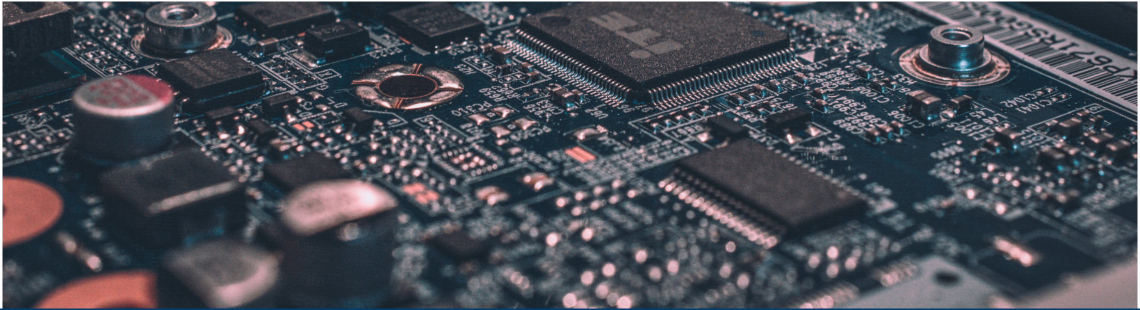


GPU ACCELERATORS AT JSC
OF THREADS AND KERNELS

21 May 2019 | Andreas Herten | Forschungszentrum Jülich

JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

Outline

JUWELS – Jülich's New Large System

- 2500 nodes with Intel Xeon CPUs (2 $\times$ 24 cores)
- 46 + 10 nodes with 4 NVIDIA Tesla V100 cards
- 10.4 (CPU) + 1.6 (GPU) PFLOP/s peak performance (Top500: #26)

JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

2020: Booster!

JUWELS – Jülich's New Large System

- 2500 nodes with Intel Xeon CPUs (2×24 cores)
- 46 + 10 nodes with 4 NVIDIA Tesla V100 cards
- 10.4 (CPU) + 1.6 (GPU) PFLOP/s peak performance (Top500: #26)

JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

JURECA – Jülich's Multi-Purpose Supercomputer

- 1872 nodes with Intel Xeon E5 CPUs (2 × 12 cores)
- 75 nodes with 2 NVIDIA Tesla K80 cards (look like 4 GPUs)
- JURECA Booster: 1640 nodes with Intel Xeon Phi *Knights Landing*
- 1.8 (CPU) + 0.44 (GPU) + 5 (KNL) PFLOP/s peak performance (Top500: #44)
- Mellanox EDR InfiniBand

JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

JURON – A Human Brain Project *Pilot System*

- 18 nodes with IBM POWER8*NVL* CPUs (2 × 10 cores)
- Per Node: 4 NVIDIA Tesla P100 cards (16 GB HBM2 memory), connected via NVLink
- GPU: 0.38 PFLOP/s peak performance

JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

JURON – A Human Brain Project *Pilot System*

- 18 nodes with IBM POWER8*NVL* CPUs (2 × 10 cores)
- Per Node: 4 NVIDIA Tesla P100 cards (16 GB HBM2 memory), connected via NVLink
- GPU: 0.38 PFLOP/s peak performance

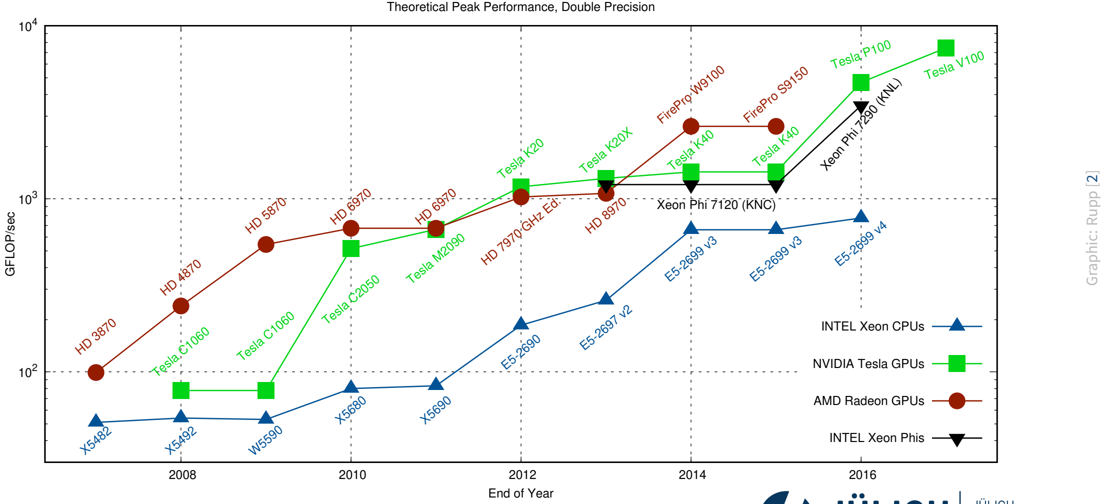
JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

GPU Architecture

Why?

Status Quo Across Architectures

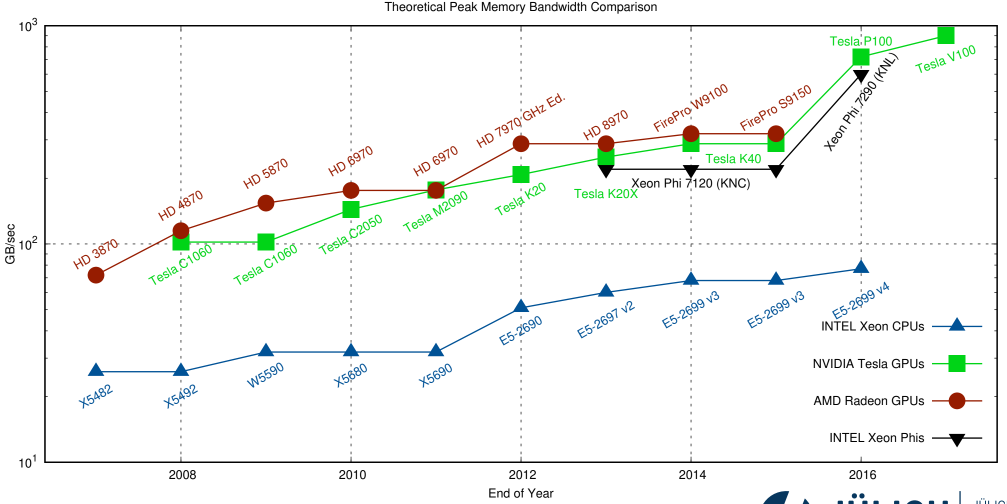
Performance



JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

Status Quo Across Architectures

Memory Bandwidth



Graphic: Rupp [2]

JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

CPU vs. GPU

A matter of specialties

Graphics: Lee [3] and Bob Adams [4]

CPU vs. GPU

A matter of specialties

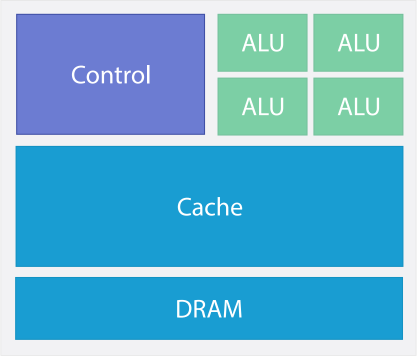
Transporting one

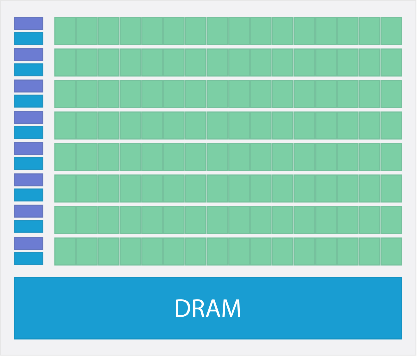
Transporting many

Graphics: Lee [3] and Bob Adams [4]

CPU vs. GPU

Chip





GPU Architecture

Overview

Aim: Hide Latency

Everything else follows

GPU Architecture

Overview

Aim: Hide Latency

Everything else follows

SIMT

Asynchronicity

Memory

GPU Architecture

Overview

Aim: Hide Latency

Everything else follows

SIMT

Asynchronicity

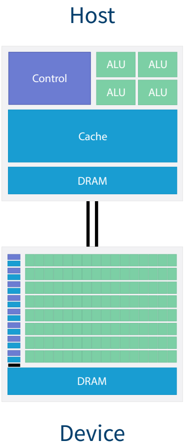
Memory

Memory

GPU memory ain't no CPU memory

- GPU: accelerator / extension card

→ Separate device from CPU



Memory

GPU memory ain't no CPU memory

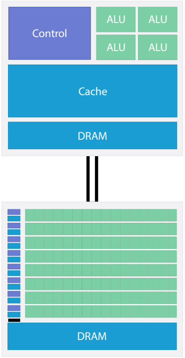
Unified Virtual Addressing

- GPU: accelerator / extension card

→ Separate device from CPU

Separate memory, but UVA

Host



Device

Memory

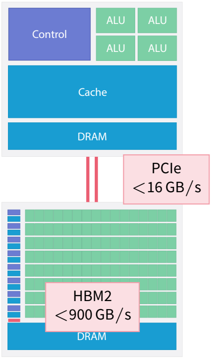
GPU memory ain't no CPU memory

- GPU: accelerator / extension card

→ Separate device from CPU

Separate memory, but UVA

Host



Device

Memory

GPU memory ain't no CPU memory

- GPU: accelerator / extension card

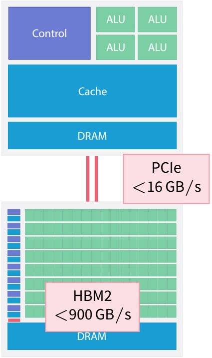
→ Separate device from CPU

Separate memory, but UVA

- Memory transfers need special consideration!

Do as little as possible!

Host



Device

Memory

GPU memory ain't no CPU memory

Unified Memory

- GPU: accelerator / extension card

→ Separate device from CPU

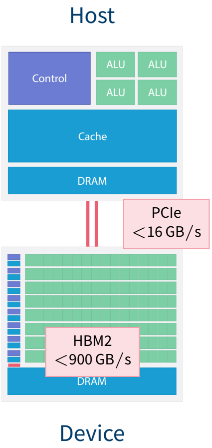
Separate memory, but UVA and UM

- Memory transfers need special consideration!

  Do as little as possible!

- Formerly: Explicitly copy data to/from GPU

  Now: Done automatically (performance…?)



JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

Memory

GPU memory ain't no CPU memory

- GPU: accelerator / extension card

→ Separate device from CPU

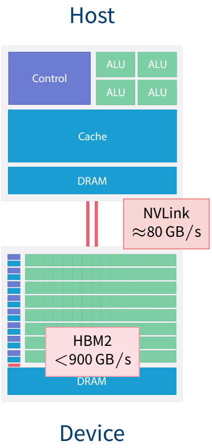
  Separate memory, but UVA and UM

- Memory transfers need special consideration!

  Do as little as possible!

- Formerly: Explicitly copy data to/from GPU

  Now: Done automatically (performance…?)

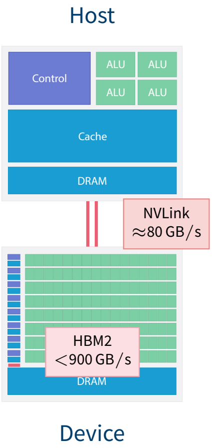


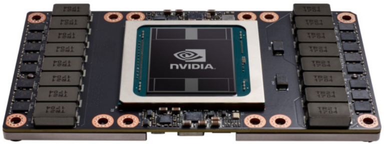
Memory

GPU memory ain’t no CPU memory

- GPU: accelerator / extension card

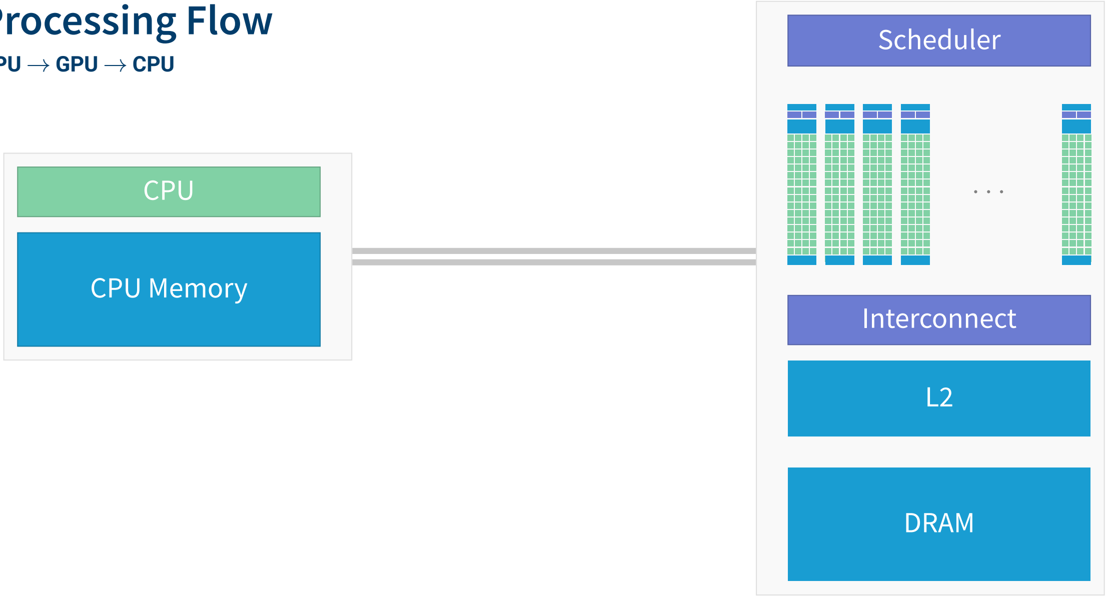
→ Separate device from CPU
  Separate memory, but UVA and UM
- Memory transfers need special consideration!
  Do as little as possible!
- Formerly: Explicitly copy data to/from GPU
  Now: Done automatically (performance…?)
- P100: 16 GB RAM, 720 GB/s; V100: 16 (32) GB RAM, 900 GB/s





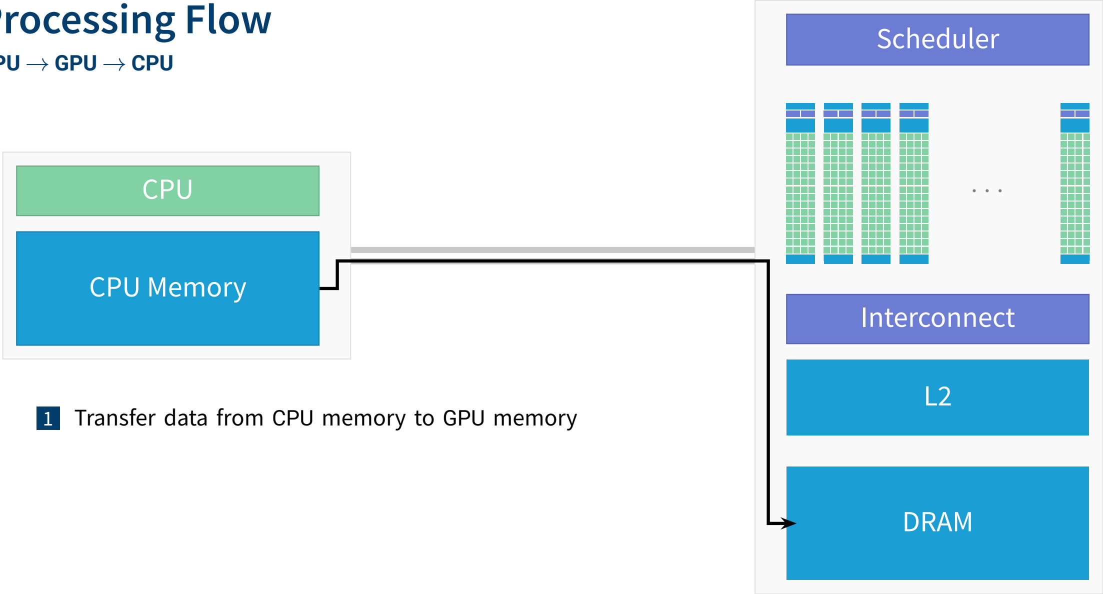
Processing Flow

CPU → GPU → CPU



Processing Flow

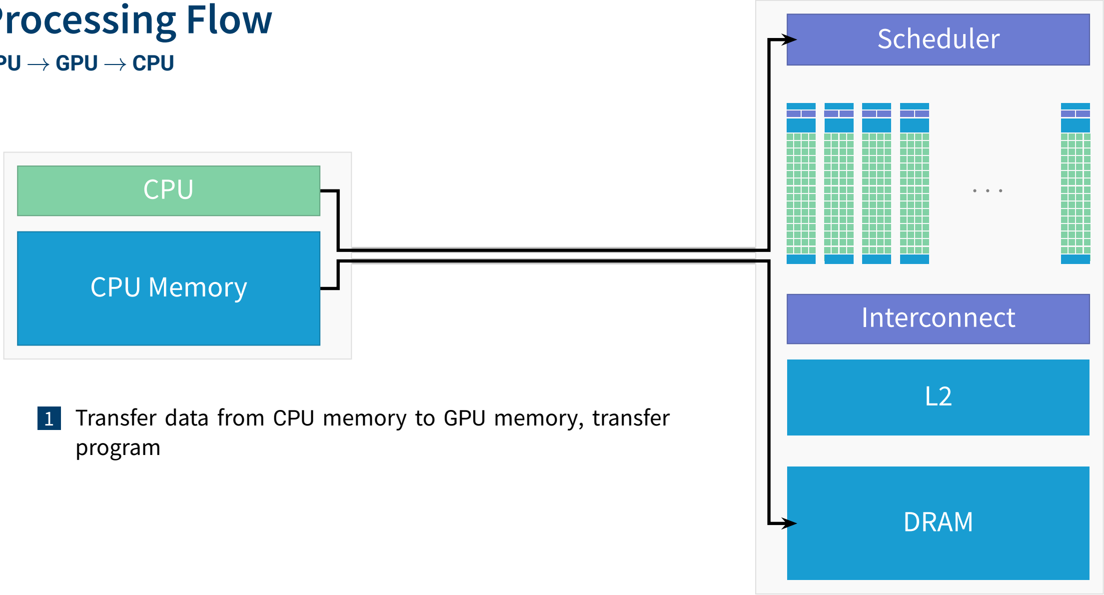
CPU → GPU → CPU



1 Transfer data from CPU memory to GPU memory

Processing Flow

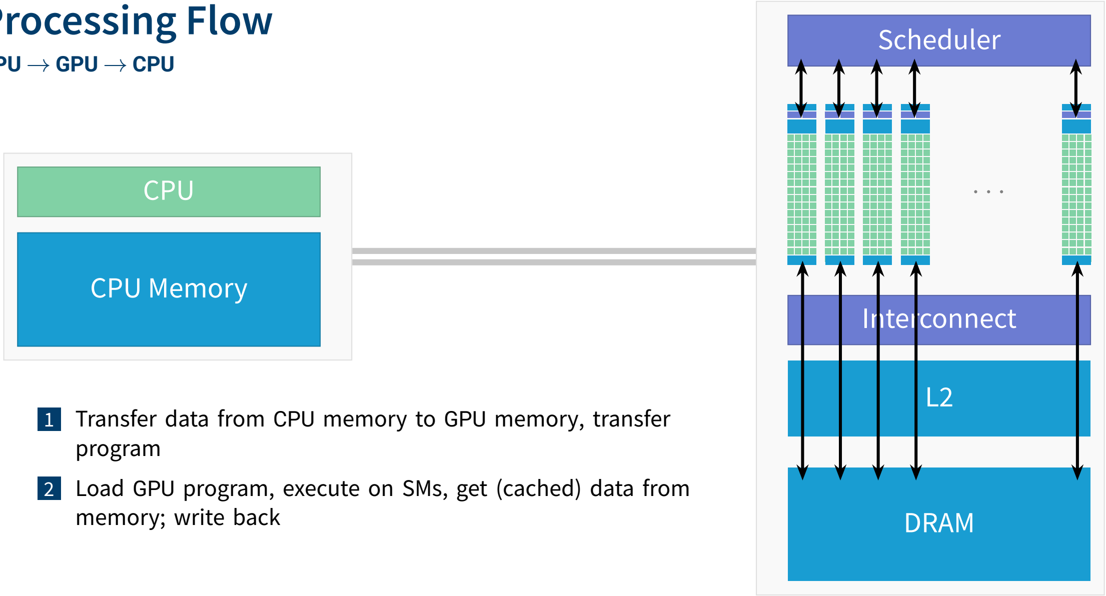
CPU → GPU → CPU



1. Transfer data from CPU memory to GPU memory, transfer program

Processing Flow

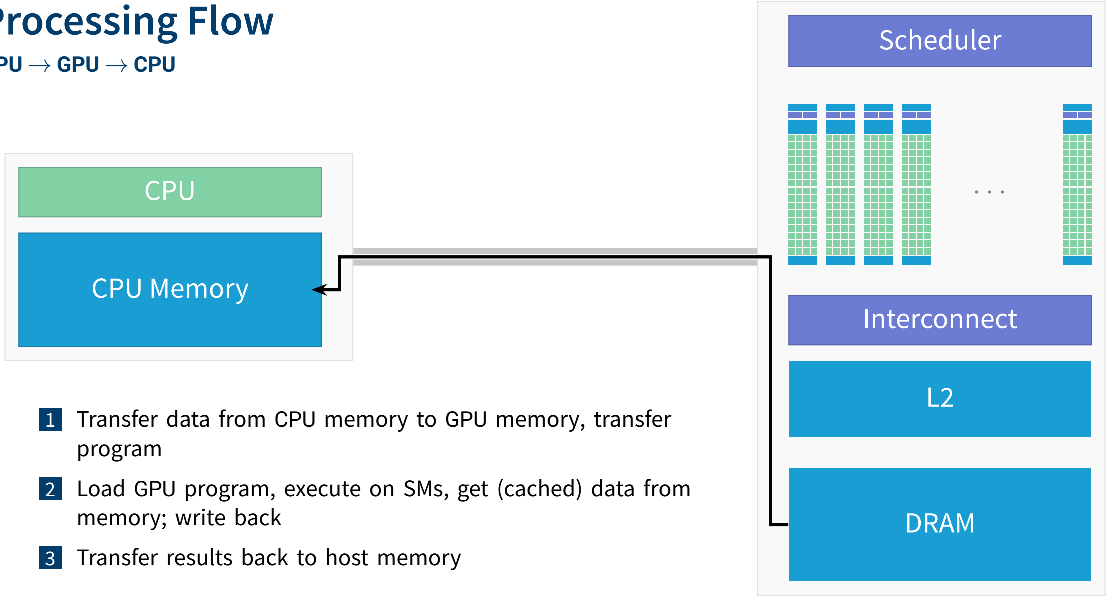
CPU → GPU → CPU



1. Transfer data from CPU memory to GPU memory, transfer program
2. Load GPU program, execute on SMs, get (cached) data from memory; write back

Processing Flow

CPU → GPU → CPU



1. Transfer data from CPU memory to GPU memory, transfer program
2. Load GPU program, execute on SMs, get (cached) data from memory; write back
3. Transfer results back to host memory

GPU Architecture

Overview

Aim: Hide Latency

Everything else follows

SIMT

Asynchronicity

Memory

GPU Architecture

Overview

Aim: Hide Latency

Everything else follows

SIMT

Asynchronicity

Memory

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

GPU Architecture

Overview

Aim: Hide Latency

Everything else follows

SIMT

Asynchronicity

Memory

GPU Architecture

Overview

Aim: Hide Latency

Everything else follows

SIMT

Asynchronicity

Memory

SIMT

SIMT $=$ SIMD $\oplus$ SMT

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

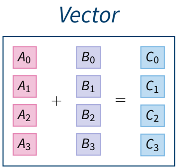
Scalar

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

SIMT

SIMT $=$ SIMD $\oplus$ SMT

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

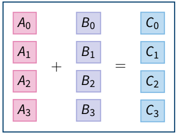


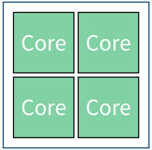
SIMT

SIMT $=$ SIMD $\oplus$ SMT

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

Vector



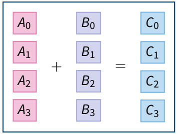


SIMT

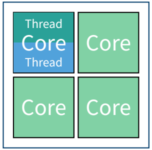
SIMT $=$ SIMD $\oplus$ SMT

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

Vector



SMT

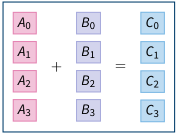


SIMT

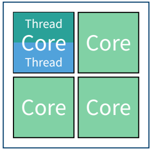
SIMT $=$ SIMD $\oplus$ SMT

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

Vector



SMT

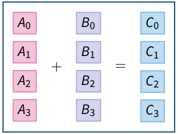


SIMT

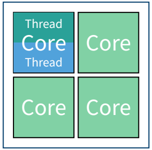
SIMT $=$ SIMD $\oplus$ SMT

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

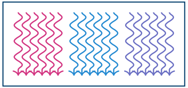
Vector



SMT



SIMT

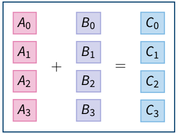


SIMT

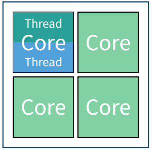
SIMT $=$ SIMD $\oplus$ SMT

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

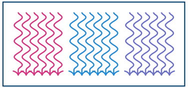
Vector



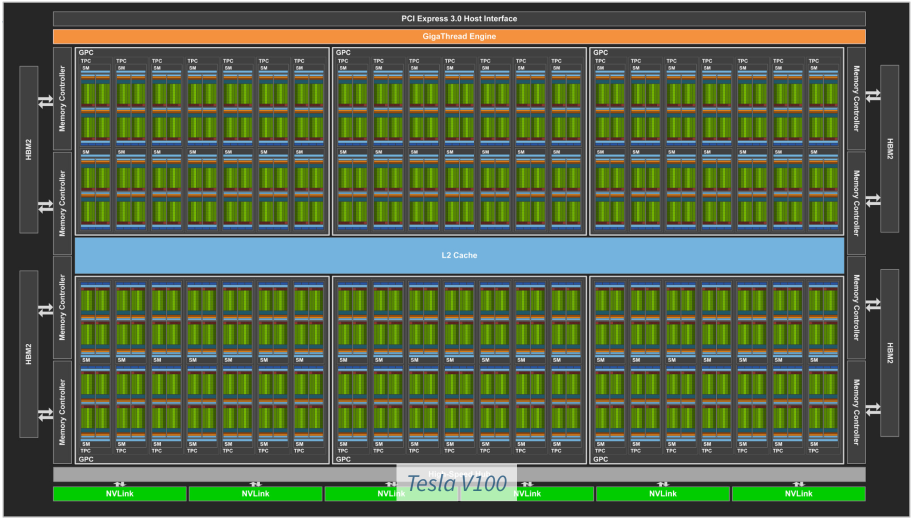
SMT



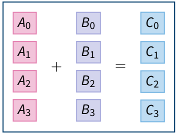
SIMT



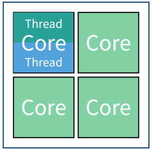
SIMT



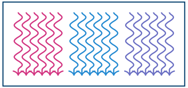
Vector



SMT



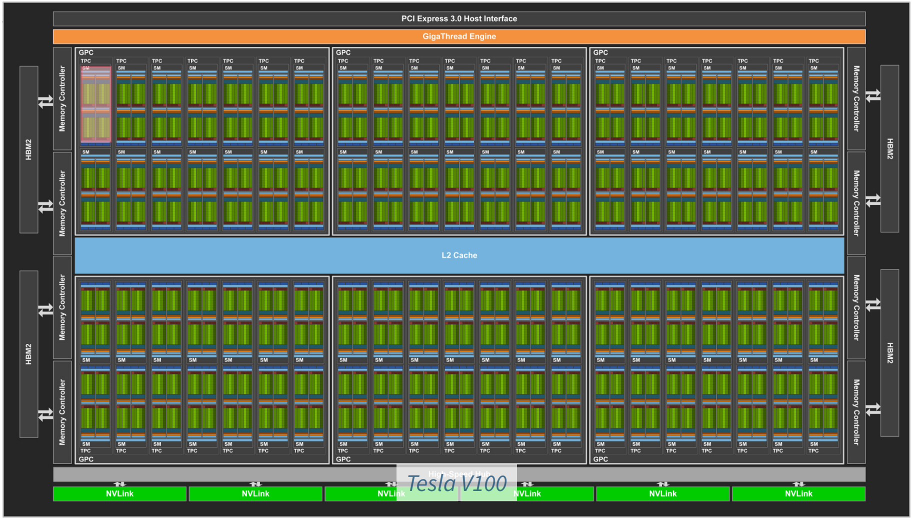
SIMT



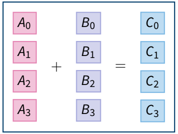
Graphics: Nvidia Corporation [5]

JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

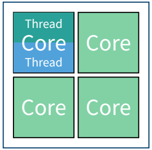
SIMT



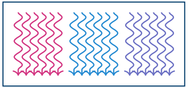
Vector



SMT



SIMT

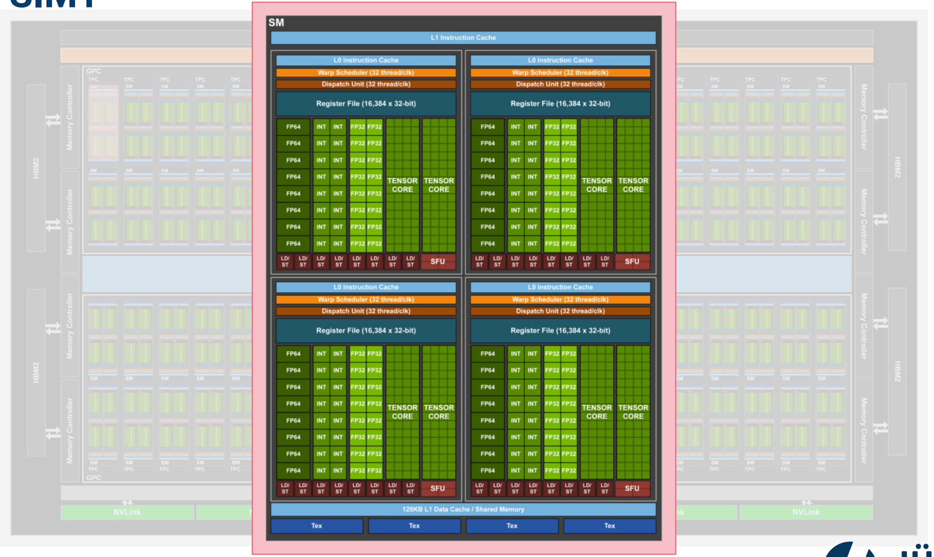


Graphics: Nvidia Corporation [5]

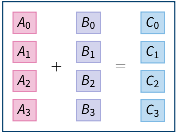
JÜLICH Forschungszentrum
JÜLICH SUPERCOMPUTING CENTRE

SIMT

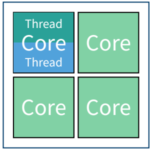
Multiprocessor



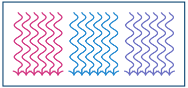
Vector



SMT



SIMT



Graphics: Nvidia Corporation [5]

JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

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

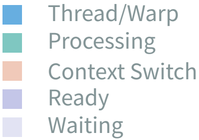
Low Latency vs. High Throughput

Maybe GPU's ultimate feature

CPU Minimizes latency within each thread

GPU Hides latency with computations from other thread warps

CPU Core: Low Latency



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

CPU Core: Low Latency

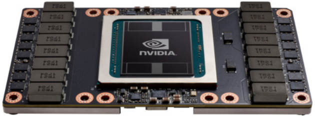
GPU Streaming Multiprocessor: High Throughput

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

JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

Programming GPUs

JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

Preface: CPU

A simple CPU program!

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

Part of LAPACK BLAS Level 1

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

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

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

Programming GPUs

Libraries

Libraries

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

Libraries

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

Use applications & libraries

JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

Libraries

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

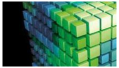
Use applications & libraries

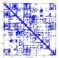
Wizard: Breazell [6]

Libraries

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

Use applications & libraries


cuBLAS


cuSPARSE

cuDNN

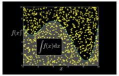
OpenCV

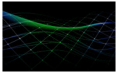
Thrust

ArrayFire

Numba


cuFFT


cuRAND


CUDA Math

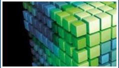
theano

Wizard: Breazell [6]

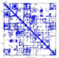
Libraries

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

Use applications & libraries



cuBLAS

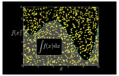


cuSPARSE

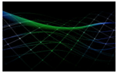
cuDNN

OpenCV

cuFFT



cuRAND



CUDA Math

Thrust

ArrayFire

Numba

theano

Wizard: Breazell [6]

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);

cublasGetVector(n, sizeof(y[0]), d_y, 1, y, 1);

cudaFree(d_x); cudaFree(d_y);
cublasDestroy(handle);
```

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);

cublasGetVector(n, sizeof(y[0]), d_y, 1, y, 1);

cudaFree(d_x); cudaFree(d_y);
cublasDestroy(handle);
```

Initialize

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);

cublasGetVector(n, sizeof(y[0]), d_y, 1, y, 1);

cudaFree(d_x); cudaFree(d_y);
cublasDestroy(handle);
```

Initialize

Allocate GPU memory

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);

cublasGetVector(n, sizeof(y[0]), d_y, 1, y, 1);

cudaFree(d_x); cudaFree(d_y);
cublasDestroy(handle);
```

Initialize

Allocate GPU memory

Copy data to GPU

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);

cublasGetVector(n, sizeof(y[0]), d_y, 1, y, 1);

cudaFree(d_x); cudaFree(d_y);
cublasDestroy(handle);
```

Initialize

Allocate GPU memory

Copy data to GPU

Call BLAS routine

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);

cublasGetVector(n, sizeof(y[0]), d_y, 1, y, 1);

cudaFree(d_x); cudaFree(d_y);
cublasDestroy(handle);
```

Initialize

Allocate GPU memory

Copy data to GPU

Call BLAS routine

Copy result to host

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);

cublasGetVector(n, sizeof(y[0]), d_y, 1, y, 1);

cudaFree(d_x); cudaFree(d_y);
cublasDestroy(handle);
```

Initialize

Allocate GPU memory

Copy data to GPU

Call BLAS routine

Copy result to host

Finalize

Programming GPUs

OpenACC/OpenMP

JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

GPU Programming with Directives

Keepin' you portable

- Annotate serial source code by directives

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

GPU Programming with Directives

Keepin' you portable

- Annotate serial source code by directives

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

- **OpenACC**: Especially for GPUs; **OpenMP**: Has GPU support
- Compiler interprets directives, creates according instructions

GPU Programming with Directives

Keepin' you portable

- Annotate serial source code by directives

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

- **OpenACC**: Especially for GPUs; **OpenMP**: Has GPU support
- Compiler interprets directives, creates according instructions

Pro

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

Con

- Compiler support only raising
- Not all the raw power available
- Harder to debug
- Easy to program wrong

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];
}

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

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

OpenACC

Code example

```c
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];
}

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

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

Programming GPUs

CUDA C/C++

JÜLICH SUPERCOMPUTING CENTRE

Programming GPU Directly

Finally…

- Two solutions:

Programming GPU Directly

Finally…

- Two solutions:

  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

Finally…

- Two solutions:

  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

  CUDA NVIDIA's GPU platform *2007*
  - Platform: Drivers, programming language (CUDA C/C++), API, compiler, debuggers, profilers, …
  - Only NVIDIA GPUs
  - Compilation with `nvcc` (free, but not open)
    `clang` has CUDA support, but CUDA needed for last step
  - Also: CUDA Fortran

Programming GPU Directly

Finally…

- Two solutions:

  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

  CUDA NVIDIA's GPU platform *2007*
  - Platform: Drivers, programming language (CUDA C/C++), API, compiler, debuggers, profilers, …
  - Only NVIDIA GPUs
  - Compilation with `nvcc` (free, but not open)
    `clang` has CUDA support, but CUDA needed for last step
  - Also: CUDA Fortran
- Choose what flavor you like, what colleagues/collaboration is using
- **Hardest: Come up with parallelized algorithm**

Programming GPU Directly

Finally…

- Two solutions:

  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

  CUDA **NVIDIA's GPU platform** *2007*
  - **Platform: Drivers, programming language (CUDA C/C++), API, compiler, debuggers, profilers, …**
  - **Only NVIDIA GPUs**
  - **Compilation with `nvcc` (free, but not open)**
    `clang` has CUDA support, but CUDA needed for last step
  - **Also: CUDA Fortran**
- Choose what flavor you like, what colleagues/collaboration is using
- **Hardest: Come up with parallelized algorithm**

CUDA’s Parallel Model

In software: Threads, Blocks

- Methods to exploit parallelism:

CUDA’s Parallel Model

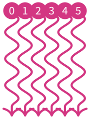
In software: Threads, Blocks

- Methods to exploit parallelism:
  - Thread

CUDA's Parallel Model

In software: Threads, Blocks

- Methods to exploit parallelism:
  - Threads



JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

CUDA's Parallel Model

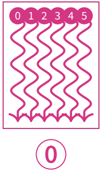
In software: Threads, Blocks

- Methods to exploit parallelism:
  - Threads → $\boxed{\text{Block}}$

CUDA’s Parallel Model

In software: Threads, Blocks

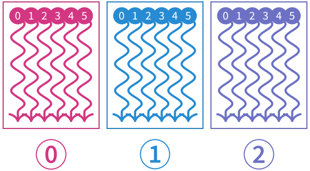
- Methods to exploit parallelism:
  - Threads → $\boxed{\text{Block}}$
  - $\boxed{\text{Block}}$



CUDA’s Parallel Model

In software: Threads, Blocks

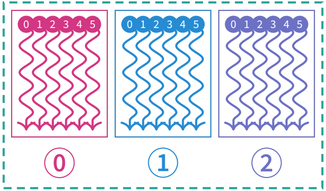
- Methods to exploit parallelism:
  - Threads → Block
  - Blocks



CUDA’s Parallel Model

In software: Threads, Blocks

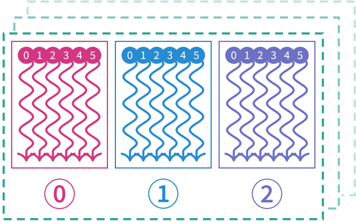
- Methods to exploit parallelism:
  - Threads → Block
  - Blocks → Grid



CUDA’s Parallel Model

In software: Threads, Blocks

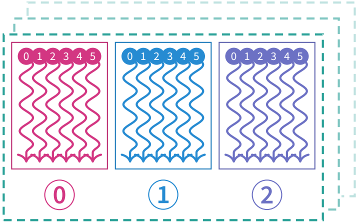
- Methods to exploit parallelism:
  - Threads → Block
  - Blocks → Grid
  - Threads & blocks in 3D



CUDA's Parallel Model

In software: Threads, Blocks

- Methods to exploit parallelism:
  - Threads → Block
  - Blocks → Grid
  - Threads & blocks in 3D
- Parallel function: **kernel**
  - `__global__ kernel(int a, float * b) { }`
  - Access own ID by global variables `threadIdx.x`, `blockIdx.y`, ...
- Execution entity: **threads**
  - Lightweight → fast switching!
  - 1000s threads execute simultaneously → order non-deterministic!



JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

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

```
__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();
```


JÜLICH Forschungszentrum JÜLICH SUPERCOMPUTING CENTRE

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();
```

Specify kernel

ID variables

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();
```

Specify kernel

ID variables

Guard against too many threads

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();
```

Specify kernel

ID variables

Guard against too many threads

Allocate GPU-capable memory

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();
```

Specify kernel

ID variables

Guard against too many threads

Allocate GPU-capable memory

Call kernel 2 blocks, each 5 threads

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();
```

- 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

Performance Analysis

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.

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.

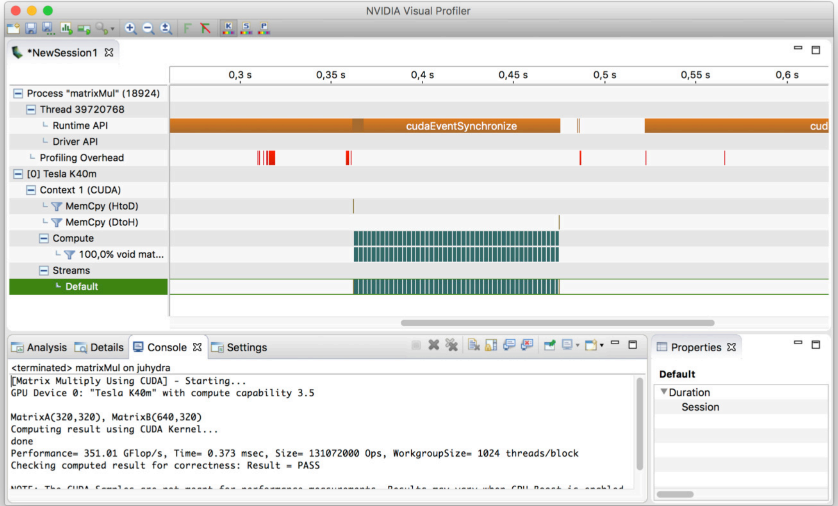
nvprof

Command that line

```
$ 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
  0.15%  612.20us      1505     406ns     361ns  1.1970us  cudaSetupArgument
  0.12%  499.01us         3  166.34us  140.45us  216.16us  cudaFree
```

Visual Profiler

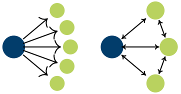


JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

Advanced Topics

So much more interesting things to show!

- Optimize memory transfers to reduce overhead
- Optimize applications for GPU architecture
- Drop-in BLAS acceleration with NVBLAS (`$LD_PRELOAD`)
- Tensor Cores for Deep Learning
- Libraries, Abstractions: Kokkos, Alpaka, Futhark, HIP, C++AMP, …
- Use multiple GPUs
  - On one node
  - Across many nodes → MPI



- …
- Some of that: Addressed at **dedicated training courses**

Using GPUs on JURECA & JUWELS

Compiling

CUDA

- Module: `module load CUDA/10.1.105`
- Compile: `nvcc file.cu`
  Default host compiler: `g++`; use `nvcc_pgc++` for PGI compiler
- cuBLAS: `g++ file.cpp -I$CUDA_HOME/include -L$CUDA_HOME/lib64 -lcublas -lcudart`

OpenACC

- Module: `module load PGI/19.3-GCC-8.3.0`
- Compile: `pgc++ -acc -ta=tesla file.cpp`

MPI

- Module: `module load MVAPICH2/2.3.1-GDR` (also needed: `GCC/8.3.0`)
  Enabled for CUDA (*CUDA-aware*); no need to copy data to host before transfer

Running

- Dedicated GPU partitions

  JUWELS

`--partition=gpus`	46 nodes (Job limits: <1 d)
`--partition=develgpus`	10 nodes (Job limits: <2 h, ≤ 2 nodes)

  JURECA

`--partition=gpus`	70 nodes (Job limits: <1 d, ≤ 32 nodes)
`--partition=develgpus`	4 nodes (Job limits: <2 h, ≤ 2 nodes)

- Needed: Resource configuration with `--gres`

  `--gres=gpu:4`

  `--gres=mem1024,gpu:2 --partition=vis` *only JURECA*

→ See online documentation

Example

- 96 tasks in total, running on 4 nodes
- Per node: 4 GPUs

```
#!/bin/bash -x
#SBATCH --nodes=4
#SBATCH --ntasks=96
#SBATCH --ntasks-per-node=24
#SBATCH --output=gpu-out.%j
#SBATCH --error=gpu-err.%j
#SBATCH --time=00:15:00

#SBATCH --partition=gpus
#SBATCH --gres=gpu:4

srun ./gpu-prog
```

Conclusion, Resources

- GPUs provide highly-parallel computing power
- We have many devices installed at JSC, ready to be used!

Conclusion, Resources

- GPUs provide highly-parallel computing power
- We have many devices installed at JSC, ready to be used!
- Training courses by JSC

  CUDA Course April 2020

  OpenACC Course 28 - 29 October 2019
- Generally: see online documentation and sc@fz-juelich.de

Conclusion, Resources

- GPUs provide highly-parallel computing power
- We have many devices installed at JSC, ready to be used!
- Training courses by JSC

  CUDA Course April 2020

  OpenACC Course 28 - 29 October 2019
- Generally: see online documentation and sc@fz-juelich.de
- Further consultation via our lab: NVIDIA Application Lab in Jülich; contact me!

Conclusion, Resources

- GPUs provide highly-parallel computing power
- We have many devices installed at JSC, ready to be used!
- Training courses by JSC

  CUDA Course April 2020

  OpenACC Course 28 - 29 October 2019
- Generally: see online documentation and sc@fz-juelich.de
- Further consultation via our lab: NVIDIA Application Lab in Jülich; contact me!
- Interested in JURON? Get access!

Conclusion, Resources

- GPUs provide highly-parallel computing power
- We have many devices installed at JSC, ready to be used!
- Training courses by JSC

  CUDA Course April 2020

  OpenACC Course 28 - 29 October 2019
- Generally: see online documentation and sc@fz-juelich.de
- Further consultation via our lab: NVIDIA Application Lab in Jüli
- Interested in JURON? Get access!

Thank you
for your attention!
a.herten@fz-juelich.de

APPENDIX

Appendix

Glossary

References

Glossary I

API A programmatic interface to software by well-defined functions. Short for application programming interface. 72, 73, 74, 75, 76

CUDA Computing platform for GPUs from NVIDIA. Provides, among others, CUDA C/C++. 2, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 100, 103, 104, 105, 106, 107, 111

JSC Jülich Supercomputing Centre, the supercomputing institute of Forschungszentrum Jülich, Germany. 2, 103, 104, 105, 106, 107, 110

JURECA A multi-purpose supercomputer with 1800 nodes at JSC. 2, 5, 99, 101

JURON One of the two HBP pilot system in Jülich; name derived from Juelich and Neuron. 6, 7

JUWELS Jülich's new supercomputer, the successor of JUQUEEN. 2, 3, 4, 99, 101

Glossary II

MPI The Message Passing Interface, a API definition for multi-node computing. 98, 100

NVIDIA US technology company creating GPUs. 3, 4, 5, 6, 7, 72, 73, 74, 75, 76, 94, 95, 103, 104, 105, 106, 107, 110, 111, 112, 113

NVLink NVIDIA's communication protocol connecting CPU $\leftrightarrow$ GPU and GPU $\leftrightarrow$ GPU with high bandwidth. 6, 7, 112

OpenACC Directive-based programming, primarily for many-core machines. 2, 65, 66, 67, 68, 69, 70, 100, 103, 104, 105, 106, 107

OpenCL The *Open Computing Language*. Framework for writing code for heterogeneous architectures (CPU, GPU, DSP, FPGA). The alternative to CUDA. 72, 73, 74, 75, 76, 94, 95

Glossary III

OpenMP Directive-based programming, primarily for multi-threaded machines. 2, 65, 66, 67, 68

P100 A large GPU with the Pascal architecture from NVIDIA. It employs NVLink as its interconnect and has fast *HBM2* memory. 6, 7

Pascal GPU architecture from NVIDIA (announced 2016). 112

POWER CPU architecture from IBM, earlier: PowerPC. See also POWER8. 112

POWER8 Version 8 of IBM's POWERprocessor, available also under the OpenPOWER Foundation. 6, 7, 112

SAXPY Single-precision $A \times X + Y$. A simple code example of scaling a vector and adding an offset. 50, 86, 87, 88, 89, 90, 91, 92

Glossary IV

Tesla The GPU product line for general purpose computing computing of NVIDIA. 3, 4, 5, 6, 7

CPU Central Processing Unit. 3, 4, 5, 6, 7, 12, 13, 14, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 50, 72, 73, 74, 75, 76, 111, 112

GPU Graphics Processing Unit. 2, 3, 4, 5, 6, 7, 8, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 49, 51, 52, 53, 54, 55, 56, 57, 65, 66, 67, 68, 71, 72, 73, 74, 75, 76, 90, 91, 92, 93, 94, 95, 98, 99, 101, 102, 103, 104, 105, 106, 107, 110, 111, 112, 113

HBP Human Brain Project. 110

SIMD Single Instruction, Multiple Data. 35, 36, 37, 38, 39, 40, 41, 42, 43, 44

Glossary V

SIMT Single Instruction, Multiple Threads. 15, 16, 17, 30, 31, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44

SM Streaming Multiprocessor. 35, 36, 37, 38, 39, 40, 41, 42, 43, 44

SMT Simultaneous Multithreading. 35, 36, 37, 38, 39, 40, 41, 42, 43, 44

References I

[2] Karl Rupp. *Pictures: CPU/GPU Performance Comparison*. URL: `https://www.karlrupp.net/2013/06/cpu-gpu-and-mic-hardware-characteristics-over-time/` (pages 10, 11).

[6] Wes Breazell. *Picture: Wizard*. URL: `https://thenounproject.com/wes13/collection/its-a-wizards-world/` (pages 52–56).

References: Images, Graphics I

[1] Alexandre Debiève. *Bowels of computer*. Freely available at Unsplash. URL: https://unsplash.com/photos/FO7JIlwjOtU.

[3] Mark Lee. *Picture: kawasaki ninja*. URL: https://www.flickr.com/photos/pochacco20/39030210/. License: Creative Commons BY-ND 2.0 (pages 12, 13).

[4] Bob Adams. *Picture: Hylton Ross Mercedes Benz Irizar coach*. URL: https://www.flickr.com/photos/satransport/13197324714/. License: Creative Commons BY-SA 2.0 (pages 12, 13).

[5] Nvidia Corporation. *Pictures: Volta GPU*. Volta Architecture Whitepaper. URL: https://images.nvidia.com/content/volta-architecture/pdf/Volta-Architecture-Whitepaper-v1.0.pdf (pages 42–44).

JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE