CS4533 Lectures 11-12 Slides/Notes

Shading and Illumination; Compositing (Notes, Ch 14, Notes)

By Prof. Yi-Jen Chiang
CSE Dept., Tandon School of Engineering
New York University

1

* **Continued on Shading and Illumination:**

- First we reviewed the ``Overall Formula'' of the Phong Reflection Model (shown in the next 2 slides) as presented last time, which is implemented in the sample program ``Handout: rotate-cube-shading.cpp".
- Discussed the sample program ``Handout: rotate-cube-shading.cpp" (complete sample program has been posted at
  https://cse.engineering.nyu.edu/cs653/Rotate-Cube-Shading.tar.gz)
- Some screenshots of the sample program with annotations are then shown next.
- Showed a demo of the sample program ``Demo-Rotate-Cube-Shading''.
- Then we finished up the last 2 pages (p.14 & p.15) of the last lecture notes/slides "Lecture-9-10.pdf" on Normal Matrix.

* **New topic: Composition Techniques.**

2

Note: component-wise multiplications: $K_a \cdot L_a$, $K_d \cdot L_d$, $K_s \cdot L_s$. They are attenuated differently.

Overall formula:

global ambient light

$$I = k_a \cdot L_{a\text{-global}} + \sum_{\text{light } i} (\text{Attenuation})_i \cdot \Big[k_a \cdot L_a + k_d \cdot L_d \cdot \max\{(l \cdot n), 0\}$$
$$+ [\text{if } l \cdot n \geq 0] \cdot k_s \cdot L_s \cdot \left(\max\{(r \cdot v), 0\}\right)^{\alpha} \Big]_i$$

replaced with $(n \cdot h)$

(1) If light i is a distant (directional) light, then

① $(\text{Attenuation})_i = 1$

② vector l (from pt p to light source i = $-$(distant light direction L)

i.e. $l = -L$

L $\quad l = -L$

(Also, use this l to compute $h = \text{normalize}(l + v)$)

(2) If light i is a point source, then

① $(\text{Attenuation})_i = \dfrac{1}{a + bd + cd^2}$ where d = distance from pt p to the light source position.

a, b, c: constant, linear, quadratic attenuations

3

(3) If light i is a spotlight then

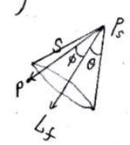
① $(\text{Attenuation})_i = \dfrac{1}{a + bd + cd^2} \cdot (\text{spotlight\_attenuation})_i$ $\quad$ a, b, c, d are as in (2) point source.

In particular $d = |\overrightarrow{P_s P}|$

$l = \text{normalize}(\overrightarrow{P P_s}) = -s$

$\therefore s = -l$

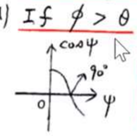
② $(\text{spotlight\_attenuation})_i = ?$



(Let $L_f = \text{normalize}(L_f)$)

θ: spotlight cut-off angle $\theta \in [0, 90°]$

(a) If $\phi > \theta$ then contribution $= 0$



In the range $[0, 90°]$

$\phi > \theta \iff \cos\phi < \cos\theta$

$\iff (L_f \cdot s) < \cos\theta$

$\iff L_f \cdot (-l) < \cos\theta$

$\therefore$ If $L_f \cdot (-l) < \cos\theta$ then $(\text{spotlight\_attenuation})_i = 0$

(b) Else,

$(\text{spotlight\_attenuation})_i = (\cos\phi)^e$ $\quad$ e: spotlight exponent

$= [L_f \cdot (-l)]^e$

(Combining (a), (b): $(\text{spotlight\_attenuation})_i = [\text{if } L_f \cdot (-l) \geq \cos\theta] \cdot [L_f \cdot (-l)]^e$)

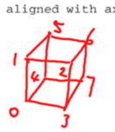
4

Mute Stop Video Security Participants Polls New Share Pause Share Annotate Remote Control More

Mouse Select Text Draw Stamp Spotlight Eraser Format Undo Redo Clear Save

Talking:

```
#include "Angel-yjc.h"

typedef Angel::vec4  color4;
typedef Angel::vec4  point4;

GLuint program;        /* shader program object id */
GLuint cube_buffer;    /* vertex buffer object id for cube */

// Projection transformation parameters
GLfloat  fovy = 45.0;  // Field-of-view in Y direction angle (in degrees)
GLfloat  aspect;       // Viewport aspect ratio
GLfloat  zNear = 0.5, zFar = 3.0;

int animationFlag = 1; // 1: animation; 0: non-animation. Toggled by key 'a' or 'A'

const int NumVertices = 36; //(6 faces)(2 triangles/face)(3 vertices/triangle)
point4 points[NumVertices];
vec3   normals[NumVertices];

// Vertices of a unit cube centered at origin, sides aligned with axes
point4 vertices[8] = {
    point4( -0.5, -0.5,  0.5, 1.0 ),  — 0
    point4( -0.5,  0.5,  0.5, 1.0 ),  — 1
    point4(  0.5,  0.5,  0.5, 1.0 ),  — 2
    point4(  0.5, -0.5,  0.5, 1.0 ),  — 3
    point4( -0.5, -0.5, -0.5, 1.0 ),  — 4
    point4( -0.5,  0.5, -0.5, 1.0 ),  — 5
    point4(  0.5,  0.5, -0.5, 1.0 ),  — 6
    point4(  0.5, -0.5, -0.5, 1.0 )   — 7
};
```




```
// Array of rotation angles (in degrees) for each coordinate axis
enum { Xaxis = 0, Yaxis = 1, Zaxis = 2, NumAxes = 3 };
int      Axis = Xaxis;
GLfloat  Theta[NumAxes] = { 0.0, 0.0, 0.0 };

// Model-view and projection matrices uniform location
GLuint  ModelView, Projection;

/*----- Shader Lighting Parameters -----*/
    color4 light_ambient( 0.2, 0.2, 0.2, 1.0 );
    color4 light_diffuse( 1.0, 1.0, 1.0, 1.0 );
```

```
//        to the vertices
void quad( int a, int b, int c, int d )
{
    // Initialize temporary vectors along the quad's edges to
    //   compute its face normal
    vec4 u = vertices[b] - vertices[a];
    vec4 v = vertices[d] - vertices[a];

    vec3 normal = normalize( cross(u, v) );

    normals[Index] = normal; points[Index] = vertices[a]; Inc
    normals[Index] = normal; points[Index] = vertices[b]; Inc
    normals[Index] = normal; points[Index] = vertices[c]; Inc
    normals[Index] = normal; points[Index] = vertices[a]; Inc
    normals[Index] = normal; points[Index] = vertices[c]; Inc
    normals[Index] = normal; points[Index] = vertices[d]; Inc
}
//----------------------------------------------------------------
// colorcube() generates 6 quad faces (12 triangles): 36 vert
void colorcube()
{
    quad( 1, 0, 3, 2 );
    quad( 2, 3, 7, 6 );
    quad( 3, 0, 4, 7 );
    quad( 6, 5, 1, 2 );
    quad( 4, 5, 6, 7 );
    quad( 5, 4, 0, 1 );
}
//----------------------------------------------------------------
// OpenGL initialization
void init()
{
    colorcube();

    // Create and initialize a vertex buffer object
    glGenBuffers( 1, &cube_buffer );
    glBindBuffer( GL_ARRAY_BUFFER, cube_buffer );
    glBufferData( GL_ARRAY_BUFFER, sizeof(points) + sizeof(nc
                  NULL, GL_STATIC_DRAW );
    glBufferSubData( GL_ARRAY_BUFFER, 0, sizeof(points), poin
    glBufferSubData( GL_ARRAY_BUFFER, sizeof(points),
                     sizeof(normals), normals );
```

5

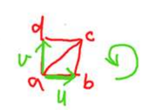
NYU Home | NYU Classes : CS 45 | Launch Meeting - Z | Lecture-9-10-Final.p | Handout-rotate-cub

Mute Stop Video Security Participants 5 Polls New Share Pause Share Annotate Remote Control More

Mouse Select Text Draw Stamp Spotlight Eraser Format Undo Redo Clear Save

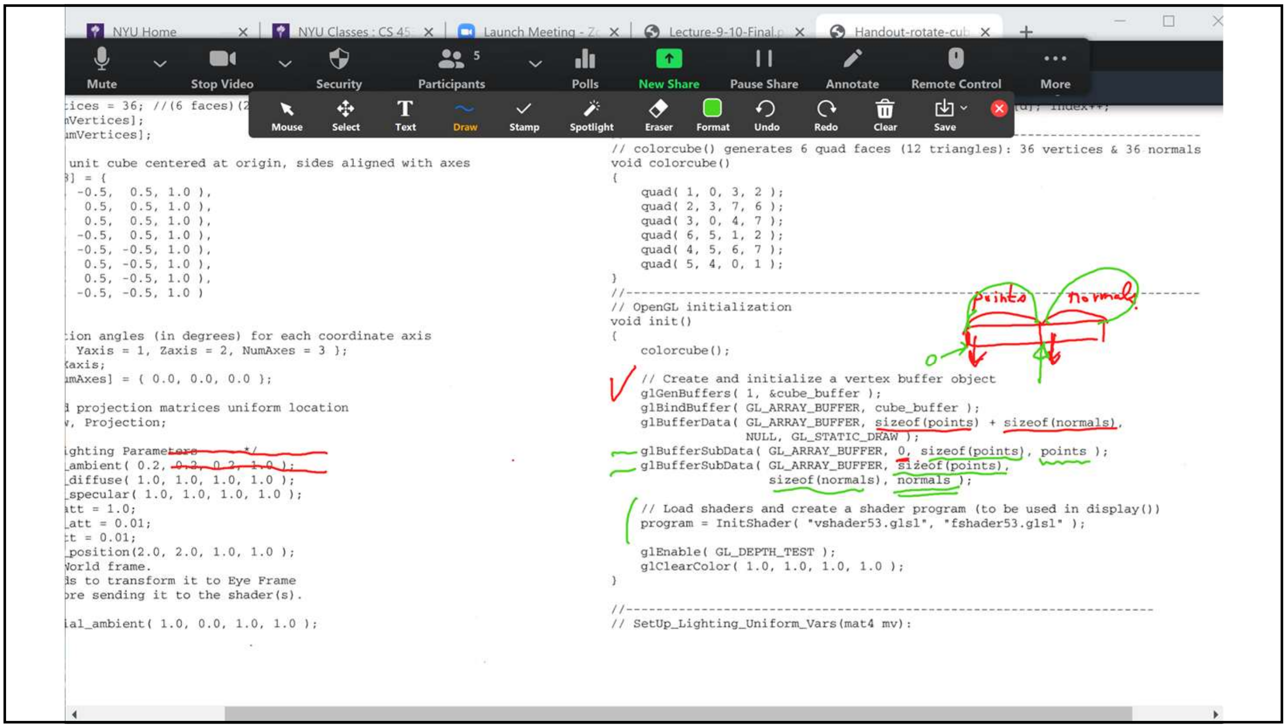
```
 user interface, etc.
 and mouse() functions f
ting cube with shading.

rial properties & Normal Matrix are sent to the shader as
les.
 computation is done in the Eye Frame (in shader).
-----------------------------------------------------
.h"

 color4;
 point4;

  /* shader program object id */
  /* vertex buffer object id for cube */

formation parameters
0;  // Field-of-view in Y direction angle (in degrees)
   // Viewport aspect ratio
5, zFar = 3.0;

 1; // 1: animation; 0: non-animation. Toggled by key 'a' or 'A'

es = 36; //(6 faces)(2 triangles/face)(3 vertices/triangle)
rtices];
ertices];

it cube centered at origin, sides aligned with axes
= {
0.5,  0.5, 1.0 ),
0.5,  0.5, 1.0 ),
0.5,  0.5, 1.0 ),
0.5,  0.5, 1.0 ),
0.5, -0.5, 1.0 ),
0.5, -0.5, 1.0 ),
0.5, -0.5, 1.0 ),
0.5, -0.5, 1.0 )

n angles (in degrees) for each coordinate axis
axis = 1, Zaxis = 2, NumAxes = 3 };
is;
xes] = { 0.0, 0.0, 0.0 };
```

```
int Index = 0;

//----------------------------------------------------------------
// quad() generates two triangles for each face and assigns normals
//        to the vertices
void quad( int a, int b, int c, int d )
{
    // Initialize temporary vectors along the quad's edges to
    //   compute its face normal
    vec4 u = vertices[b] - vertices[a];     ab = u
    vec4 v = vertices[d] - vertices[a];     ad = v

    vec3 normal = normalize( cross(u, v) );

    normals[Index] = normal; points[Index] = vertices[a]; Index++;  } △abc
    normals[Index] = normal; points[Index] = vertices[b]; Index++;
    normals[Index] = normal; points[Index] = vertices[c]; Index++;
    normals[Index] = normal; points[Index] = vertices[a]; Index++;  } △acd
    normals[Index] = normal; points[Index] = vertices[c]; Index++;
    normals[Index] = normal; points[Index] = vertices[d]; Index++;
}
//----------------------------------------------------------------
// colorcube() generates 6 quad faces (12 triangles): 36 vertices & 36 normals
void colorcube()
{
    quad( 1, 0, 3, 2 );   — CCW
    quad( 2, 3, 7, 6 );   } as before.
    quad( 3, 0, 4, 7 );
    quad( 6, 5, 1, 2 );
    quad( 4, 5, 6, 7 );
    quad( 5, 4, 0, 1 );
}
//----------------------------------------------------------------
// OpenGL initialization
void init()
{
    colorcube();

    // Create and initialize a vertex buffer object
```



normal vector is pointing outward.

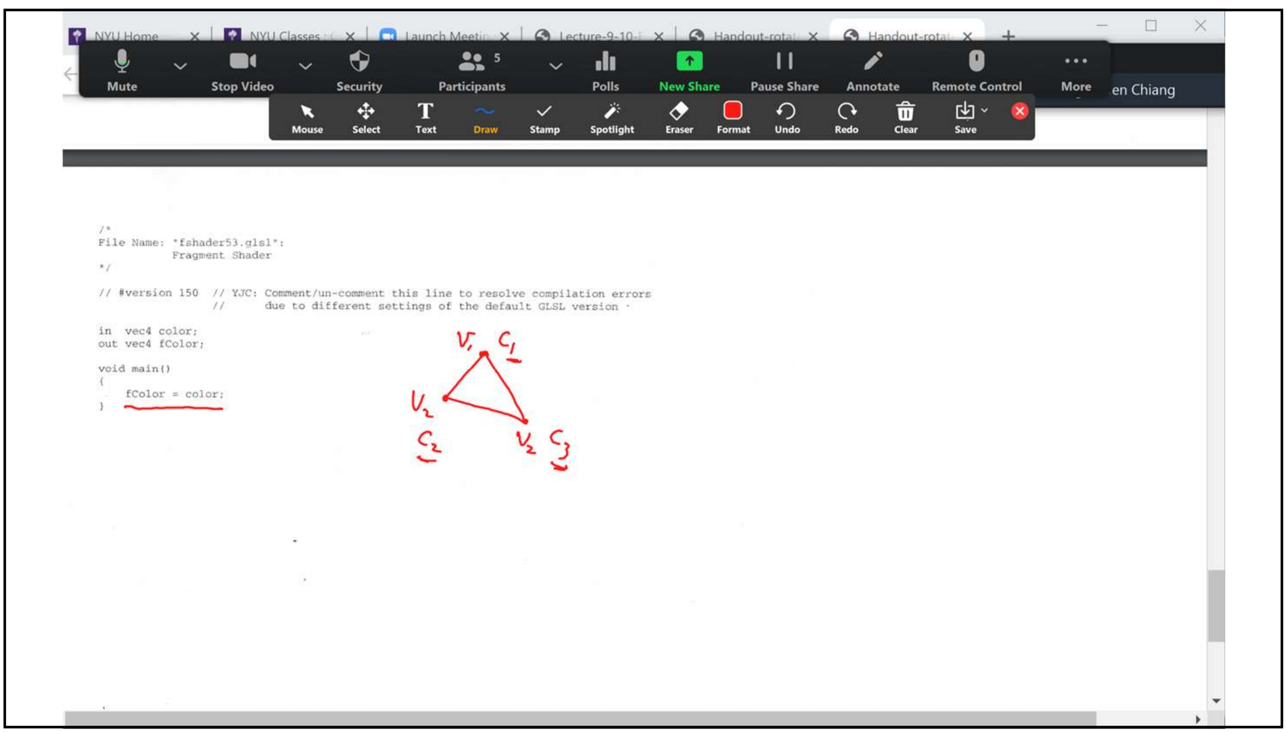
6



```
ices = 36; //(6 faces)(2
nVertices];
umVertices];

 unit cube centered at origin, sides aligned with axes
3] = {
  -0.5,  0.5, 1.0 ),
   0.5,  0.5, 1.0 ),
   0.5,  0.5, 1.0 ),
  -0.5,  0.5, 1.0 ),
  -0.5, -0.5, 1.0 ),
   0.5, -0.5, 1.0 ),
   0.5, -0.5, 1.0 ),
  -0.5, -0.5, 1.0 )

ion angles (in degrees) for each coordinate axis
 Yaxis = 1, Zaxis = 2, NumAxes = 3 };
Xaxis;
umAxes] = { 0.0, 0.0, 0.0 };

d projection matrices uniform location
v, Projection;

ighting Parameters      */
_ambient( 0.2, 0.2, 0.2, 1.0 );
_diffuse( 1.0, 1.0, 1.0, 1.0 );
_specular( 1.0, 1.0, 1.0, 1.0 );
att = 1.0;
_att = 0.01;
tt = 0.01;
_position(2.0, 2.0, 1.0, 1.0 );
World frame.
ds to transform it to Eye Frame
ore sending it to the shader(s).

ial_ambient( 1.0, 0.0, 1.0, 1.0 );
```

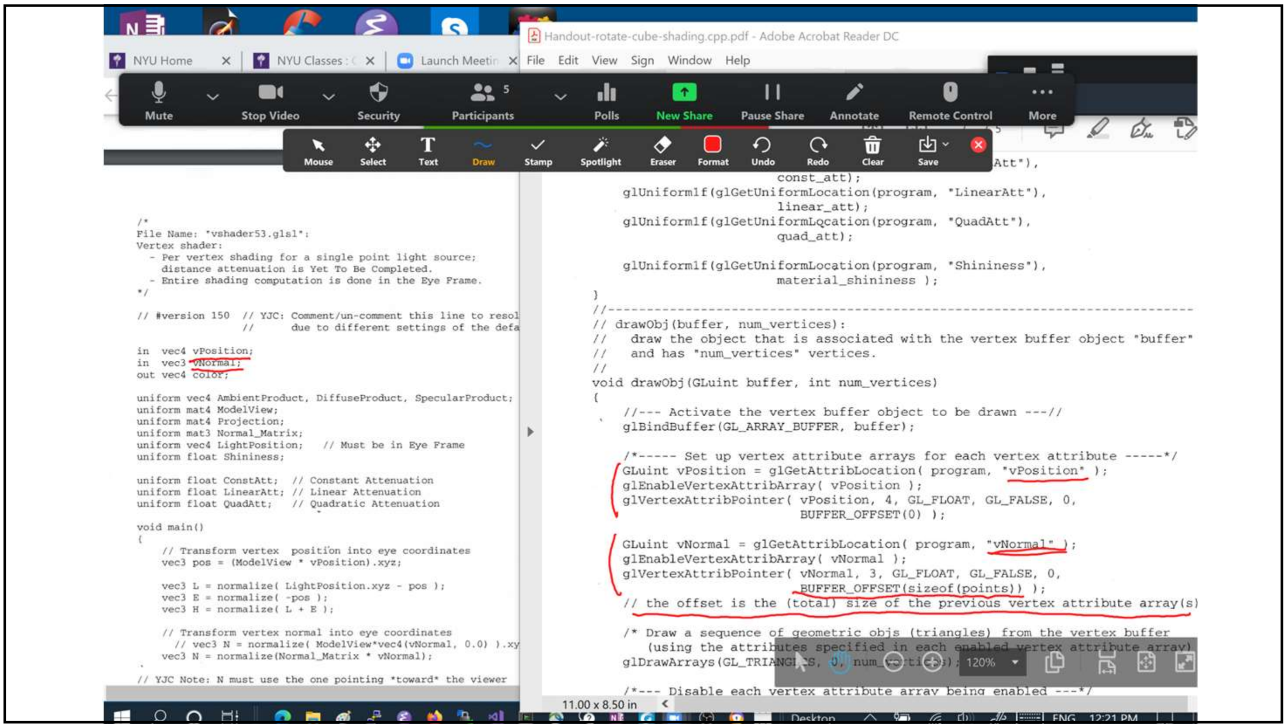
```
// colorcube() generates 6 quad faces (12 triangles): 36 vertices & 36 normals
void colorcube()
{
    quad( 1, 0, 3, 2 );
    quad( 2, 3, 7, 6 );
    quad( 3, 0, 4, 7 );
    quad( 6, 5, 1, 2 );
    quad( 4, 5, 6, 7 );
    quad( 5, 4, 0, 1 );
}
//----------------------------------------------------------------------
// OpenGL initialization
void init()
{
    colorcube();

    // Create and initialize a vertex buffer object
    glGenBuffers( 1, &cube_buffer );
    glBindBuffer( GL_ARRAY_BUFFER, cube_buffer );
    glBufferData( GL_ARRAY_BUFFER, sizeof(points) + sizeof(normals),
                  NULL, GL_STATIC_DRAW );
    glBufferSubData( GL_ARRAY_BUFFER, 0, sizeof(points), points );
    glBufferSubData( GL_ARRAY_BUFFER, sizeof(points),
                     sizeof(normals), normals );

    // Load shaders and create a shader program (to be used in display())
    program = InitShader( "vshader53.glsl", "fshader53.glsl" );

    glEnable( GL_DEPTH_TEST );
    glClearColor( 1.0, 1.0, 1.0, 1.0 );
}

//----------------------------------------------------------------------
// SetUp_Lighting_Uniform_Vars(mat4 mv):
```


7

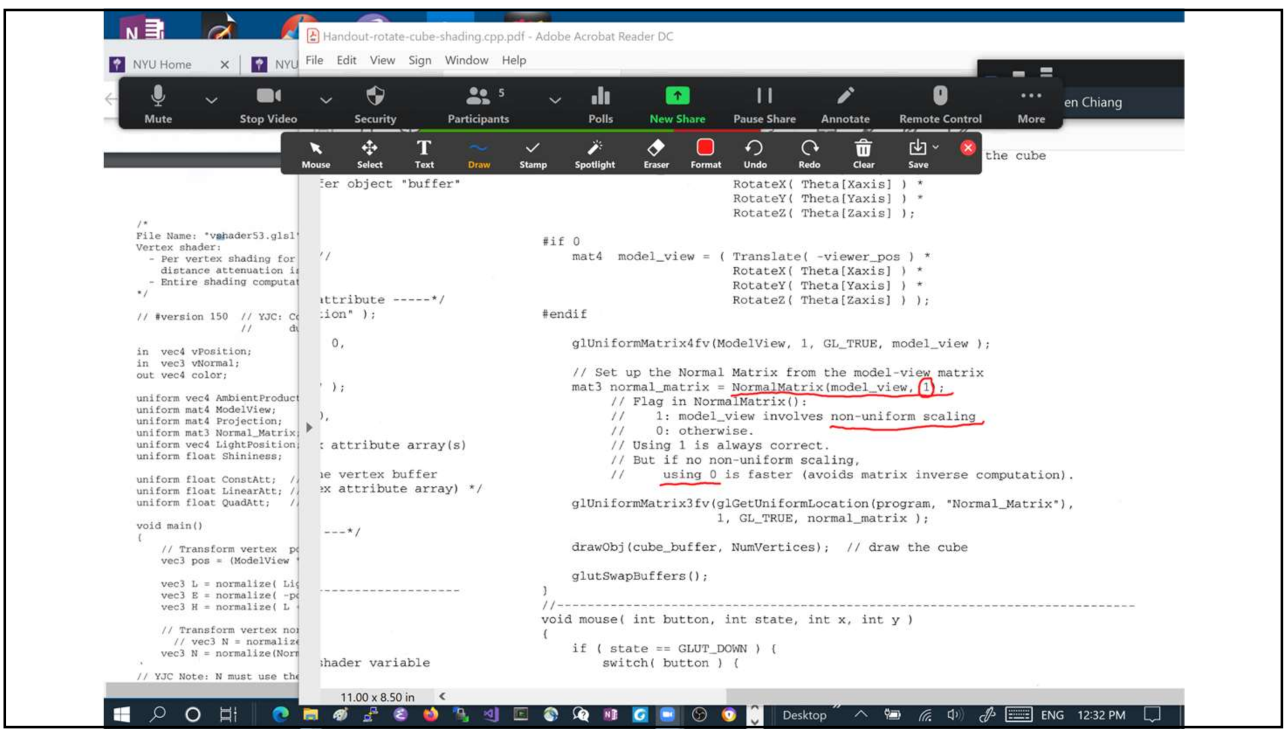


```
/*
File Name: "fshader53.glsl":
           Fragment Shader
*/

// #version 150  // YJC: Comment/un-comment this line to resolve compilation errors
                 //      due to different settings of the default GLSL version

in  vec4 color;
out vec4 fColor;

void main()
{
    fColor = color;
}
```


8


Handout-rotate-cube-shading.cpp.pdf - Adobe Acrobat Reader DC
File Edit View Sign Window Help
Mute Stop Video Security Participants Polls New Share Pause Share Annotate Remote Control More
Mouse Select Text Draw Stamp Spotlight Eraser Format Undo Redo Clear Save
/*
File Name: "vshader53.glsl";
Vertex shader:
- Per vertex shading for a single point light source;
distance attenuation is Yet To Be Completed.
- Entire shading computation is done in the Eye Frame.
*/
in vec4 vPosition;
in vec3 vNormal;
out vec4 color;
uniform vec4 AmbientProduct, DiffuseProduct, SpecularProduct;
uniform mat4 ModelView;
uniform mat4 Projection;
uniform mat3 Normal_Matrix;
uniform vec4 LightPosition; // Must be in Eye Frame
uniform float Shininess;
uniform float ConstAtt; // Constant Attenuation
uniform float LinearAtt; // Linear Attenuation
uniform float QuadAtt; // Quadratic Attenuation
void main()
// Transform vertex position into eye coordinates
vec3 pos = (ModelView * vPosition).xyz;
vec3 L = normalize(LightPosition.xyz - pos);
vec3 E = normalize(-pos);
vec3 H = normalize(L + E);
// Transform vertex normal into eye coordinates
vec3 N = normalize(Normal_Matrix * vNormal);
// YJC Note: N must use the one pointing *toward* the viewer
glUniform1f(glGetUniformLocation(program, "LinearAtt"),
linear_att);
glUniform1f(glGetUniformLocation(program, "QuadAtt"),
quad_att);
glUniform1f(glGetUniformLocation(program, "Shininess"),
material_shininess);
// drawObj(buffer, num_vertices):
// draw the object that is associated with the vertex buffer object "buffer"
// and has "num_vertices" vertices.
void drawObj(GLuint buffer, int num_vertices)
//--- Activate the vertex buffer object to be drawn ---//
glBindBuffer(GL_ARRAY_BUFFER, buffer);
/*----- Set up vertex attribute arrays for each vertex attribute -----*/
GLuint vPosition = glGetAttribLocation(program, "vPosition");
glEnableVertexAttribArray(vPosition);
glVertexAttribPointer(vPosition, 4, GL_FLOAT, GL_FALSE, 0,
BUFFER_OFFSET(0));
GLuint vNormal = glGetAttribLocation(program, "vNormal");
glEnableVertexAttribArray(vNormal);
glVertexAttribPointer(vNormal, 3, GL_FLOAT, GL_FALSE, 0,
BUFFER_OFFSET(sizeof(points)));
// the offset is the (total) size of the previous vertex attribute array(s)
/* Draw a sequence of geometric objs (triangles) from the vertex buffer
11.00 x 8.50 in

9


Handout-rotate-cube-shading.cpp.pdf - Adobe Acrobat Reader DC
File Edit View Sign Window Help
Mute Stop Video Security Participants Polls New Share Pause Share Annotate Remote Control More
Mouse Select Text Draw Stamp Spotlight Eraser Format Undo Redo Clear Save
RotateX(Theta[Xaxis]) *
RotateY(Theta[Yaxis]) *
RotateZ(Theta[Zaxis]);
#if 0
mat4 model_view = (Translate(-viewer_pos) *
RotateX(Theta[Xaxis]) *
RotateY(Theta[Yaxis]) *
RotateZ(Theta[Zaxis]));
#endif
glUniformMatrix4fv(ModelView, 1, GL_TRUE, model_view);
// Set up the Normal Matrix from the model-view matrix
mat3 normal_matrix = NormalMatrix(model_view, 1);
// Flag in NormalMatrix():
// 1: model_view involves non-uniform scaling
// 0: otherwise.
// Using 1 is always correct.
// But if no non-uniform scaling,
// using 0 is faster (avoids matrix inverse computation).
glUniformMatrix3fv(glGetUniformLocation(program, "Normal_Matrix"),
1, GL_TRUE, normal_matrix);
drawObj(cube_buffer, NumVertices); // draw the cube
glutSwapBuffers();
void mouse(int button, int state, int x, int y)
if (state == GLUT_DOWN) {
switch(button) {
11.00 x 8.50 in
Desktop ENG 12:32 PM

10

* Normal Matrix

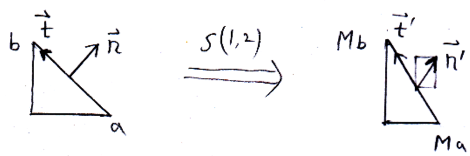
* Typically we perform shading computation in the (eye frame) (i.e. the right-handed eye frame where the eye/camera is at the origin looking at the $-z$ direction. This is the frame obtained by applying LookAt( ) to the world frame)

Let $\vec{t}$ be the tangent at pt p being shaded.
$\vec{n}$ " normal "

$\vec{n}, \vec{t}$ are in the model frame
M the model-view matrix
i.e. Mp puts p in the eye frame

(1) Suppose M involves (non-uniform scaling) (i.e. scaling factors in x-, y-, z- dimensions are different)

e.g. $S(1,2)$ in 2D



$$\vec{t'} = Mb - Ma = M(b-a) = M\vec{t} \text{ is the tangent after transformation}$$

i.e. We can still apply M to $\vec{t}$ to obtain the new tangent $\vec{t'}$ correctly.

But applying M to $\vec{n}$ does NOT give the correct normal vector. (since $\vec{n'}$ is NOT perpendicular to $\vec{t'}$)

(2) Deriving the correct matrix for normal vector: the (normal matrix)

Let $\vec{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \\ 0 \end{bmatrix}$ $\quad \vec{n} \cdot \vec{t} = 0$ $\quad$ The dot product can be expressed as matrix multiplication:

$$\underbrace{\vec{n} \cdot \vec{t} = [\quad]\begin{bmatrix} \\ \end{bmatrix} = (\vec{n})^t \vec{t}}_{=0} \text{ —— } (*)$$

($(\vec{n})^t$: transpose of $\vec{n}$ = $[\ ]$)

From $(*)$ we have
$$0 = (\vec{n})^t \vec{t} = \underbrace{((\vec{n})^t M^{-1})(M}_{= I}\vec{t}) \text{ —— } (**)$$

But $M = \begin{bmatrix} \ell & T \\ 0 & 1 \end{bmatrix}$ and the 4-th component of $\vec{t}$ is 0 $\Rightarrow$ We can ignore the 4th column of M. i.e. $\begin{bmatrix} T \\ 1 \end{bmatrix} = \begin{bmatrix} T_x \\ T_y \\ T_z \\ 1 \end{bmatrix}$

$\Rightarrow$ Then the 4th row of the remaining columns are 0 and can be ignored

$\therefore$ In $(**)$ we can use ℓ to replace M:

$$\underbrace{((\vec{n})^t \ell^{-1})}_{(\vec{x})^t}\underbrace{(\ell \vec{t})}_{=\text{transformed tangent } \vec{t'}} = 0$$

$(\vec{x})^t$ where $\vec{x}$ is the transformed normal, in the form of $(*)$:

$\therefore$ $(\vec{x})^t = (\vec{n})^t \ell^{-1} \Rightarrow \vec{x} = \left[(\vec{n})^t \ell^{-1}\right]^t = (\ell^{-1})^t (\vec{n})$

cf: In $(*)$: $(\vec{n})^t \vec{t} = 0$
Here: $(\vec{x})^t \vec{t'} = 0$.

$\Rightarrow$ Desired normal $\vec{x}$ is obtained by $N \overbrace{\begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}}^{\vec{n}}$ where the 3×3 matrix N (normal matrix) is $(\ell^{-1})^t$

Simplification:

(scaling factors in x-, y-, z-dim are all the same)

(3) If M only involves translations, rotations, uniform scaling, and LookAt( )

then: translations have no effect on ℓ
LookAt( ) has translation and rotation
$\Rightarrow$ ℓ only involves rotations and uniform scaling.

But uniform scaling has no effect after we normalize the transformed normal vector

$\Rightarrow \ell \equiv R$. But $R^{-1} = R^t$

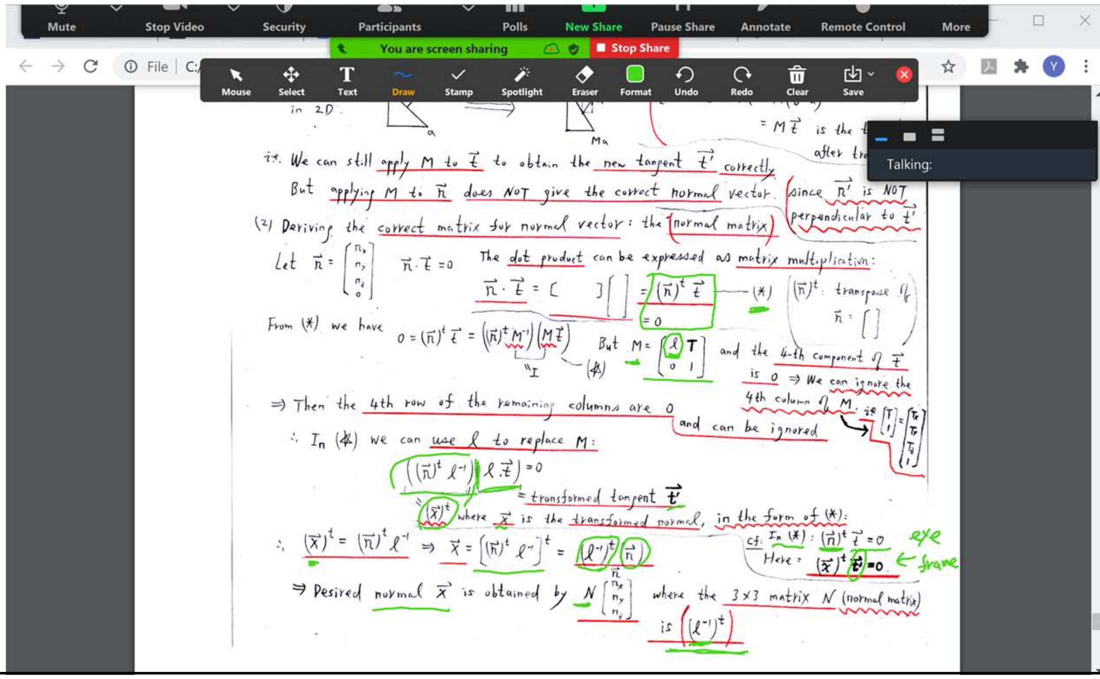
$\therefore (\ell^{-1})^t \equiv (R^{-1})^t = (R^t)^t = R \equiv \ell$

ie We can use (ℓ) to replace $(\ell^{-1})^t$ ①

(ie We can use the model-view matrix M (4x4) to apply to normal ② $\vec{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \\ 0 \end{bmatrix}$ 4 components)

① ≡ ②

Screenshot for Elaboration:



11

New Topic: Compositing Techniques

Recall:
* Fragments : generated by the rasterization of geometric primitives (polygons, etc.)
  Each fragment corresponds to a single pixel

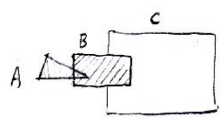
* Compositing Techniques : compositing, α-blending
  * How do we model transparent objects? — the alpha channel

    RGBA (RGBα) color : (r, g, b, α) → opacity : 1 opaque ↕ 0 transparent

    (transparency = $1-\alpha$)

  * α value controls how the RGB values are written to the frame buffer

    eg.



    B is opaque, blocking C in the overlapped portion.
    A is transparent, the portion overlapped with B is blended with the color of B (blending the colors of A & B)

    * Many fragments, each coming from a different object, may correspond to the same pixel ⇒ each such fragment contributes to the color of the pixel;
      the final color of the pixel is obtained by (blending) the fragment colors;
      The corresponding objects are (blended) or (composited) together

* When a polygon is processed, pixel-size fragments are computed.
  The fragments are assigned colors based on the shading model used.

  Regard the fragment as the (source pixel)
  the frame-buffer pixel as the (destination pixel)

  Previously : z-buffer, opaque : source pixel is closer to viewer ⇒ source pixel (replaces) the destination pixel
  destination pixel : ⇒ source pixel is (blocked) no action.

  Now : blend the source and destination pixels in various ways color of source pixel: $s = [s_r \; s_g \; s_b \; s_a]$ source blending factor $b = [b_r \; b_g \; b_b \; b_a]$

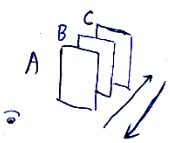
destination : $d = [d_r \; d_g \; d_b \; d_a]$, destination : $c = [c_r \; c_g \; c_b \; c_a]$

* $\boxed{d' \leftarrow bs + cd.}$

compositing : replace d with $d' = [b_r s_r + c_r d_r \quad b_g s_g + c_g d_g \quad b_b s_b + c_b d_b \quad b_a s_a + c_a d_a]$

the resulting r, g, b, a values are clamped to $[0.0, 1.0]$ $\left(\begin{array}{l} \geq 1 \Rightarrow 1.0 \\ \leq 0 \Rightarrow 0.0 \end{array} \right)$

"Over" operation : back-to-front.



$$\begin{cases} C_{d'} = \alpha_s C_s + \underbrace{(1-\alpha_s)}_{\text{transparency.}} C_d \\ \alpha_{d'} = \alpha_s + (1-\alpha_s)\alpha_d. \end{cases}$$

transparency. the fraction that the "behind color" survives

Depth Cueing and Fog

* Depth Cueing : create illusion of depth by drawing objects farther from the viewer dimmer

** $\boxed{\text{See Handout for full details}}$ ← (A over (B over C)) : back to front
((A over B) over C) : front to back.

* Fog Effect : extend depth cueing.

create the illusion of partially translucent space (fog) between the object and the viewer, by blending in a (distance-dependent color) as each fragment is processed

f : fog factor, given by the fog equation $f(z)$, $(f = f(z))$

C_s : fragment color

C_f : fog color

z : distance between a (fragment) being rendered and the (viewer) given in the (eye coordinates)

(** Note: The Handout for the ``Over'' operation has been posted at NYU Brightspace:
``Handouts -> CS4533_Over-Op-Associativity.pdf'')

Resulting color : $C_{s'} = f\, C_s + (1-f)\, C_f$ — (*)

fog-mode	fog equation $f(z) = f$	
linear fog	$f = \dfrac{end - z}{end - start}$	linear, depth-cueing effect.
exponential fog	$f = e^{-(density \cdot z)}$	exponential } fog effect
exponential square fog	$f = e^{-(density \cdot z)^2}$	Gaussian } fog effect

* f specified is clamped to $[0,1]$ and then used in (*) to compute $C_{s'}$

o From fog equation:
$z \uparrow \quad f \downarrow$ (f is clamped to $[0,1]$)
Plug in f into (*)
$\Rightarrow$ C_f has more weight
i.e. when object is farther ($z \uparrow$)
we see more of the fog color (C_f).