This handout was compiled on 2025-09-01 21:12.

CS-C3100 Computer Graphics, Fall 2025

Lehtinen / Kemppinen, Kallio, Kautto, Míchal

Assignment 1: Warmup (Due September 14, 2025 at 23:59.)

1 Overview and Requirements

This assignment will guide you to the coding environment we'll be using for the semester, and gently introduce you to drawing, generating, and moving 3D models.

Requirements (maximum 10 p) *on top of which you can do extra credit*

1. **Moving an object (1 p)**
2. **Generating a simple cone mesh and normals (3 p)**
3. **Converting mesh data for OpenGL viewing (3 p)**
4. **Loading a large mesh from file (3 p)**

2 Getting Started

- On Windows, make sure you have Visual Studio 2022 (the freely available Community Edition suffices) installed with C++ development options enabled (link).
- Fork the assignment repository at Aalto GitLab and clone it to a suitable location on your machine:
    1. Pick a good location to store your code in. If you are using a virtual Windows instance on `vdi.aalto.fi`, make sure you use a persistent storage like your home directory that is mapped onto the `Z:` drive. Otherwise you risk losing any work when the ephemeral storage on the instance gets destroyed upon shutdown. (Not that reasonable students would stop their working sessions without committing their code to remote source control, anyway.)
    2. After signing in with your Aalto credentials at the above URL, click "Fork" in the upper right corner.
    3. In the screen that comes up, make sure the fork gets placed under your own username and not any GitLab group you might be member of.
    4. *In the same screen, make sure you set your fork's visibility to "Private". This is important.*

5. Navigate to your shiny new fork and clone the repository. On Windows, this happens by opening "x64 Native Tools Command Prompt for VS2022" from Start Menu, navigating to your location of choice, and running `git clone` with your repo's address. On a VDI virtual machine, this could look like

   ```
   C:\Program Files\Microsoft Visual Studio\2022\Community>z: Enter
   Z:\>cd studies Enter
   Z:\studies>git clone https://version.aalto.fi/gitlab/[USERNAME]/cs-c3100-2025.git Enter
   ```

6. We strongly recommend setting up SSH public key authentication to use with GitLab so that you do not have to enter usernames and passwords every time you pull or push code. See GitLab instructions (link).

- Open `README.txt`, inspect the contents and fill in what you can at this point. You will turn in this file together with your code. Update it while you work on the assignment, like a to-do list.
- Optionally: go to the MyCourses system and make sure you can submit files to your "Assignment 1" folder. You can submit as many times as you want; we will inspect the last submission before deadline.
- Try out the provided `reference.exe` executable. Your program will work like this when it fulfills the requirements. The example also implements a few minor extra credit features. *Note that it only runs on the Windows platform, so if you're working on another platform, you can try it out in a virtual machine at* `vdi.aalto.fi`.
- Prepare the code for building using the CMake build system generator.

  On Windows, the process is as follows:

  1. Open "x64 Native Tools Command Prompt for VS2022" from the Windows Start Menu. *The x64 bit is important! There is also an x86 version.*
  2. In the command prompt, navigate to the directory `assignment1` cloned from GitLab and run the CMake configuration step for the `configure-vs2022` preset. If, for instance, you cloned the repo on a VM into your home directory under `studies\cs3100\assignment1`, this could look like

     ```
     C:\Program Files\Microsoft Visual Studio\2022\Community>z: Enter
     Z:\>cd studies\cs-c3100-2025\assignment1 Enter
     Z:\studies\cs-c3100-2025\assignment1>cmake -S . -B build --preset=configure-vs2022 Enter
     ```

     The last step downloads the necessary external libraries using the `vcpkg` package manager, and generates a Visual Studion solution file `build\assignment1.sln`.

  The `vcpkg` configuration that we provide also includes presets for generating XCode projects on MacOS, as well as presets for building Debug and Release builds directly for use on, e.g., Linux systems. We do not officially support other platforms than Windows except in a best effort fashion. Like with all content-related questions, we recommend asking actively on the assignment's Slack channel for pointers and help if you run into issues.

- In Windows explorer, double click the file `build\assignment1.sln`. This should open the code in Visual Studio 2022. Choose Build > Build Solution. Once the build finishes, run your program by pressing F5. You should see a triangle floating above a reference plane, like in the reference. Try clicking on the buttons in the control window to change the geometry and shading mode.
- At least skim the rest of this PDF before you start coding, especially Section 6 about submitting the assignment!

3 Tour of the environment and the code

3.1 Environment and tools

The Aalto classrooms should have Visual Studio 2022 installed. For working from home, you can get the free VS2022 Community for Windows Desktop (link). This requires signing in on a Microsoft account but is free.

The `assignment.sln` file you opened is a VS2022 *solution*, essentially a workspace. It contains three *build targets*, of which `assignment1` is the one relevant to you. You should never need to modify the project settings or add new files to complete the requirements, but you may do so. If you expand `assignment1` in the Solution Explorer, you see folders for source and header files. You should only need to modify `App.cpp` and `App.h` to complete the requirements.

There are four *build configurations* in the Visual Studio solution you can choose from: Debug, Release, MinSizeRel, and RelWithDebInfo. You don't need to care about the last two. Debug has more error checking enabled, so start with it. If your program feels slow, always try running it in Release before assuming there's something wrong with your code; Debug builds can sometimes run ten times slower than Release builds. While working with larger data, you'll probably want to use Release and switch to Debug only while tracking down problems. Sometimes your code has a serious problem that causes Debug builds to crash while Release builds *seem* to work; don't ignore these problems, fix them!

3.2 Libraries, frameworks, and standards

We avoid introducing technology for its own sake; you are supposed to be learning the theory via the practice. We try to make it so that whatever technology you encounter is standard and widely applicable, not just useful on this course.

We make heavy use of the C++ standard library (STL) – this allows us to concentrate on the important things instead of reinventing the wheel too often. You'll recognize standard library code because it resides in the C++ namespace `std`, for instance `std::vector`. In addition, we use the following cross-platform libraries through the `vcpkg` C++ package manager:

- `GLFW` for window creation and management, as well as handling keyboard and mouse input;
- `ImGui` for immediate-mode graphical user interfaces;
- `Eigen`, a header-only template library, for linear algebra;
- `fmt` for formatting strings in a modern fashion[1];
- `nativefiledialog-extended` for portable "Open File" dialogs;
- `argparse` for parsing command line options;
- `nlohmann/json` for JSON serialization and deserialization.

[1] Yes, we could use the very similar `std::format` if we were compiling on C++20. However, it is not supported on XCode except on the latest MacOS version, which we find a little limiting. We stick with C++17 for now.

For most graphics tasks we use pure OpenGL. You will not need to write OpenGL calls yourself to fill requirements, but you might want to for extra credit. The assignment code should work on computers which support OpenGL 3.3 or later.

Some parts of the base code use the Google naming style. We do not judge your code based on style.

3.3 On the starter code

The starter code, when compiled and run, will initially display a colored triangle floating on top of a colored plane. You can rotate the view by the HOME and END keys. Try out `reference.exe` to see what the buttons that display different objects do. A text output window is opened alongside the main window. The starter code uses it for outputting relevant information, and you can use it as a debugging aid yourself.

The overall structure of the program is simple. It's a great idea to get familiar with it before starting to work on the requirements. The source file `main.cpp` contains the entry point. It parses some command line options[2], constructs an object of type `App`, and calls `App::run(...)`. This function creates a window using the GLFW library, sets up OpenGL rendering, and then runs in a busy loop, rendering frames until the command to exit is given, e.g., by pressing Esc. Every frame, the main loop, the beginning of which is marked with a comment, draws the actual 3D content by calling `App::render(...)` and displays a GUI window using the immediate-mode GUI library ImGui.

What to draw is specified to `render(...)` by a structure called `AppState`. It contains, among other things, information about what object (scene) we are to draw in the `string` member variable `scene_mode`, specifies how much the camera has been rotated around the y axis in the `float` member variable `camera_rotation_angle`, and, importantly for requirement R1, the current translation of the object in an `Eigen::Vector3f` member variable `model_translation`.

To enable automatic generation of JSON serialization code, `AppState` is defined in a slightly odd fashion using the `STATE_FIELDS(...)` preprocessor macro in `app.h`, where each line defines the type, name, and default value for a new member of the structure. This definition, along with the additional magic in `app_state.h`, ends up creating `struct AppState` with the appropriate member variables, as well as automatically generated code to serialize to and from JSON. Using the member variables in code happens exactly as with usual `structs`.

We use the JSON serialization functionality to make debugging and verification of correct behavior easier for you. In particular, we ship a number of predefined *reference states* with the starter code. You can load those reference states by pressing Ctrl-F1...F4 in both your code as well as using `reference.exe`. Furthermore, the subdirectory `saved_states` contain corresponding PNG screenshots taken with the reference executable. When you've implemented the requirements correctly, you should, upon loading the appropriate configuration, see an image virtually identical to the reference we provide. The individual requirement instructions provide more details. In addition to loading reference states provided by us, you can save your own states by Shift-F1...F12 and load those states with F1...F12, i.e., without the Ctrl modifier. This will likely enable you to hunt bugs down faster.

On further inspection, you will notice that the `render(...)` function is marked as `const`. This means it is not supposed to change any state in the application, apart from the two cache variables marked `mutable` in the header file `app.h`. It is supposed to get all information as to what render from the reference to the `AppState` struct passed in as a parameter.

[2] which are only required when using scripts to render test images, something we do not initially provide

Finally, a few words about Eigen, our linear algebra library. We mostly use vector and matrix types that consist out of 32-bit floating point numbers (type `float` in C++) and static dimensions set at compile time. For instance, a three-element column vector has type `Vector3f` — 3 for dimensions, f for float — and a 4×4 matrix is `Matrix4f`. You can access the individual components using the funtion call syntax. For example, `Vector3f v = Vector3f::Zero(); v(1) = 3.0f;` constructs a 3-vector of zeros and sets its second component to the value 3. Note that Eigen does not initialize the contents of matrices and vectors by default, so explicit initialization is necessary. You can consult a gentle introduction to Eigen before getting started.

4 Detailed instructions

Requirements 1-3 do not depend on each other, so if you get stuck on one, you can start work on another. You can also work on R4, but to see its results you have to complete R3 first. There are more instructions and hints in the code comments, marked with `Rx` to make it easier to search for comments related to a particular requirement.

R1 Moving an object (1 p)

Your job is to give the user a way to translate the object in space along any axis using the keyboard. In `reference.exe`, arrow keys and PgUp/PgDn keys do this; we recommend you replicate its behavior. Specifically,

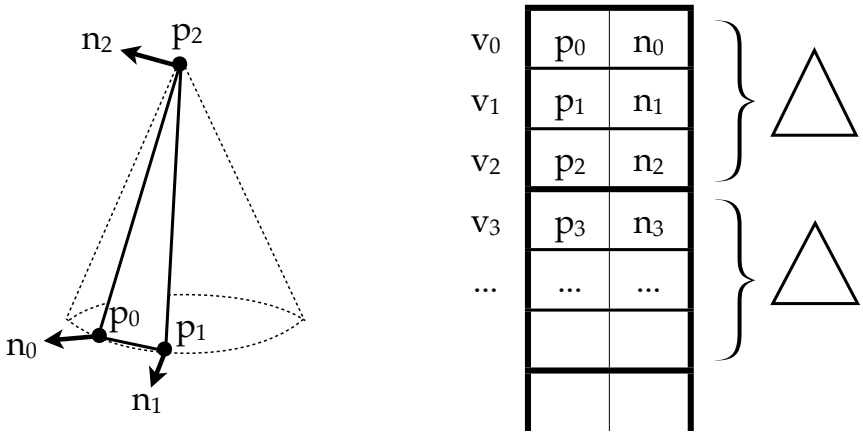
- add code to the `App::handleKeypress` function to react to user keypresses and change the current model translation stored in the `Eigen::Vector3f` member `model_translation` of App's state structure `m_state`. Each keypress should change the translation on one axis by 0.03 units to match the reference. See the lines that handle rotation keypresses for inspiration.
- Using the values in `m_state.model_translation`, change the correct entries of the 4x4 `Matrix4f` `modelToWorld` transformation matrix (initialized to identity) within the `App::render` function to transform the model position correctly. For this, you need to understand matrix representations of translations as described on Lecture 2, but you can also get to know all you need for this by looking at the Wikipedia article on affine transformations, and particularly its *Augmented matrix* subsection.

When you have implemented this correctly, you should see the brightly colored triangle move around according to your keypresses.

The first reference state, loaded by pressing Ctrl-F1, depicts a situation where the triangle has been moved by → → → → ↑ ↑ ↑ ↑ PgUp PgUp PgUp PgUp Home Home Home Home. Check that your image matches the reference image `saved_states/reference_state_01.png`.

R2 Generating a simple cone and normals (3 p)

Your job is to complete the `generateConeMesh` function so it generates a model of an upright cone with its tip at the origin, a height of 1 and a radius of 0.25. You can leave the cone open at the bottom. Be sure to change to the correct scene by clicking on the GUI button to see your results.



The finished cone model will have 40 *faces* (triangles). The faces are represented as an array of 120 *vertices*; every set of three vertices in the array describe one face. Each vertex contains its position coordinates and its normal direction (see the definition of `struct Vertex` in `App.h`). For reference, you can see the vertex array data of a single triangle in `generateSingleTriangleMesh` and the vertex array data of the reference plane (two triangles) in `reference_plane_data`.

For every face, you need to figure out the positions for its three vertices so that taken together the faces form a cone. When the vertex positions are correct, the cone will look right in the default shading mode.

Then, get the normal of the face from the vertex positions using cross product. You can use the same normal for all three vertices. This will result in a "flat shaded", not completely smooth look. When the normals are correct, the cone will look right in the directional light shading mode (press S or the GUI button to activate this) – compare with the reference, it's easy to get negative normals that are pointing inside the cone!

The function returns the data in a `std::vector` container. A `vector` in C++ is simply an array of objects of a specific type; `vector<int>` is an array of integers, `vector<Vertex>` is an array of vertices and so on. `vectors` are efficient and convenient; unless you have a reason to do otherwise, use a `vector` to store your data.

Pressing Ctrl-F2 loads a state with the cone generated and simple shading turned on. This should enable you to verify that your normals are oriented correctly.

R3 Converting mesh data for OpenGL viewing (3 p)

In R4 we are going to be loading 3D models in a compact, indexed representation. In this representation, every unique vertex position is stored only once in an array of positions, and likewise for vertex normals. Therefore a vertex can be represented as one index into the position array and one index into the normal array, and a face/triangle (which consists of three vertices) is represented as a set of six indices. You can see the indexed representation of a tetrahedron model in `generateIndexedTetrahedronMesh`.

This kind of indexing scheme - where the data needed to draw a single vertex has to be gathered using more than one index - is not supported by graphics hardware. To efficiently render the mesh using the

GPU we must convert to a simpler representation. What our OpenGL rendering code pushes to the GPU is a simple array of vertices where every vertex contains its position and normal directly, and every three subsequent vertices will be drawn as one triangle, as described in R2.

Your job is to fill in the `unpackIndexedData` function which converts indexed mesh data to vertex array form. This should take about 10 lines of code. When your code is correct, `generateIndexedTetrahedronMesh` will start working and load the tetrahedron model as in `reference.exe`.

We need some datatype to hold the data of an individual face (six indices). We could use `vector<unsigned>`, but for clarity we use `array<unsigned, 6>` instead. The size of an `array` is spelled out in the code; it cannot grow or shrink like `vector` can. So the last function argument, which needs to represent all the faces, ends up as `vector<array<unsigned, 6>>` (an array of arrays of exactly 6 unsigned integers).

There is a bit more you should note about `unpackIndexedData`'s argument types, like `const vector<Vector3f>&`. In C++, function arguments are *passed by value* by default; if the argument type was defined as `vector<Vector3f>`, the entire `vector` would be copied every time the function is called. `&` denotes that the argument is instead *passed by reference*; the `vector` inside the function is the same object it was called with, not a copy. `const` indicates the function is not supposed to modify the argument, and gives you a compiler error if you try.

Pressing Ctrl-F3 loads a reference state that shows the tetrahedron in its default pose.

R4 Loading a large mesh from file (3 p)

Before this we have used 3D models whose data is placed directly in the code or generated from scratch. This is impractical for all but the simplest models. To be able to use arbitrarily complex models, we will load them from separate files using the Wavefront OBJ format. OBJ is a widely used text-based file format that can describe a large variety of model data. In this assignment we will only read a part of that data and ignore the rest.

Your job is to fill in the missing parts of the `App::loadObjFile` function. It reads mesh data from a file into the same indexed representation as the hard-coded tetrahedron in R3, then uses the `unpackIndexedData` function you wrote in R3 to convert the data to viewable form.

In the `assets` folder there are three files: `sphere.obj`, `torus.obj` and `garg.obj`. These are the models we'll be testing your program with. Make sure you are able to load and view all three without crashing.

Let's take a closer look at `sphere.obj`. It's a big file, but it can be summarized as follows:

```
#This file uses ...
 ...
v 0.148778 -0.987688 -0.048341
v 0.126558 -0.987688 -0.091950
 ...
vn 0.252280 -0.951063 -0.178420
vn 0.295068 -0.951063 -0.091728
...
f 22/23/1 21/22/2 2/2/3
f 1/1/4 2/2/3 21/22/2
...
```

Each line of this file starts with a token followed by some arguments. The lines starting with `v` define vertex positions, the lines starting with `vn` define normals, and the lines starting with `f` define faces. There are other types of lines, and your code should ignore these.

Conceptually each type of line corresponds to a list of elements, with each line of that type giving the next element in the list. Thus the handling of positions ("v") is straightforward; you read their three numbers into a `Vector3f` and add it to `positions`. Then, do the same for the normals ("vn"), adding them into `normals`.

The faces ("f") are a little more complicated. Each face is defined using nine numbers in the following format: `a/b/c d/e/f g/h/i`. This defines a face with three vertices with position indices a, d, g and normal indices c, f, and i (you can ignore b, e, and h for this assignment). The position and normal indices correspond to the lists of positions and normals, that is, the order that the positions and normals appear in the file. The general OBJ format allows faces with an arbitrary number of vertices; you only have to handle triangles. Read the indices into an `array<unsigned, 6>` and add it to `faces`.

One thing you have to watch out for is that the indices in OBJ format start from 1, but when we index into C++ containers we start counting from 0. Thus, you have to subtract one from every index you read.

C++ input and output is usually performed with *streams*. You can write some debug information in the console by using the standard *output stream*, `std::cout`, and the stream write operator << like so:

```
cout << "The number is: " << 123 << endl;
```

Note that writing a large number of lines to the console slows the program down considerably, so it's best to disable such debug prints after everything works correctly.

In this requirement, we open an *input stream* that represents the contents of a disk file (`ifstream`). We use `getline()` to read one line at a time into the string `line`. We then represent that string as an `istringstream`, which is also an input stream. That allows us to use the stream read operator >> to read individual pieces of data from the string. (Note that `istringstream`'s operator >> uses whitespace in the string to tell where the next piece to be read begins and ends. The / characters between numbers in the file would confuse >>, so we must replace them with whitespace before creating the `istringstream`.)

```
ifstream input(filename, ios::in);
string line;
while(getline(input, line)) {
  istringstream iss(line);
  int i; float f; string s;
  iss >> i >> f >> s;
  ...
}
```

Pressing Ctrl-F4 loads a reference state that loads `assets/meshes/garg.obj` and displays it with shading on.

5 Extra credit

Here are some ideas that might spice up your project. The amount of extra credit given will depend on the difficulty of the task and the quality of your implementation. Feel free to suggest your own extra credit ideas!

We always recommend some particular extras that we think would best round out your knowledge. These will range from easy to medium difficulty. The base code will usually be written to accommodate the recommended extras, and may already contain some inert code and/or comments to help you out with them.

Especially recommended

- **Version control (1 p)**
  Use the `git` version control running on Aalto GitLab to store your assignment code. It protects your work from accidental destruction, and allows you to return to a working version of your code if you end up writing a bug and can't find it. Using a network repository will also help you work on multiple computers. *But make sure the repository you use to store assignment code is private!* We supply a `.gitignore` file with every assignment that will help you ignore useless files while using `git`.

  While this has nothing to do with computer graphics as such, you'll get a bonus point as an incentive because we think using a version control system will improve the rest of your work. We strongly recommend you use Aalto GitLab, which is where you got the starter code by forking in the first place. To claim your bonus point, submit a log of your repository history or a screenshot of it. Adding `> logfile.txt` will redirect the log output straight to a file.

  ```
  git log --graph --all --format=format:"(%h) %ci <%ce>%n%s"
  ```

- **Rotate and scale transforms (1 p)**
  In addition to the object translation in requirement R1, allow the user to scale the current object (non-uniformly) along x axis, and to rotate the object around y axis. Pay attention to the order of the transforms so the result makes sense; translating or rotating the object shouldn't change its size.

- **Transforming normals in vertex shader (1 p)** *(requires rotate and scale transforms)*
  As you rotate the object in light shaded mode, you'll see the shading does not change, as if the light was stuck to the object being rotated. You have uncovered a bug; obviously the assistent who wrote the vertex shader forgot to transform the vertex normal before it's used to do the shading calculation. Write the missing GLSL shader code in the vertex shader to fix the bug. For a full point, make sure shading also looks correct with uneven scaling (stretch the torus model to test this). **Harder alternative in Medium section.**

- **Better camera (up to 3 p)**
  The base code has a very limited camera. Write your own camera matrix to replace the existing one in `App::render`, and give your camera different/better functionality. For example, you could allow freely moving and rotating the camera, or centering the camera around the object's position instead of the origin. See comments in `App::handleMouseMovement` about adding mouse control. A working virtual trackball implementation is one way to get full 3 points.

Easy

- **Animation (0.5 p)**
  In `reference.exe`, you can press R to start and stop camera rotation. Implement this in your code. See the `Timer` class in the shared sources. You can use it for checking how much time has passed since the last frame and act accordingly. You can animate something else instead of the camera if you like, such as a transformation for the object.
- **Viewport and perspective (1p)**
  Allow the user to choose the field of view in the `x` direction and adjust the other to match. Use an ImGui slider to allow the user to control it.

Medium

- **Efficiently transforming normals in vertex shader (2 p)** *(requires rotate and scale transforms)*
  This is an alternative for the Recommended extra. You might want to do it before attempting this. Again, you must transform normals correctly also when the object is being scaled along one axis. Just modifying the GLSL code to do this results in an expensive calculation being carried out for every vertex. Since that calculation is the exact same at every vertex, we don't want to do it in the vertex shader. Your job is to calculate the transform matrix for normals in the C++ code, add a new *uniform variable* (a shader variable common to all vertices) for passing the matrix into the shader, and use it inside the shader code to transform the normal. Check out how the existing uniforms work.
- **Add support for loading another file format (up to 4 p)**
  Allow the user to load models from another 3D model format such as PLY.
  Include a model for testing your code.

Hard

- **Mesh simplification (? p)**
  Large meshes are quite difficult to draw and process. For interactive applications, such as video games, it's often desirable to simplify meshes as much as possible without sacrificing too much quality. Implement a mesh simplification method, such as the one described in Surface Simplification Using Quadric Error Metrics (Garland and Heckbert, SIGGRAPH 97).
- **Rendering Signed Distance Fields (? p)**
  While meshes are the typical representation actually drawn using graphics hardware, nothing says that the vertex positions and connectivity have to be specified directly "by hand". *Signed distance fields* are a common volumetric geometry representation that can be converted to meshes using, for instance, the "Marching Cubes" algorithm. Implement signed distance fields, including conversion to a mesh for display. The representation allows you to do interesting things that are hard to do with meshes directly, such as enlarging or shrinking surfaces so that they do not intersect themselves. Demonstrate something like that. Be sure to include any assets needed by your code in your submission package.

Varying

- **Shading**. Implement fancier forms of shading by modifying `src/vertex_shader.glsl` and `src/pixel_shader.glsl`, as well as passing in any additional information you need through the uniforms and potentially vertex attributes. Make sure to put these features behind a GUI toggle so as not to break the rendering of your requirements! Possible ideas include animating the light source, increasing their number, implementing a more interesting surface material model (BRDF), and so on. Be creative!

6 Submission

- Make sure your code compiles and runs both in Release and Debug modes on Windows with Visual Studio 2022, preferably in the VDI VMs. You may develop on your own platform, but the TAs will grade the solutions on Windows.
- Comment out any functionality that is so buggy it would prevent us seeing the good parts. Use the `reference.exe` to your advantage: does your solution look the same? Remember that crashing code in Debug mode is a sign of problems.
- Check that your `README.txt` (which you hopefully have been updating throughout your work) accurately describes the final state of your code. Fill in whatever else is missing, including any feedback you want to share. We were not kidding when we said we prefer brutally honest feedback.
- Package all your code, project and CMake+vcpkg configuration files, required to build your submission, `README.txt` and any screenshots, logs or other files you want to share into a ZIP archive. *Do not* include your `build` subdirectory or the reference executable. Beware of large hidden `.git`-folders if you use version control - those should not be included.
- Sanity check: look inside your ZIP archive. Are the files there? Test and see that it actually works: unpack the archive into another folder, run the CMake configuration, and see that you can still compile and run the code.
- If you experience a system failure that leaves you unable to submit your work to MyCourses on time, prepare the submission package as usual, then compute its MD5 hash, and email the hash to us at `cs-c3100@aalto.fi` before the deadline. Then make the package that matches the MD5 hash available to us e.g. using `filesender.funet.fi`. *This is only to be done when truly necessary; it's extra work for the TAs.*

Submit your archive in MyCourses folder "Assignment 1: Warmup / Introduction".