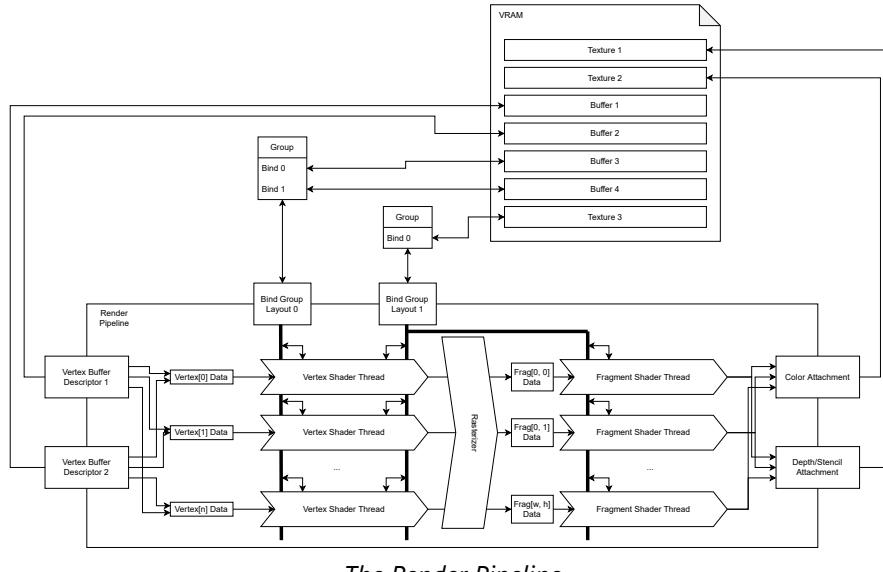


# Lab 3

## Render Pipeline

### The Render Pipeline



### Vertex Buffers

- Data attached to **each Vertex**
- Vertex Shader Thread can only access **one** Vertex's Data
- Examples:
  - position
  - normal
  - color
  - texture coordinates
  - ...
- Can be indexed by an Index Buffer

```

vertex_data = np.array(
    [
        #   x,      y,      z,      xn,     yn,     zn,      u,      v
        [ 0.5,  0.5,  0.5,  0.0,  0.0,  1.0,  0.0,  0.0],
        [-0.5,  0.5,  0.5,  0.0,  0.0,  1.0,  0.0,  1.0],
        [-0.5, -0.5,  0.5,  0.0,  0.0,  1.0,  1.0,  1.0],
        [ 0.5, -0.5,  0.5,  0.0,  0.0,  1.0,  1.0,  0.0],
        [ 0.5,  0.5,  0.5,  1.0,  0.0,  0.0,  0.0,  0.0],
        [ 0.5, -0.5,  0.5,  1.0,  0.0,  0.0,  0.0,  1.0],
        [ 0.5, -0.5, -0.5,  1.0,  0.0,  0.0,  1.0,  1.0],
        [ 0.5,  0.5, -0.5,  1.0,  0.0,  0.0,  1.0,  0.0],
        [ 0.5,  0.5, -0.5,  0.0,  0.0, -1.0,  0.0,  0.0],
        [ 0.5, -0.5, -0.5,  0.0,  0.0, -1.0,  0.0,  1.0],
        [-0.5, -0.5, -0.5,  0.0,  0.0, -1.0,  1.0,  1.0],
        [-0.5,  0.5, -0.5,  0.0,  0.0, -1.0,  1.0,  0.0],
        [-0.5,  0.5,  0.5, -1.0,  0.0,  0.0,  0.0,  0.0],
        [-0.5,  0.5, -0.5, -1.0,  0.0,  0.0,  0.0,  1.0],
        [-0.5, -0.5, -0.5, -1.0,  0.0,  0.0,  1.0,  1.0],
        [-0.5, -0.5,  0.5, -1.0,  0.0,  0.0,  1.0,  0.0],
        [ 0.5,  0.5,  0.5,  0.0,  1.0,  0.0,  0.0,  0.0],
        [ 0.5,  0.5, -0.5,  0.0,  1.0,  0.0,  0.0,  1.0],
        [-0.5,  0.5, -0.5,  0.0,  1.0,  0.0,  1.0,  1.0],
        [-0.5,  0.5,  0.5,  0.0,  1.0,  0.0,  1.0,  0.0],
        [ 0.5, -0.5,  0.5,  0.0, -1.0,  0.0,  0.0,  0.0],
        [-0.5, -0.5,  0.5,  0.0, -1.0,  0.0,  0.0,  1.0],
        [-0.5, -0.5, -0.5,  0.0, -1.0,  0.0,  1.0,  1.0],
        [ 0.5, -0.5, -0.5,  0.0, -1.0,  0.0,  1.0,  0.0],
    ],
    dtype=np.float32,
)

```

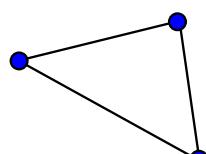
```

index_data = np.array(
    [
        0,  1,  2,  0,  2,  3,
        4,  5,  6,  4,  6,  7,
        8,  9,  10, 8,  10, 11,
        12, 13, 14, 12, 14, 15,
        16, 17, 18, 16, 18, 19,
        20, 21, 22, 20, 22, 23,
    ],
    dtype=np.uint32,
)

```

## Vertex Shader

- One thread per Vertex



*Vertices*

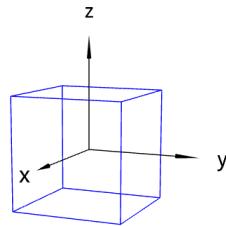
- Must produce:
  - Vertex position in **Clip Space**
  - Any data needed for the Fragment Shader

## Espaces

- Vertex positions go through multiple **transformations**:
  - Object Space
  - World Space
  - Camera Space
  - Clipping Space

## Espace Object

- Axes attached to the object



## Projective Geometry

- Transition to projective geometry

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} k \cdot x \\ k \cdot y \\ k \cdot z \\ k \end{pmatrix}$$

For all  $k$ . We often choose  $k = 1$

## World Space

- Transition from object space to world space

$$\begin{pmatrix} x_w \\ y_w \\ z_w \\ t_w \end{pmatrix} = \text{ModelMatrix} \cdot \begin{pmatrix} x_o \\ y_o \\ z_o \\ t_o \end{pmatrix}$$

- This matrix is a combination of translation, rotation and scaling.

## Camera Space

- Transition from world space to camera space

$$\begin{pmatrix} x_{\text{cam}} \\ y_{\text{cam}} \\ z_{\text{cam}} \\ t_{\text{cam}} \end{pmatrix} = \text{ViewMatrix} \cdot \begin{pmatrix} x_w \\ y_w \\ z_w \\ t_w \end{pmatrix}$$

- This matrix is a combination of translation and rotation. We sometimes combine the ModelMatrix and the ViewMatrix matrices.

$$\text{ModelViewMatrix} = \text{ViewMatrix} \cdot \text{ModelMatrix}$$

## View Matrix

```
def look_at(
    eye: ArrayLike, target: ArrayLike, up: ArrayLike
) → NDArray:
    """
    Convert world coordinates to camera coordinates where the
    point in the direction of -z axis.
    """
    eye = np.array(eye, dtype=np.float32)
    target = np.array(target, dtype=np.float32)
    up = np.array(up, dtype=np.float32)
    f = target - eye
    f = f / np.linalg.norm(f)
    s = np.cross(f, up)
    s = s / np.linalg.norm(s)
    u = np.cross(s, f)

    return np.array([[s[0], s[1], s[2], -eye @ s],
                    [u[0], u[1], u[2], -eye @ u],
                    [-f[0], -f[1], -f[2], eye @ f],
                    [0, 0, 0, 1]], dtype=np.float32)
```

## Clip Space

- Projection of the vertices by the camera.

$$\begin{pmatrix} x_{\text{clip}} \\ y_{\text{clip}} \\ z_{\text{clip}} \\ t_{\text{clip}} \end{pmatrix} = \text{ProjectionMatrix} \cdot \begin{pmatrix} x_{\text{cam}} \\ y_{\text{cam}} \\ z_{\text{cam}} \\ t_{\text{cam}} \end{pmatrix}$$

- Vertices outside the interval  $([-t, t], [-t, t], [0, t], t)$  are **clipped**.

## Projection Matrix

```
def perspective(
    fovy_deg: float, aspect: float, near: float, far: float)
) -> NDArray:
    """
    Convert camera coordinates to wgpu clip coordinates where,
    from -1.0 to 1.0 and z goes from 0.0 to 1.0.
    """

    angle = fovy_deg * np.pi / 180

    yspan = near * np.tan(angle)
    xspan = yspan * aspect

    c0r0 = 2 * near / xspan
    c1r1 = 2 * near / yspan
    c2r2 = -(far + near) / (far - near) / 2 - 0.5
    c3r2 = -far * near / (far - near)

    return np.array([[c0r0,      0,      0,      0],
                   [      0, c1r1,      0,      0],
                   [      0,      0, c2r2, c3r2],
                   [      0,      0,     -1,      0]], dtype=np.float)
```

## Normalized Device Coordinates (NDC)

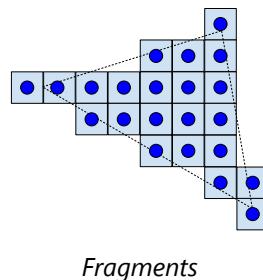
- We leave the projective geometry
- Not in Vertex Shader
- Called **perspective division**

$$\begin{pmatrix} x_{\text{ndc}} \\ y_{\text{ndc}} \\ z_{\text{ndc}} \end{pmatrix} = \begin{pmatrix} \frac{x_{\text{clip}}}{t_{\text{clip}}} \\ \frac{y_{\text{clip}}}{t_{\text{clip}}} \\ \frac{z_{\text{clip}}}{t_{\text{clip}}} \end{pmatrix}$$

## Rasterizer

- Get data from the Vertex Stage

- Compose Primitives  
Triangles, Lines, Points, ...
- Divide primitives into Fragments (*pixels*)



- Interpolate data from the Vertex Stage across primitives

## Fragment Shader

- One thread per Fragment
- Compute the color of the fragment

The Shading

## Depth Texture / z-buffer

- Store  $z_{clip}$  for each pixel
- Enables **hidden surface removal**  
avoid rendering a fragment that is behind the current rendered fragment at that pixel
- Required for **3D rendering pipelines**  
We cannot always render from back to front
- Can be sampled in shaders for post-processing effects

## The Window

Terminal

```
> pip install rendercanvas glfw
```

```

from rendercanvas.auto import RenderCanvas, loop
import wgpu

adapter = wgpu.gpu.request_adapter_sync(power_preference="high")
device = adapter.request_device_sync()

canvas = RenderCanvas(
    size=(640, 480), title="WebGPU Example",
    update_mode="continuous", max_fps=60,
)
context = canvas.get_wgpu_context()
render_texture_format = context.get_preferred_format(device.adapter)
context.configure(device=device, format=render_texture_format)

@canvas.request_draw
def draw_frame():
    screen_texture = context.get_current_texture()
    # render in the screen_texture

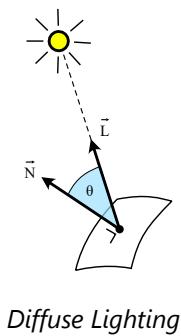
loop.run()

```

## Shading

- Diffuse lighting
  - The most basic lighting model

The diffuse lighting corresponds to the light reflected in all directions by the illuminated surface. It does not depend on the point of view.



- $N$  is the normal vector to the surface.
- $L$  is the vector directed towards the light.

These two vectors are normalized.

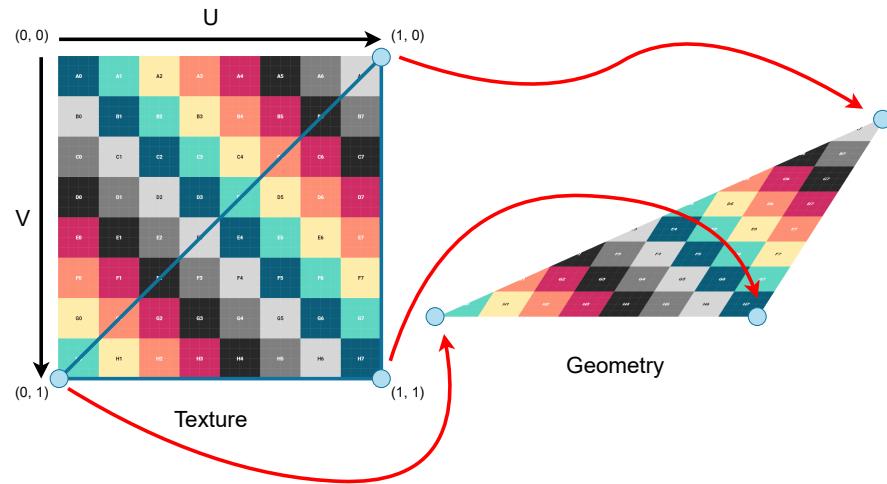
The diffuse intensity reflected  $I_d$  is calculated by

$$I_d = (L \cdot N)C_d$$

where  $C_d$  is the diffuse color (i.e. the color of the object).

Colors are  $(r, g, b)$  vectors.

## Texture Coordinates



## Cube

```
from rendercanvas.auto import RenderCanvas, loop
import wgpu
import numpy as np
import PIL.Image as Image
from primitives import cube
from camera import Camera

class App:
    def __init__(self):
        adapter = wgpu.gpu.request_adapter_sync(power_preference='high-performance')
        self.device = adapter.request_device_sync()

        self.size = (0, 0)

        self.canvas = RenderCanvas(
            size=(640, 480),
            title="WebGPU Example",
            update_mode="continuous",
            max_fps=60,
        )
        self.context = self.canvas.get_wgpu_context()

        render_texture_format = self.context.get_preferred_format()
        self.context.configure(device=self.device, format=render_texture_format)

        vertex_data, index_data = cube()

        self.vertex_buffer = self.device.create_buffer_with_data(
            data=vertex_data, usage=wgpu.BufferUsage.VERTEX
        )

        self.index_buffer = self.device.create_buffer_with_data(
            data=index_data, usage=wgpu.BufferUsage.INDEX
        )

        bg_layout = self.device.create_bind_group_layout(
            entries=[
                {
                    "binding": 0,
                    "visibility": wgpu.ShaderStage.VERTEX | wgpu.ShaderStage.FRAGMENT,
                    "buffer": {"type": wgpu.BufferBindingType.ARRAY_BUFFER}
                },
                {
                    "binding": 1,
                    "visibility": wgpu.ShaderStage.FRAGMENT,
                    "texture": {}
                },
                {
                    "binding": 2,
                    "visibility": wgpu.ShaderStage.FRAGMENT,
                    "sampler": {}
                }
            ]
        )

        p_layout = self.device.create_pipeline_layout(bind_group_layouts=[bg_layout])

        self.render_params_buffer = self.device.create_buffer(
            size=4 * 4 + 2 * 4 * 4 * 4,
            usage=wgpu.BufferUsage.UNIFORM | wgpu.BufferUsage.COPY_DST
        )

        img = Image.open("./texel_checker.png")
        texture_size = img.size + (1,)
```

```
texture = self.device.create_texture(
    size=texture_size,
    format=wgpu.TextureFormat.rgb8unorm_srgb,
    usage=wgpu.TextureUsage.TEXTURE_BINDING | wgpu.TextureUsage.RENDER_ATTACHMENT)
self.device.queue.write_texture(
    destination={
        "texture": texture,
    },
    data=np.asarray(img),
    data_layout={
        "bytes_per_row": img.size[0] * 4,
    },
    size=texture_size,
)
sampler = self.device.create_sampler()

self.render_params_bind_group = self.device.create_bind_group(
    layout=bg_layout,
    entries=[
        {
            "binding": 0,
            "resource": {
                "buffer": self.render_params_buffer,
                "offset": 0,
                "size": self.render_params_buffer.size
            },
        },
        {
            "binding": 1,
            "resource": texture.create_view(),
        },
        {
            "binding": 2,
            "resource": sampler,
        },
    ],
)
self.canvas.add_event_handler(
    self.process_event, "pointer_up", "pointer_down", "pointer_cancel"
) # type: ignore

self.camera = Camera(45, 640 / 480, 0.1, 100, 3, np.pi)

vertex_buffer_descriptor = {
    "array_stride": 8 * 4,
    "step_mode": wgpu.VertexStepMode.vertex,
    "attributes": [
        {
            "format": wgpu.VertexFormat.float32x3,
            "offset": 0,
            "shader_location": 0,
        },
        {
            "format": wgpu.VertexFormat.float32x3,
            "offset": 3 * 4,
            "shader_location": 1,
        },
        {
            "format": wgpu.VertexFormat.float32x2,
            "offset": 6 * 4,
            "shader_location": 2,
        },
    ],
},
```

```
}

with open("./render.wgsl") as file:
    shader_module = self.device.create_shader_module(file.read())

self.pipeline = self.device.create_render_pipeline(
    layout=p_layout,
    vertex={
        "module": shader_module,
        "entry_point": "vs_main",
        "buffers": [vertex_buffer_descriptor],
    },
    primitive={
        "topology": wgpu.PrimitiveTopology.triangle_list,
        "front_face": wgpu.FrontFace.ccw,
        "cull_mode": wgpu.CullMode.back,
    },
    depth_stencil={
        "format": wgpu.TextureFormat.depth32float,
        "depth_write_enabled": True,
        "depth_compare": wgpu.CompareFunction.less,
    },
    multisample=None,
    fragment={
        "module": shader_module,
        "entry_point": "fs_main",
        "targets": [
            {
                "format": render_texture_format,
                "blend": {
                    "color": {},
                    "alpha": {},
                },
            },
        ],
    },
)
)

def process_event(self, event):
    self.camera.process_event(event)

def loop(self):
    screen_texture: wgpu.GPUTexture = self.context.get_current_texture()
    size = screen_texture.size
    if size[:2] != self.size:
        self.depth_texture = self.device.create_texture(
            size=size,
            format=wgpu.TextureFormat.depth32float,
            usage=wgpu.TextureUsage.RENDER_ATTACHMENT
            | wgpu.TextureUsage.TEXTURE_BINDING,
        )
        self.size = size[:2]
        self.camera.aspect = size[0] / size[1]

    # light_position must be vec4 for memory alignment
    light_position = np.array([-10, 10, 10, 0], dtype=np.float32)

    proj_matrix, view_matrix = self.camera.get_matrices()

    render_params_data = light_position.tobytes()
    # Must send transpose version of matrices, because GPU
    # in column major order
    render_params_data += view_matrix.T.tobytes()
    render_params_data += proj_matrix.T.tobytes()
```

```
        self.device.queue.write_buffer(
            buffer=self.render_params_buffer, data=render_params)
    )

    command_encoder = self.device.create_command_encoder()

    render_pass = command_encoder.begin_render_pass(
        color_attachments=[
            {
                "view": screen_texture.create_view(),
                "resolve_target": None,
                "clear_value": (0.9, 0.9, 0.9, 1.0),
                "load_op": wgpu.LoadOp.clear,
                "store_op": wgpu.StoreOp.store,
            }
        ],
        depth_stencil_attachment={
            "view": self.depth_texture.create_view(),
            "depth_clear_value": 1.0,
            "depth_load_op": wgpu.LoadOp.clear,
            "depth_store_op": wgpu.StoreOp.store,
        },
    )

    render_pass.set_pipeline(self.pipeline)
    render_pass.set_vertex_buffer(0, self.vertex_buffer)
    render_pass.set_index_buffer(self.index_buffer, wgpu.IndexFormat.uint16)
    render_pass.set_bind_group(0, self.render_params_bind_group)
    render_pass.draw_indexed(36)
    render_pass.end()

    self.device.queue.submit([command_encoder.finish()])

def run(self):
    self.canvas.request_draw(self.loop)
    loop.run()

App().run()
```

## Shader

```
struct RenderParams {
    light: vec4<f32>,
    view: mat4x4<f32>,
    proj: mat4x4<f32>;
};

@group(0) @binding(0) var<uniform> params: RenderParams;
@group(0) @binding(1) var texture: texture_2d<f32>;
@group(0) @binding(2) var samplr: sampler;

struct VertexInput {
    @location(0) position: vec3<f32>,
    @location(1) normal: vec3<f32>,
    @location(2) uv: vec2<f32>;
};

struct VertexOutput {
    @builtin(position) clip: vec4<f32>,
    @location(0) position: vec3<f32>,
    @location(1) normal: vec3<f32>,
    @location(2) uv: vec2<f32>;
};

@vertex
fn vs_main(in: VertexInput) → VertexOutput {
    var out: VertexOutput;
    out.clip = params.proj * params.view * vec4<f32>(in.position);
    out.position = in.position;
    out.normal = in.normal;
    out.uv = in.uv;
    return out;
}

@fragment
fn fs_main(in: VertexOutput) → @location(0) vec4<f32> {
    let light_dir = normalize(params.light.xyz - in.position);
    let shading = clamp(dot(light_dir, normalize(in.normal)), 0.0, 1.0);
    let color = textureSample(texture, samplr, in.uv);
    return vec4<f32>(color.xyz * shading, 1.0);
}
```

## camera.py

```
import numpy as np
from numpy.typing import NDArray, ArrayLike
from cgmath import look_at, perspective

class Camera:
    def __init__(
        self,
        fovy_deg: float,
        aspect: float,
        near: float,
        far: float,
        radius: float,
        longitude: float,
        latitude: float,
        target: ArrayLike = [0.0, 0.0, 0.0],
        up: ArrayLike = [0.0, 1.0, 0.0],
    ):
        self.pointer_down = False
        self.last_pointer_pos = np.array([0.0, 0.0])
        self.fovy_deg = fovy_deg
        self.aspect = aspect
        self.near = near
        self.far = far
        self.radius = radius
        self.longitude = longitude
        self.latitude = latitude
        self.target = np.array(target)
        self.up = np.array(up)

    def get_matrices(self) → tuple[NDArray, NDArray]:
        camera_position = np.array([
            [
                np.cos(self.latitude) * np.cos(self.longitude),
                np.sin(self.latitude),
                np.cos(self.latitude) * np.sin(self.longitude)
            ]
        ])
        camera_position = self.target + camera_position * self

        view_matrix = look_at(camera_position, self.target, self.up)
        proj_matrix = perspective(self.fovy_deg, self.aspect, self.near, self.far)

        return proj_matrix, view_matrix

    def process_event(self, event):
        if event["event_type"] == "pointer_down":
            self.pointer_down = True
        elif event["event_type"] == "pointer_up":
            self.pointer_down = False
        elif event["event_type"] == "pointer_move":
            pointer_pos = np.array([event["x"], event["y"]])
            delta = pointer_pos - self.last_pointer_pos
            self.last_pointer_pos = pointer_pos
            if self.pointer_down:
                self.longitude = (self.longitude + delta[0] * 0.01) % (np.pi * 2)
                self.latitude = np.clip(
                    self.latitude + delta[1] * 0.01, -np.pi / 2, np.pi / 2
                )
        elif event["event_type"] == "wheel":
            self.radius = max(0.1, self.radius + event["dy"] * 0.01)
```

## Exercices

- [Exercices](#)
- [The texture `texel\_checker.png`](#)
- [Memory Alignment Calculator](#)