Getting Started with LLGL

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Part I

Introduction

1 In a nutshell

1.1 What can LLGL do for me?

- **Unification**
  LLGL provides a unified interface across all supported renderers. Write your graphics render passes once and use them across multiple rendering APIs and platforms.

- **Low Overhead**
  LLGL is meant to be a thin abstraction layer which only adds as less overhead between your application and the underlying rendering API as possible. At best, a function is just a wrapper that passes the parameters to the actual renderer. For example, the implementation of the `CommandBuffer::DrawIndexed` interface for Direct3D11:

```
void D3D11CommandBuffer::DrawIndexed(std::uint32_t numVertices, std::uint32_t firstIndex) {
    context_->DrawIndexed(numVertices, firstIndex, 0);
}
```

- **Compatibility**
  LLGL provides various compatibility functionalities between the renderers. For example, some image formats that are supported by OpenGL but not by Direct3D are converted 'on the fly' by LLGL. However, some compromises are inevitable, due to different hardware restrictions. All incompatibilities are well documented though.

- **Simplification**
  Where close access to the hardware is not necessary, LLGL provides useful simplifications. For example, creating a render context as well as a device context across multiple platforms requires a lot of work when done manually. With LLGL, this can be done with a few lines of code, but still have plenty of control thanks to the rich descriptor structures.

1.2 What can LLGL *not* do for me?

- **Shader Cross Compilation**
  LLGL unifies the underlying rendering APIs as far as possible, but since each rendering API has its own shading language, all shaders need to be provided for each desired renderer explicitly by the user. That said, there are several shader cross compilers available:

  - XShaderCompiler (github.com/LukasBanana/XShaderCompiler),
  - SPIRV-Cross (github.com/KhronosGroup/SPIRV-Cross),
  - hlsl2glsl (github.com/aras-p/hlsl2glslfork).
  - HLSLCrossCompiler (github.com/James-Jones/HLSLCrossCompiler)

- **Scene Management**
  LLGL is a low-level render system which does not provide any high-level scene management or animation system. It provides you with a set of functions to submit draw commands and render states to the graphics hardware as well as managing raw hardware buffers. 'Game engine'-like functionality or anything beyond graphics is not part of LLGL.

2   Prerequisites

LLGL (Low Level Graphics Library) is a thin abstraction layer for graphics APIs such as OpenGL, Direct3D, and Vulkan. It is meant to abstract these rendering technologies to one uniform interface. The library is written entirely in C++11, so you'll need a modern C++ compiler, i.e. at least **VisualC++ 2015** for Windows, **g++ 4.8** for Linux, or **Clang 3.1** for MacOS. To work with this library you should be familiar with these subjects:

- **Basic C++11 Programming**
  Since the library is written in C++11, you should know something about *smart pointers*, *raw pointers*, and basic *object-oriented programming* (OOP) in C++.

- **Basic Linear Algebra**
  You should be familiar with at least *Vectors* and *Matrices*.

- **Fundamentals in Graphics Programming**
  You should be familiar with the fundamentals of graphics programming, since this is only a low-level graphics library. You should also be familiar with at least one of the major graphics APIs, i.e. *OpenGL*, *Direct3D*, *Vulkan*, or *Metal*, because LLGL does only little to no higher abstractions.

- **Shading Languages**
  LLGL forces you to always write your own shaders, so you should be familiar with GLSL or HLSL.

3 Progress

This project is still in its early steps. Here is a short overview of its progress:

3.1 Platforms

- **Windows**
  Windows 10 is the main development environment of the author, so this platform has the best support.

- **MacOS**
  The MacOS port is in its early steps, but a few tutorials are already running. The development environment for the MacOS port is *macOS Sierra*.

- **Linux**
  Kubuntu 16 (GNU/Linux) is used inside a virtual machine by the author to develop the linux port. This platform is partially supported (i.e. anti-aliasing or other features are not complete on this platform).

3.2 Renderers

- **OpenGL**
  OpenGL renderer is almost done (~85% complete).

- **Direct3D 11**
  Direct3D 11 renderer is almost done (~85% complete).

- **Direct3D 12**
  Direct3D 12 renderer is only in an experimental state (~5% complete).

- **Vulkan**
  Vulkan renderer is only in an experimental state (~5% complete).

4 Build Process

4.1 Dependencies

4.1.1 GaussianLib

The only required dependency is the header-only library GAUSSIANLIB, which is used for basic linear algebra computations with vectors and matrices.

4.1.2 OpenGL

To build the OpenGL render system you need the OpenGL extension header files and an up-to-date graphics driver. For Windows the header files `glext.h` and `wglext.h` are required. For Linux the header files `glext.h` and `glxext.h` are required. For MacOS no header files need to be downloaded, since the OpenGL version depends on the OS version. You can find the header files at the OpenGL registry page. Place the header files in the `include/GL/` folder of your compiler environment or add the include path later in your build settings.

4.1.3 Direct3D

Since VisualStudio 2013, the DirectX framework (of which Direct3D is a part of) is included within the VisualStudio setup, so no further SDK needs to be installed.

4.2 Build Tool

To build the LLGL project files you need the build tool CMake 2.8 or later. The build process is now demonstrated with the CMake GUI on Windows, but it can also be configured on a command line (more about this see cmake.org/runningcmake).

Set the source directory ("Where is the source code:") to the LLGL repository and set the build directory ("Where to build the binaries") where you want your project files. In this example (see Figure 1) the source directory is `<...>/LLGL/repository` and the build directory is `<...>/LLGL/build_msvc14` because the project files are build for MSVC14 (VisualStudio 2015).

Now set the GAUSSIANLIB include directory (in this example `<...>/GaussianLib/repository/include`) and click on "Configure". If everything worked quite well, you should see the message "Configuring done" in the lower box. To finally create the project files, click on "Generate". Then your project files should be located in the build directory you just set up previously.
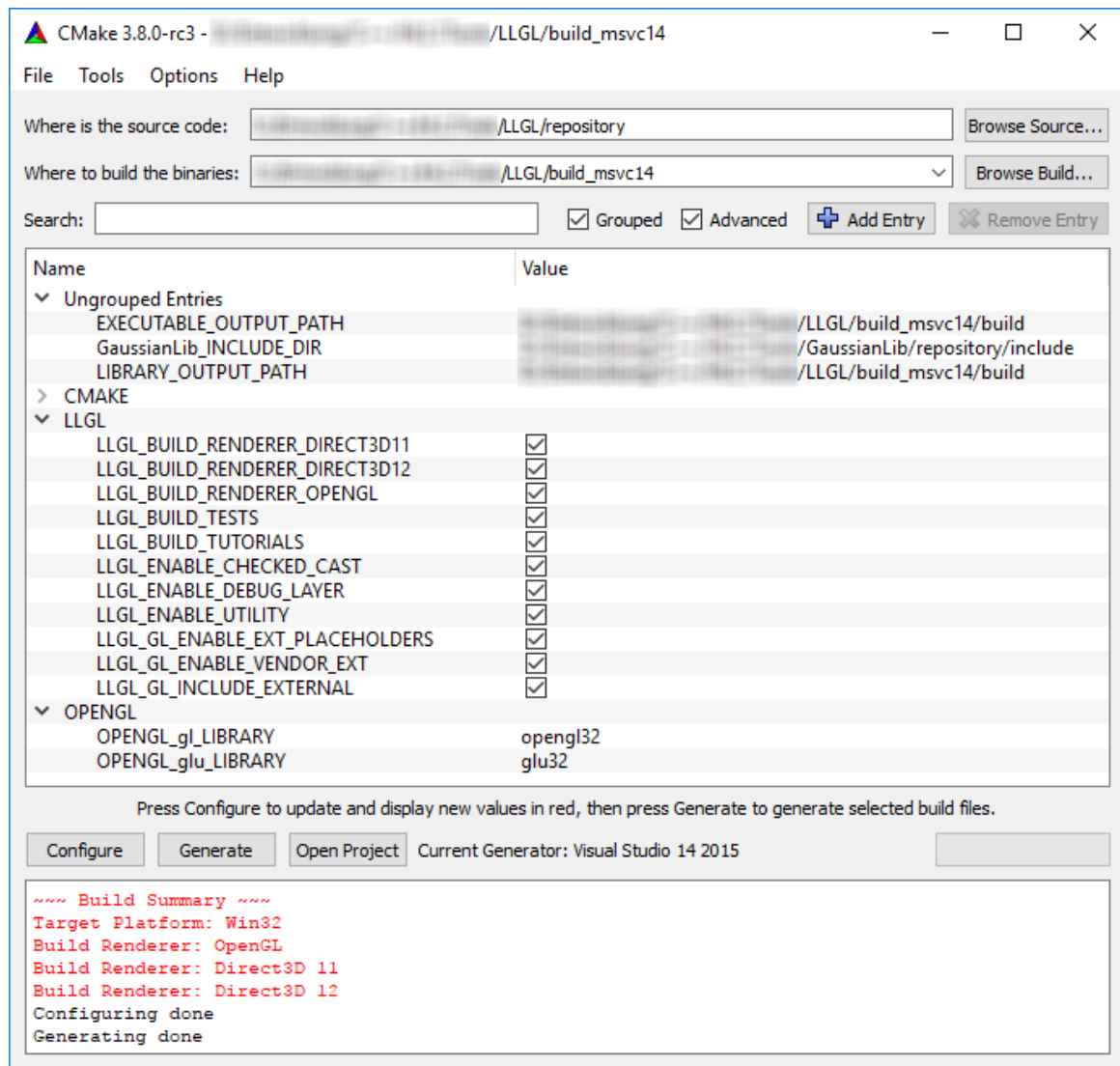
Figure 1: CMake GUI mask to set up the project files for VisualStudio 2015 (MSVC14).

There are a few options you can switch on and off, which will enable or disable the respective macro when you compile the project:

- `LLGL_BUILD_(TESTS/TUTORIALS/RENDERER_...)`
  Specifies whether to include all test, all tutorials, or the repsective renderer projects.

- `LLGL_ENABLE_CHECKED_CAST`
  Specifies whether to enable or disable dynamic checked casts. This is only available in debug mode.

- `LLGL_ENABLE_DEBUG_LAYER`
  Specifies whether to enable or disable the debug layer. This is a wrapper around the render system and all other render objects for effective debugging.

- `LLGL_ENABLE_UTILITY`
  Specifies whether to enable or disable utility functions, which can be used to easily initialize descriptor structures. They must be included separately with the `LLGL/Utility.h` header file.

- `LLGL_GL_ENABLE_EXT_PLACEHOLDERS`
  Specifies whether OpenGL extensions should be replaced by placeholder procedures when they are not available. This may help debugging and should not influence the runtime performance.

- `LLGL_GL_ENABLE_VENDOR_EXT`
  Specifies whether vendor specific OpenGL extensions should be enabled or disabled. One of these extensions is for conservative rasterization (`GL_NV_conservative_raster` and `GL_INTEL_conservative_rasterization`) for instance. These extensions will only be loaded and used by the runtime if they are available on the host platform.

5 API Overview

LLGL has a very simple and unified API design. For object creation, there is commonly a "`...Descriptor`" structure (e.g. `LLGL::BufferDescriptor`), which contains all necessary information to describe the object which is to be created.

5.1 Rendering Interfaces

There are three major interfaces for rendering: *RenderSystem* is mainly used for object creation and memory read/write operations, *RenderContext* is used to configure each framebuffer and its back buffer (or rather swap chain), and *CommandBuffer* which is used to set render states, draw primitives, and dispatch compute commands.

5.1.1 RenderSystem

In the `RenderSystem` interface there are several functions of the following form:

```
// Create a new object
Create...

// Update the data of an object
Write...

// Read the data from an object
Read...

// Map the memory of an object from GPU to CPU memory space
Map...

// Unmap the memory from an object
Unmap...

// Release an object
Release
```

5.1.2 RenderContext

The most important function in the `RenderContext` interface is `Present`, to show the content of the back buffer on the screen. There are a few other functions to access the context window and change the video mode:

```
// Access context window
GetWindow

// Set video mode (i.e. resolution, fullscreen/windowed mode etc.)
SetVideoMode

// Set vertical synchronization (Vsync) for swap-chain
SetVsync
```

5.1.3 CommandBuffer

There are several overloaded functions for drawing operations with the naming convention "`Draw`", "`DrawIndexed`", "`DrawInstanced`", or "`DrawIndexedInstanced`". The most other functions are used to configure the command buffer of the graphics API, which have the following form:

```
// Set a hardware buffer/ texture/ sampler etc.
Set...

// Begin and always end a state (e.g. BeginQuery/ EndQuery)
Begin...
End...

// Draw primitives
Draw...
```

5.2 Windowing System

LLGL has the `Window` interface for a very basic but platform independent windowing system. Use its static function `Create` to create an instance of this interface for the host platform. A custom implementation of this interface can also be written and used for any renderer. In section 7 an example of a custom implementation with GLFW is shown.

Part II
Tutorials

6   Hello Triangle

After we have set up and build the library, we can start rendering some geometry. Our example will consist of a single C++ source file (e.g. "main.cpp") and two shader files (e.g. "vertex.glsl" and "fragment.glsl"). The include path for a project, that uses LLGL, must be set to *<your-LLGL-repository>*/include/, and the LLGL library file must be added to the linker (for Windows this is "LLGL.lib" when compiling in Release mode and "LLGLD.lib" when compiling in Debug mode). All the other library files don't need to be added to the linker (e.g. "LLGL_OpenGL.lib"), since the respective renderer module is loaded at runtime.

Now let's start with a small example. At first we need to include the header files. The main header we need is LLGL/LLGL.h where the entire LLGL interface is declared. For our example we also need basic I/O classes from iostream for standard output, fstream to read the shader files, and Gauss/Gauss.h for some matrix classes:

```cpp
#include <LLGL/LLGL.h>
#include <Gauss/Gauss.h>
#include <iostream>
#include <fstream>
```

Next we define the C++ main function and wrap the entire example code into a large try-catch block, to quit the application with a meaningful error message if any failure happens:

```cpp
int main() {
    try {
        /* example code here ... */
    } catch (const std::exception& e) {
        std::cerr << e.what() << std::endl;
    }
    return 0;
}
```

To create an LLGL renderer instance in our main function, we load a renderer module (a *module* here denotes a dynamic shared library) from the static Load function of the RenderSystem interface:

```cpp
std::shared_ptr<LLGL::RenderSystem> renderer = LLGL::RenderSystem::Load("OpenGL");
```

Here we could actually use the C++11 keyword auto to simplify the code, but for explanation purposes we keep the types explicit. Most creation or load functions return a new instance wrapped in a std::unique_ptr, but in this case LLGL needs to keep track of the instance to check if it has already been expired, which is only feasible with an std::shared_ptr.

Moreover, most functions use enumerations instead of strings to specify some type, but in this case a module can be loaded dynamically at runtime and further modules can be added or removed independently. Therefore the renderer module is specified by a string (here "OpenGL"). Other modules are named "Direct3D11", "Direct3D12", and "Vulkan". Whenver you load a new renderer, there must not remain any references to this shared object, because only a single renderer can be loaded at a time. When this shared object expires, all objects allocated by this renderer will be deleted automatically.

If loading the renderer failed, an std::runtime_error exception will be thrown, which can be cached to show an error message and/or load another renderer module instead. This can be very handy if a specific Direct3D version is not installed on the host Windows platform, so another Direct3D version or OpenGL renderer can be loaded as fallback without disturbing the user with akward error messages and program crashes.

After we created the renderer we need a graphics context to draw into. This is done by the CreateRenderContext function which takes a descriptor structure:

```cpp
LLGL::RenderContextDescriptor contextDesc;
{
    contextDesc.videoMode.resolution = { 640, 480 };
}
LLGL::RenderContext* context = renderer->CreateRenderContext(contextDesc);
```

This is a minimal example for the render context descriptor. There are much more attributes to specify multi-sampled anti-aliasing, vertical-synchronisation, etc. See the API documentation for more information about these attributes.

This render context will create its own window, but we could also specifiy our own one. However, in this example we keep it simple. To access this window and change the title, we use the GetWindow function of the RenderContext interface which returns a reference to its window:

```
context->GetWindow().SetTitle(L"LLGL Tutorial 01: Hello Triangle");
```

Since some platforms (such as Win32) support Unicode window titles, our string literal starts with the 'L' token.

Next we create a vertex buffer to store our geometry. For this example we give up an index buffer, since we only draw a single triangle and no complex models. At first we define our vertex data and the vertex format, which is required to tell the rendering API how the vertex attributes are located within the vertex buffer:

```
// Vertex data structure
struct Vertex {
    Gs::Vector2f    position;
    LLGL::ColorRGBf color;
};

// Vertex data (3 vertices for our triangle)
Vertex vertices[] = {
    { {  0,  1 }, { 1, 0, 0 } }, // 1st vertex: center-top, red
    { {  1, -1 }, { 0, 1, 0 } }, // 2nd vertex: right-bottom, green
    { { -1, -1 }, { 0, 0, 1 } }, // 3rd vertex: left-bottom, blue
};

// Vertex format
LLGL::VertexFormat vertexFormat;
vertexFormat.AppendAttribute({ "position", LLGL::VectorType::Float2 }); // position has 2D float vector
vertexFormat.AppendAttribute({ "color",    LLGL::VectorType::Float3 }); // color has 3D float vector
```

The AppendAttribute function adds the attributes to the vertex format. The order of these function calls determines the location in the vertex data, so they must match the order of the member fields in the vertex data structure (here "struct Vertex").

Now we can create our vertex buffer and upload the vertex data to the GPU by passing a pointer to the initialData parameter:

```
LLGL::BufferDescriptor bufferDesc;

// Set the common buffer attributes
bufferDesc.type = LLGL::BufferType::Vertex; // Buffer type
bufferDesc.size = sizeof(vertices);         // Size (in bytes) of the buffer

// Set vertex buffer specific attributes
bufferDesc.vertexBuffer.format = vertexFormat; // Copy the vertex format

LLGL::Buffer* vertexBuffer = renderer->CreateBuffer(bufferDesc, vertices);
```

To update an entire hardware buffer or texture (or only a portion of it) there is a respective "Write..." function.

Now we have the vertex buffer complete and we can cross over to shader creation. In LLGL the shaders (Vertex, Tessellation-Control, Tessellation-Evaluation, Geometry, Fragment, and Compute shaders) are created independently, and then attached and linked together with a shader program. For our example we only need a Vertex- and Fragment (also called "Pixel") shader:

```
LLGL::Shader* vertexShader   = renderer->CreateShader(LLGL::ShaderType::Vertex);
LLGL::Shader* fragmentShader = renderer->CreateShader(LLGL::ShaderType::Fragment);
```

Now we have two empty shaders. Next we load the shader code from file with our custom "ReadFileContent" lambda function:

```
// Define the lambda function to read an entire text file
auto ReadFileContent = [](const std::string& filename) {
    std::ifstream file(filename);
    return std::string( ( std::istreambuf_iterator<char>(file) ),
                        ( std::istreambuf_iterator<char>(     ) ) );
};

// Load vertex- and fragment shader code from file
std::string vertexShaderCode   = ReadFileContent("vertex.glsl");
std::string fragmentShaderCode = ReadFileContent("fragment.glsl");
```

After reading the shader code into strings we can compile the shaders:

```
auto CompileShader = [](LLGL::Shader* shader, const std::string& code) {
    // Compile shader
    shader->Compile(code);

    // Print info log (warnings and errors)
    std::string log = shader->QueryInfoLog();
```

```
        if (!log.empty()) {
            std::cerr << log << std::endl;
        }
};

CompileShader(vertexShader, vertexShaderCode);
CompileShader(fragmentShader, fragmentShaderCode);
```

Shader compilation works a little different between GLSL (for OpenGL) and HLSL (for Direct3D). For HLSL shader compilation there is a second overloaded "Compile" function with more parameters, to specifiy the entry point and shader version target.

Having the shaders compiled, we can now create a shader program, attach all shaders to it, bind the vertex attribute layout, and finally link the shader program:

```
// Create shader program which is used as composite
LLGL::ShaderProgram* shaderProgram = renderer->CreateShaderProgram();

// Attach vertex- and fragment shader to the shader program
shaderProgram->AttachShader(*vertexShader);
shaderProgram->AttachShader(*fragmentShader);

// Build vertex layout for input assembly (this is not required for a compute shader program)
shaderProgram->BuildInputLayout(vertexFormat);

// Link shader program and check for errors
if (!shaderProgram->LinkShaders()) {
    throw std::runtime_error(shaderProgram->QueryInfoLog());
}
```

The "BuildInputLayout" function binds the vertex attributes to the shader program. This must be called after shader attachment but before shader linking (except a compute shader program is used).

Before we continue with the C++ code, we first take a look at the shader code:

vertex.glsl

```
// GLSL shader version 1.30 (for OpenGL 3.1)
#version 130

// Vertex attributes (these names must match our vertex format attributes)
in vec2 position;
in vec3 color;

// Vertex output to the fragment shader
out vec3 vertexColor;

// Vertex shader main function
void main() {
    gl_Position = vec4(position, 0, 1);
    vertexColor = color;
}
```

This simple vertex shader only passes the vertex position and color (with default interpolation) to the fragment shader. And here is the fragment shader:

fragment.glsl

```
// GLSL shader version 1.30 (for OpenGL 3.1)
#version 130

// Fragment input from the vertex shader
in vec3 vertexColor;

// Fragment output color
out vec4 fragColor;

// Fragment shader main function
void main() {
    fragColor = vec4(vertexColor, 1);
}
```

Now we are finally done with setting up the shader. Next we need to create a graphics pipeline. This concept is derived from modern graphics APIs such as Direct3D 12 and Vulkan. The major pipeline state is stored inside this pipeline state object. For older graphics APIs (such as OpenGL) LLGL will set the respective render states by its internal state manager, to reduce state changes.

The graphics pipeline specifies the depth-, stencil-, rasterizer-, blending-, and shader states and is created as follows:

```
LLGL::GraphicsPipelineDescriptor pipelineDesc;
{
    pipelineDesc.shaderProgram = shaderProgram;
}
LLGL::GraphicsPipeline* pipeline = renderer->CreateGraphicsPipeline(pipelineDesc);
```

In our example we can use all default settings of the graphics pipeline descriptor except the shader program, which must always be set by the client programmer.

Before we start with the render main loop, we need a command buffer which can send render state and draw commands to the GPU:

```
// Create command buffer to submit subsequent graphics commands to the GPU
LLGL::CommandBuffer* commands = renderer->CreateCommandBuffer();

// Set the render context as the initial render target
commands->SetRenderTarget(*context);
```

We now have all render objects, so we can start with the main loop:

```
// Run main loop until the main window is closed
while (context->GetWindow().ProcessEvents()) {
    /* render code here ... */
}
```

This main loop will run until the user clicks the close button on the window of the render context. The rest of the code is pretty simple, since the most work is done during initialization. What we need to do is to clear the color buffer of the previous frame, set the graphics pipeline, set the vertex buffer, draw the primitives, and present the result on the frame buffer:

```
// Set viewport (left: 0, top: 0, width: 640, height: 480)
commands->SetViewport({ 0, 0, 640, 480 });

// Clear color buffer
commands->Clear(LLGL::ClearFlags::Color);

// Bind graphics pipeline
commands->SetGraphicsPipeline(*pipeline);

// Bind vertex buffer
commands->SetVertexBuffer(*vertexBuffer);

// Generate 3 vertices to draw a triangle
commands->Draw(3, 0);

// Present the result on the frame buffer (or rather on the screen)
context->Present();
```

When you have done everything right, you should see something like shown in figure 2 after compilation and program start (set working directory to `tutorial/Tutorial01_HelloTriangle`).
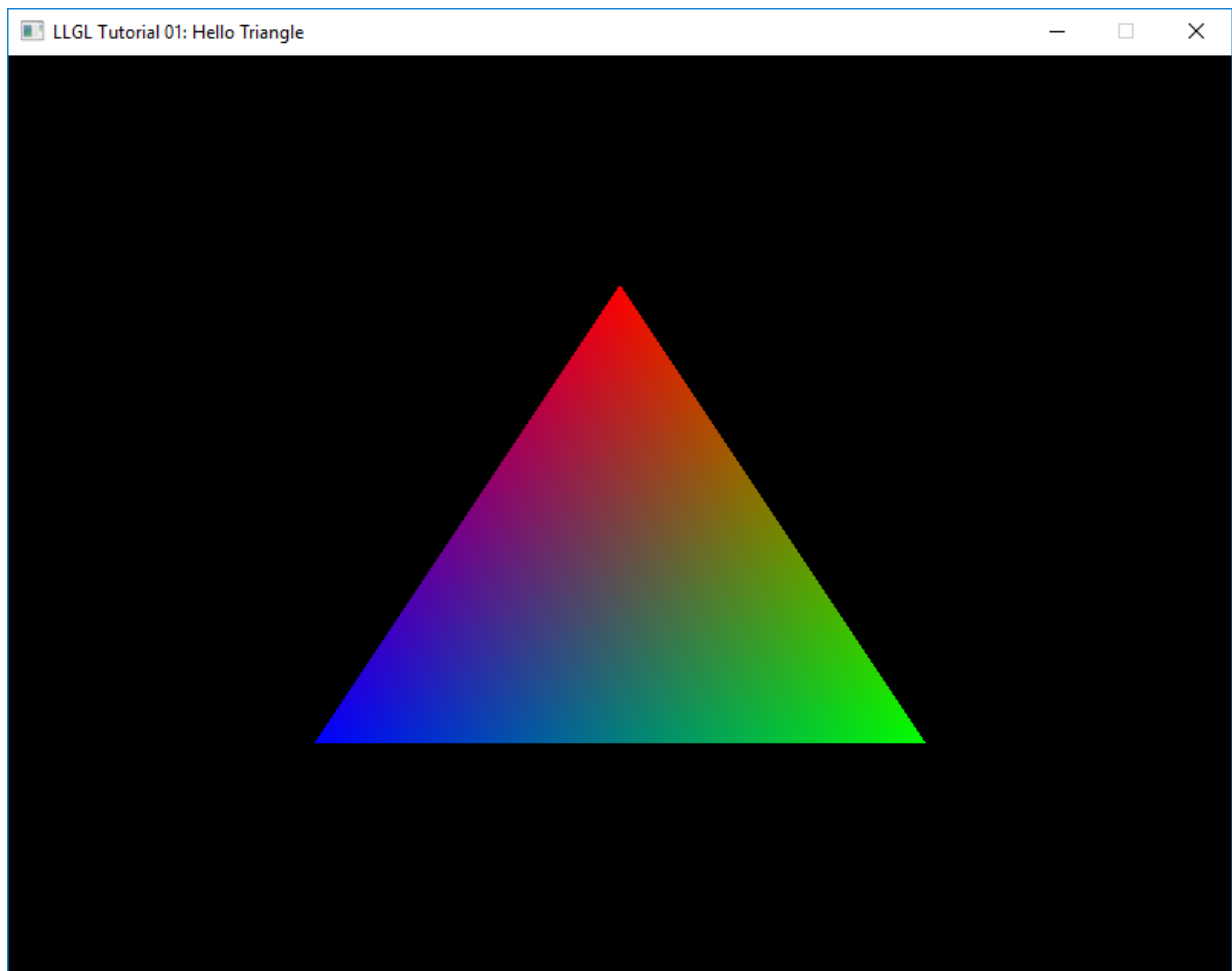
Figure 2: Output of the "Tutorial01: HelloTriangle" running on Windows 10.

Part III
Extensibility

7 Custom Surface Class

In this example a simple custom implementation of the Surface interface is demonstrated, to show how LLGL can be used with other windowing system libraries. Here we will use the popular cross-platform library GLFW.

We start with the include files of GLFW and LLGL:

```cpp
// Include GLFW library (in this example we use the Win32 platform)
#define GLFW_EXPOSE_NATIVE_WIN32
#include <GLFW/glfw3.h>
#include <GLFW/glfw3native.h>

// Include LLGL and also the native handle structures
#include <LLGL/LLGL.h>
#include <LLGL/Platform/NativeHandle.h>
```

Now we declare our custom surface class and override all necessary interface functions. We could also inherit from the Window interface but this is not really meaningful here:

```cpp
class CustomSurface : public LLGL::Surface
{
public:
    // Constructor and destructor
    CustomSurface(const LLGL::Size& size, const std::string& title);
    ~CustomSurface();

    // Interface implementation
    void GetNativeHandle(void* nativeHandle) const override;
    void Recreate() override;
    LLGL::Size GetContentSize() const override;
    bool AdaptForVideoMode(LLGL::VideoModeDescriptor& videoModeDesc) override;

    // Additional class functions
    void PollEvents();

private:
    GLFWwindow* CreateGLFWWindow();

    std::string title_;
    LLGL::Size  size_;
    GLFWwindow* wnd_ = nullptr; // GLFW window pointer

};
```

This is an example of a minimal interface implementation. We start implementing the constructor, destructor, and the CreateGLFWWindow function:

```cpp
CustomSurface::CustomSurface(const LLGL::Size& size, const std::string& title) :
    title_( title                ),
    size_ ( size                 ),
    wnd_  ( CreateGLFWWindow() )
{
}

CustomSurface::~CustomSurface()
{
    // Destroy GLFW window
    glfwDestroyWindow(wnd_);
}

GLFWwindow* CustomSurface::CreateGLFWWindow()
{
    // Create GLFW window with class members
    auto wnd = glfwCreateWindow(size_.x, size_.y, title_.c_str(), nullptr, nullptr);
    if (!wnd)
        throw std::runtime_error("failed to create GLFW window");
    return wnd;
}
```

Now we cross over to the major functions in the `Surface` interface. The first one is `Recreate`. It is mainly used by the OpenGL renderer when a multi-sampled render context is created on Win32. In our custom class we merely destroy the GLFW window and create a new one:

```
void CustomSurface::Recreate()
{
    // Destroy and recreate GLFW window
    glfwDestroyWindow(wnd_);
    wnd_ = CreateGLFWWindow();
}
```

Next we implement the `GetNativeHandle` function. This is also very important, because any renderer needs access to the native window handle. On MS/Windows this is from the type `HWND` from the Win32 API. On GNU/Linux we need to pass three parameters: `Display*` from the X11 lib, `::Window` from the X11 lib (unfortunately the same name but in the global scope), and `XVisualInfo*` from GLX. On MacOS it is from the type `NSWindow*` from the Cocoa API. In this example we only implement it for Win32:

```
void CustomSurface::GetNativeHandle(void* nativeHandle) const
{
    // This function must always return a valid native handle!
    auto handle = reinterpret_cast<LLGL::NativeHandle*>(nativeHandle);
    handle->window = glfwGetWin32Window(wnd_);
}
```

There are two (rather secondary) interface functions left. They are used inside the `RenderContext` class, to update or query the video mode suitable for the surface:

```
LLGL::Size CustomSurface::GetContentSize() const
{
    // Actually the client-area size of the window must be returned,
    // but for this example the entire window size is sufficient.
    return size_;
}

bool CustomSurface::AdaptForVideoMode(LLGL::VideoModeDescriptor& videoModeDesc)
{
    // Resize GLFW window for the new video mode resolution.
    size_ = videoModeDesc.resolution;
    glfwSetWindowSize(wnd_, size_.x, size_.y);
    return true;
}
```

The last function we have to implement is the additional class function `PollEvents`. Here we poll all window events from GLFW and return false when the user clicked the close button to terminate the application:

```
bool CustomSurface::PollEvents()
{
    // Poll events from GLFW windowing system
    glfwPollEvents();

    // Return true until the user pressed the close button
    return !glfwWindowShouldClose(wnd_);
}
```

Finally we are done with our custom window class :-) Now we can start using it with a render context in our main function:

```
// Initialize GLFW
if (!glfwInit())
    return -1;

// Create an instance of our custom window class
auto surface = std::make_shared<CustomSurface>(LLGL::Size(640, 480), L"LLGL test with GLFW");

// Create render context and pass the custom window
LLGL::RenderContextDescriptor contextDesc;
contextDesc.videoMode.resolution = { 640, 480 };
LLGL::RenderContext* context = renderer->CreateRenderContext(contextDesc, surface);

// Scene construction ...

while (surface->PollEvents()) { /* Rendering ... */ }
```

That's all folks. The rest can be seen in the tutorials.

8 Custom Render System

This is only a very short explanation on how to implement your own render system with LLGL, since it will take a lot of familiarization time anyways.

First of all you have to extend the `CMakeLists.txt` file in your local LLGL repository for a new library. Here is an example on how it could look for a custom OpenGL renderer:

```
# Find OpenGL headers and libraries
FIND_PACKAGE(OpenGL)

IF(OpenGL_FOUND)
    # Add OpenGL include path
    INCLUDE_DIRECTORIES(${OPENGL_INCLUDE_DIR})

    # Add "LLGL_CustomOpenGL" library project to the solution,
    # where "FilesGL" denotes the variable containing all filenames for this render system.
    # The render system can later be loaded with the name "CustomOpenGL".
    ADD_LIBRARY(LLGL_CustomOpenGL SHARED "${FilesGL}")

    # Add "D" postfix to debug mode (this is required so that LLGL loads the correct module)
    SET_TARGET_PROPERTIES(
        LLGL_CustomOpenGL PROPERTIES
        LINKER_LANGUAGE CXX # CXX is for C++
        DEBUG_POSTFIX "D" # Postfix "D" for debug mode
    )

    # Add library dependencies (On Win32 this is LLGL.lib and opengl32.lib)
    TARGET_LINK_LIBRARIES(LLGL_CustomOpenGL LLGL "${OPENGL_LIBRARIES}")

    # Tell CMake to build a project with C++11 support
    TARGET_COMPILE_FEATURES(LLGL_CustomOpenGL PRIVATE cxx_range_for)
ELSE()
    MESSAGE("Missing OpenGL -> LLGL_CustomOpenGL renderer will be excluded from project")
ENDIF()
```

After you integrated your source files into the LLGL project solution, you have to implement a few module interface functions. They are the only functions that need to be exported from the shared library, and they need to be exported as `extern "C"` functions:

```
// Include the "ModuleInterface.h" file and your custom render system
#include "sources/Renderer/ModuleInterface.h"
#include "CustomOpenGLRenderSystem.h"

// Declare the following functions to be exported as "C" functions
extern "C"
{

// This function must always return "LLGL_BUILD_ID" to ensure a library,
// which is about to be loaded, has been compiled with the same compiler toolchain.
LLGL_EXPORT int LLGL_RenderSystem_BuildID()
{
    return LLGL_BUILD_ID;
}

// Here you can return your own renderer ID or one of the pre-defined values
LLGL_EXPORT int LLGL_RenderSystem_RendererID()
{
    return LLGL::RendererID::OpenGL;
}

// Here you can return the name of your renderer
LLGL_EXPORT const char* LLGL_RenderSystem_Name()
{
    return "Custom OpenGL";
}

// Here you have to return a raw pointer of your custom implementation of the
// LLGL::RenderSystem interface, where the instance must be allocated with "new",
// so it can be moved into an std::shared_ptr.
LLGL_EXPORT void* LLGL_RenderSystem_Alloc()
{
    return new CustomOpenGLRenderSystem();
}

} // /extern "C"
```

That's all you have to do, except of implementing the entire `RenderSystem` interface in your `CustomOpenGLRenderSystem` class ;-). After that, you can load your render system like this:

```cpp
// Load custom render system (library name is "LLGL_CustomOpenGL", so the passed name is "CustomOpenGL")
std::shared_ptr<LLGL::RenderSystem> renderer = LLGL::RenderSystem::Load("CustomOpenGL");

// Start using the custom renderer ...
```