXM2-16GB" with compute capability 6.0

MatrixA(1024,1024), MatrixB(1024,1024)
Computing result using CUDA Kernel...
==37122== Some kernel(s) will be replayed on device 0 in order to collect all events/metrics.
done122== Replaying kernel "void matrixMulCUDA<int=32>(float*, float*, float*, int, int)" (0 of 2)...
Performance= 26.61 GFlop/s, Time= 80.697 msec, Size= 2147483648 Ops, WorkgroupSize= 1024 threads/block
Checking computed result for correctness: Result = PASS
==37122== Profiling application: ./matrixMul -wA=1024 -hA=1024 -wB=1024 -hB=1024
==37122== Profiling result:
==37122== Metric result:
Invocations                               Metric Name                            Metric Description         Min         Max         Avg
Device "Tesla P100-SXM2-16GB (0)"
    Kernel: void matrixMulCUDA<int=32>(float*, float*, float*, int, int)
        301                        flop_sp_efficiency              FLOP Efficiency(Peak Single)      22.96%      23.40%      23.15%
```

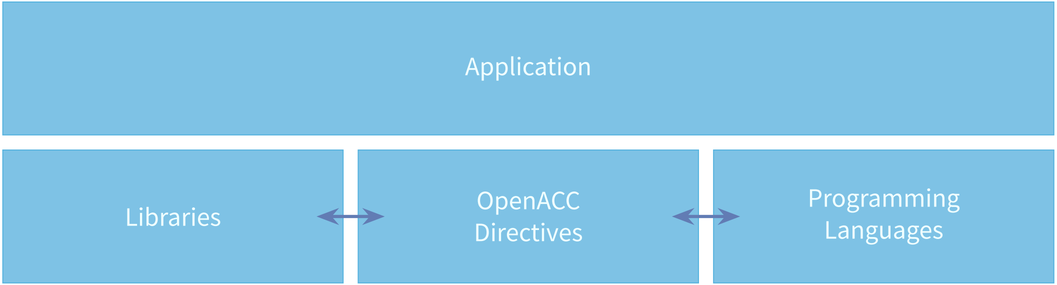
Visual Profiler

Your new favor



Conclusions

Summary of Acceleration Possibilities

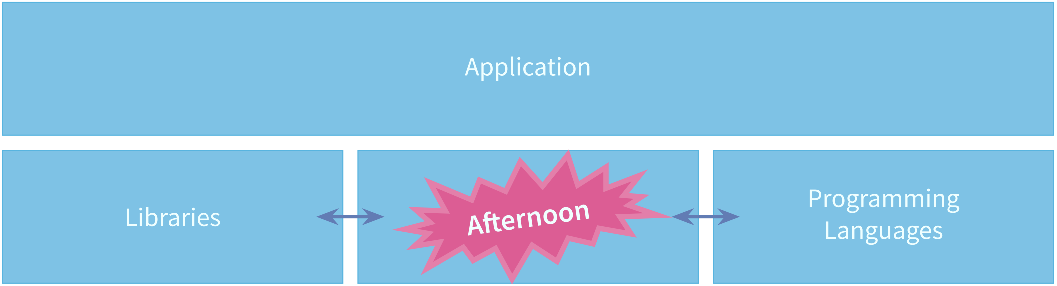


Drop-in Acceleration

Easy Acceleration

Flexible Acceleration

Summary of Acceleration Possibilities



Drop-in Acceleration

Easy Acceleration

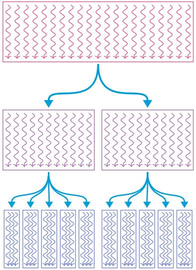
Flexible Acceleration

Omitted

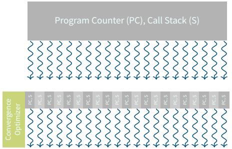
There's so much more!

What I did not talk about

- Atomic ⚛ operations
- Shared memory
- Pinned memory
- Managed memory
- Debugging
- Overlapping streams
- Multi-GPU programming (intra-node; MPI)
- Cooperative groups
- Independent thread progress
- Half precision FP16
- …



Cooperative Groups



Independent Thread Progress

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Summary & Conclusion

- GPUs can improve your performance many-fold
- For a fitting, parallelizable application
- Libraries are easiest
- Direct programming (plain CUDA) is most powerful
- OpenACC is somewhere in between (and portable)
- There are many tools helping the programmer

→ See it in action this afternoon at **OpenACC tutorial**

Summary & Conclusion

- GPUs can improve your performance many-fold
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→ See it in action this afternoon at **OpenACC tutorial**

Thank you for your attention!

a.herten@fz-juelich.de

APPENDIX

Appendix

- Further Reading & Links
- GPU Performances
- Glossary
- References

Further Reading & Links

More!

- A discussion of SIMD, SIMT, SMT by Y. Kreinin.
- NVIDIA's documentation: `docs.nvidia.com`
- NVIDIA's Parallel For All blog

Volta Performance

9- @ &*>+3/ 2	9- @ CD0	9- @ E D0	9- @ &100	9- @ V100
GPU	GK180 (Kepler)	GM200 (Maxwell)	GP100 (Pascal)	GV100 (Volta)
SMs	15	24	56	80
TPCs	15	24	28	40
FP32 Cores / SM	1B2	128	64	64
FP32 Cores / GPU	2880	30C2	3584	5120
FP64 Cores / SM	64	4	32	32
FP64 Cores / GPU	B60	B6	1OB2	2560
TeDsor Cores / SM	EF	EF	EF	8
TeDsor Cores / GPU	EF	EF	EF	640
GPU Goost ClocH	810/8C5 MI J	1114 MI J	1480 MI J	1462 MI J
PeaHFP32 TFKL PS[1]	5	6M	10M	15
PeaHFP64 TFKL PS[1]	1MC	M1	5M	OM
PeaHTeDsor TFKL PS[1]	EF	EF	EF	120
TextNre UDOs	240	1B2	224	320
MeP orQRDterSace	384TUDGVWW	384TUDGVWW	40B6TUDI GM2	40B6TUDI GM2
MeP orQSOe	Up to 12 GG	Up to 24 GG	16 GG	16 GG
K2 CacXe SOe	1536 KG	30C2 KG	40B6 KG	6144 KG
SXareY MeP orQSOe / SM	16 KG/32 KG/48 KG	B6 KG	64 KG	CoDSZNraUe Np to B6 KG
WeZOter FOe SOe / SM	256 KG	256 KG	256 KG	256KG
WeZOter FOe SOe / GPU	3840 KG	6144 KG	14336 KG	20480 KG
TVP	235 [atts	250 [atts	300 [atts	300 [atts
TraDsGtors	OM UDOD	8 UDOD	15M UDOD	21M UDOD
GPU VO SOe	551 PP\	601 PP\	610 PP\	815 PP\
MaDNSactNOZ Process	28 DP	28 DP	16 DP FOF] T^	12 DP FFE
[1] PeaHTFKL PS rates are UaseY oDGPU Goost ClocH				

Figure: Tesla V100 performance characteristics in comparison [**volta-pictures**]

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Appendix

Glossary & References

Glossary I

API A programmatic interface to software by well-defined functions. Short for application programming interface. 69, 70, 71, 77, 78, 79, 80, 81

ATI Canada-based GPUs manufacturing company; bought by AMD in 2006. 4

CUDA Computing platform for GPUs from NVIDIA. Provides, among others, CUDA C/C++. 4, 65, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 100, 101, 113, 114, 121

DSL A Domain-Specific Language is a specialization of a more general language to a specific domain. 2, 3, 99, 100, 101

MPI The Message Passing Interface, a API definition for multi-node computing. 112

Glossary II

NVIDIA US technology company creating GPUs. 2, 3, 4, 77, 78, 79, 80, 81, 104, 105, 117, 120, 122

OpenACC Directive-based programming, primarily for many-core machines. 72, 73, 74, 75, 100, 101, 113, 114

OpenCL The *Open Computing Language*. Framework for writing code for heterogeneous architectures (CPU, GPU, DSP, FPGA). The alternative to CUDA. 77, 78, 79, 80, 81, 104, 105

OpenMP Directive-based programming, primarily for multi-threaded machines. 72

POWER CPU architecture from IBM, earlier: PowerPC. See also POWER8. 2, 3, 121

POWER8 Version 8 of IBM's POWERprocessor, available also under the OpenPOWER Foundation. 121

Glossary III

SAXPY Single-precision $A \times X + Y$. A simple code example of scaling a vector and adding an offset. 49, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98

Thrust A parallel algorithms library for (among others) GPUs. See `https://thrust.github.io/`. 65

Volta GPU architecture from NVIDIA (announced 2017). 43

References I

[2] Chris McClanahan. "History and Evolution of GPU Architecture". In: *A Survey Paper* (2010). URL: http://mcclanahoochie.com/blog/wp-content/uploads/2011/03/gpu-hist-paper.pdf (page 4).

[3] Karl Rupp. *Pictures: CPU/GPU Performance Comparison*. URL: https://www.karlrupp.net/2013/06/cpu-gpu-and-mic-hardware-characteristics-over-time/ (pages 5–7).

[7] Wes Breazell. *Picture: Wizard*. URL: https://thenounproject.com/wes13/collection/its-a-wizards-world/ (pages 50–54, 63, 64).

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[1] Igor Ovsyannykov. *Yarn*. Freely available at Unsplash. URL: https://unsplash.com/photos/hvILKk7SlH4.

[4] Mark Lee. *Picture: kawasaki ninja*. URL: https://www.flickr.com/photos/pochacco20/39030210/ (pages 13, 14).

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[6] Nvidia Corporation. *Pictures: Volta GPU*. Volta Architecture Whitepaper. URL: https://images.nvidia.com/content/volta-architecture/pdf/Volta-Architecture-Whitepaper-v1.0.pdf.

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