LINMA2710 - Scientific Computing Graphics processing unit (GPU)

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☐ Full Width Mode ☐ Present Mode

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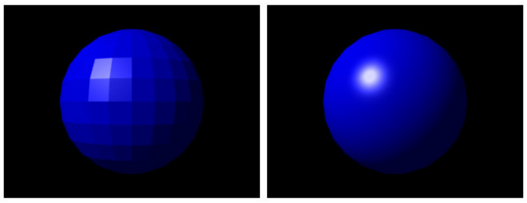
Introduction

Context

- Most *dedicated* GPUs produced by NVIDIA and AMD
- *Integrated* GPUs by intel used in laptops to reduce power consumption
- Designed for 3D rendering through ones of the APIs : Microsoft DirectX, OpenGL, WebGL, WebGPU, Vulkan or Apple's Metal
- Illustration on the right is from Charge's film, it show how 3D modeling work.

General-Purpose computing on GPU (GPGPU)

Also known as *compute shader* as they abuses the programmable shading of GPUs by treating the data as texture maps.

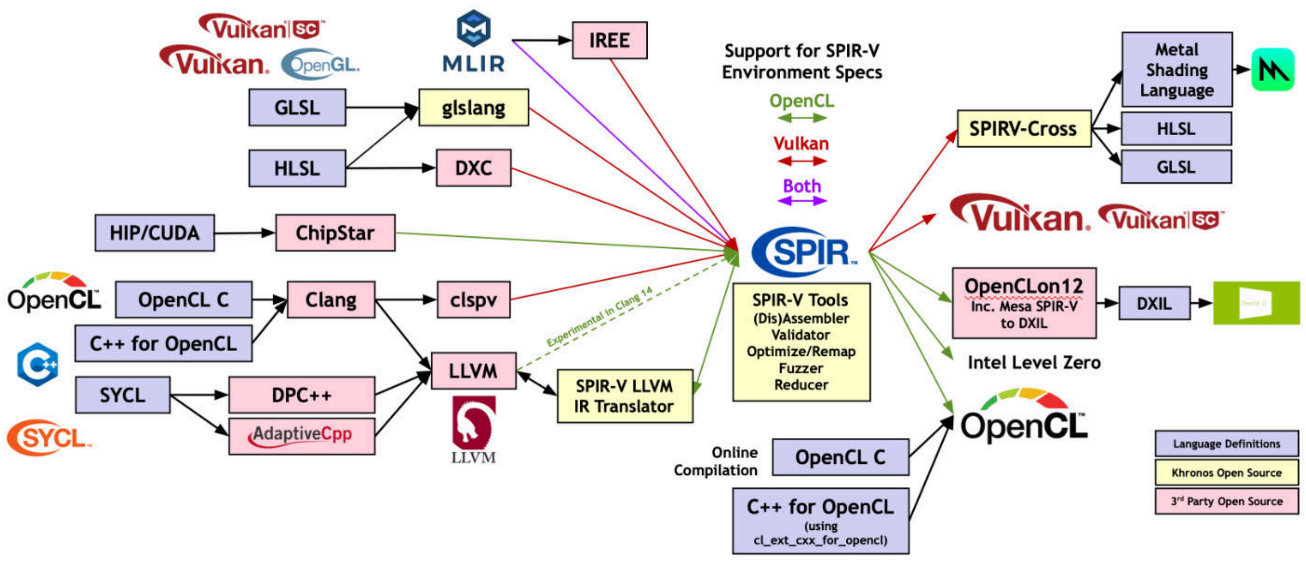


Hardware-specific — NVIDIA CUDA, AMD ROCm, intel oneAPI

Common interface — OpenCL™, SYCL™, OpenACC Directives for Accelerators

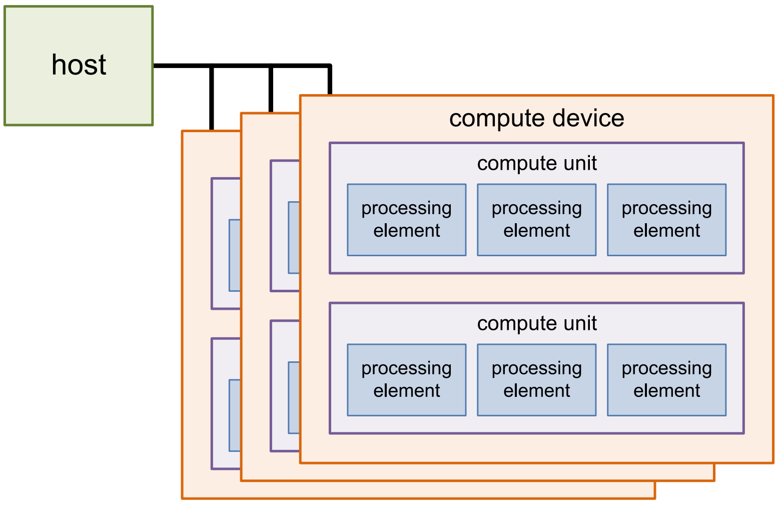
Standard Portable Intermediate Representation (SPIR)

Similar to LLVM IR : Intermediate representation for accelerated computation.



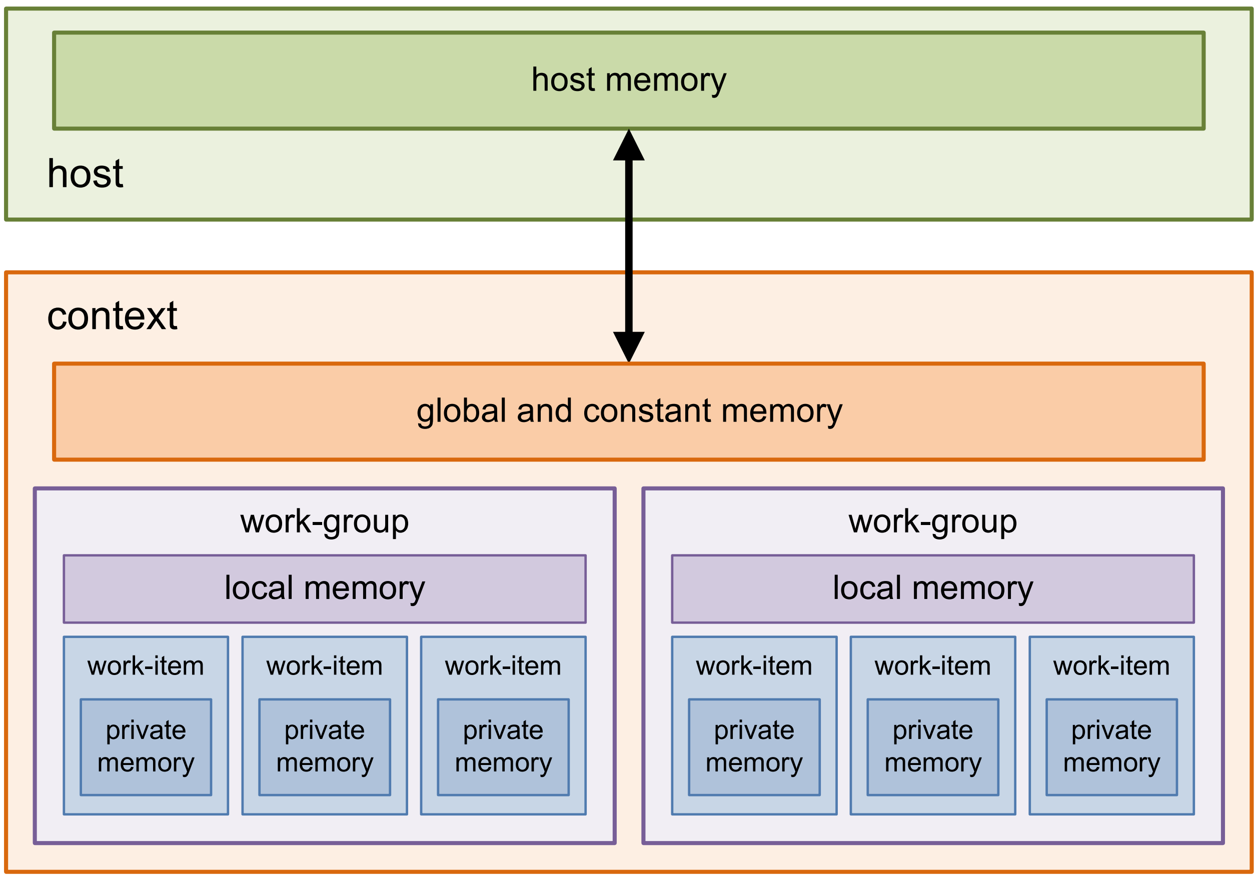
Hierarchy

- CPUs:
  - All CPUs part of same device
  - 1 Compute Unit per core
  - Number of processing elements equal to SIMD width
- GPUs:
  - One device per GPU



compute device	compute unit	processing element
get_global_id	get_group_id	get_local_id
get_global_size	get_num_groups	get_local_size

Memory



OpenCL Platforms and Devices

- Platforms are OpenGL implementations, listed in `/etc/OpenCL/vendors`
- Devices are actual CPUs/GPUs
- ICD allows to change platform at runtime

```julia
OpenCL.versioninfo()
```

```
OpenCL.jl version 0.10.2

Toolchain:
 - Julia v1.11.4
 - OpenCL_jll v2024.5.8+1

Available platforms: 1
 - Portable Computing Language
   OpenCL 3.0, PoCL 6.0  Linux, Release, RELOC, SPIR-V, LLVM 16.0.6jl, SLEE
F, DISTRO, POCL_DEBUG
    · cpu-haswell-AMD EPYC 7763 64-Core Processor (usm, fp16, fp64, il)
```

See also `clinfo` command line tool and `examples/OpenCL/common/device_info.c`.

Tip

▶ **tl;dr To refresh the list of platforms, you need to quit Julia and open a new session**

Important stats

- Platform
  - name: Portable Computing Language
  - profile: FULL_PROFILE
  - vendor: The pocl project
  - version: PoCL 6.0 Linux, Release, RELOC, SPIR-V, LLVM 16.0.6jl, SLEEF, DISTRO, POCL_DEBUG
- Device
  - name: cpu-haswell-AMD EPYC 7763 64-Core Processor
  - type: cpu

`clGetDeviceInfo`	Value
CL_DEVICE_GLOBAL_MEM_SIZE	13.62 GiB
CL_DEVICE_MAX_COMPUTE_UNITS	4
CL_DEVICE_LOCAL_MEM_SIZE	512.00 KiB
CL_DEVICE_MAX_WORK_GROUP_SIZE	4096

CL_DEVICE_NATIVE_VECTOR_WIDTH_HALF	16
CL_DEVICE_NATIVE_VECTOR_WIDTH_FLOAT	8
CL_DEVICE_NATIVE_VECTOR_WIDTH_DOUBLE	4
CL_DEVICE_MAX_CLOCK_FREQUENCY	2445 MHz
CL_DEVICE_PROFILING_TIMER_RESOLUTION	1.000 ns

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Examples

Vectorized sum

```
__kernel void vadd(
    __global const float *a,
    __global const float *b,
    __global float *c,
    int verbose) {
  int i = get_global_id(0);
  c[i] = a[i] + b[i];
```

vadd_size = 512   vadd_verbose = 0

```
5 warnings generated.
CL_KERNEL_WORK_GROUP_SIZE                      │ 4096
CL_KERNEL_COMPILE_WORK_GROUP_SIZE              │ (0, 0, 0)
CL_KERNEL_LOCAL_MEM_SIZE                       │ 0 bytes
CL_KERNEL_PRIVATE_MEM_SIZE                     │ 0 bytes
CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE   │ 8
Send command from host to device  │ 1.222 μs
Including data transfer           │ 315.323 ms
Execution of kernel               │ 34.404 μs
```

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```
vadd (generic function with 1 method)
```

Mandelbrot

```
__kernel void mandelbrot(__global float2 *q,
    __global ushort *output, ushort const maxit) {

  int gid = get_global_id(0), it;
  if (gid == 0)
    printf("%d\n", get_num_groups(0));
  float tmp, real = 0, imag = 0;
  output[gid] = 0;
  for(it = 0; it < maxit; it++) {
    tmp = real * real - imag * imag + q[gid].x;
    imag = 2 * real * imag + q[gid].y;
    real = tmp;
    if (real * real + imag * imag > 4.0f)
        output[gid] = it;
```

mandel_size = 512   maxiter = 100

```
q = [ComplexF32(r,i) for i=1:-(2.0/mandel_size):-1, r=-1.5:
(3.0/mandel_size):0.5];
```

```
mandel_image = mandel(q, maxiter, mandel_device; global_size=length(q));
```

```
1 warning generated.
CL_KERNEL_WORK_GROUP_SIZE                     | 4096
CL_KERNEL_COMPILE_WORK_GROUP_SIZE             | (0, 0, 0)
CL_KERNEL_LOCAL_MEM_SIZE                      | 0 bytes
CL_KERNEL_PRIVATE_MEM_SIZE                    | 0 bytes
CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE  | 8
57
Send command from host to device  | 1.142 μs
Including data transfer           | 295.568 ms
Execution of kernel               | 14.021 ms
```

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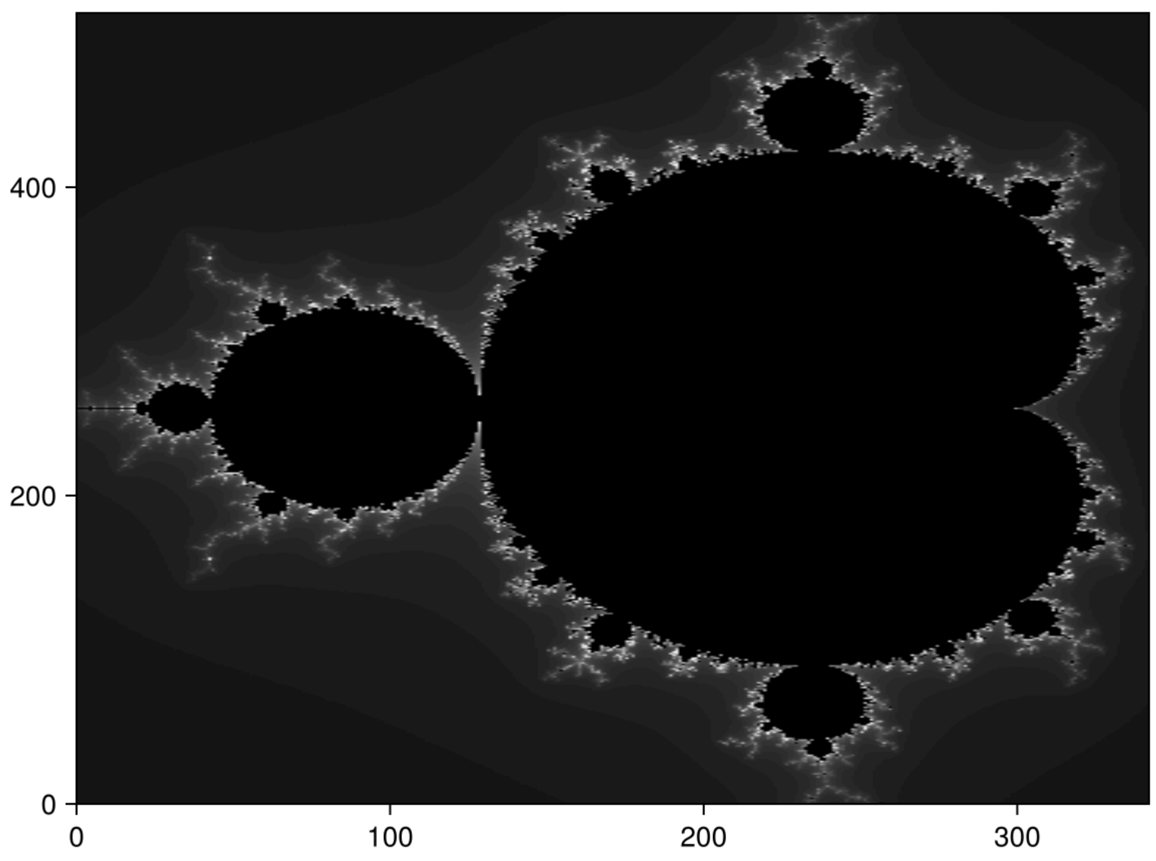

```
mandel (generic function with 1 method)
```

```julia
function mandel(q::Array{ComplexF32}, maxiter::Int64, device; kws...)
    cl.device!(device)
    q = CLArray(q)
    o = CLArray{Cushort}(undef, size(q))

    prg = cl.Program(; source = mandel_source.code) |> cl.build!
    k = cl.Kernel(prg, "mandelbrot")

    timed_clcall(k, Tuple{Ptr{ComplexF32}, Ptr{Cushort}, Cushort},
           q, o, maxiter; kws...)

    return Array(o)
end
```

```julia
mandel_source = code(Example("OpenCL/mandelbrot/mandel.cl"));
```

Compute π

```
3.1418869495391846
```

```
mypi()
```

```
CL_KERNEL_WORK_GROUP_SIZE                    │ 4096
CL_KERNEL_COMPILE_WORK_GROUP_SIZE            │ (0, 0, 0)
CL_KERNEL_LOCAL_MEM_SIZE                     │ 0 bytes
CL_KERNEL_PRIVATE_MEM_SIZE                   │ 0 bytes
CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE │ 8
Send command from host to device  │ 1.493 μs
Including data transfer           │ 46.823 ms
Execution of kernel               │ 63.028 ms
```

▶ **How to compute π with a kernel ?**

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```
mypi (generic function with 1 method)
```

First element

Let's write a simple kernel that returns the first element of a vector in global memory.

```
__kernel void first_el(__global float* glob, __global float* result) {
  int item = get_local_id(0);
  if (item == 0)
    *result = glob[item];
}
```

```
0.8174594f0
```

```
first_el(rand(Float32, first_el_len))
```

```
CL_KERNEL_WORK_GROUP_SIZE                     | 4096
CL_KERNEL_COMPILE_WORK_GROUP_SIZE             | (0, 0, 0)
CL_KERNEL_LOCAL_MEM_SIZE                      | 0 bytes
CL_KERNEL_PRIVATE_MEM_SIZE                    | 0 bytes
CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE  | 8
Send command from host to device    | 1.362 μs
Including data transfer             | 31.317 ms
Execution of kernel                 | 20.568 μs
```

```
first_el (generic function with 1 method)
```

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first_el_len = 16

Copy to local memory

```
__kernel void copy_to_local(__global float* glob, __local float* shared) {
  int global_size = get_global_size(0);
  int local_size = get_local_size(0);
  int item = get_local_id(0);
  shared[item] = 0;
  for (int i = 0; i < global_size; i += local_size) {
    shared[item] += glob[i + item];
  }
}
```

```
copy_to_local(copy_global_len, copy_local_len)
```

```
CL_KERNEL_WORK_GROUP_SIZE                     | 4096
CL_KERNEL_COMPILE_WORK_GROUP_SIZE             | (0, 0, 0)
CL_KERNEL_LOCAL_MEM_SIZE                      | 0 bytes
CL_KERNEL_PRIVATE_MEM_SIZE                    | 0 bytes
CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE  | 8
Send command from host to device    | 641.000 ns
Including data transfer             | 57.512 ms
Execution of kernel                 | 19.567 μs
```

```
copy_to_local (generic function with 1 method)
```

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`copy_global_len =` 16

`copy_local_len =` 16

Reduction on GPU

Many operations can be framed in terms of a MapReduce operation.

- Given a vector of data
- It first map each elements through a given function
- It then reduces the results into a single element

The mapping part is easily embarassingly parallel but the reduction is harder to parallelize. Let's see how this reduction step can be achieved using arguably the simplest example of `mapreduce`, the sum (corresponding to an identity map and a reduction with `+`).

Sum

```
(OpenCL = 8.81811, Classical = 8.81811)
```

```julia
local_sum(global_len, local_len, local_code, local_device)
```

```
CL_KERNEL_WORK_GROUP_SIZE                     | 4096
CL_KERNEL_COMPILE_WORK_GROUP_SIZE             | (0, 0, 0)
CL_KERNEL_LOCAL_MEM_SIZE                      | 0 bytes
CL_KERNEL_PRIVATE_MEM_SIZE                    | 0 bytes
CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE  | 8
Send command from host to device      | 1.022 μs
Including data transfer               | 82.574 ms
Execution of kernel                   | 21.641 μs
```

▶ **How to compute the sum an array in local memory with a kernel ?**

```
local_sum (generic function with 1 method)
```

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global_len = 16

local_len = 16

Blocked sum

```
▸ (OpenCL = 8.81811, Classical = 8.81811)
block_local_sum(block_global_len, block_local_len, factor)
```

```
CL_KERNEL_WORK_GROUP_SIZE                    │ 4096
CL_KERNEL_COMPILE_WORK_GROUP_SIZE            │ (0, 0, 0)
CL_KERNEL_LOCAL_MEM_SIZE                     │ 0 bytes
CL_KERNEL_PRIVATE_MEM_SIZE                   │ 0 bytes
CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE │ 8
Send command from host to device │ 931.000 ns
Including data transfer          │ 88.202 ms
Execution of kernel              │ 21.861 μs
```

▶ **How to reduce the amount of `barrier` synchronizations ?**

▶ **Was it beneficial in terms of performance for GPUs like in the case of OpenMP ?**

`block_local_sum` (generic function with 1 method)

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block_global_len = 16

block_local_len = 16

factor = 16

Back to SIMD

- Also called Single Instruction Multiple Threads (SIMT)
- CUDA Warp : width of 32 threads
- AMD wavefront : width of 64 threads
- In general : `CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE`
- Consecutive `get_local_id()` starting from 0
    - So the thread of local id from 0 to 31 are in the same CUDA warp.
- Threads execute the **same instruction** at the same time so no need for `barrier` .

Warp divergence

Suppose a kernel is executed on a nvidia GPU with `global_size` threads. How much time will it take to execute it ?

```
__kernel void diverge(n)
{
  int item = get_local_id(0);
  if (item < n) {
    do_task_A(); // `a` ns
  } else {
    do_task_B(); // `b` ns
  }
}
```

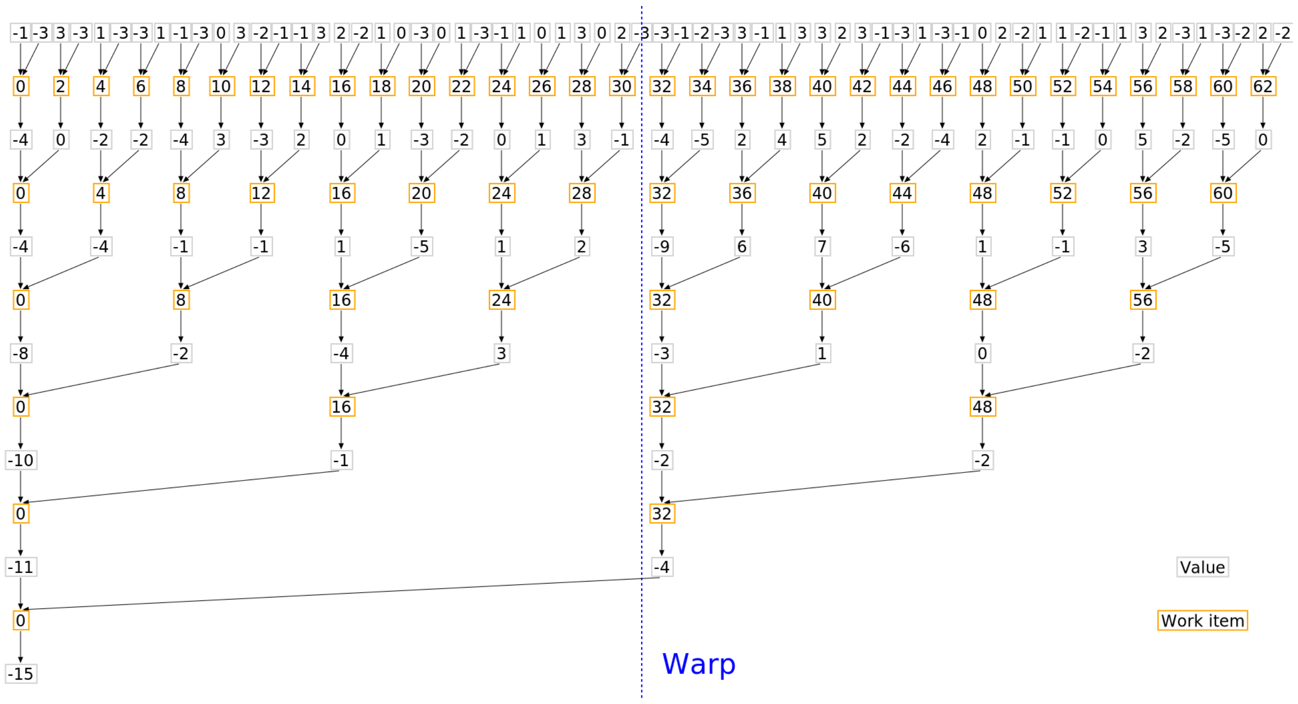
▶ **How much time will it take to execute it if `global_size` is 32 and `n` is 16 ?**

▶ **How much time will it take to execute it if `global_size` is 64 and `n` is 32 ?**

Are the threads that are still active in the same warp for you sum example ?

Warp diversion for our sum

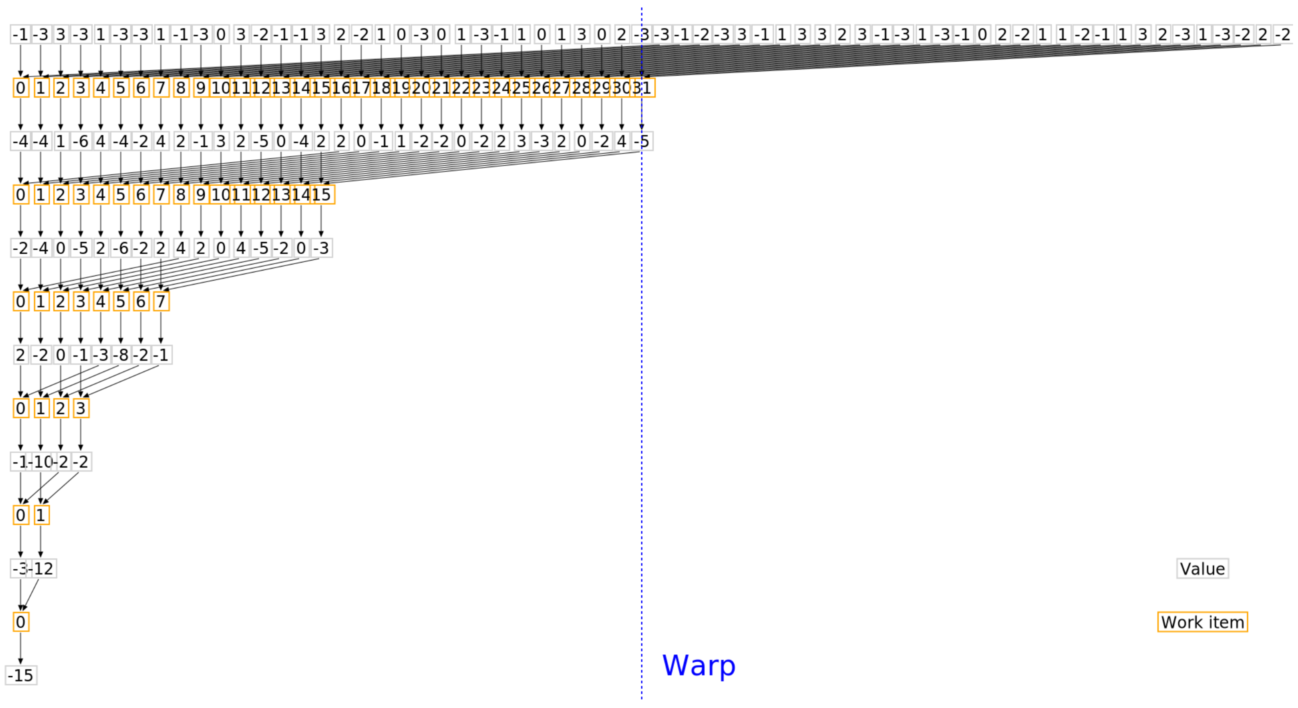
▶ **We are still using different warps until the end. Is that a good thing ?**



How should we change the sum to keep the working threads on the same warp ?

No warp divergence

Now the same warp is used for all threads so we don't need `barrier` and it frees other warps to stay idle (reducing power consumption) or do other tasks.



Reordered local sum

```
__kernel void local_sum(__local float* shared)
{
  int items = get_local_size(0);
  int item = get_local_id(0);
  int stride = items / 2;
  float other_val = 0;
  while (stride > 0) {
    barrier(CLK_LOCAL_MEM_FENCE);
    if (item < stride) {
      other_val = 0;
      if (item + stride < items)
        other_val = shared[item+stride];
      shared[item] += other_val;
    }
    stride /= 2;
  }
}
```

▸ (OpenCL = 8.81811, Classical = 8.81811)

```
CL_KERNEL_WORK_GROUP_SIZE                    │ 4096
CL_KERNEL_COMPILE_WORK_GROUP_SIZE            │ (0, 0, 0)
CL_KERNEL_LOCAL_MEM_SIZE                     │ 0 bytes
CL_KERNEL_PRIVATE_MEM_SIZE                   │ 0 bytes
CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE │ 8
Send command from host to device   │ 661.000 ns
Including data transfer            │ 83.727 ms
Execution of kernel                │ 17.513 μs
```

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reordered_global_size = 16

reordered_local_size = 16

SIMT sum

```
__kernel void simt_sum(volatile __local float* shared)
{
  int items = get_local_size(0);
  int item = get_local_id(0);
  barrier(CLK_LOCAL_MEM_FENCE);
  while (items > 1) {
    items /= 2;
    shared[item] += shared[item + items];
  }
}
```

▸ (OpenCL = 2.52133, Classical = 8.81811)

```
local_sum(simt_global_size, simt_local_size, simt_code, simt_device)
```

```
CL_KERNEL_WORK_GROUP_SIZE                    | 4096
CL_KERNEL_COMPILE_WORK_GROUP_SIZE            | (0, 0, 0)
CL_KERNEL_LOCAL_MEM_SIZE                     | 0 bytes
CL_KERNEL_PRIVATE_MEM_SIZE                   | 0 bytes
CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE | 8
Send command from host to device  | 621.000 ns
Including data transfer           | 66.286 ms
Execution of kernel               | 22.362 μs
```

▸ **Why don't we check any condition on `item`, aren't some thread computing data that won't be used ?**

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simt_global_size = 16

simt_local_size = 16

Beware!

POCL does not synchronize, even for `simt_len <= 8`

▸ **Why do we need `volatile` ?**

Unrolled sum

▸ **How to get even faster performance by assuming that `items` is a power of 2 smaller than 512 and that the SIMT width is 32 ?**

```
(OpenCL = 2.52133, Classical = 8.81811)
```

```julia
local_sum(unrolled_global_size, unrolled_local_size, unrolled_code,
unrolled_device)
```

```
CL_KERNEL_WORK_GROUP_SIZE                  │ 4096
CL_KERNEL_COMPILE_WORK_GROUP_SIZE          │ (0, 0, 0)
CL_KERNEL_LOCAL_MEM_SIZE                   │ 0 bytes
CL_KERNEL_PRIVATE_MEM_SIZE                 │ 0 bytes
CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE │ 8
Send command from host to device │ 681.000 ns
Including data transfer          │ 156.671 ms
Execution of kernel              │ 19.426 μs
```

How to have portable code using unrolling ?

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unrolled_global_size = 16

unrolled_local_size = 16

Utils

```
_pretty_time (generic function with 1 method)
```

```julia
_pretty_time(x) = BenchmarkTools.prettytime(minimum(x))
```

timed_clcall (generic function with 1 method)

```julia
function timed_clcall(kernel, args...; kws...)
    info = cl.work_group_info(kernel, cl.device())
    # See https://registry.khronos.org/OpenCL/sdk/3.0/docs/man/html/clGetKernelWorkGroupInfo.html
    println("CL_KERNEL_WORK_GROUP_SIZE                    | ", info.size)
    println("CL_KERNEL_COMPILE_WORK_GROUP_SIZE            | ", info.compile_size)
    println("CL_KERNEL_LOCAL_MEM_SIZE                     | ", BenchmarkTools.prettymemory(info.local_mem_size))
    println("CL_KERNEL_PRIVATE_MEM_SIZE                   | ", BenchmarkTools.prettymemory(info.private_mem_size))
    println("CL_KERNEL_PREFERRED_WORK_GROUP_SIZE_MULTIPLE | ", info.prefered_size_multiple)

    # `:profile` sets `CL_QUEUE_PROFILING_ENABLE` to the command queue
    queued_submit = Float64[]
    submit_start = Float64[]
    start_end = Float64[]
    cl.queue!(:profile) do
        for _ in 1:num_runs
            evt = clcall(kernel, args...; kws...)
            wait(evt)

            # See https://registry.khronos.org/OpenCL/sdk/3.0/docs/man/html/clGetEventProfilingInfo.html
            push!(queued_submit, evt.profile_submit - evt.profile_queued)
            push!(submit_start, evt.profile_start - evt.profile_submit)
            push!(start_end, evt.profile_end - evt.profile_start)
        end
    end
    println("Send command from host to device  | $(_pretty_time(queued_submit))")
    println("Including data transfer           | $(_pretty_time(submit_start))")
    println("Execution of kernel               | $(_pretty_time(start_end))")
end
```

num_runs = 1

```
Activating project at `~/work/LINMA2710/LINMA2710/Lectures`
```

```julia
using OpenCL, pocl_jll # `pocl_jll` provides the POCL OpenCL platform for CPU
devices
```