Efficient Scientific Computing School – 12th Edition

Performance Portability With *alpaka*

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Life After CUDA

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Previously on ESC21 …

- Parallel programming models:
  - Intel TBB
  - `std::thread`
  - NVIDIA CUDA
- Many more available:
  - AMD HIP
  - OpenCL & SYCL / Intel oneAPI
  - OpenMP
  - OpenACC
  - Boost.Fiber
  - …
- Challenge: How to keep programs portable?

Introduction to alpaka

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alpaka – Abstraction Library for Parallel Kernel Acceleration

alpaka is…

- A parallel programming library: Accelerate your code by exploiting your hardware‘s parallelism!
- An abstraction library: Create portable code that runs on CPUs and GPUs!
- Free & open-source software

Introduction to alpaka

Programming with alpaka

- C++ only!
- Header-only library: No additional runtime dependency introduced
- Modern library: alpaka is written entirely in C++14, transitioning to C++17 soon
- Supports a wide range of modern C++ compilers (g++, clang++, Apple LLVM, MS Visual Studio)
- Portable across operating systems: Linux, macOS, Windows are supported

Introduction to alpaka

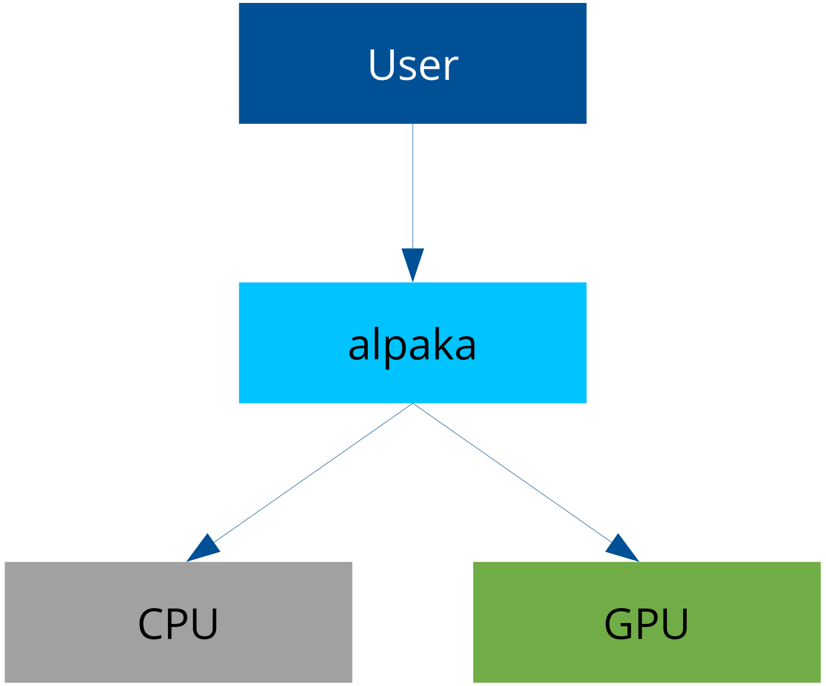
alpaka's purpose

Without alpaka

- Multiple hardware types commonly used (CPUs, GPUs, …)
- Increasingly heterogeneous hardware configurations available
- Platforms not inter-operable → parallel programs not easily portable

alpaka: one API to rule them all

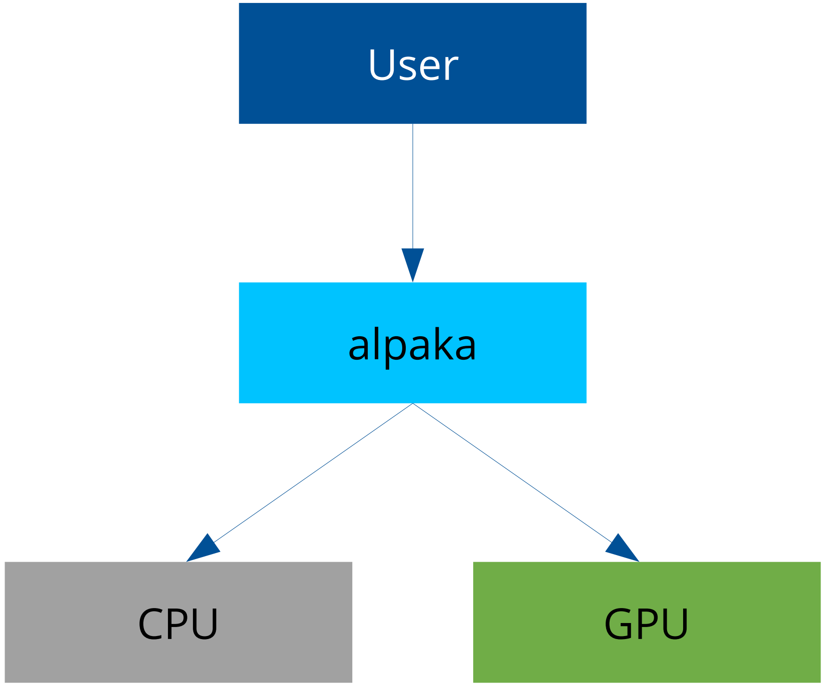
- Abstraction (not hiding!) of the underlying hardware & software platforms
- Code needs only minor adjustments to support different accelerators



Portable Heterogeneous Parallel Programming

alpaka enables portability!

- Idea: Write algorithms once…
  - … independently of target architecture
  - … independently of available programming models
- Decision on target platform made during compilation
  - Choosing another platform just requires another compilation pass
- alpaka defines an abstract programming model
- alpaka utilizes C++14 to support many architectures
  - CUDA, HIP, OpenMP, TBB, …



Portable Heterogeneous Parallel Programming

alpaka enables full utilization of heterogeneous systems!

- Algorithms are generally independent of chosen target architecture

```
auto const taskCpu = alpaka::createTaskKernel<AccCpu>(workDivCpu, kernel, …);
auto const taskGpu = alpaka::createTaskKernel<AccGpu>(workDivGpu, kernel, …);
```

- Optimization for specific architecture is still possible

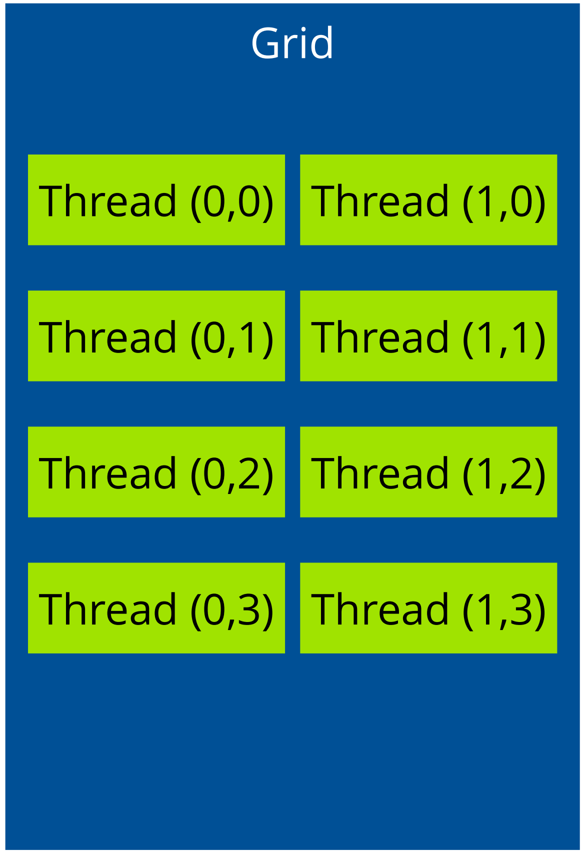
```
// general case
template <typename TAcc>
void computationallyIntensiveFunction(TAcc const & acc) { … };

// specialization for AccGpu
template <>
void computationallyIntensiveFunction<AccGpu>(AccGpu const & acc) { … };
```

Portable Heterogeneous Parallel Programming

How parallelism is achieved, Part I: The grid, a digital frontier

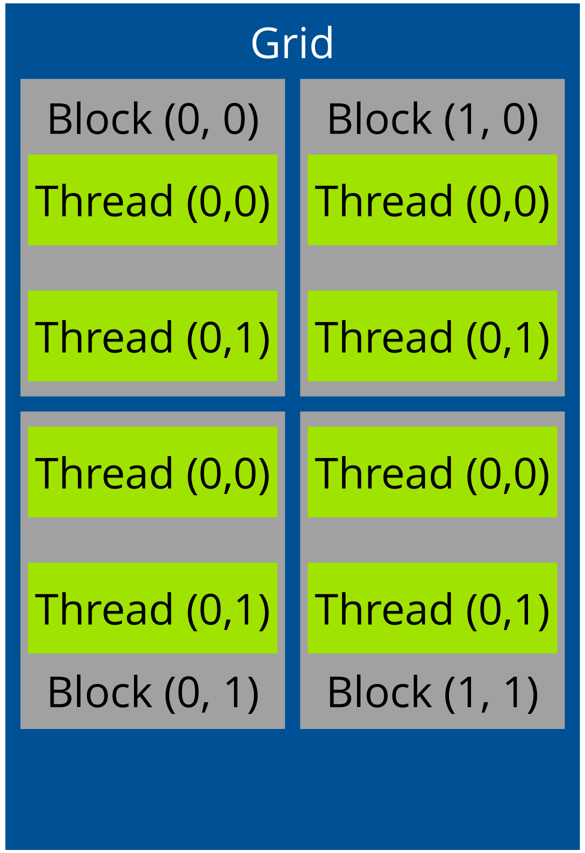
- alpaka is ideal for data-parallel algorithms
  → execute the same algorithm on different data elements
- alpaka **kernel**: sequence of commands forming the algorithm on a per-element level
- alpaka **thread:** execution of a kernel for a single (execution) element
- threads are executed in parallel and are independent of each other
- alpaka **grid**: n-dimensional grid of all **threads** executing a specific kernel
  - each thread is assigned a unique index on the grid
  - threads on the grid are able to communicate through high-latency **global memory**



Portable Heterogeneous Parallel Programming

How parallelism is achieved, Part II: Blocks on the grid

- Grids are divided into independent **blocks** of equal size
- Each thread is assigned to exactly one block
- Each thread is assigned an unique index on the block
- All threads inside a block are executed in parallel
- All threads inside a single block can be **synchronized**
  → no synchronization on the grid level!
- All threads inside a block can communicate through low-latency **shared memory**



Portable Heterogeneous Parallel Programming

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Summary

- alpaka is ideal for data-parallel algorithms
- Algorithms are written per data element (**kernel**)
- data parallelism achieved through a hierarchy of independent **threads** and **blocks** on a **grid**
- All threads can communicate through high-latency **global memory**
- Threads inside a block can be **synchronized**
- Threads inside a block can communicate through low-latency **shared memory**

Download & Installation

Download

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How to download alpaka

- Install `git` for your operating system:
  - Linux: `sudo dnf install git` (RPM) or `sudo apt install git` (DEB)
  - macOS: Enter `git --version` in your terminal, you will be asked if you want to install `git`
  - Windows: Download the installer from **https://git-scm.com/download/win**
- Open the terminal (Linux / macOS) or PowerShell (Windows)
- Navigate to a directory of your choice: `cd /path/to/some/directory`
- Download alpaka: `git clone -b 0.7.0 https://github.com/alpaka-group/alpaka.git`

Dependencies

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Install alpaka's dependencies

- alpaka only requires Boost and a modern C++ compiler (`g++`, `clang++`, Visual C++, …)
  - Linux:
    - `sudo dnf install boost-devel` (RPM)
    - `sudo apt install libboost-all-dev` (DEB)
  - macOS:
    - `brew install boost` (Using Homebrew, **https://brew.sh**)
    - `sudo port install boost` (Using MacPorts, **https://macports.org**)
  - Windows: `vcpkg install boost` (Using vcpkg, **https://github.com/microsoft/vcpkg**)
- Depending on your target platform you may need additional packages
  - NVIDIA GPUs: CUDA Toolkit (**https://developer.nvidia.com/cuda-toolkit**)
  - AMD GPUs: ROCm / HIP (**https://rocmdocs.amd.com/en/latest/index.html**)

Installation

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(Optional) Install alpaka's headers

- alpaka is already ready to use!
- Create an installation directory for the headers:
  ```
  mkdir /some/install/dir/
  ```
- Copy the alpaka headers to the new directory:
  ```
  cp -r alpaka/include /some/install/dir
  ```

Test Your Installation

- Create a small program that includes the main alpaka header:

```cpp
#include <alpaka/alpaka.hpp>

#include <cstdlib>

int main()
{
    return EXIT_SUCCESS;
}
```

- Compile:

```
$ nvcc -std=c++14 -I/some/install/dir/include tutorial.cpp
$ ./a.out
```

- Add the following compiler flag to silence the warnings:

```
-Xcudafe=--diag_suppress=esa_on_defaulted_function_ignored
```

Exercise 0: Set up alpaka on your system!

Before we proceed...

Lecture Notes

- Find the cheatsheet: **https://alpaka.readthedocs.io/en/0.7.0/basic/cheatsheet.html**
- Assume `using namespace alpaka;` everywhere!

Calculating AXPY

Introduction to alpaka

AXPY

$$\vec{y} \leftarrow a \cdot \vec{x} + \vec{y}$$

```
struct AxpyKernel
{
    template <typename TAcc>
    ALPAKA_FN_ACC void operator()(TAcc const& acc,
      std::size_t numElements, int a, int const* X, int* Y) const
    {
        auto gridThreadIdx = getIdx<Grid, Threads>(acc)[0u];
        auto threadElems = getWorkDiv<Thread, Elems>(acc)[0u];
        auto first = gridThreadIdx * threadElems;

        if(first < numElements)
        {
            auto last = first + threadElems;
            for(auto i = first; i < last; ++i)
                Y[i] = a * X[i] + Y[i];
        }
    }
};
```

Introduction to alpaka

AXPY

$$\vec{y} \leftarrow a \cdot \vec{x} + \vec{y}$$

```
using namespace alpaka;
using Dim = DimInt<1u>;
using Idx = std::size_t;
using Acc = AccGpuCudaRt<Dim, Idx>;

auto const host = getDevByIdx<DevCpu>(0u);
auto const dev = getDevByIdx<Acc>(0u);
using myQueue = Queue<Acc, property::Blocking>;
auto queue = myQueue{dev};

auto const ext = Vec<Dim, Idx>{1024};
auto hostBufY = allocBuf<int, Idx>(host, ext);
/* Initialize … */
auto devBufY = allocBuf<int, Idx>(dev, ext);

memcpy(queue, devBufY, hostBufY, ext);

auto workDiv = getValidWorkDiv<Acc>(dev, ext, Idx{1u});
auto taskKernel = createTaskKernel<Acc>(
                    workDiv, AxpyKernel{}, /* params … */);
enqueue(queue, taskKernel);

memcpy(queue, hostBufY, devBufY, ext);
```

alpaka's Programming Model

Handling Parallelism

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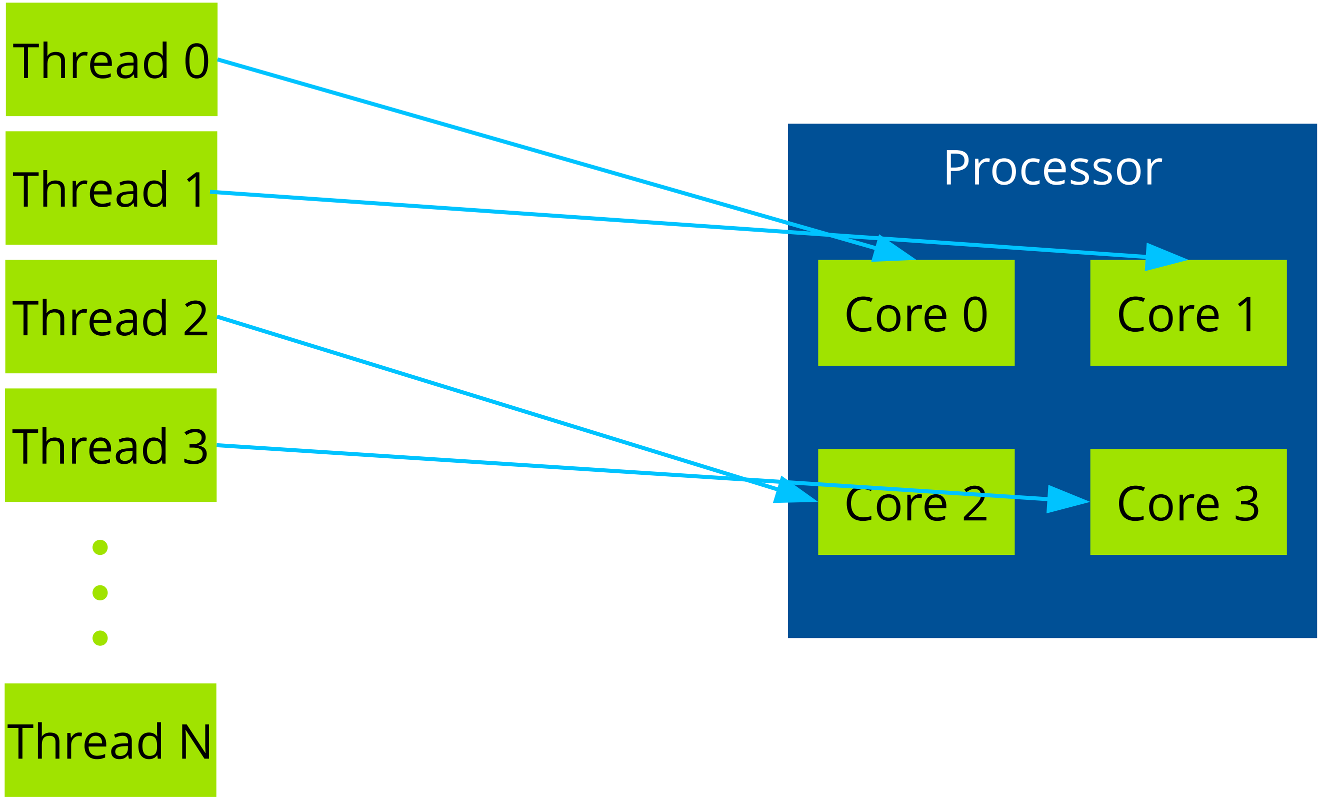
Threads and cores

- alpaka Threads are different from pthreads, `std::threads`, OpenMP threads, CUDA threads, etc.
- alpaka Thread: execution of command sequence
- Command sequence: algorithm performed on single data element (Kernel)
- Cores are physical execution units
- Cores are capable of executing alpaka Threads
- Example: AMD Threadripper 3990X with 64 CPU cores
- Example: NVIDIA Tesla V100 with 5,120 CUDA cores

Handling Parallelism

Mapping Threads to cores

- alpaka Threads are mapped to hardware cores
- While running, one Thread is executed by exactly one core
- Threads may run on other cores after rescheduling
- Usually many more Threads than cores (*oversubscription*)
- Waiting Threads make room for ready Threads



Handling Parallelism

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alpaka Devices

- A set of cores is called a Device
- A single core can only belong to exactly one Device (N:1 mapping)
- All cores on the Device have access to global memory
- alpaka Devices correspond to physical devices
- Example: AMD Threadripper 3990X with 64 CPU cores is a Device with 128 cores (simultaneous multithreading!)
- Example: NVIDIA Tesla V100 with 5,120 CUDA cores is a Device with 5,120 cores

Handling Parallelism

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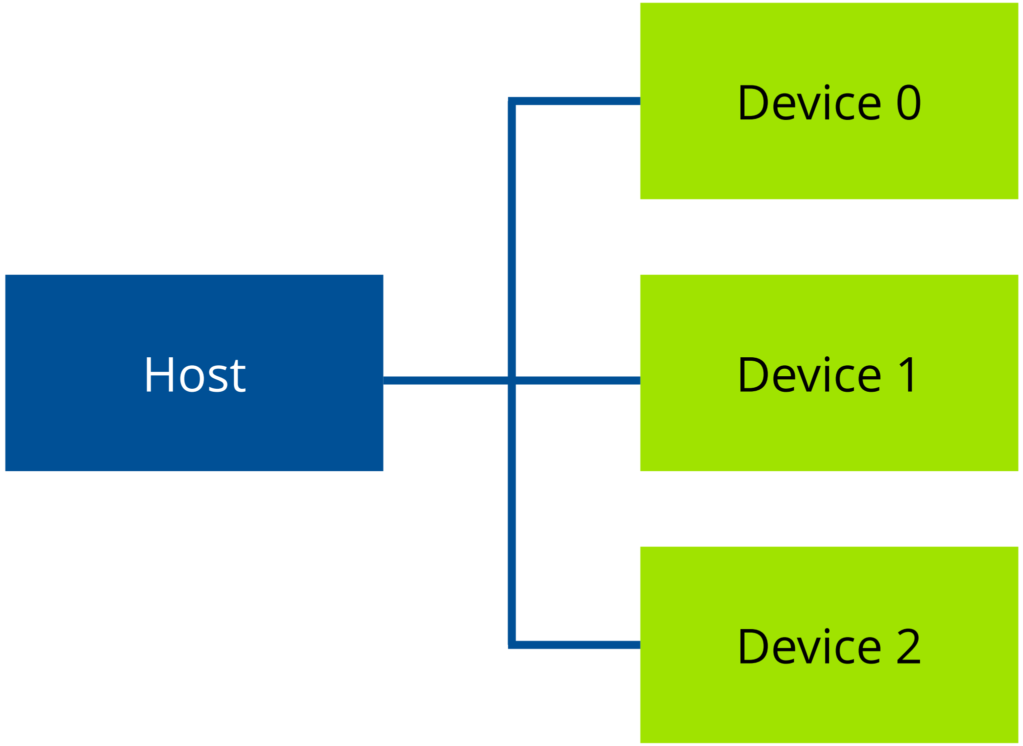
Host and Device

- An alpaka Host controls the overall program flow
- An alpaka Device executes Kernels
- All Devices are attached to a single Host
- It is impossible to have more than one Host per process



Kernels

What is a Kernel?

- Contains the algorithm
- Written on per-data-element basis
- alpaka Kernels are functors (function-like C++ structs / classes)
- `operator()` is annotated with `ALPAKA_FN_ACC` specifier
- `operator()` must return `void`
- `operator()` must be `const`

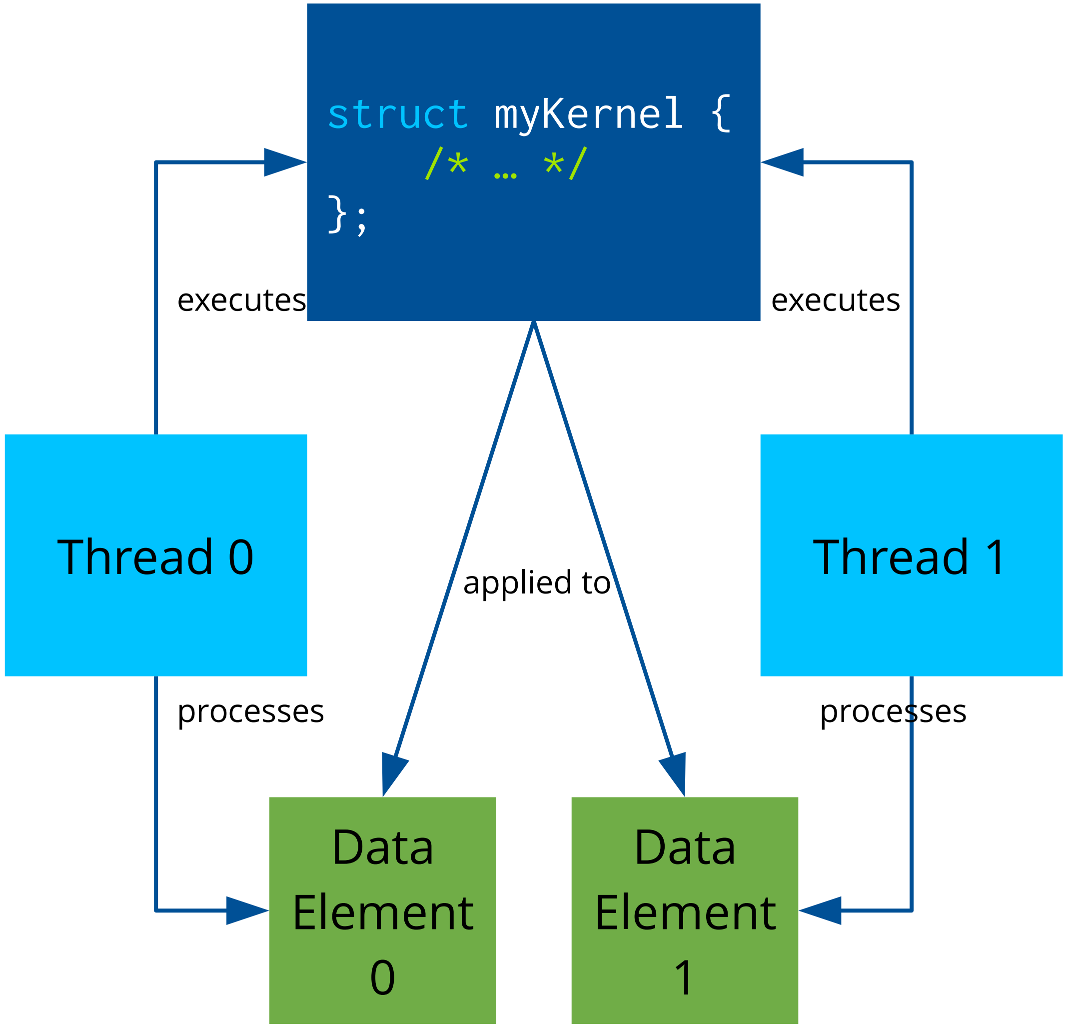
```
struct HelloWorldKernel
{
    template <typename Acc>
    ALPAKA_FN_ACC void operator()(Acc const & acc) const
    {
        uint32_t threadIdx = getIdx<Grid, Threads>(acc)[0];

        printf("Hello, World from alpaka thread %u!\n", threadIdx);
    }
};
```

Kernels

Threads and Kernels

- A Kernel is executed by a number of Threads
- Threads are executing the same algorithm for different data elements

- A Kernel **defines** an algorithm
- A Thread **applies** an algorithm



Kernels

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Scheduling

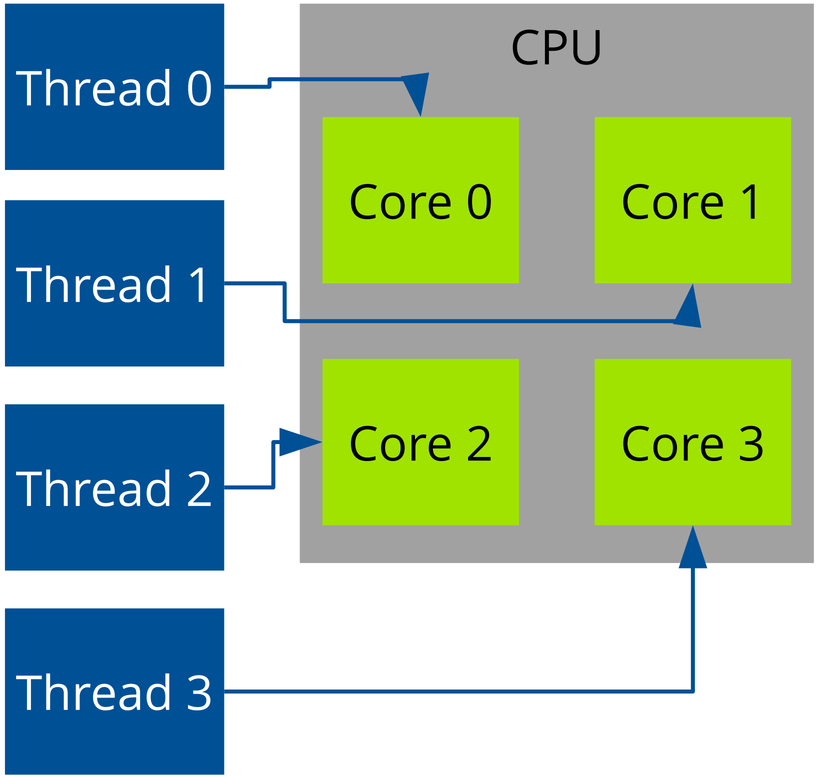
- Threads are mapped to cores
- Many more Threads than cores → Thread scheduling required
- **Thread order is unspecified!**

  → Programmer cannot control the order of element processing
- Hardware specifics need to be taken into account

Kernels

Example: Thread mapping on CPUs

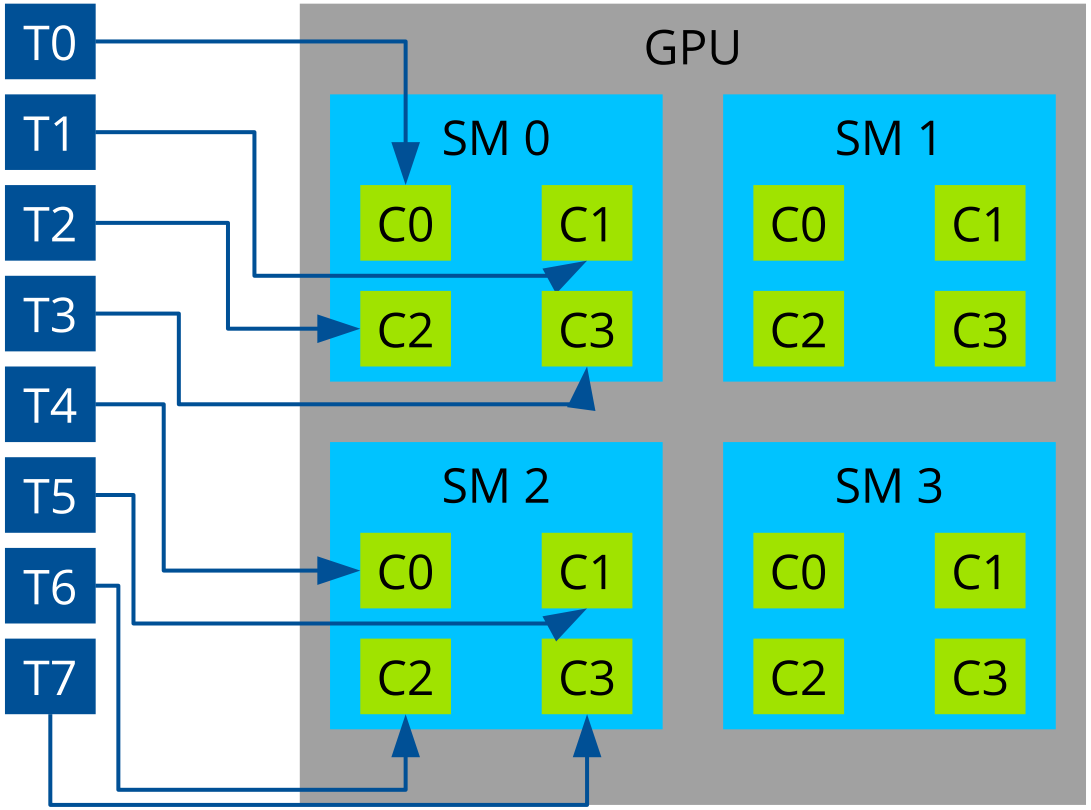
- CPU consists of multiple cores
  - Because of simultaneous multithreading there can be more logical than physical cores!
- alpaka Threads are executed by CPU cores



Kernels

Example: Thread mapping on GPUs

- GPU consists of streaming multiprocessors (SMs)
- Each SM consists of multiple cores
- alpaka Threads are executed by individual SM cores



The Problem Size

Problem size and hardware capabilities

- The programmer's questions:
  - How large is the problem? (= How many data elements need processing?)
  - Which capabilities are offered by the hardware? (= How many cores are available?)
- The programmer's challenge:
  - Problem size and number of cores completely disjoint
  - How to distribute the former amongst the latter?

The Problem Size

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How to choose the number of alpaka Threads

- The two important factors:
  - Problem size → number of data elements
  - Hardware capabilities → number of cores
- Rule of thumb: One Thread per data element
  - Not always ideal (depending on algorithm)
  - Chance for optimisation

The Problem Size

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Choosing the number of Threads

- (Usually) you have more Threads than cores
- In alpaka, the overall number of Threads is `blocksPerGrid * threadsPerBlock`
  - We will introduce Thread Blocks later!

```
using Idx = std::uint32_t;

Idx blocksPerGrid = 8;
Idx threadsPerBlock = 1;
```

The Problem Size

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Beware!

- Don’t run too many Threads in parallel!
  - An exact definition of “too many” depends on your hardware.
- Some hardware resources are always shared between Threads
- Having too many Threads accessing shared resources results in bottlenecks
  - Can seriously impact your program’s performance
  - Chance for optimisation

The Problem Size

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Example: I/O buffer

- All Threads call `printf`
- The access to the output buffer needs to be serialized
- More Threads
  → more serialization
  → worse performance

```
template <typename Acc>
ALPAKA_FN_ACC void operator()(Acc const & acc) const
{
    auto threadIdx = getIdx<Grid, Threads>(acc)[0];
    printf("Hello, World from alpaka thread %u!\n", threadIdx);
}
```

Thread Hierarchy

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The "magic" Thread index

```
template <typename Acc>
ALPAKA_FN_ACC void operator()(Acc const & acc) const
{
    auto threadIdx = getIdx<Grid, Threads>(acc)[0];
    printf("Hello, World from alpaka thread %u!\n", threadIdx);
}
```

Thread Hierarchy

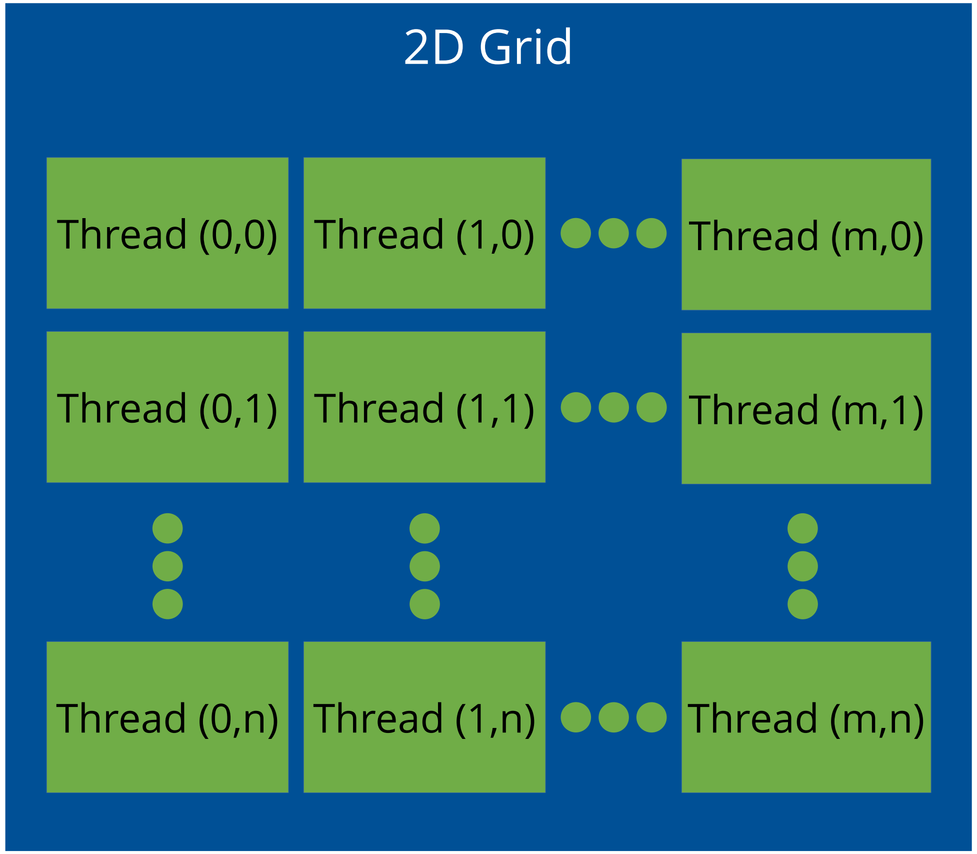
Understanding the index

- Understanding alpaka's Thread indices is the key to understanding alpaka!
- After this section, you will understand:
  - How to navigate the grid
  - How to form Thread Blocks (and why)
  - The relations between Threads, Blocks and the Grid
  - How to compute Thread indices yourself

Thread Hierarchy

Threads and the Grid

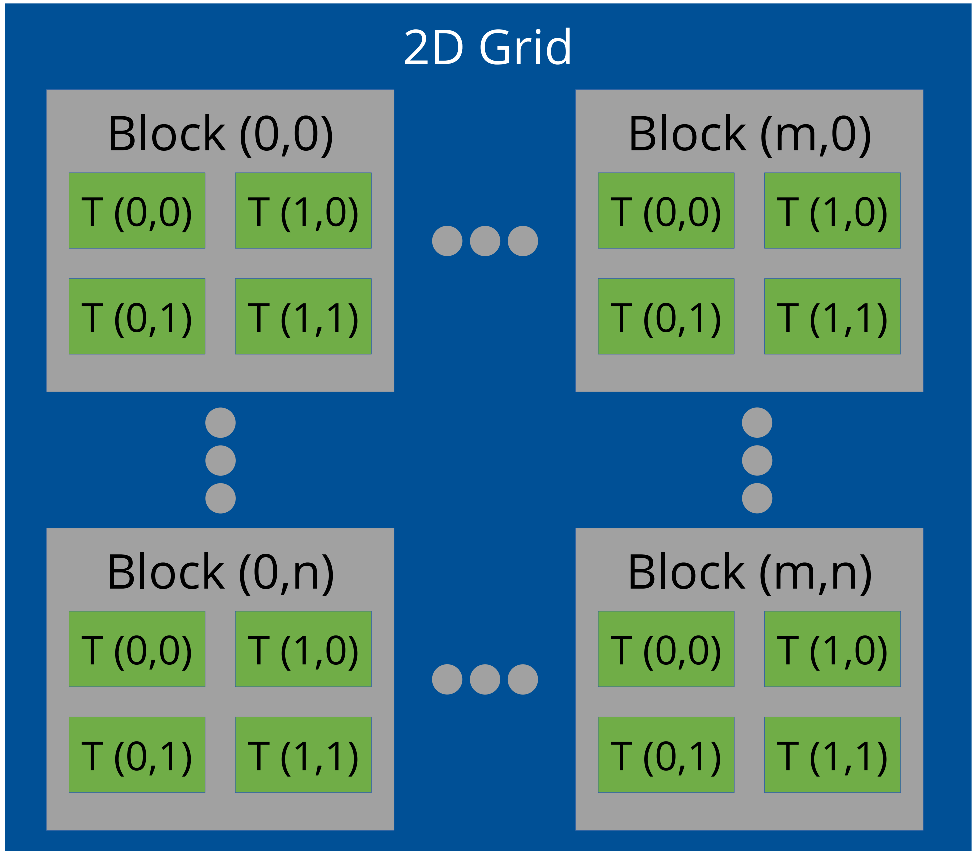
- A Grid consists of all Threads executing the same kernel
  → One Grid per Kernel execution
- Threads are distributed along one, two or three dimensions
- Each Thread on the Grid is identified by its unique index (`gridThreadIdx`)
- All Threads have access to (large but high-latency) global memory



Thread Hierarchy

Thread Blocks

- Threads can be grouped into Thread Blocks
- All Blocks on the same Grid have the same size
- Each Block on the Grid is identified by its unique index (`gridBlockIdx`)
- Each Thread inside a Block is identified by its Block-local unique index (`blockThreadIdx`)
- Threads inside a Block have access to (small but low-latency) shared memory
- Threads inside a Block can be synchronized



Thread Hierarchy

Obtaining the indices

- alpaka provides several API functions for obtaining indices:
  - Index of Thread on the Grid: `getIdx<Grid, Threads>(acc)[dim];`
  - Index of Thread on a Block: `getIdx<Block, Threads>(acc)[dim];`
  - Index of Block on the Grid: `getIdx<Grid, Blocks>(acc)[dim];`
- You can also obtain the extents of the Grid or the Blocks:
  - Number of Threads on the Grid: `getWorkDiv<Grid, Threads>(acc)[dim];`
  - Number of Threads on a Block: `getWorkDiv<Block, Threads>(acc)[dim];`
  - Number of Blocks on the Grid: `getWorkDiv<Grid, Blocks>(acc)[dim];`
- Exercise: compute the index of a Thread on the Grid yourself using a combination of the remaining indices and extents!

2D Work Division

From 1D to 2D

- *n*-dimensional grids work in a similar way to 1D grids
  - `getIdx<Grid, Threads>(acc)` returns a vector containing *n* indices
  - `getIdx<Grid, Threads>(acc)[dim]` returns an integer
- **Beware**: In a 2D grid, *y* is dimension zero and *x* is dimension one
  - `getIdx<Grid, Threads>(acc)` returns a vector containing 2 indices: the *y*-index at position `0` and the *x*-index at position `1`
  - `getIdx<Grid, Threads>(acc)[0]` returns the *y*-index

Computing π

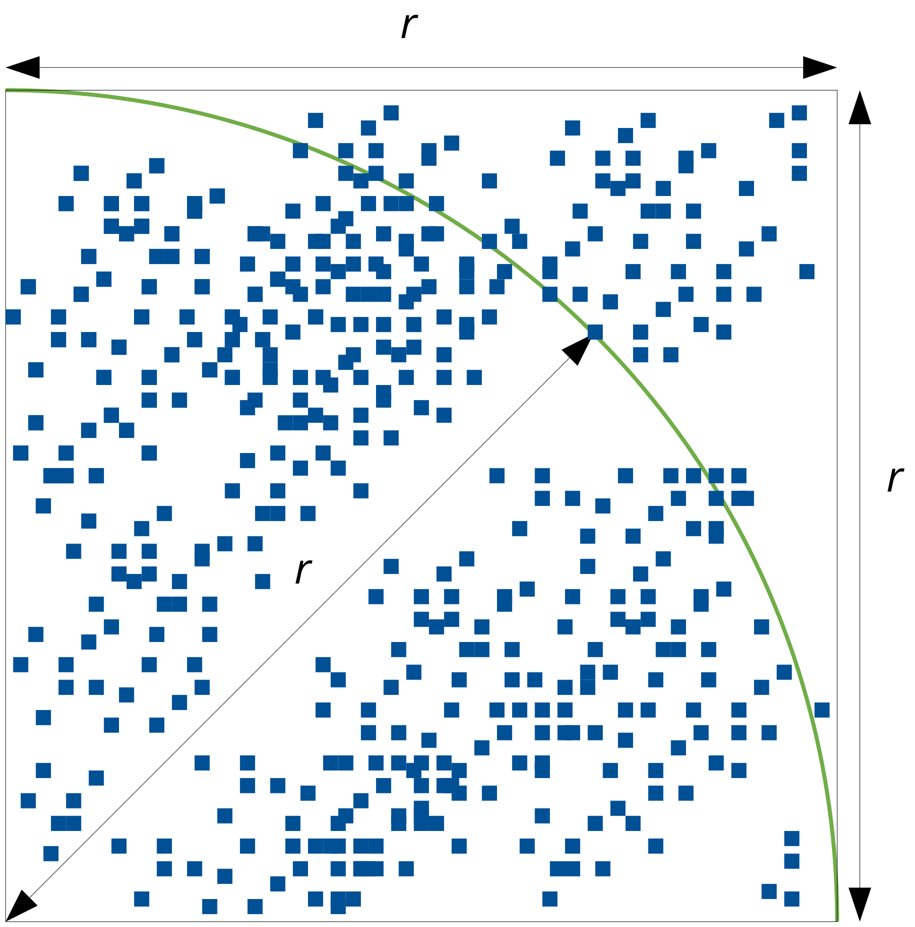
Computing π

- Focus of the next four lessons
- Good example for Thread parallelism
- Introduces parameter passing and memory management
- Initial algorithm: Find points in a circle

Computing π – Part I

Points in a circle

- Task: Given a circle quarter with the radius *r* and a set of *n* randomly scattered points, find all points inside the circle quarter
- Approach:
  - Create a Grid with *n* Threads
  - Each Thread evaluates a single point



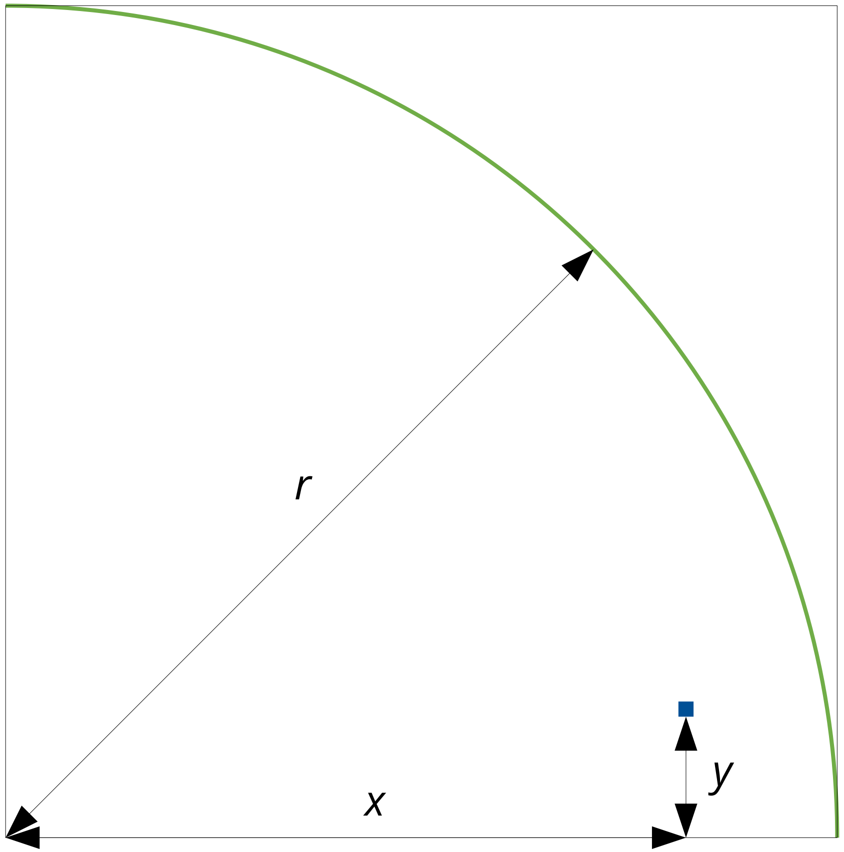
Computing π – Part I

Algorithm

- Using Pythagoras' theorem, the distance *d* from a point to the origin can be calculated:

  $$d = \sqrt{x^2 + y^2}$$

- If $d \leq r$, return `true`, otherwise `false`



Computing π – Part I

Kernel requirements

- For the computation we need:
  - The point coordinates:
    ```
    struct Points {
        float* x;
        float* y;
        bool* inside;
    };
    ```
  - The radius: `float r;`
- How do we pass these to the kernel?

Computing π – Part I

Passing parameters

- alpaka kernels accept three different parameter types:
  - The accelerator: `Acc const & acc` (required)
  - Pointers to memory buffers of any data type: `float* bufferA`, `MyDataType* bufferB`
  - Scalar values of trivially copyable types: `float scalar`, `struct Composed { int a; float b; }`
- Signature of the `PixelFinderKernel`'s `operator()`:

```
template <typename Acc>
ALPAKA_FN_ACC void operator()(Acc const & acc, // required
                              Points points,   // this struct contains memory buffers
                              float r          // this is a scalar
) const
```

Computing π – Part II

Grid dimensionality

- No spatial relationship between points
- Points can be evaluated independently
- This makes a multi-dimensional grid unnecessary

```
struct PixelFinderKernel
{
    template <typename Acc>
    ALPAKA_FN_ACC void operator()(Acc const & acc, Points points, float r) const {

        uint32_t gridThreadIdx = getIdx<Grid, Threads>(acc)[0];
        /* … */
```

Computing π – Part II

Accessing memory

- Iterating over a buffer works differently in alpaka
- `for` loop: One thread accesses elements sequentially
- Thread index: Threads access elements in parallel
- If required, you can mix both approaches!

```
// Using a for loop for buffer access
for(std::size_t i = 0; i < n; ++i)
{
    float x = points.x[i];
    float y = points.y[i];
}
```

```
// Using the thread index for buffer access
float x = points.x[gridThreadIdx];
float y = points.y[gridThreadIdx];
```

Computing π – Part II

Computing the distance

- Use Pythagoras' theorem for computing the distance
- Use `sqrt()` for computing the square root
  - Requires the `acc` parameter!

```
        /* … */
        float d = sqrt(acc, x * x + y * y);

        bool isInside = (d <= r);

        points.inside[gridThreadIdx] = isInside;
    }
};
```

Computing π – Part II

The complete Kernel

```
struct PixelFinderKernel
{
    template <typename Acc>
    ALPAKA_FN_ACC void operator()(Acc const & acc, Points points, float r) const {

        uint32_t gridThreadIdx = getIdx<Grid, Threads>(acc)[0];

        float x = points.x[gridThreadIdx];
        float y = points.y[gridThreadIdx];
        float d = sqrt(acc, x * x + y * y);

        bool isInside = (d <= r);

        points.inside[gridThreadIdx] = isInside;
    }
};
```

Computing π – Part III

Kernel requirements

- alpaka kernels accept pointers to Device memory
- Challenge: Host and Device don’t always share memory
- Memory buffers need to be allocated on both the Host and the Device
- Memory needs to be transferred from the Host to the Device and vice versa
- In case of CPU Devices there is optimisation potential in avoiding unnecessary copies!

Computing π – Part III

Allocating memory on the Host

- Memory can be allocated using `allocBuf()`

```
using Host = /* … */;                                   // not important now
using BufHost = Buf<Host, float, Dim, Idx>;             // Host buffer type
using MyVec = Vec<Dim, Idx>;                            // Vector type

auto const devHost = getDevByIdx<Host>(0u);             // create host device
Vec const extents(n);                                   // create extents
BufHost hostBuffer = allocBuf<float, Idx>(devHost, extents);
```

- Pre-allocated memory can be used with alpaka:

```
std::vector<float> plainBuffer(n);
using ViewHost = ViewPlainPtr<Host, float, Dim, Idx>;
ViewHost hostViewPlainPtr(plainBuffer.data(), devHost, Vec(plainBuffer.size());
```

Computing π – Part III

Allocating memory on the Device

- Allocating memory on the Device works the same way!
- Memory can be allocated using `allocBuf()`

```
using Acc = /* … */;                                    // not important now
using BufAcc = Buf<Acc, float, Dim, std::size_t>;       // Accelerator buffer type

auto const devAcc = getDevByIdx<Acc>(0u);               // create accelerator device

BufAcc accBuffer = allocBuf<float, std::size_t>(devAcc, extents);
```

Computing π – Part III

Memory transfers

- After initializing the Host buffer (`for` loop, `<algorithm>`, `memset`, …) memory can be transferred
- In alpaka all memory operations are explicit
- Use `memcpy()` to initiate transfers:

```
memcpy(devQueue,            // queue (explained later)
       devBuffer,           // copy target
       hostBuffer,          // copy source
       extents);            // number of elements
```

```
memcpy(devQueue,
       devBuffer,
       hostViewPlainPtr,    // for pre-allocated memory
       extents);
```

Computing π – Part IV

Approach

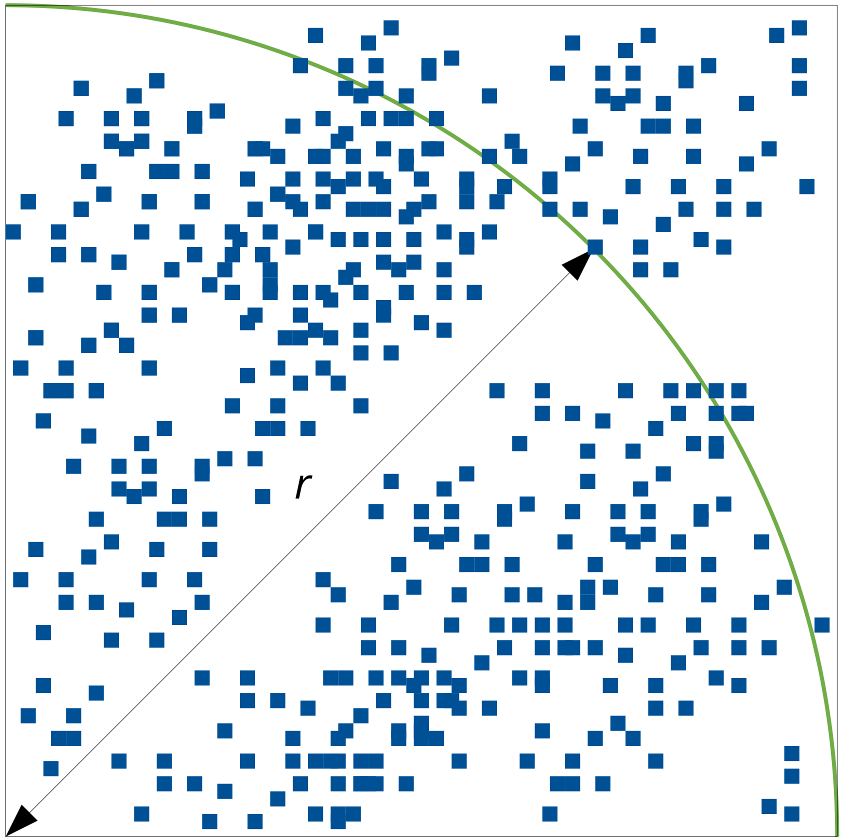
- We will use the formula for the area of a circle quarter:

  $$A = \frac{\pi \cdot r^2}{4}$$

- The number of points inside the circle (*P*) can be used to approximate *A:*

  $$\frac{P}{n} \approx \frac{A}{r^2} = \frac{\pi}{4} \rightarrow \pi \approx \frac{4P}{n}$$

- The `PixelFinderKernel` does the counting on the Device, integration is done by the Host.



Lesson 26: Computing π – Part IV

Kernel execution and memory transfer

- We will measure the execution time:

```
auto start = std::chrono::steady_clock::now();
```

- Execute the kernel using `enqueue()`:

```
PixelFinderKernel pixelFinderKernel;
auto taskRunKernel = createTaskKernel<Acc>(workDiv, pixelFinderKernel, pointsAcc, r);
enqueue(queue, taskRunKernel);
```

- Copy back the results and synchronize:

```
memcpy(devQueue, insideBufferHost, insideBufferAcc, extents);
wait(devQueue);
```

Computing π – Part IV

Integration

- First, determine *P*:

```
std::uint64_t P = 0;
for(std::size_t i = 0; i < n; ++i)
{
    if(pointsHost.inside[i])
        ++P;
}
```

- Then, divide by the radius to approximate π:

```
float pi = (4.f * P) / n;
```

- Measure the execution time:

```
auto end = std::chrono::steady_clock::now();
```

Computing π – Part IV

Aftermath

- Print out π and execution time:

```
std::chrono::duration<double, std::milli> duration = end - start;
std::cout << "Computed pi is " << pi << "\n";
std::cout << "Execution time: " << duration.count() << "ms" << std::endl;
```

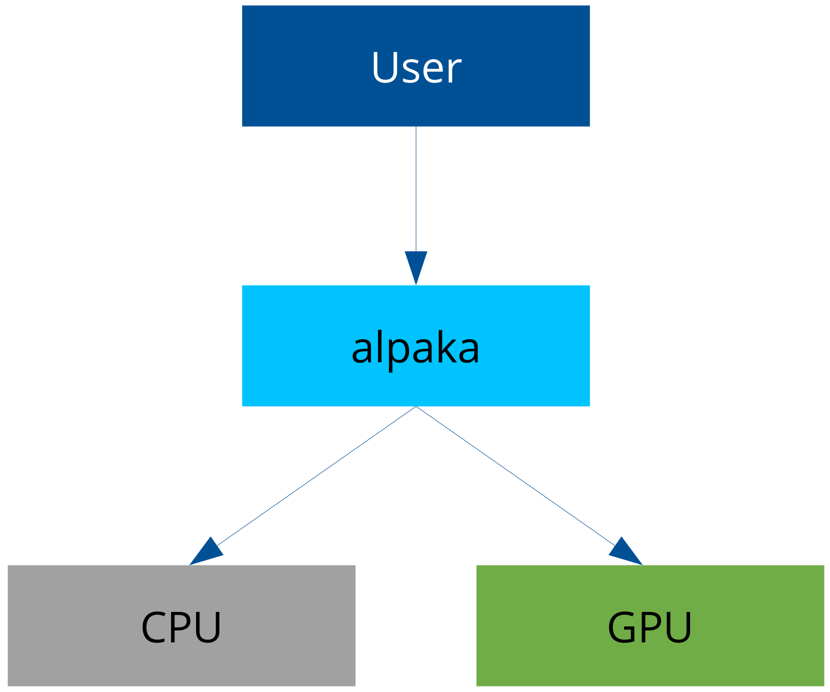
- Homework #1: Play around with *n*. How does this affect the precision of π and the execution time?
- Homework #2: Implement the kernel in a more generic way, so that it works for any number of threads, blocks and grids.
  - The workload has to be distributed between all threads in the grid.
  - It requires to have a loop over points inside the kernel.

Changing the Back-end

Moving from CPU to GPU

alpaka allows for easy …

- … exchange of the accelerator
- … porting of programs across accelerators
- … experimentation with different devices
- … mixing of accelerator types



Changing the Back-end

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Switching the Accelerator

- alpaka provides a number of pre-defined back-ends (called *Accelerators)*
- For GPUs:
  - `AccGpuCudaRt` for NVIDIA GPUs
  - `AccGpuHipRt` for AMD (and NVIDIA) GPUs
- For CPUs
  - `AccCpuFibers` based on Boost.Fiber
  - `AccCpuOmp2Blocks` based on OpenMP 2.x
  - `AccCpuOmp5` based on OpenMP 5.x
  - `AccCpuTbbBlocks` based on TBB
  - `AccCpuThreads` based on `std::thread`

```
// Example: CPU accelerator
using Acc = AccCpuOmp2Blocks<Dim, Idx>;

// Example: CUDA GPU accelerator
using Acc = AccGpuCudaRt<Dim, Idx>;

// Example: HIP GPU accelerator
using Acc = AccGpuHipRt<Dim, Idx>;
```

Changing the Back-end

Changing the work division

- GPUs have many more cores than CPUs
  → More parallel threads possible
- GPUs have several multiprocessors
- Each multiprocessor can execute multiple threads
- Threads are grouped into blocks
- Blocks are scheduled to run on multiprocessors

```
// CPU work division (example)
Idx blocksPerGrid     = 8;
Idx threadsPerBlock   = 1;
Idx elementsPerThread = 1;

// GPU work division (example)
Idx blocksPerGrid     = 64;
Idx threadsPerBlock   = 512;
Idx elementsPerThread = 1;
```

Changing the Back-end

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GPU performance hints

- Avoid divergent `if`-`else`-blocks
  - GPU threads are organized into groups (NVIDIA: *warp*, AMD: *wavefront*)
  - Groups are executed in lock step
    → If there is divergence, all threads execute the `if` block first and the `else` block next
- GPU threads are much more lightweight than CPU threads
  - Context switch is much cheaper on GPUs
  - Spawn many more threads than you have GPU cores
    → Hide memory latency behind computation

The Accelerator Concept

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Introduction

- alpaka's Accelerator concept is an important tool
- Accelerator hides hardware specifics behind alpaka's abstract API
- Chosen by programmer:

```
using Acc = AccGpuCudaRt<Dim, Idx>;
```

- Used on both Host and Device
- Inside Kernel: contains thread state, provides access to alpaka's device-side API
- On Host: Meta-parameter for choosing correct physical device and dependent types

The Accelerator Concept

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Accelerators and devices

- Accelerator concept is an abstraction of concrete devices and programming models
- The programmer changes the accelerator in just one line of code
- In the background, an entirely different code path for the “new” device is chosen
- Accelerator provides portable access to device-specific functions

```
/* Before the code change */
using Acc = AccCpuOmp2Blocks<Dim, Idx>;

/* Kernels will run on CPUs */
/* Parallelism provided by OpenMP 2.x */
```

```
/* After the code change */
using Acc = AccGpuHipRt<Dim, Idx>;

/* Kernels will run on AMD + NVIDIA GPUs */
/* Parallelism provided by HIP */
```

The Accelerator Concept

Grid navigation

- The Accelerator provides the means to navigate the grid:

```
// get thread index on the grid
auto gridThreadIdx = getIdx<Grid, Threads(acc);
```

```
// get block index on the grid
auto gridBlockIdx = getIdx<Grid, Blocks>(acc);
```

```
// get thread index on the block
auto blockThreadIdx = getIdx<Block, Threads>(acc);
```

```
// get number of blocks on the grid
auto gridBlockExtent = getWorkDiv<Grid, Blocks>(acc);
```

```
// get number of threads on the block
auto blockThreadExtent = getWorkDiv<Block, Threads>(acc);
```

The Accelerator Concept

Memory management and synchronization

- The Accelerator gives access to alpaka's shared memory (for threads inside the same block):

```
// allocate a variable in block shared static memory
auto & mySharedVar = declareSharedVar<int, __COUNTER__>(acc);
```

```
// get pointer to the block shared dynamic memory
float * mySharedBuffer = getDynSharedMem<float>(acc);
```

- It also enables synchronization on the block level:

```
// synchronize all threads within the block
syncBlockThreads(acc);
```

```
// synchronize some threads within the block and evaluate predicate
syncBlockThreadsPredicate(acc, predicate);
```

The Accelerator Concept

Device-side functions

- Internally, the accelerator maps all device-side functions to their native counterparts
- Device-side functions require the accelerator as first argument:
  - `sqrt(acc, /* … */);` (Math functions)
  - `atomicOp<AtomicOr>(acc, /* … */, hierarchy::Grids);` (Atomics)
  - `rand::distribution::createNormalReal<float>(acc);` (Random-number generation)
  - `clock(acc);` (Clock cycles)

The Device Concept

alpaka Devices

- alpaka Devices represent physical devices
- Determined by programmer’s Accelerator choice
- Easy management of physical devices

```
/* Chosen by programmer */
using Acc = AccGpuHipRt<Dim, Idx>;

/* Return number of HIP GPU devices */
auto const numDevs = getDevCount<Acc>();

/* Return the first entry from vector of HIP GPU devices */
auto myDev = getDevByIdx<Acc>(0u);

/* Return list of all HIP GPU devices */
auto devs = getDevs<Acc>();
```

The Device Concept

Devices and hardware

- Each alpaka Device represents a single physical device
- Contains device information:

```
auto const name = getName(myDev);          // Back-end-defined device name
auto const bytes = getMemBytes(myDev);     // Size of device memory
auto const free = getFreeMemBytes(myDev); // Size of available device memory
```

- Provides the means for device management:

```
reset(myDev);                              // Reset GPU device state
```

- Encapsulates back-end device:

```
auto nativeDevice = getDev(myDev);         // nativeDevice is not portable!
```

The Device Concept

alpaka Devices and the Accelerator concept

- Device and Accelerator are different concepts!
- An alpaka Accelerator is an abstract view of all physical devices (for the chosen back-end)
  - Kernel POV: thread state, device functions, memory management, synchronization
  - Host POV: meta-parameter for overall abstraction
- An alpaka Device is a representation of exactly one physical device
  - Device information
  - Device management

The Queue Concept

Connecting Host and Device

- alpaka Queues enable communication between Host and Device
- Two queue types: blocking and non-blocking
- Blocking queues block the Host until Device-side command returns
- Non-blocking queues return control to Host immediately, Device-side command runs asynchronously

```
// Choose queue behaviour - Blocking or NonBlocking
using QueueProperty = property::NonBlocking;

// Define queue type
using MyQueue = Queue<Acc, QueueProperty>;

// Create queue for communication with myDev
auto myQueue = MyQueue{myDev};
```

The Queue Concept

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Queue operations

- Queues execute Tasks (see next slide):

```
enqueue(myQueue, taskRunKernel);
```

- Check for completion:

```
bool done = empty(myQueue);
```

- Wait for completion, Events (see next slide), or other Queues:

```
wait(myQueue);                 // blocks caller until all operations have completed
wait(myQueue, myEvent);        // blocks myQueue until myEvent has been reached
wait(myQueue, otherQueue);     // blocks myQueue until otherQueue’s ops have completed
```

The Queue Concept

Tasks and Events

- Device-side operations (kernels, memory operations) are called Tasks
- Tasks on the same queue are executed in order (FIFO principle)

```
enqueue(queueA, task1);
enqueue(queueA, task2); // task2 starts after task1 has finished
```

- Order of tasks in different queues is unspecified

```
enqueue(queueA, task1);
enqueue(queueB, task2); // task2 starts before, after or in parallel to task1
```

- For easier synchronization, alpaka Events can be inserted before, after or between Tasks:

```
auto myEvent = event::Event<Queue>(myDev);
enqueue(queueA, myEvent);
wait(queueB, myEvent); // queueB will only resume after queueA reached myEvent
```

The Queue Concept

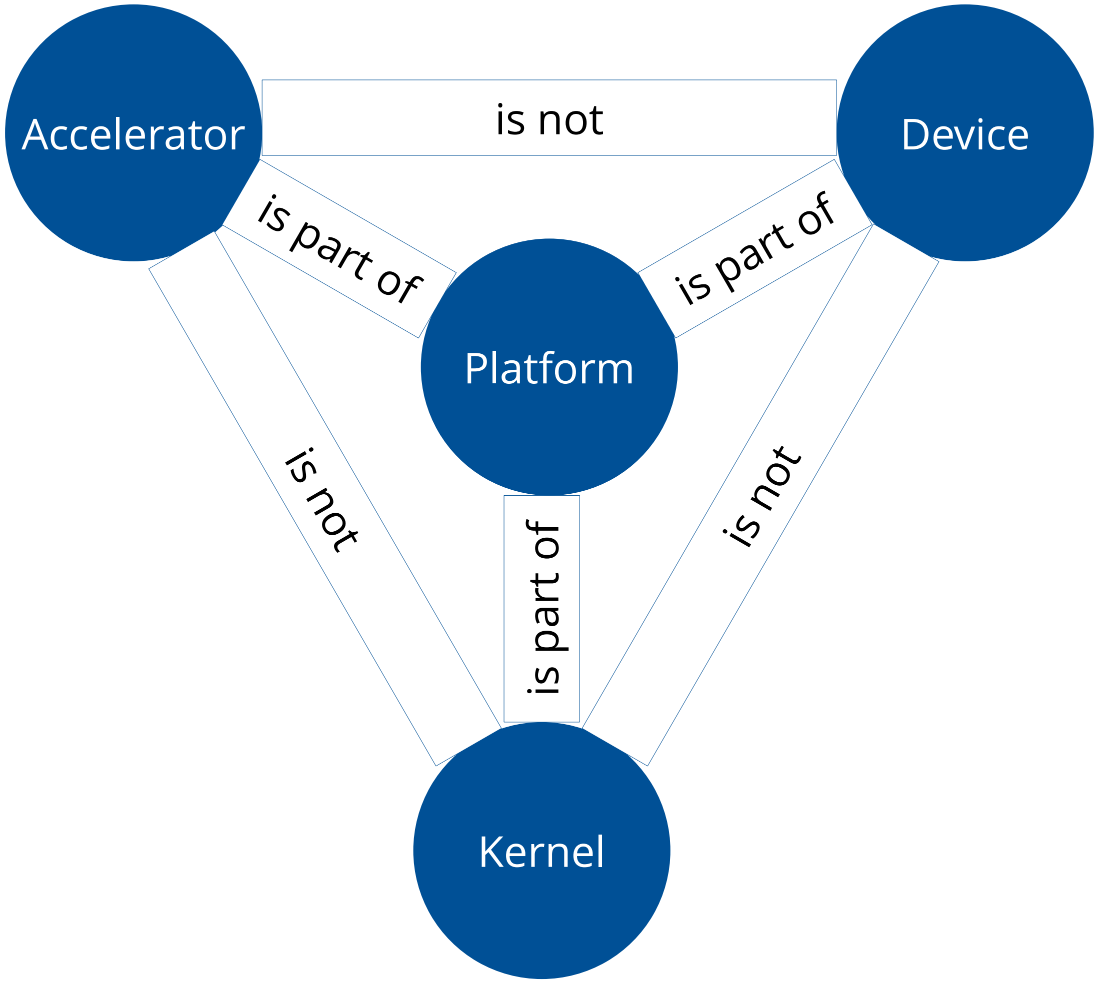
Setting up Accelerator, Device and Queue

```
// Choose types for dimensionality and indices
using Dim = DimInt<1>;
using Idx = std::size_t;

// Choose the back-end
using Acc = AccGpuHipRt<Dim, Idx>;

// Obtain first device in the HIP GPU list
auto myDev = getDevByIdx<Acc>(0u);

// Create non-blocking queue for chosen device
using Queue = Queue<Acc, property::NonBlocking>;
auto myQueue = Queue{myDev};

// Done! We can now enqueue device-side operations.
```

The Platform Concept

alpaka Platform

- Platform is meta-concept in alpaka
- Union of Accelerator, Device and Kernel functionality
  - Accelerator gives structure to the host side and functionality to the device side
  - Device gives functionality to the host side
  - Kernels are agnostic of Device details
    → Portable Kernels



The Platform Concept

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Changing the target platform

```
using namespace alpaka;

using Dim = DimInt<1u>;
using Idx = std::size_t;

/*** BEFORE ***/
using Acc = AccCpuOmp2Blocks<Dim, Idx>;

/*** AFTER ***/
using Acc = AccGpuHipRt<Dim, Idx>;

/* No change required - dependent types and variables are automatically changed */
auto myDev = getDevByIdx<Acc>(0u);

using Queue = Queue<Acc, property::NonBlocking>;
auto myQueue = Queue{myDev};
```

The Platform Concept

What alpaka does for you

- Configuration with standalone headers:
  - Enables chosen back-ends for your system
- After changing the Accelerator:
  - Back-end switched automatically
  - All Queue operations will be executed on associated devices

The Platform Concept

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What you have to do for alpaka

- Standalone mode: Handle back-end dependencies and compiler flags
- Device side: Make no assumptions about your hardware!
  - Program your Kernels as abstract and portably as possible
  - Use the Accelerator for device-side operations
  - Kernels are instantiated for a specific platform at compile-time
  - This is what the Accelerator template parameter is for!

```
template <typename Acc>
ALPAKA_FN_ACC void operator()(Acc const & acc, /* … */) const;
```

- Host side: Know your hardware!
  - Use Devices for management of physical devices
  - Adapt the work division (Blocks per Grid, Threads per Block, elements per Thread) to your hardware and problem size

Programming Heterogeneous Systems

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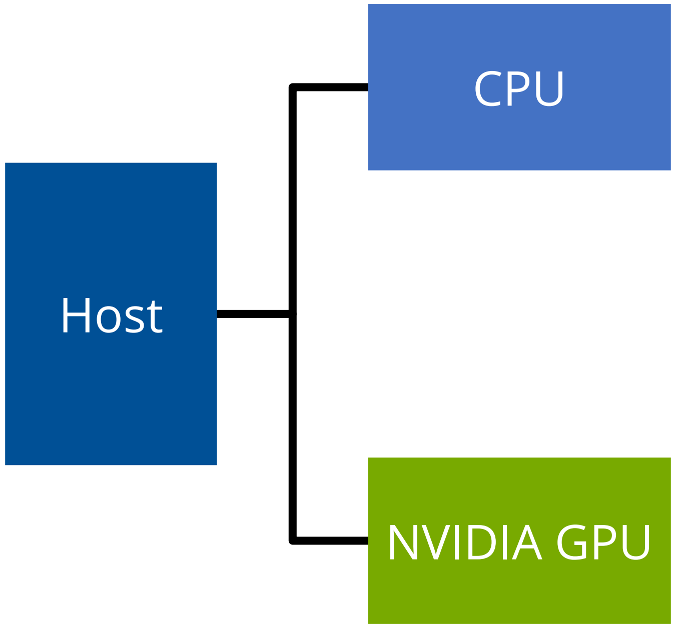
Heterogeneous Systems

- Real-world scenario: Use all available compute power
- Also real-world scenario: Multiple different hardware types available
- Requirement: Usage of one back-end per hardware platform
- Requirement: Back-ends need to be interoperable



Programming Heterogeneous Systems

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Using multiple Platforms

- alpaka enables easy heterogeneous programming!
- Create one Accelerator per back-end
- Acquire at least one Device per Accelerator
- Create one Queue per Device

```
// Define Accelerators
using AccCpu = AccCpuOmp2Blocks<Dim, Idx>;
using AccGpu = AccGpuCudaRt<Dim, Idx>;

// Acquire Devices
auto devCpu = getDevByIdx<AccCpu>(0u);
auto devGpu = getDevByIdx<AccGpu>(0u);

// Create Queues
using QueueProperty = property::NonBlocking;
using QueueCpu = Queue<AccCpu, QueueProperty>;
using QueueGpu = Queue<AccGpu, QueueProperty>;

auto queueCpu = QueueCpu{devCpu};
auto queueGpu = QueueGpu{devGpu};
```

Programming Heterogeneous Systems

Communication

- Buffers are defined and created per Device
- Buffers can be copied between different Devices / Queues
- Not restricted to a single platform!
- **Restriction**: CPU to GPU copies (and vice versa) require GPU queue

```
// Allocate buffers
auto bufCpu = allocBuf<float, Idx>(devCpu, extent);
auto bufGpu = allocBuf<float, Idx>(devGpu, extent);

/* Initialization … */

// Copy buffer from CPU to GPU - destination comes first
memcpy(gpuQueue, bufGpu, bufCpu, extent);

// Execute GPU kernel
enqueue(gpuQueue, someKernelTask);

// Copy results back to CPU and wait for completion
memcpy(gpuQueue, bufCpu, bufGpu, extent);

// Wait for GPU, then execute CPU kernel
wait(cpuQueue, gpuQueue);
enqueue(cpuQueue, anotherKernelTask);
```

Programming Heterogeneous Systems

Heterogeneous programming with alpaka

- alpaka gives you access to all of your system's computation resources
- alpaka eases programming for different device types
- alpaka enables simple data transfers between different devices
- alpaka makes your code reusable
- alpaka makes your code portable

Write once, scale everywhere!

Heterogeneous Programming With the Caravan Ecosystem

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I already have a CUDA program. Do I really need to port everything?

- No. Try our CUDA portability layer *cupla*.
- Kernels need to be ported to alpaka-style kernels
- `cudaApiCall()` becomes `cuplaApiCall()`
- **https://github.com/alpaka-group/cupla**

Heterogeneous Programming With the Caravan Ecosystem

How can I easily switch between different memory layouts?

- Example: From array-of-struct to struct-of-array and back
- Problem: Changing memory layout requires changing of algorithm
- Solution: LLAMA
- **https://github.com/alpaka-group/llama**

Heterogeneous Programming With the Caravan Ecosystem

But I just want to do transform & reduce!

- Solution: vikunja
- More standard algorithms planned soon
- **https://github.com/alpaka-group/vikunja**

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