Modern C++, heterogeneous computing & OpenCL SYCL

Ronan Keryell

Khronos OpenCL SYCL committee

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IWOCL 2015 SYCL Tutorial

Outline

1. C++14
2. C++ dialects for OpenCL (and heterogeneous computing)
3. OpenCL SYCL 1.2
   - C++... putting everything altogether
4. OpenCL SYCL 2.1...
5. Conclusion

C++14

- 2 Open Source compilers available *before* ratification (GCC & Clang/LLVM)
- Confirm new momentum & pace: 1 major (C++11) and 1 minor (C++14) version on a 6-year cycle
- Next big version expected in 2017 (C++1z)
  - Already being implemented! ☺
- Monolithic committee replaced by many smaller *parallel* task forces
  - Parallelism TS (Technical Specification) with Parallel STL
  - Concurrency TS (threads, mutex...)
  - Array TS (multidimensional arrays *à la* Fortran)
  - Transactional Memory TS...

Race to parallelism! Definitely matters for HPC and heterogeneous computing!

C++ is a complete new language

- Forget about C++98, C++03...
- Send your proposals and get involved in C++ committee (pushing heterogeneous computing)!

Modern C++ & HPC (I)

- Huge library improvements
  - <thread> library and multithread memory model <atomic> ⤳ HPC
  - Hash-map
  - Algorithms
  - Random numbers
  - ...
- Uniform initialization and range-based for loop

```
std::vector<int> my_vector { 1, 2, 3, 4, 5 };
for (int &e : my_vector)
  e += 1;
```

- Easy functional programming style with *lambda* (anonymous) functions

```
std::transform(std::begin(v), std::end(v), [] (int v) { return 2*v; });
```

Modern C++ & HPC (II)

- Lot of meta-programming improvements to make meta-programming ~~easy~~ easier: variadic templates, type traits <type_traits>...
- Make simple things simpler to be able to write generic numerical libraries, etc.
- Automatic type inference for terse programming
  - Python 3.x (interpreted):

```
def add(x, y):
  return x + y
print(add(2, 3))      # 5
print(add("2", "3")) # 23
```

  - Same in C++14 but compiled + static compile-time type-checking:

```
auto add = [] (auto x, auto y) { return x + y; };
std::cout << add(2, 3) << std::endl;        // 5
std::cout << add("2"s, "3"s) << std::endl; // 23
```

Without using templated code! ~~`template <typename >`~~ ☺

Modern C++ & HPC (III)

- R-value references & std::move semantics
  - matrix_A = matrix_B + matrix_C
    - Avoid copying (TB, PB, EB... ☹) when assigning or function return
- Avoid raw pointers, `malloc()/free()/delete[]`: use references and smart pointers instead

```
// Allocate a double with new() and wrap it in a smart pointer
auto gen() { return std::make_shared<double> { 3.14 }; }
[...]
{
  auto p = gen(), q = p;
  *q = 2.718;
  // Out of scope, no longer use of the memory: deallocation happens here
}
```

- Lot of other amazing stuff...
- Allow both low-level & high-level programming... Useful for heterogeneous computing

Outline

OpenCL 2.1 C++ kernel language (I)

- Announced at GDC, March 2015
- Move from C99-based kernel language to C++14-based

```
// Template classes to express OpenCL address spaces
local_array<int, N> array;
local<float> v;
constant_ptr<double> p;
// Use C++11 generalized attributes, to ignore vector dependencies
[[safelen(8), ivdep]]
for (int i = 0; i < N; i++)
  // Can infer that offset >= 8
  array[i+offset] = array[i] + 42;
```

OpenCL 2.1 C++ kernel language (II)

- Kernel side enqueue
  - Replace OpenCL 2 infamous Apple GCD block syntax by C++11 lambda

```
kernel void main_kernel(int N, int *array) {
  // Only work-item 0 will launch a new kernel
  if (get_global_id(0) == 0)
    // Wait for the end of this work-group before starting the new kernel
    get_default_queue().enqueue_kernel(CLK_ENQUEUE_FLAGS_WAIT_WORK_GROUP,
                                       ndrange { N },
                                       [=] kernel {
                                         array[get_global_id(0)] = 7;
                                       });
}
```

- C++14 memory model and atomic operations
- Newer SPIR-V binary IR format

OpenCL 2.1 C++ kernel language (III)

- Amazing progress but no single source solution *à la* CUDA yet
  - Still need to play with OpenCL host API to deal with buffers, etc.

Bolt C++ (I)

- Parallel STL + map-reduce `https://github.com/HSA-Libraries/Bolt`
- Developed by AMD on top of OpenCL, C++AMP or TBB

```
#include <bolt/cl/sort.h>
#include <vector>
#include <algorithm>
int main() {
  // generate random data (on host)
  std::vector<int> a(8192);
  std::generate(a.begin(), a.end(), rand);
  // sort, run on best device in the platform
  bolt::cl::sort(a.begin(), a.end());
  return 0;
}
```

- Simple!

Bolt C++ (III)

- But...
  - No direct interoperability with OpenCL world
  - No specific compiler required with OpenCL $\rightsquigarrow$ some special syntax to define operation on device
    - OpenCL kernel source strings for complex operations with macros `BOLT_FUNCTOR()`, `BOLT_CREATE_TYPENAME()`, `BOLT_CREATE_CLCODE()`...
    - Work better with AMD Static C++ Kernel Language Extension (now in OpenCL 2.1) & best with C++AMP (but no OpenCL interoperability...)

Boost.Compute (I)

- Boost library accepted in 2015 `https://github.com/boostorg/compute`
- Provide 2 levels of abstraction
  - High-level parallel STL
  - Low-level C++ wrapping of OpenCL concepts

Boost.Compute (II)

```cpp
// Get a default command queue on the default accelerator
auto queue = boost::compute::system::default_queue();
// Allocate a vector in a buffer on the device
boost::compute::vector<float> device_vector { N, queue.get_context() };
boost::compute::iota(device_vector.begin(), device_vector.end(), 0);

// Create an equivalent OpenCL kernel
BOOST_COMPUTE_FUNCTION(float, add_four, (float x), { return x + 4; });

boost::compute::transform(device_vector.begin(), device_vector.end(),
                          device_vector.begin(), add_four, queue);

boost::compute::sort(device_vector.begin(), device_vector.end(), queue);
// Lambda expression equivalent
boost::compute::transform(device_vector.begin(), device_vector.end(),
                          device_vector.begin(),
                          boost::compute::lambda::_1 * 3 - 4, queue);
```

Boost.Compute (III)

- Elegant implicit C++ conversions between OpenCL and Boost.Compute types for finer control and optimizations

```
auto command_queue = boost::compute::system::default_queue();
auto context = command_queue.get_context();
auto program =
    boost::compute::program::create_with_source_file(kernel_file_name,
                                                      context);
program.build();
boost::compute::kernel im2col_kernel { program, "im2col" };

boost::compute::buffer im_buffer { context, image_size*sizeof(float),
                                   CL_MEM_READ_ONLY };
command_queue.enqueue_write_buffer(im_buffer, 0 /* Offset */,
  im_data.size()*sizeof(decltype(im_data)::value_type),
  im_data.data());
```

Boost.Compute (IV)

```
im2col_kernel.set_args(im_buffer,
                       height, width,
                       ksize_h, ksize_w,
                       pad_h, pad_w,
                       stride_h, stride_w,
                       height_col, width_col,
                       data_col);

command_queue.enqueue_nd_range_kernel(kernel,
  boost::compute::extents<1> { 0 } /* global work offset */,
  boost::compute::extents<1> { workitems } /* global work-item */,
  boost::compute::extents<1> { workgroup_size }; /* Work group size */);
```

- Provide program caching
- Direct OpenCL interoperability for extreme performance
- No specific compiler required ⇝ some special syntax to define operation on device
- Probably the right tool to use to translate CUDA & Thrust to OpenCL world

VexCL (I)

- Parallel STL similar to Boost.Compute + mathematical libraries
  `https://github.com/ddemidov/vexcl`
  - Random generators (Random123)
  - FFT
  - Tensor operations
  - Sparse matrix-vector products
  - Stencil convolutions
  - ...
- OpenCL (CL.hpp or Boost.Compute) & CUDA back-end
- Allow device vectors & operations to span different accelerators from different vendors in a same context

```
vex::Context ctx { vex::Filter::Type { CL_DEVICE_TYPE_GPU }
                   && vex::Filter::DoublePrecision };
vex::vector<double> A { ctx, N }, B { ctx, N }, C { ctx, N };
A = 2 * B - sin(C);
```

VexCL (II)

- Allow easy interoperability with back-end

```
// Get the cl_buffer storing A on the device 2
auto clBuffer = A(2);
```

- Use heroic meta-programming to generate kernels without using specific compiler with deep embedded DSL
  - Use symbolic types (prototypal arguments) to extract function structure

```
// Set recorder for expression sequence
std::ostringstream body;
vex::generator::set_recorder(body);
vex::symbolic<double> sym_x { vex::symbolic<double>::VectorParameter };
sym_x = sin(sym_x) + 3;
sym_x = cos(2*sym_x) + 5;
// Build kernel from the recorded sequence
auto foobar = vex::generator::build_kernel(ctx, "foobar",
                                            body.str(), sym_x);
```

VexCL (III)

```
// Now use the kernel
foobar(A);
```

- VexCL is probably the most advanced tool to generate OpenCL without requiring a specific compiler...

- Interoperable with OpenCL, Boost.Compute for extreme performance & ViennaCL
- Kernel caching to avoid useless compiling
- Probably the right tool to use to translate CUDA & Thrust to OpenCL world

ViennaCL (I)

`https://github.com/viennacl/viennacl-dev`

- OpenCL/CUDA/OpenMP back-end
- Similar to VexCL for sharing context between various platforms
- Linear algebra (dense & sparse)
- Iterative solvers
- FFT
- OpenCL kernel generator from high-level expressions
- Some interoperability with Matlab

C++AMP

```cpp
// Use iota algorithm in C++AMP
#include <amp.h>
#include <iostream>

enum { NWITEMS = 512 };

int data[NWITEMS];

// To avoid writing Concurrency:: everywhere
using namespace Concurrency;

void iota_n(size_t n, int dst[]) {
  // Select the first true accelerator found as the default one
  for(auto const & acc : accelerator::get_all())
    if (!acc.get_is_emulated()) {
      accelerator::set_default(acc.get_device_path());
      break;
    }

  // Define the iteration space
  extent<1> e(n);
  // Create a buffer from the given array memory
  array_view<int, 1> a(e, dst);
  // Is there a better way to express write-only data?
  a.discard_data();
  // Execute a kernel in parallel
  parallel_for_each(e,
                    // Define the kernel to execute
                    [=] (Concurrency::index<1> i) restrict(amp) {
                      a[i] = i[0];
                    });
  // In the destruction of array_view "a" happening here,
  // the data are copied back before iota_n() returns
}
```

- Developed by Microsoft, AMD & MultiCoreWare
- Single source: easy to write kernels
- Require specific compiler
- Not pure C++ (`restrict`, `tile_static`)
- No OpenCL interoperability
- Difficult to optimize the data transfers

OpenMP 4

```c
#include <stdio.h>

enum { NWITEMS = 512 };
int array[NWITEMS];

void iota_n(size_t n, int dst[n]) {
#pragma omp target map(from: dst[0:n-1])
#pragma omp parallel for
  for (int i = 0; i < n; i++)
    dst[i] = i;
}

int main(int argc, const char *argv[]) {

  iota_n(NWITEMS, array);

  // Display results
  for (int i = 0; i < NWITEMS; i++)
    printf("%d %d\n", i, array[i]);

  return 0;
}
```

- Old HPC standard from the 90's
- Use `#pragma` to express parallelism
- OpenMP 4 extends it to accelerators
  - Work-group parallelism
  - Work-item parallelism
- Deal with CPU & heterogeneous computing parallelism
- No LDS support
- No OpenCL interoperability
- But quite simple! Single source...

Other (non-)OpenCL C++ framework (I)

- ArrayFire, Aura, CLOGS, hemi, HPL, Kokkos, MTL4, SkelCL, SkePU, EasyCL...
- nVidia CUDA 7 now C++11-based
  - Single source $\rightsquigarrow$ simpler for the programmer
  - nVidia Thrust ≈ parallel STL+map-reduce on top of CUDA, OpenMP or TBB
    `https://github.com/thrust/thrust`
    - Not very clean because device pointers returned by `cudaMalloc()` do not have a special type $\rightsquigarrow$ use some ugly casts
- OpenACC ≈ OpenMP 4 restricted to accelerators + LDS finer control

Missing link...

- No tool providing
  - OpenCL interoperability
  - Modern C++ environment
  - Single source for programming productivity

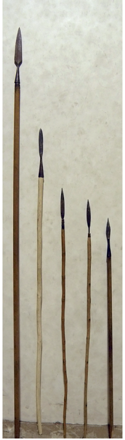
Outline

Puns and pronunciation explained

OpenCL SYCL

sickle ['si-kəl]

OpenCL SPIR



spear ['spir]

OpenCL SYCL goals

- Ease of use
  - Single source programming model
    - Take advantage of CUDA & C++AMP simplicity and power
    - Compiled for host *and* device(s)
- Easy development/debugging on host: *host* fall-back target
- Programming interface based on abstraction of OpenCL components (data management, error handling...)
- Most modern C++ features available for OpenCL
  - Enabling the creation of higher level programming models
  - C++ templated libraries based on OpenCL
  - Exceptions for error handling
- Portability across platforms and compilers
- Providing the full OpenCL feature set and seamless integration with existing OpenCL code
- Task graph programming model with interface *à la* TBB/Cilk (C++17)
- High performance

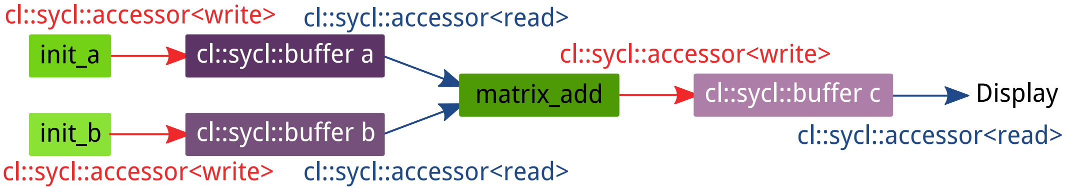
`http://www.khronos.org/opencl/sycl`

Complete example of matrix addition in OpenCL SYCL

```
#include <CL/sycl.hpp>
#include <iostream>

using namespace cl::sycl;

constexpr size_t N = 2;
constexpr size_t M = 3;
using Matrix = float[N][M];

int main() {
 Matrix a = { { 1, 2, 3 }, { 4, 5, 6 } };
 Matrix b = { { 2, 3, 4 }, { 5, 6, 7 } };

 Matrix c;

 {// Create a queue to work on
  queue myQueue;
  // Wrap some buffers around our data
  buffer<float, 2> A { a, range<2> { N, M } };
  buffer<float, 2> B { b, range<2> { N, M } };
  buffer<float, 2> C { c, range<2> { N, M } };
  // Enqueue some computation kernel task
  myQueue.submit([&](handler& cgh) {
   // Define the data used/produced
   auto ka = A.get_access<access::read>(cgh);
   auto kb = B.get_access<access::read>(cgh);
   auto kc = C.get_access<access::write>(cgh);
   // Create & call OpenCL kernel named "mat_add"
   cgh.parallel_for<class mat_add>(range<2> { N, M },
      [=](id<2> i) { kc[i] = ka[i] + kb[i]; }
   );
  }); // End of our commands for this queue
 } // End scope, so wait for the queue to complete.
   // Copy back the buffer data with RAII behaviour.
 return 0;
}
```

Asynchronous task graph model

- Theoretical graph of an application described *implicitly* with kernel tasks using buffers through accessors



- Possible schedule by SYCL runtime:

⇝ Automatic overlap of kernels & communications
  - Even better when looping around in an application
  - Assume it will be translated into pure OpenCL event graph
  - Runtime uses as many threads & OpenCL queues as necessary (AMD synchronous queues, AMD compute rings, AMD DMA rings...)

Task graph programming — the code

```
#include <CL/sycl.hpp>
#include <iostream>
using namespace cl::sycl;
// Size of the matrices
const size_t N = 2000;
const size_t M = 3000;
int main() {
  { // By sticking all the SYCL work in a {} block, we ensure
    // all SYCL tasks must complete before exiting the block

    // Create a queue to work on
    queue myQueue;
    // Create some 2D buffers of float for our matrices
    buffer<double, 2> a({ N, M });
    buffer<double, 2> b({ N, M });
    buffer<double, 2> c({ N, M });
    // Launch a first asynchronous kernel to initialize a
    myQueue.submit([&](auto &cgh) {
        // The kernel write a, so get a write accessor on it
        auto A = a.get_access<access::write>(cgh);

        // Enqueue parallel kernel on a N*M 2D iteration space
        cgh.parallel_for<class init_a>({ N, M },
                            [=] (auto index) {
                              A[index] = index[0]*2 + index[1];
                            });
      });
    // Launch an asynchronous kernel to initialize b
    myQueue.submit([&](auto &cgh) {
        // The kernel write b, so get a write accessor on it
        auto B = b.get_access<access::write>(cgh);
        /* From the access pattern above, the SYCL runtime detect
           this command_group is independant from the first one
           and can be scheduled independently */

        // Enqueue a parallel kernel on a N*M 2D iteration space
        cgh.parallel_for<class init_b>({ N, M },
                            [=] (auto index) {
                              B[index] = index[0]*2014 + index[1]*42;
                            });
      });
    // Launch an asynchronous kernel to compute matrix addition c = a + b
    myQueue.submit([&](auto &cgh) {
        // In the kernel a and b are read, but c is written
        auto A = a.get_access<access::read>(cgh);
        auto B = b.get_access<access::read>(cgh);
        auto C = c.get_access<access::write>(cgh);
        // From these accessors, the SYCL runtime will ensure that when
        // this kernel is run, the kernels computing a and b completed

        // Enqueue a parallel kernel on a N*M 2D iteration space
        cgh.parallel_for<class matrix_add>({ N, M },
                            [=] (auto index) {
                              C[index] = A[index] + B[index];
                            });
      });
    /* Request an access to read c from the host-side. The SYCL runtime
       ensures that c is ready when the accessor is returned */
    auto C = c.get_access<access::read, access::host_buffer>();
    std::cout << std::endl << "Result:" << std::endl;
    for(size_t i = 0; i < N; i++)
      for(size_t j = 0; j < M; j++)
        // Compare the result to the analytic value
        if (C[i][j] != i*(2 + 2014) + j*(1 + 42)) {
          std::cout << "Wrong value " << C[i][j] << " on element "
                    << i << ' ' << j << std::endl;
          exit(-1);
        }
  } /* End scope of myQueue, this wait for any remaining operations on the
       queue to complete */
  std::cout << "Good computation!" << std::endl;
  return 0;
}
```

From work-groups & work-items to hierarchical parallelism

```
const int size = 10;
int data[size];
const int gsize = 2;
buffer<int> my_buffer { data, size };

my_queue.submit([&](auto &cgh) {
  auto in = my_buffer.get_access<access::read>(cgh);
  auto out = my_buffer.get_access<access::write>(cgh);
  // Iterate on the work-group
  cgh.parallel_for_workgroup<class hierarchical>({ size,
                                                   gsize
    [=](group<> grp) {
      // Code executed only once per work-group
      std::cerr << "Gid=" << grp[0] << std::endl;
      // Iterate on the work-items of a work-group
      cgh.parallel_for_workitem(grp, [=](item<1> tile) {
        std::cerr << "id = " << tile.get_local()[0]
                  << " " << tile.get_global()[0]
                  << std::endl;
        out[tile] = in[tile] * 2;
      });
      // Can have other cgh.parallel_for_workitem() here...
    });
});
```

Very close to OpenMP 4 style! ☺

- Easy to understand the concept of work-groups
- Easy to write work-group only code
- Replace code + barriers with several parallel_for_workitem()
  - Performance-portable between CPU and GPU
  - No need to think about barriers (automatically deduced)
  - Easier to compose components & algorithms
  - Ready for future GPU with non uniform work-group size

C++11 allocators

- $\exists$ C++11 `allocator`s to control the way objects are allocated in memory
  - For example to allocate some vectors on some storage
  - Concept of `scoped_allocator` to control storage of nested data structures
  - Example: vector of strings, with vector data and string data allocated in different memory areas (speed, power consumption, caching, read-only...)
- SYCL reuses `allocator` to specify how `buffer` and `image` are allocated on the host side

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Exascale-ready

- Use your own C++ compiler
  - Only kernel outlining needs SYCL compiler
- SYCL with C++ can address most of the hierarchy levels
  - MPI
  - OpenMP
  - C++-based PGAS (Partitioned Global Address Space) DSeL (Domain-Specific embedded Language, such as Coarray C++...)
  - Remote accelerators in clusters
  - Use SYCL buffer allocator for
    - RDMA
    - Out-of-core, mapping to a file
    - PiM (Processor in Memory)
    - ...

Debugging

- Difficult to debug code or detect precondition violation on GPU and at large...
- Rely on C++ to help debugging
  - Overload some operations and functions to verify preconditions
  - Hide tracing/verification code in constructors/destructors
  - Can use pure-C++ host implementation for bug-tracking with favorite debugger

Poor-man SVM with C++11 + SYCL

- For complex data structures
  - Objects need to be in buffers to be shipped between CPU and devices
  - Do not want marshaling/unmarshaling objects...
  - Use C++11 `allocator` to allocate some objects in 1 SYCL `buffer`
    - Useful to send efficiently data through MPI and RDMA too!
  - But since no SVM, not same address on CPU and GPU side...
    - How to deal with pointers? ☹
    - Override all pointer accessed (for example use `std::pointer_trait`) to do address translation on kernel side ☺
      Cost: 1 addition per `*p`
- When no or inefficient SVM...
  - Also useful optimization when need to work on a copy only on the GPU
    - Only allocation on GPU side
    - Spare some TLB trashing on the CPU

¿¿¿Fortran???

- Fortran 2003 introduces C-interoperability that can be used for C++ interoperability... SYCL
- C++ boost::multi_array & others provides *à la* Fortran arrays
  - Allows triplet notation
  - Can be used from inside SYCL to deal with Fortran-like arrays
- Perhaps the right time to switch your application to modern C++? ☺

Using SYCL-like models in other areas

- SYCL $\equiv$ generic heterogeneous computing model beyond OpenCL
  - `queue` expresses where computations happen
  - `parallel_for` launches computations
  - `accessor` defines the way we access data
  - `buffer` for storing data
  - `allocator` for defining how data are allocated/backed
- Example for HSA: almost direct mapping *à la* OpenCL
- Example in PiM world
  - Use `queue` to run on some PiM chips
  - Use `allocator` to distribute data structures or to allocate `buffer` in special memory (memory page, chip...)
  - Use `accessor` to use alternative data access (split address from computation, streaming only, PGAS...)
  - Use `pointer_trait` to use specific way to interact with memory
  - ...

Outline

SYCL 2.1 is coming!

- Skip directly to OpenCL 2.1 and C++14
- Kernel side enqueue
- Shared memory between host and accelerator
- Parallel STL C++17
- Array TS

SYCL and fine-grain system shared memory (OpenCL 2)

```
#include <CL/sycl.hpp>
#include <iostream>
#include <vector>
using namespace cl::sycl;
int main() {
  std::vector a { 1, 2, 3 };
  std::vector b { 5, 6, 8 };
  std::vector c(a.size());
  // Enqueue a parallel kernel
  parallel_for(a.size(), [&] (int index) {
    c[index] = a[index] + b[index];
  });
  // Since there is no queue or no accessor, we assume parallel_for are blocking kernels
  std::cout << std::endl << "Result:" << std::endl;
  for(auto e : c)
    std::cout << e << " ";
  std::cout << std::endl;
  return 0;
}
```

- Very close to OpenMP simplicity
- Can still use of buffers & accessors for compatibility & finer control (task graph, optimizations...)
  - SYCL can remove the copy when possible

Outline

Conclusion

- $\exists$ Many C++ frameworks to leverage OpenCL
  - None of them provides seamless single source
    - Require some kind of macros & weird syntax
  - But they should be preferred to plain OpenCL C for productivity
- SYCL provides seamless single source with OpenCL interoperability
  - Can be used to improve other higher-level frameworks
- SYCL $\equiv$ pure C++ $\rightsquigarrow$ integration with other C/C++ HPC frameworks: OpenCL, OpenMP, libraries (MPI, numerical), C++ DSeL (PGAS...)...
- SYCL also interesting as co-design tool for architectural & programming model research (PiM, Near-Memory Computing, various computing models...)
- Modern C++ is not just C program in `.cpp` file ☺ $\rightsquigarrow$ Invest in learning modern C++