Grafika Komputerowa. Podstawy oświetlenia w OpenGL

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Najnowsza wersja tego dokumentu dostępna jest pod adresem

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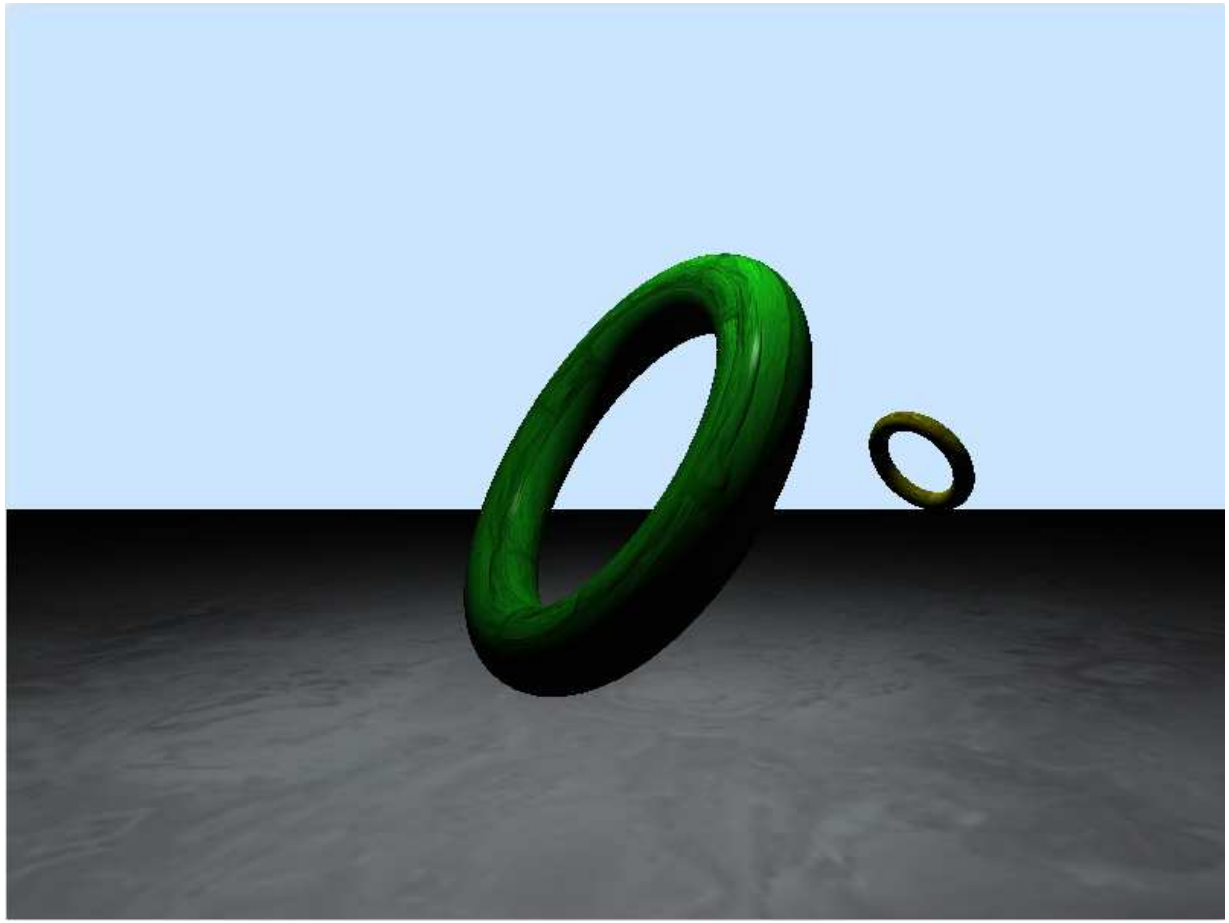
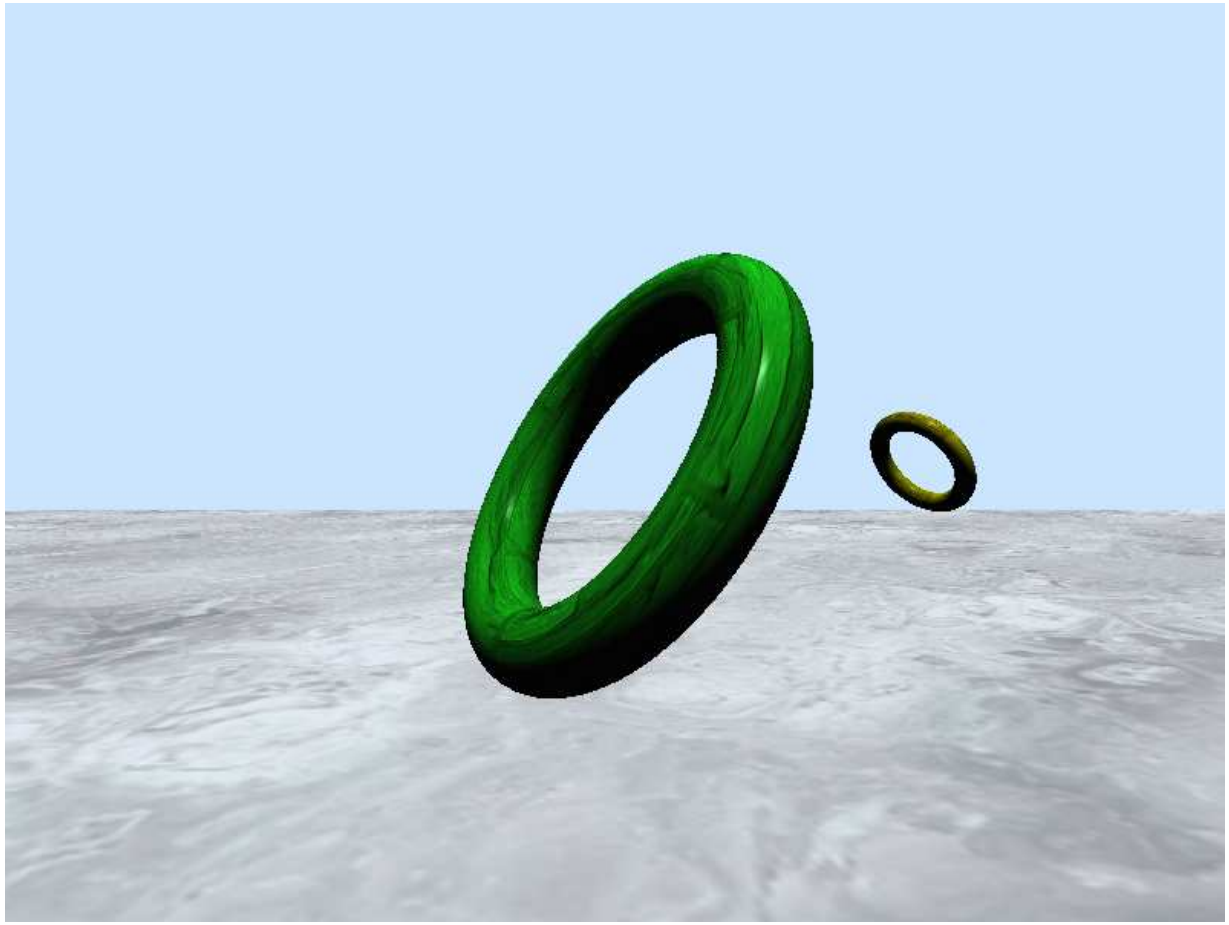
Trzy rodzaje światła

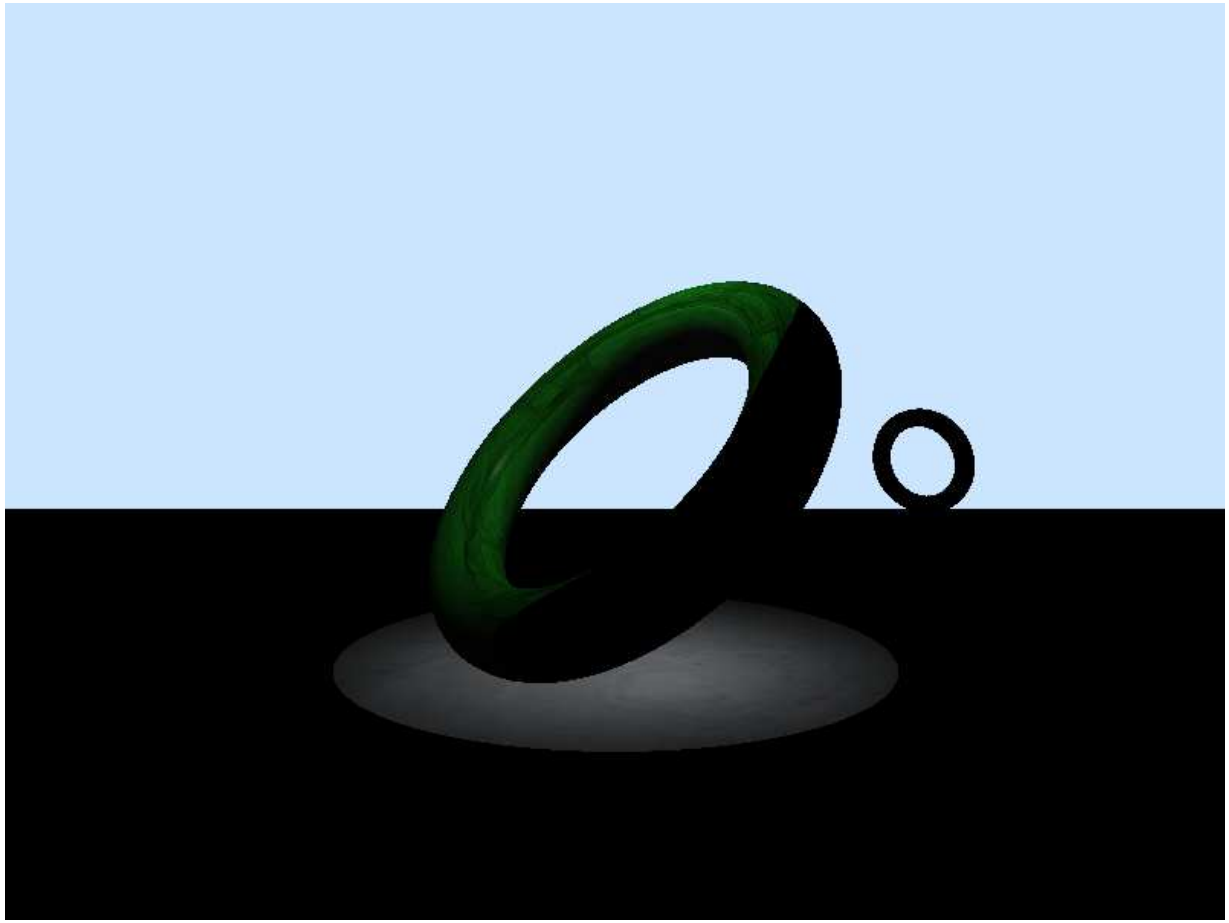
Światło punktowe z tłumieniem



Światło kierunkowe



Światło spot



Światło punktowe

- $I = I_s + I_d + I_a + I_e$
  - $I_d = \rho_d I_d^{In} \cos\theta$
  - $I_s = \rho_s I_s^{In} (\cos\varphi)^f$
  - $I_a = \rho_a I_a^{In}$
  - $I_e = \mathrm{Const}$
- Tłumienie światła
  - współczynnik tłumienia

$$a = \frac{1}{a_0 + a_1 d + a_2 d^2},$$

  - gdzie d jest odległością od źródła świata

Światło kierunkowe (Sun)

- jak światło punktowe
- żródło świata umieszczone jest w nieskończoności
- $(x_0, y_0, z_0, 0)$

Światło spot

- jak światło punktowe
- kierunek
- kąt obcinania (cutoff), ψ_0
- wskaźnik tłumienia, p
- $$I = \begin{cases} I_0(\cos\psi)^p, & \text{jeżeli } \psi < \psi_0 \\ 0 \end{cases}$$
  - Uwaga: $\psi < \psi_0 \iff \cos\psi > \cos\psi_0$
  - Do shadera przekażemy cosinus (czemu?)

Cieniowanie Phonga

- Oblicza się wektor normalny w wierzchołkach.
- Wektor normalny interpoluje się na całą powierzchnię wieloboku.
- Na tej podstawie oblicza się kolor w każdym pikselu

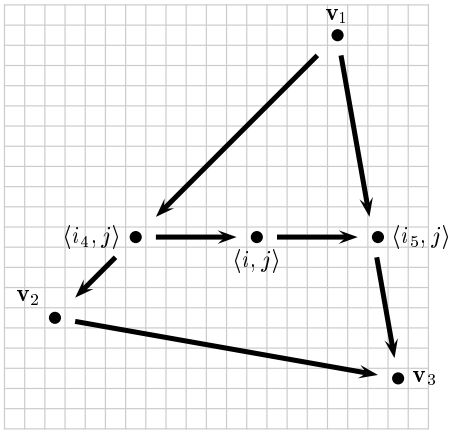
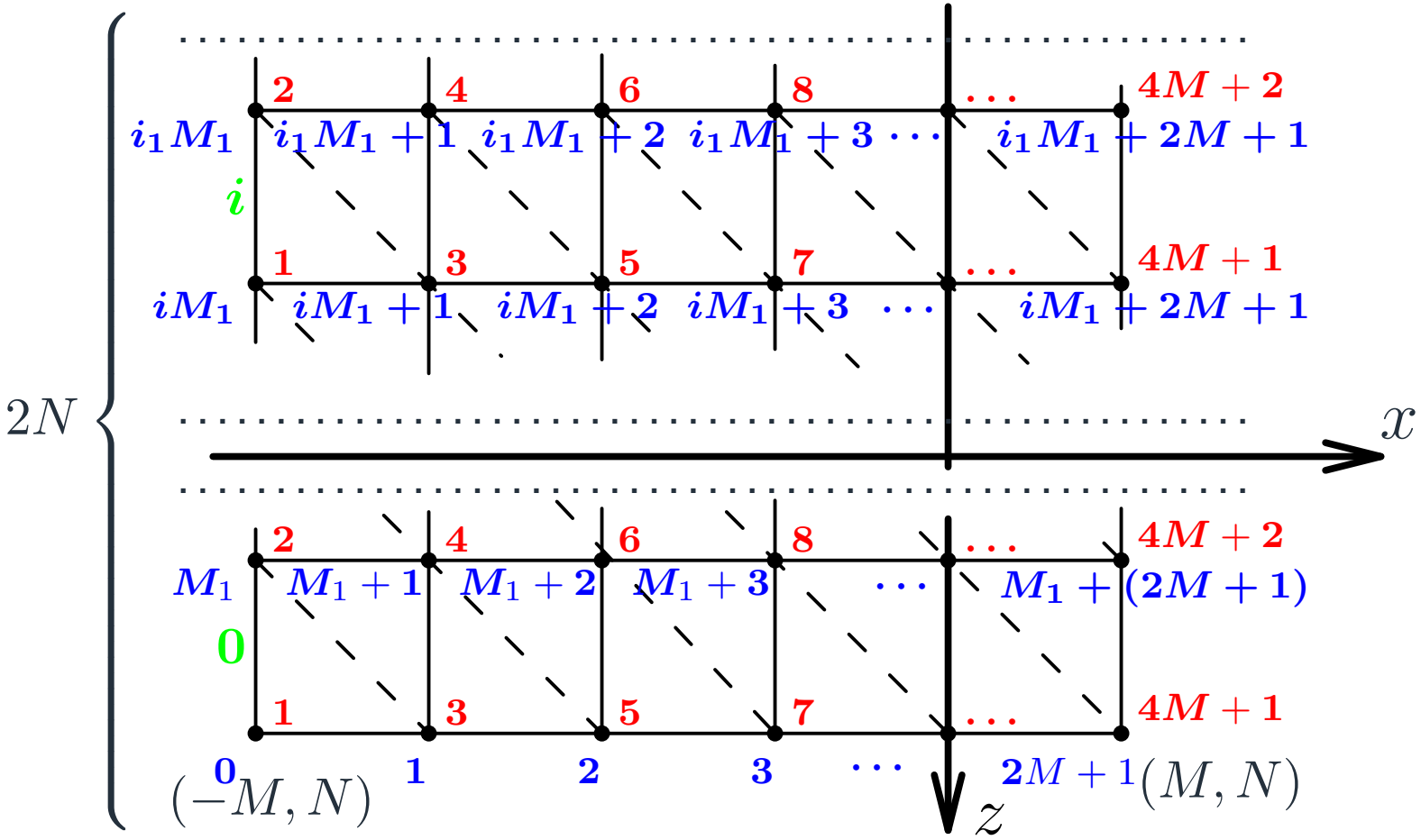


Figure II.25: The scan line interpolation method first interpolates along the edges of the triangle, then interpolates along the horizontal rows of pixels in the interior of the triangle. The interpolation directions are shown with arrows. If you look closely, you will note that the rightmost pixel, $\langle i_5, j\rangle$, on the horizontal scan line is not exactly on the line segment forming the right edge of the triangle — this is necessary since its position must be rounded to the nearest pixel.



- wierzchołki, $M_1 = 2M + 2$, $i_1 = i + 1$
- indeksy
- paski (`GL_TRIANGLE_STRIP`)

Zmiana wektora normalnego przy transformacjach

- Przy transformacjach afinicznych na zmianę wektoru normali nie ma wpływu przesunięcie równoległe
- Niech $A : \mathbb{R}^3 \to \mathbb{R}^3$ bedzie transformacją liniową
  - wtedy $x \cdot Ay = A^t x \cdot y$
    - wniosek: przy transformacji A wektor normalny zmienia się według zasady: $n' = (A^t)^{-1} n$
- Uwagi:
  1. dla transformacji sztywnych $(A^t)^{-1} = A$
  2. $(A^t)^{-1} = (A^{-1})^t$
  3. $(A_1 A_2)^{-1} = A_2^{-1} A_1^{-1}$

Wektory normalne torusa

- $P(\theta, \varphi) = \begin{pmatrix} (R + r\cos\varphi)\sin\theta \\ r\sin\varphi \\ (R + r\cos\varphi)\cos\theta \end{pmatrix}$,
- $0 \leqslant \theta, \varphi \leqslant 2\pi$
- $n(\theta, \varphi) = \begin{pmatrix} \cos\varphi\sin\theta \\ \sin\varphi \\ \cos\phi\cos\theta \end{pmatrix}$

Shadery

Vertex Shader. Dane wejściowe i zmienne uniform


```
#version 430 core

layout(location=0) in vec4 in_position;
layout(location=2) in vec2 in_texture;
layout(location=3) in vec3 in_normal;

uniform mat4 model_matrix;
uniform mat3 normal_matrix;
uniform mat4 view_matrix;
uniform mat4 projection_matrix;
```

Światło i struktura wyjściowa


```
uniform struct PointLight{
    vec4 position;
    vec4 ambient;
    vec4 diffuse;
    vec4 specular;
    vec3 attenuation;
} light;


out struct Vertex {
    vec2  texcoord;
    vec3  normal;
    vec3  light_dir;
    vec3  view_dir;
    float dist;
} frag_vertex;
```

```
void main(void){
  vec4 vertex = model_matrix * in_position;
  frag_vertex.light_dir = (light.position.xyz
                                    - vertex.xyz);
  frag_vertex.normal= normal_matrix * in_normal;
  vec4 camera = -view_matrix*vec4(0.0, 0.0, 0.0, 1);
  frag_vertex.view_dir = camera.xyz-vertex.xyz;
  frag_vertex.dist = distance(light.position, vertex);
  gl_Position = (projection_matrix
        * view_matrix) * vertex;
  frag_vertex.texcoord = in_texture;
}
```

Fragment Shader. Dane wejściowe i wyjściowe


```
#version 430 core
layout (location = 0) out vec4 color;

in struct Vertex {
    vec2  texcoord;
    vec3  normal;
    vec3  light_dir;
    vec3  view_dir;
    float dist;
} frag_vertex;
```

```
uniform struct PointLight{
    vec4 position;
    vec4 ambient;
    vec4 diffuse;
    vec4 specular;
    vec3 attenuation;
}light;

uniform struct Material{
  vec4  ambient;
  vec4  diffuse;
  vec4  specular;
  vec4  emission;
  float shininess;
}material;

uniform   sampler2D texture_unit;
```

main Tłumienie i wektory

```
void main(void){
  float attenuation = 1.0 /(light.attenuation[0] +
  light.attenuation[1] * frag_vertex.dist +
  light.attenuation[2] * frag_vertex.dist
                       * frag_vertex.dist);

  vec3 normal    = normalize(frag_vertex.normal);
  vec3 light_dir = normalize(frag_vertex.light_dir);
  vec3 view_dir  = normalize(frag_vertex.view_dir);
```

Obliczenie oświetlenia


```
    color = material.emission;
    color += material.ambient * light.ambient;
    float n_dot_l = max(dot(normal, light_dir), 0.0);
    color += material.diffuse * light.diffuse * n_dot_l;
    float r_dot_v_pow = max(pow(dot(
          reflect(-light_dir, normal), view_dir),
                                material.shininess), 0.0);
    color += material.specular * light.specular
                                * r_dot_v_pow;
    color *= texture(texture_unit,
                     frag_vertex.texcoord)* attenuation;
}
```

SunLightShader.vertex.glsl


```
uniform struct SunLight{
    vec4 position;
    vec4 ambient;
    vec4 diffuse;
    vec4 specular;
} light;

out Vertex {
    vec2  texcoord;
    vec3  normal;
    vec3  light_dir;
    vec3  view_dir;
} frag_vertex;

.....................................

frag_vertex.light_dir = light.position.xyz;
```

Shader fragmentów

- jak dla światła punktowego
  - bez tłumienia (`attenuation`)

- jak światło punkowe

Shader fragmentów


```
float spot_effect = dot(normalize(light.direction),
                        -light_dir);
float spot = float(spot_effect > light.cutoff);
spot_effect = max(pow(spot_effect, light.exponent),
                                                0.0);
float attenuation = spot * spot_effect / (
    light.attenuation[0]
       + light.attenuation[1] * frag_vertex.dist
       + light.attenuation[2] * frag_vertex.dist
                              * frag_vertex.dist);

.....................................

color *= texture(texture_unit,
                 frag_vertex.texcoord) * attenuation;
```

Implementacja

Nowe klasy C++

- `LightableModel` — model z macierzą `normal_matrix`
- `MaterialModel` — model z materiałem
- `Tori` — dwa torusy
- `Plane` — płaszczyzna
- `LightProgram` — klasa bazowa dla programów ze światłami
- `PointLightProgram` — światło punktowe
- `SunLightProgram` — światło kierunkowe
- `SpotLightProgram` — światło spot
- `light.h` — struktury dla światła
- `material.h` — struktury dla materiałów

```
typedef struct PointLight{
  GLfloat position[4];
  GLfloat ambient[4];
  GLfloat diffuse[4];
  GLfloat specular[4];
  GLfloat attenuation[3];
} PointLight;
```

Światło kierunkowe


```
typedef struct SunLight{
  GLfloat position[4];
  GLfloat ambient[4];
  GLfloat diffuse[4];
  GLfloat specular[4];
} SunlLight;
```

Światło spot


```
typedef struct SpotLight{
  GLfloat position[4];
  GLfloat ambient[4];
  GLfloat diffuse[4];
  GLfloat specular[4];
  GLfloat attenuation[3];
  GLfloat direction[3];
  GLfloat cutoff;
  GLfloat exponent;
} SpotLight;
```

Struktura materiału


```
typedef struct Material{
  GLfloat ambient[4];
  GLfloat diffuse[4];
  GLfloat specular[4];
  GLfloat emission[4];
  GLfloat shininess;
} Material;
```

Macierz 3×3


```
class Mat3{
public:
    Mat3(); // Unit matrix
    operator const float* () const{return matrix_;}
    void RotateAboutX(GLfloat angle); //gedrees
    void RotateAboutY(GLfloat angle); //gedrees
    void RotateAboutZ(GLfloat angle); //gedrees
    void Scale(GLfloat x_scale,
               GLfloat y_scale, GLfloat z_scale);
    void SetUnitMatrix();
    void Log();
private:
    GLfloat matrix_[9]; // column-major
    void MultiplyBy(const Mat3 &);
    explicit Mat3(float);
};
```

Nowa struktura dla wierzchołków


```
typedef struct NormalTextureVertex{
    float position[4];
    float texture[2];
    float normal[3];
} NormalTextureVertex;
```

MovableModel: dwie macierze

MovableModel
model_matrix_ : Mat4
model_matrix_prim_ : Mat4

```
class MovableModel{
protected:
    Mat4 model_matrix_;
    Mat4 model_matrix_prim_;
};
```

Model z macierzami `normal_matrix`

LightableModel
normal_matrix_ : Mat3
normal_matrix_prim_ : Mat3

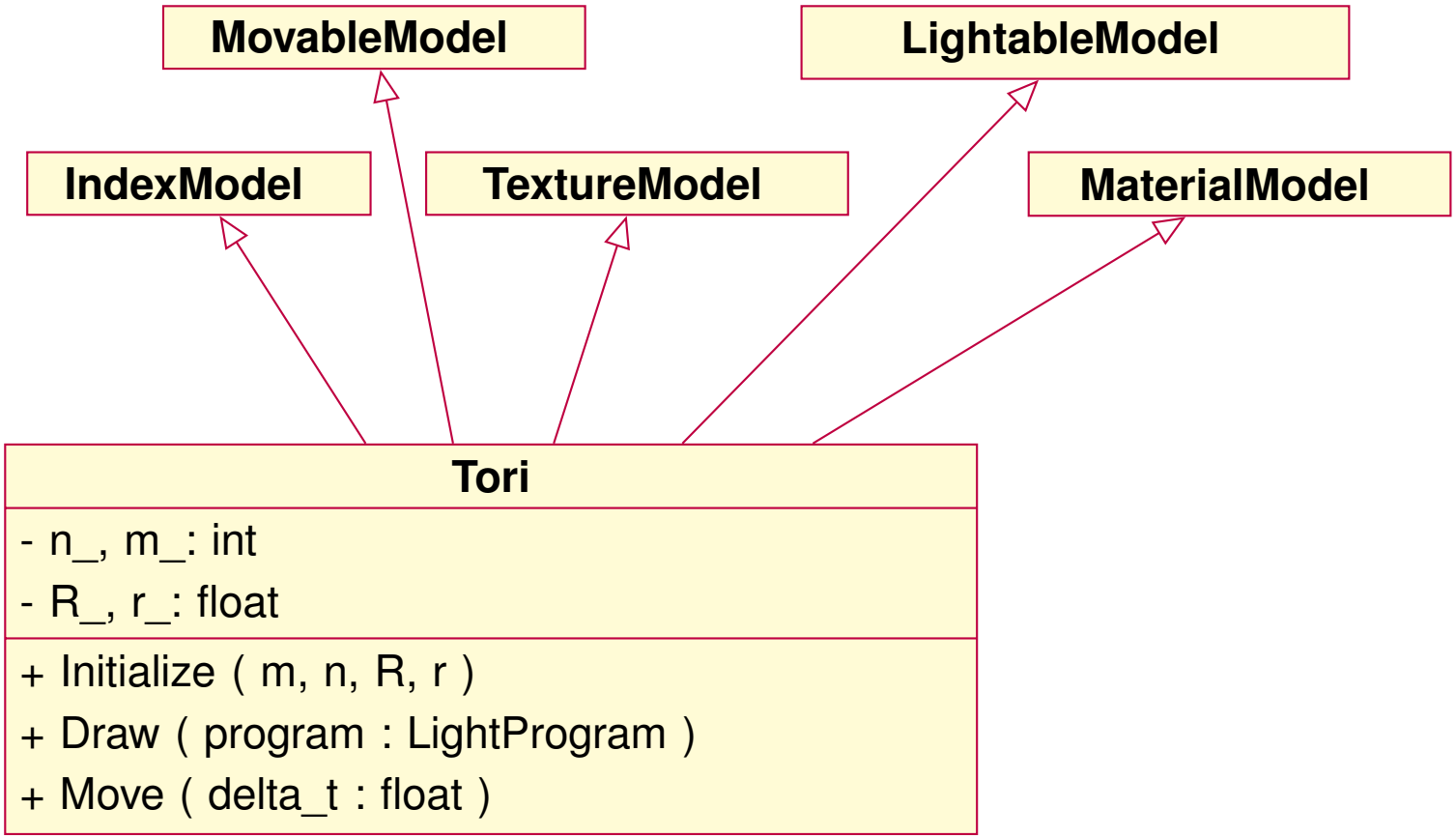
```
class LightableModel{
protected:
    Mat3 normal_matrix;
    Mat3 normal_matrix_prim_;
};
```

Model z dwoma materiałami

MaterialModel
material_ : Material # material_prim_ : Material
+ SetMaterial (mat: Material) + SetMaterialPrim (mat: MaterialPrim)

```
class MaterialModel{
public:
    void SetMaterial(const Material & material){
      material_=material;}
    void SetMaterialPrim(const Material & material){
      material_prim_=material;}
protected:
    Material material_;
    Material material_prim_;
};
```

Dwa torusy



Uzupełnienie inicjalizacji


```
NormalTextureVertex * vertices
    =new NormalTextureVertex[(m_ + 1)*(n_ + 1)];
for (i=0; i<=n_; i++) {
  GLfloat phi=2*M_PI/(float)n_*i;
  for (j=0;j<=m_;j++){
   GLfloat theta=2*M_PI/(float)m_*j;
   vertices[i*(m_ + 1)+j].position[0]
          =(R + r*cos(phi))*sin(theta);
   vertices[i*(m_ + 1)+j].position[1]=r*sin(phi);

.....................................

  vertices[i*(m_+1)+j].normal[0]=cos(phi)*sin(theta);
  vertices[i*(m_+1)+j].normal[1]=sin(phi);
  vertices[i*(m_+1)+j].normal[2]=cos(phi)*cos(theta);
 }
}
```

Trzeci argument dla shadera wierzchołków


```
glVertexAttribPointer(3, 3, GL_FLOAT,
        GL_FALSE, sizeof(vertices[0]),
        (GLvoid*)(sizeof(vertices[0].position)
            + sizeof(vertices[0].texture)));
glEnableVertexAttribArray(3);
```

Move(). Pierwszy torus


```
void Tori::Move(GLfloat delta_t){
  if (!animated_) return;
  angle_ += delta_t * velocity_;
  if(angle_>360) angle_ -= 360;
  if(angle_<-360) angle_ += 360;

  model_matrix_.SetUnitMatrix();
  model_matrix_.RotateAboutX(angle_);
  model_matrix_.RotateAboutY(angle_);
  normal_matrix_.SetUnitMatrix();
  normal_matrix_.RotateAboutY(-angle_);
  normal_matrix_.RotateAboutX(-angle_);
```

Move(). Drugi torus


```
    model_matrix_prim_.SetUnitMatrix();
    model_matrix_prim_.Scale(0.2, 0.2, 0.2);
    model_matrix_prim_.RotateAboutX(2*angle_);
    model_matrix_prim_.Translate(-3, 0, 2);
    model_matrix_prim_.RotateAboutY(angle_);
    normal_matrix_prim_.SetUnitMatrix();
    normal_matrix_prim_.RotateAboutY(-angle_);
    normal_matrix_prim_.RotateAboutX(-2*angle_);
    normal_matrix_prim_.Scale(5.0, 5.0, 5.0);
}
```

Draw(). Działania wstępne


```
void Tori::Draw(const Program &program) const{

    glBindVertexArray(vao_);
    glUseProgram(program);

    glActiveTexture(texture_unit_);
    glBindTexture(GL_TEXTURE_2D, texture_);

    glEnable(GL_CULL_FACE);
    glCullFace(GL_BACK);
    glFrontFace(GL_CW);
```

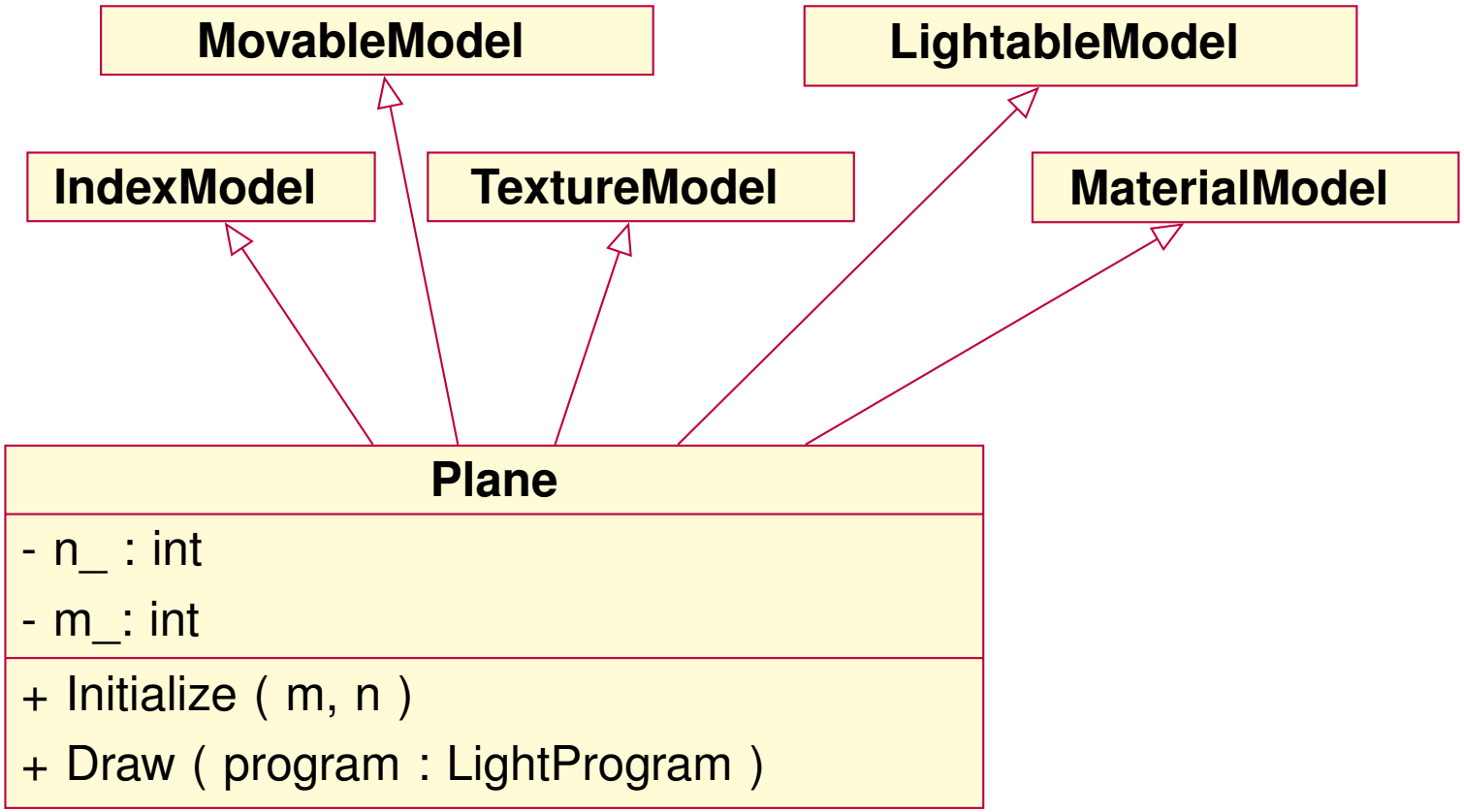
Draw(). Pierwszy torus


```
program.SetModelMatrix(model_matrix_);
program.SetMaterial(material_);
program.SetNormalMatrix(normal_matrix_);
for (int i=0;i<n_;i++){
  glDrawElements(GL_TRIANGLE_STRIP,
    2*(m_ + 1),
    GL_UNSIGNED_INT,
    (GLvoid*)(sizeof(GLuint) * 2 * i * (m_ + 1))
  );
}
```

Draw(). Drugi torus


```
program.SetModelMatrix(model_matrix_prim_);
program.SetMaterial(material_prim_);
program.SetNormalMatrix(normal_matrix_prim_);
for (int i=0;i<n_;i++){
  glDrawElements(GL_TRIANGLE_STRIP,
    2*(m_ + 1),
    GL_UNSIGNED_INT,
    (GLvoid*)(sizeof(GLuint) * 2 * i * (m_ + 1))
  );
}
```

Płaszczyzna



Zmiany w inicjalizacji


```
NormalTextureVertex* vertices
      = new NormalTextureVertex[(m_ + m_ + 1)
                        *(n_ + n_ +1)];
for (i=n_; i>= -n_; i--) {
  for (j=-m_; j<=m_; j++){
    int pos=(n_-i)*(m_+m_+1)+j+m_;
    vertices[pos].position[0]=j;
    vertices[pos].position[1]=0.0f;
    vertices[pos].position[2]=i;
    vertices[pos].position[3]=1.0f;
    vertices[pos].texture[0]=(float)j/(float)m_;
    vertices[pos].texture[1]=(float)i/(float)n_;
    vertices[pos].normal[0]=0.0f;
    vertices[pos].normal[1]=1.0f;
    vertices[pos].normal[2]=0.0f;
  }
}
```

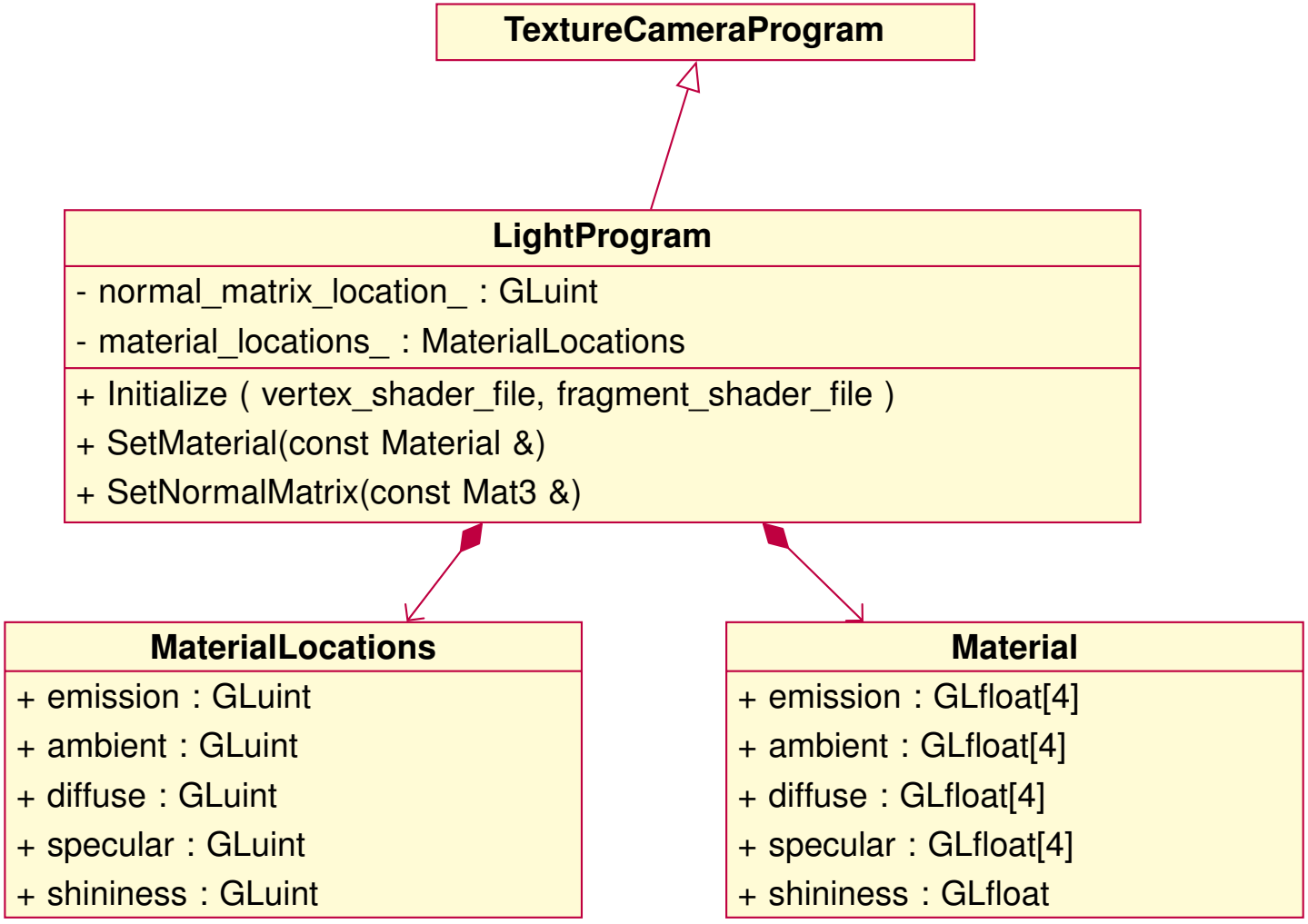
```
GLuint* indices = new GLuint[4*n_*(2*m_+1)];

int k=0;

for(i=0; i<2*n_; i++){
  for(j=0; j<(2*m_+1); j++){
    pos=2*(i*(2*m_+1)+j);
    indices[pos]=k;
    indices[pos+1]=k+(2*m_+1);
    k++;
  }
}
```

```
glBindVertexArray(vao_);
glUseProgram(program);
program.SetModelMatrix(model_matrix_);
program.SetNormalMatrix(normal_matrix_);
program.SetMaterial(material_);
glActiveTexture(texture_unit_);
glBindTexture(GL_TEXTURE_2D, texture_);
glEnable(GL_CULL_FACE);
glCullFace(GL_BACK);
glFrontFace(GL_CW);
for (int i=0;i<2*n_;i++){
  glDrawElements(GL_TRIANGLE_STRIP, 2*(2*n_+1),
   GL_UNSIGNED_INT,
   (GLvoid*)(sizeof(GLuint) * 2*i*(2*m_+1)));
}
```

LightProgram

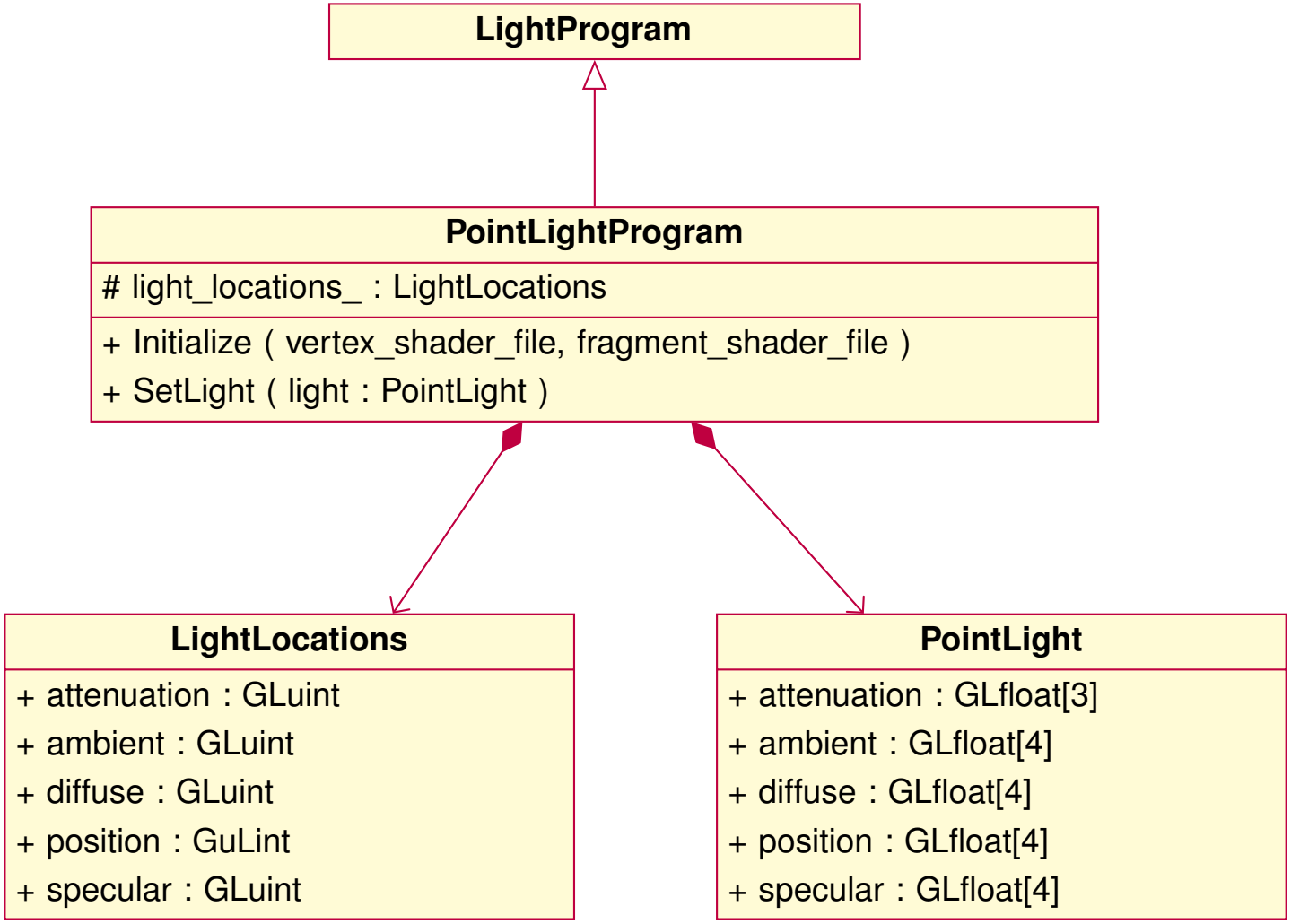


Inicjalizacja


```
void LightProgram::Initialize(
        const char *vertex_shader_file,
        const char *fragment_shader_file){
    TextureCameraProgram::Initialize(
      vertex_shader_file, fragment_shader_file);
    normal_matrix_location_
      = GetUniformLocationOrDie("normal_matrix");
    material_locations_.emission
      = GetUniformLocationOrDie("material.emission");
    material_locations_.ambient
      = GetUniformLocationOrDie("material.ambient");
    material_locations_.diffuse
      = GetUniformLocationOrDie("material.diffuse");
    material_locations_.specular
      = GetUniformLocationOrDie("material.specular");
    material_locations_.shininess
      = GetUniformLocationOrDie("material.shininess");
}
```

```
void LightProgram::SetMaterial(
    const Material & material) const{
     glUniform4fv(material_locations_.ambient,
       1, material.ambient);
     glUniform4fv(material_locations_.emission,
       1, material.emission);
     glUniform4fv(material_locations_.diffuse,
       1, material.diffuse);
     glUniform4fv(material_locations_.specular,
       1, material.specular);
     glUniform1f(material_locations_.shininess,
       material.shininess);
}
void LightProgram::SetNormalMatrix(
    const Mat3 & matrix) const{
     glUniformMatrix3fv(normal_matrix_location_,
       1, GL_TRUE, matrix);
}
```

Program ze światłem punktowym



```
void PointLightProgram::Initialize(
        const char *vertex_shader_file,
        const char *fragment_shader_file){
    LightProgram::Initialize(vertex_shader_file,
        fragment_shader_file);
    light_locations_.ambient
      = GetUniformLocationOrDie("light.ambient");
    light_locations_.attenuation
      = GetUniformLocationOrDie("light.attenuation");
    light_locations_.diffuse
      = GetUniformLocationOrDie("light.diffuse");
    light_locations_.position
      = GetUniformLocationOrDie("light.position");
    light_locations_.specular
    = GetUniformLocationOrDie("light.specular");
}
```

```
void PointLightProgram::SetLight(
    const PointLight & light) const{
     glUniform4fv(light_locations_.ambient,
       1, light.ambient);
     glUniform4fv(light_locations_.diffuse,
       1, light.diffuse);
     glUniform4fv(light_locations_.specular,
       1, light.specular);
     glUniform4fv(light_locations_.position,
       1, light.position);
     glUniform3fv(light_locations_.attenuation,
       1, light.attenuation);
}
```

SunLightProgram, SpotLightProgram

- Analogicznie

Stałe dla materiałów


```
const Material  kYellowMaterial={
    {0.2f, 0.2f, 0.2f, 1.0f}, //Ambient
    {1.0f, 1.0f, 0.0f, 1.0f}, //Diffuse
    {0.6f, 0.6f, 0.6f, 1.0f}, //Specular
    {0.0f, 0.0f, 0.0f, 1.0f}, //Emission
    60.0f
  };

const Material  kIceMaterial={
    {0.4f, 0.4f, 0.4f, 1.0f}, //Ambient
    {0.95f, 0.95f, 0.99f, 1.0f}, //Diffuse
    {0.99f, 0.99f, 0.99f, 1.0f}, //Specular
    {0.0f, 0.0f, 0.0f, 1.0f}, //Emission
    10.0f
  };
```

Stałe dla świateł


```
const PointLight kPointLight={
    {0.0f, 7.5f, 3.0f, 1.0f}, //position
    {0.1f, 0.1f, 0.1f, 1.0f}, //ambient
    {1.0f, 1.0f, 1.0f, 1.0f}, //diffuse
    {1.0f, 1.0f, 1.0f, 1.0f}, //specular
    {0.5f, 0.005f, 0.0125f}     //attenuation
};

const SunLight kSunLight={
    {0.0f, 7.5f, 3.0f, 0.0f}, //position
    {0.1f, 0.1f, 0.1f, 1.0f}, //ambient
    {1.0f, 1.0f, 1.0f, 1.0f}, //diffuse
    {1.0f, 1.0f, 1.0f, 1.0f} //specular
};
```

Światło spot


```
const SpotLight kSpotLight={
    {0.0f, 7.5f, 3.0f, 1.0f}, //position
    {0.3f, 0.3f, 0.3f, 1.0f}, //ambient
    {1.0f, 1.0f, 1.0f, 1.0f}, //diffuse
    {1.0f, 1.0f, 1.0f, 1.0f}, //specular
    {0.5f, 0.005f, 0.0125f},    //attenuation
    {0.0f, -6.0f, -3.0f},       //direction
    20,                  //cutoff, degrees
    20                   //exponent
};
```

```
public:
  void MouseButton(int button,
         int state, int x_coord, int y_coord);
  void MouseMove(int x_coord, int y_coord);
private:
  PointLightProgram point_program_;
  SunLightProgram sun_program_;
  SpotLightProgram spot_program_;

  int x_origin_;
  int y_origin_;

  enum {POINT_PROGRAM,
    SUN_PROGRAM, SPOT_PROGRAM} current_program_;

  void SetViewMatrix();
  void SetProjectionMatrix();
```

```
void Window::InitModels(){
    tori_.Initialize(kTorusN, kTorusM,
                     kTorusR, kTorusr);
    tori_.SetTexture(color_texture_);
    tori_.SetTextureUnit(GL_TEXTURE0);
    tori_.SetMaterial(kBlueMaterial);
    tori_.SetMaterialPrim(kYellowMaterial);

    plane_.Initialize(kPlaneM, kPlaneN);
    plane_.SetTexture(ice_texture_);
    plane_.SetTextureUnit(GL_TEXTURE0);
    plane_.SetMaterial(kIceMaterial);
}
```

```
void Window::InitPrograms(){
 view_matrix_.Translate(0, 0, -10);
 projection_matrix_
  = Mat4::CreateProjectionMatrix(60,
     (float)width_/(float)height_,
                          0.1f, 100.0f);
```

```
//point
point_program_.Initialize(kPointLightVertexShader,
                          kPointLightFragmentShader);
glUseProgram(point_program_);
point_program_.SetLight(kPointLight);
point_program_.SetTextureUnit(0);
point_program_.SetProjectionMatrix(projection_matrix_);
point_program_.SetViewMatrix(view_matrix_);
```

InitPrograms. SunProgram, SpotProgram

- Analogicznie

```
void Window::SetViewMatrix(){
  glUseProgram(point_program_);
  point_program_.SetViewMatrix(view_matrix_);
  glUseProgram(sun_program_);
  sun_program_.SetViewMatrix(view_matrix_);
  glUseProgram(spot_program_);
  spot_program_.SetViewMatrix(view_matrix_);
  glUseProgram(0);
}
```

```
void Window::SetProjectionMatrix(){
  glUseProgram(point_program_);
  point_program_.SetProjectionMatrix(
        projection_matrix_);
  glUseProgram(sun_program_);
  sun_program_.SetProjectionMatrix(
        projection_matrix_);
  glUseProgram(spot_program_);
  spot_program_.SetProjectionMatrix(
        projection_matrix_);
  glUseProgram(0);
}
```

```
void Window::Resize(int new_width,
                    int new_height){
  width_ = new_width;
  height_ = new_height;
  projection_matrix_
   = Mat4::CreateProjectionMatrix(60,
    (float)width_/(float)height_, 0.1f, 100.0f);
  SetProjectionMatrix();
  glViewport(0, 0, width_, height_);
}
```

```
switch (current_program_){
case POINT_PROGRAM:
    tori_.Draw(point_program_);
    plane_.Draw(point_program_);
break;
case SUN_PROGRAM:
    tori_.Draw(sun_program_);
    plane_.Draw(sun_program_);
break;
case SPOT_PROGRAM:
    tori_.Draw(spot_program_);
    plane_.Draw(spot_program_);
break;
```

Zmiany w `KeyEvent`


```
case GLFW_KEY_F1:
    current_program_ = POINT_PROGRAM;
break;
case GLFW_KEY_F2:
    current_program_ = SUN_PROGRAM;
break;
case GLFW_KEY_F3:
    current_program_ = SPOT_PROGRAM;
break;
```

Rejestracja callbacków w `main.cpp`


```
void MouseScroll(GLFWwindow* /*window*/,
  double xoffset, double yoffset){
    window.MouseScroll(xoffset, yoffset);
}
void MouseButton(GLFWwindow* /*window*/,
  int button, int action, int mods){
    window.MouseButton(button, action, mods);
}
void MouseMove(GLFWwindow* /*window*/,
   double x_pos, double y_pos){
    window.MouseMove(x_pos, y_pos);

.....................................

glfwSetScrollCallback(window, MouseScroll);
glfwSetMouseButtonCallback(window, MouseButton);
glfwSetCursorPosCallback(window, MouseMove);
```

Sterowanie kamerą za pomocą kółka myszy


```
void Window::MouseScroll(double /* xoffset */,
                         double yoffset){
  view_matrix_.Translate(0, 0, -0.25f*yoffset);
  SetViewMatrix();
}
```

Lewy przycisk


```
void Window::MouseButton(int button, int action,
                         int /*mods*/) {
// only start motion if the left button is pressed
    if (button == GLFW_MOUSE_BUTTON_LEFT) {
        // when the button is released
        if (action == GLFW_RELEASE) {
            x_origin_ = -1;
            y_origin_ = -1;
        }
        else  {// state = GLFW_PRESS
            double x_pos, y_pos;
            glfwGetCursorPos(*this,
                             &x_pos, &y_pos);
            x_origin_ = x_pos;
            y_origin_ = y_pos;
        }
    }
}
```

```
void Window::MouseMove(double x_pos,
                                double y_pos){
  float delta_x_angle=0;
  float delta_y_angle=0;
  if (x_origin_ >= 0 && y_origin_ >=0) {
    // update deltaAngle
    delta_x_angle = (x_pos - x_origin_) * 0.1f;
    delta_y_angle = (y_pos - y_origin_) * 0.1f;
    x_origin_=x_pos;
    y_origin_=y_pos;

    // update camera's direction
    view_matrix_.RotateAboutY(delta_x_angle);
    view_matrix_.RotateAboutX(delta_y_angle);
    SetViewMatrix();
  }
}
```