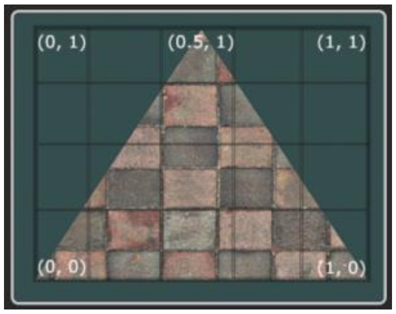
TEXTURES



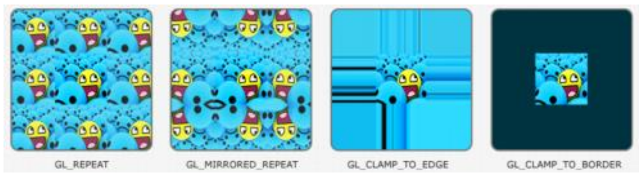
A texture is a 2D image (usually) that is used to add detail to an object.
To map a texture to an object, each vertex must have a texture coordinate associated with it that specifies what part of the texture image to sample from.

- Fragment interpolation handles the in-between of the texture coordinates for the other fragments.

Texture coordinates range from 0 to 1 in the x and y axis, from bottom-left to top-right.
Retrieving the texture color using texture coordinates is called sampling.

- Texture sampling has a loose interpretation and can be done in many different ways, so it is our job to tell OpenGL how it should sample its textures.

Texture Wrapping



By default, if you specify texture coordinates outside of the range of (0, 0) to (1, 1), the texture will be repeated.
You can also tell OpenGL specifically how to interpret texture coordinates outside this range:

- **GL_REPEAT:** The default wrapping for textures. Repeats the texture image.
- **GL_MIRRORED_REPEAT:** Same as GL_REPEAT, but mirrors the texture image with each repeat.
- **GL_CLAMP_TO_EDGE:** Clamps the coordinates between 0 and 1. The result is that higher coordinates become clamped to the edge, resulting in a stretched edge pattern.
- **GL_CLAMP_TO_BORDER:** Coordinates outside the range are now given a user-specified border color.

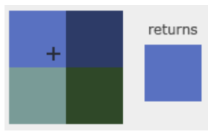
These options can be set per coordinate axis(s, t (and r if using 3D textures) equivalent to x, y, z).

Configure the texture coordinates of the brick texture to a triangle and set the wrapping type to mirrored. Also, set up code for clamping to the borders.

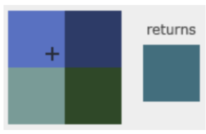
- Brick Wall Texture
- Configuring Texture Coordinates and Wrapping

Texture Filtering

Nearest



Linear



Texture coordinates do not depend on resolution but can be any floating point value. Because of this, OpenGL has to figure out which texture pixel, or texel, to map the coordinate to. This is known as texture filtering.

- This becomes especially important when mapping a low-resolution texture to a large object.

There are two common ways to approach this problem in OpenGL (though there are others):

- **GL_NEAREST:** The default filtering for textures. The texel that's center is closest to the texture coordinate is the sampled color for the fragment.
  - Also known as **Nearest Neighbor** or **Point** filtering.
  - Causes the texture to look pixelated.
- **GL_LINEAR:** The sampled color for the fragment is interpolated from the texture coordinate's neighboring texels, approximating a color between the texels.
  - Also known as **Linear** filtering.
  - Causes the texture to look blurry.

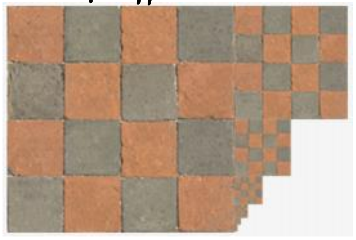
Texture filtering can be set for **magnifying** and **minifying** operations (when scaling up or down) so you could, for example, use nearest neighbor filtering when textures are scaled down and linear filtering for upscaled textures.

Configure the texture filtering technique for the minifying operation to be nearest neighbor filtering and the magnifying operation to be linear filtering.

- Configuring Minifying and Magnifying Operations

Mipmaps

Mipmapped Texture



A mipmap is a collection of texture images where each subsequent texture is a fourth the size compared to the previous one.
After a certain distance from the camera has been reached, OpenGL will use a different mipmap texture that best suits the distance to the object.

- Makes texel sampling easier and more accurate, reducing the cache memory required for sampling.

When switching between mipmap levels during rendering, OpenGL may show some artifacts, like sharp edges visible between the two mipmap layers.

- It is possible to filter between mipmap levels using `NEAREST` and `LINEAR` filtering (just like with normal texture filtering) for switching between mipmap levels.
- To do so, we can replace the original filtering methods with one of the following:
  - **GL_NEAREST_MIPMAP_NEAREST:** Takes the nearest mipmap to match the pixel size and uses nearest neighbor interpolation for texture sampling.
  - **GL_LINEAR_MIPMAP_NEAREST:** Takes the nearest mipmap to match the level and samples that level using linear interpolation.
  - **GL_NEAREST_MIPMAP_LINEAR:** Linearly interpolates between the two mipmaps that most closely match the size of a pixel and samples the interpolated level via nearest neighbor interpolation.
  - **GL_LINEAR_MIPMAP_LINEAR:** Linearly interpolates between the two closest mipmaps and samples the interpolated level via linear interpolation.

NOTE: Mipmap filtering options do not typically get set for magnifying operations because mipmaps are primarily used for when textures get downscaled.

Change the minifying operation to linearly interpolate between mipmaps and sample the interpolated level using nearest neighbor interpolation. Also, change the magnifying operation to use linear filtering for textures.

- Configuring Mipmaps

Loading and Creating Textures

In order to use textures in an application, their data needs to be loaded, depending on their file type (.png, .jpg, .gif, etc.), using an image loader.
Rather than creating our own image loader for each different type of image we want to load, we can use an image-loading library that supports multiple popular formats.

std_image.h

stb_image.h is a very popular, single-header image-loading library that is able to load most popular file formats and is easy to intergrate into a project.

- STB Image Header Repository
- Setting Up stb_image

For the following texture sections, use this texture:

- Wooden Container Texture

Add texture coordinates as a vertex attribute. Load the wooden container texture image using stb_image.h, then generate and configure the texture object.

- Loading and Configuring a Texture

Texture Units

We can set multiple textures at once in a fragment shader by assigning a location value to the sampler. This location of a texture is commonly known as a texture unit.

Texture units allow us to use more than one texture in our shaders.

- By assigning texture units to the samplers, we can bind to multiple textures at once as long as we activate the corresponding texture unit first.
- OpenGL should have at least 16 texture units for you to use. You can also, for example, select the 9th texture unit like this: `GL_TEXTURE0 + 8` (useful for iteration)

Assign the container texture to the 0th texture unit and the smiley texture to the 1st texture unit. Display a 50/50 mix of the textures on the object.

- Smiley Texture
- **NOTE:** Images usually have (0, 0) at the top-left of the image, but OpenGL expects (0, 0) at the bottom-left. Don't forget to flip the image right-side up!
- Using Texture Units

EXERCISES

1. Make sure **only** the happy face looks in the other/reverse direction by changing the fragment shader.
2. Experiment with the different texture wrapping methods by specifying texture coordinates in the range of `0.0f` to `2.0f` instead of `0.0f` to `1.0f`. See if you can display 4 smiley faces on a single container image clamped at its edge. Also, see if you can experiment with other wrapping methods as well.
3. Try to display only the center pixels of the texture image on the rectangle in such a way that the individual pixels are getting visible by changing the texture coordinates. Try to set the texture filtering method to `GL_NEAREST` to see the pixels more clearly.
4. Use a uniform variable as a mix function's third parameter to vary the amount the two textures are visible. Use the up and down arrow keys to change how much the container or the brick wall is visible.

Configuring Texture Coordinates and Wrapping

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```
// Texture coordinates from triangle
float texCoords[] = {
    0.5f, 1.0f,      // top-center
    0.0f, 0.0f,      // bottom-left
    1.0f, 0.0f       // bottom-right
};
```

```
// Sets the wrapping type on the s and t (x and y) axes for mirrored repeating
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_MIRRORED_REPEAT);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_MIRRORED_REPEAT);
```

```
// Sets the wrapping type on the s and t axes for clamping to the border
float borderColor[] = { 1.0f, 1.0f, 0.0f, 1.0f };
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_BORDER);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_CLAMP_TO_BORDER);
glTexParameterfv(GL_TEXTURE_2D, GL_TEXTURE_BORDER_COLOR, borderColor);
```

Configuring Minifying and Magnifying Operations

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```
// Sets the minifying operation to use nearest neighbor filtering and the magnifying operation to use linear filtering
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_NEAREST);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);
```

Configuring Mipmaps

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```
// Sets the minifying filter to use linear filtering for mipmaps and textures
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR_MIPMAP_LINEAR);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);
```

Setting Up stb_image

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stb_image.h enables use of certain functions depending on what macros you define.\
In order to use the functions we want, we must define the following macro at the top of our main.cpp:

```
#define STB_IMAGE_IMPLEMENTATION
```

NOTE: This must be done before including stb_image.h, otherwise the header file is loaded without considering the macro we defined.

Loading and Configuring a Texture

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Fragment Shader

```
#version 330 core

out vec4 FragColor;
in vec4 vertexColor;
in vec2 texCoord;

uniform sampler2D texture1;

void main() {
   FragColor = texture(texture1, texCoord);
}
```

Vertex Shader

```
#version 330 core

layout (location = 0) in vec3 aPos;
layout (location = 1) in vec4 aColor;
layout (location = 2) in vec2 aTexCoord;

out vec4 vertexColor;
out vec2 texCoord;

void main() {
   gl_Position = vec4(aPos, 1.0);
   vertexColor = aColor;
   texCoord = aTexCoord;
}
```

main.cpp

```
// Generates and binds a texture object
unsigned int texture;
glGenTextures(1, &texture);
glBindTexture(GL_TEXTURE_2D, texture);

// Loads the textured data and configures it to a texture object with automatically generated mipmaps
int width, height, numChannels;
unsigned char* data = stbi_load("Textures/container.jpg", &width, &height, &numChannels, 0);
if (data) {
    glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB, width, height, 0, GL_RGB, GL_UNSIGNED_BYTE, data);
    glGenerateMipmap(GL_TEXTURE_2D);
}
else {
    std::cout << "Failed to load texture" << std::endl;
}
// Frees the image data memory and unbinds the texture object
stbi_image_free(data);
glBindTexture(GL_TEXTURE_2D, 0);
```

Don't forget to bind the texture in the render loop!

Using Texture Units

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Fragment Shader

```
#version 330 core

out vec4 FragColor;
in vec4 vertexColor;
in vec2 texCoord;

uniform sampler2D texture1;
uniform sampler2D texture2;

void main() {
   FragColor = mix(texture(texture1, texCoord), texture(texture2, texCoord), 0.5);
}
```

main.cpp

```
// Generates and binds a texture object to the 0th texture unit
unsigned int texture1;
glGenTextures(1, &texture1);
glActiveTexture(GL_TEXTURE0); // This is technically redundant because texture unit 0 is active by default.
glBindTexture(GL_TEXTURE_2D, texture1);

// Loads the textured data and configures it to a texture object with automatically generated mipmaps
int width, height, numChannels;
stbi_set_flip_vertically_on_load(true); // Flips images to be right-side up, due to different orientation standards
unsigned char* data = stbi_load("Textures/container.jpg", &width, &height, &numChannels, 0);
if (data) {
   glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB, width, height, 0, GL_RGB, GL_UNSIGNED_BYTE, data);
   glGenerateMipmap(GL_TEXTURE_2D);
}
else {
   std::cout << "Failed to load texture1" << std::endl;
}
glBindTexture(GL_TEXTURE_2D, 0);

// Generates and binds a texture object to the 1st texture unit
unsigned int texture2;
glGenTextures(1, &texture2);
glActiveTexture(GL_TEXTURE1);
glBindTexture(GL_TEXTURE_2D, texture2);
data = stbi_load("Textures/brick_wall.jpg", &width, &height, &numChannels, 0);
if (data) {
   glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB, width, height, 0, GL_RGB, GL_UNSIGNED_BYTE, data);
   glGenerateMipmap(GL_TEXTURE_2D);
}
else {
   std::cout << "Failed to load texture2" << std::endl;
}
// Frees the image data memory and unbinds the texture object
stbi_image_free(data);
glBindTexture(GL_TEXTURE_2D, 0);

// Tells OpenGL to use the shaders in the shader program for rendering
shaderProgram.use();

// Sets the texture uniforms
glUniform1i(glGetUniformLocation(shaderProgram.id, "texture1"), 0); // Set it manually
shaderProgram.setInt("texture2", 1); // Set it using our shader class
```

Render Loop

```
// Binds the textures to render
glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, texture1);
glActiveTexture(GL_TEXTURE1);
```

```
glBindTexture(GL_TEXTURE_2D, texture2);

// Binds the object we want to render
glBindVertexArray(vao);

// Renders the rectangle to the screen
glDrawElements(GL_TRIANGLES, 6, GL_UNSIGNED_INT, 0);

// Unbinds the vao
glBindVertexArray(0);

// Unbinds the textures
glActiveTexture(GL_TEXTURE0);
glBindTexture(GL_TEXTURE_2D, 0);
glActiveTexture(GL_TEXTURE1);
glBindTexture(GL_TEXTURE_2D, 0);
```