# CS4533 Lecture 11 Slides/Notes

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

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* **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

http://cse.poly.edu/cs653/Rotate-Cube-Shading.tar.gz;

PDF file listing of the major files has been posted at

``NYU Classes -> Resources -> PDF Listing of Sample Code Major Files -> Handout-rotate-cube-shading.cpp.pdf'')

- Some screenshots of the sample program PDF with annotations are then shown next.
- Watched demo videos at ``NYU Classes -> Media Gallery'': ``Demo-Rotate-Cube-Shading'' and ``Demo-HW3-Parts-c-d''.

* **Then we discussed a new topic: Composition Techniques.**

Overall formula:

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

global ambient light

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

$(r \cdot v)$ replaced with $(n \cdot h)$

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

① $(\text{Attenuation})_i = 1$

② vector $\ell$ (from pt $p$ to light source $i$) $= -(\text{distant light direction } L)$

i.e. $\ell = -L$ (Also, use this $\ell$ to compute $h = \text{normalize}(\ell + v)$)

$L$ $\quad \ell = -L$

(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

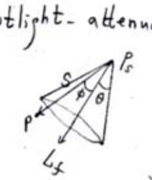
(3) If light $i$ is a spotlight then

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

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

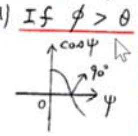
② $(\text{spotlight\_attenuation})_i = ?$




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

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

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




In the range $[0, 90°]$

$\phi > \theta \iff \cos\phi < \cos\theta$
$\iff (L_f \cdot S) < \cos\theta$
$\iff L_f \cdot (-\ell) < \cos\theta$

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

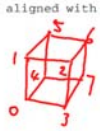
(b) Else,

$(\text{spotlight\_attenuation})_i = (\cos\phi)^e$
$= [L_f \cdot (-\ell)]^e$

$e$: spotlight exponent

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

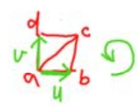
```
#include "Angel-yjc.h"

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 );
```

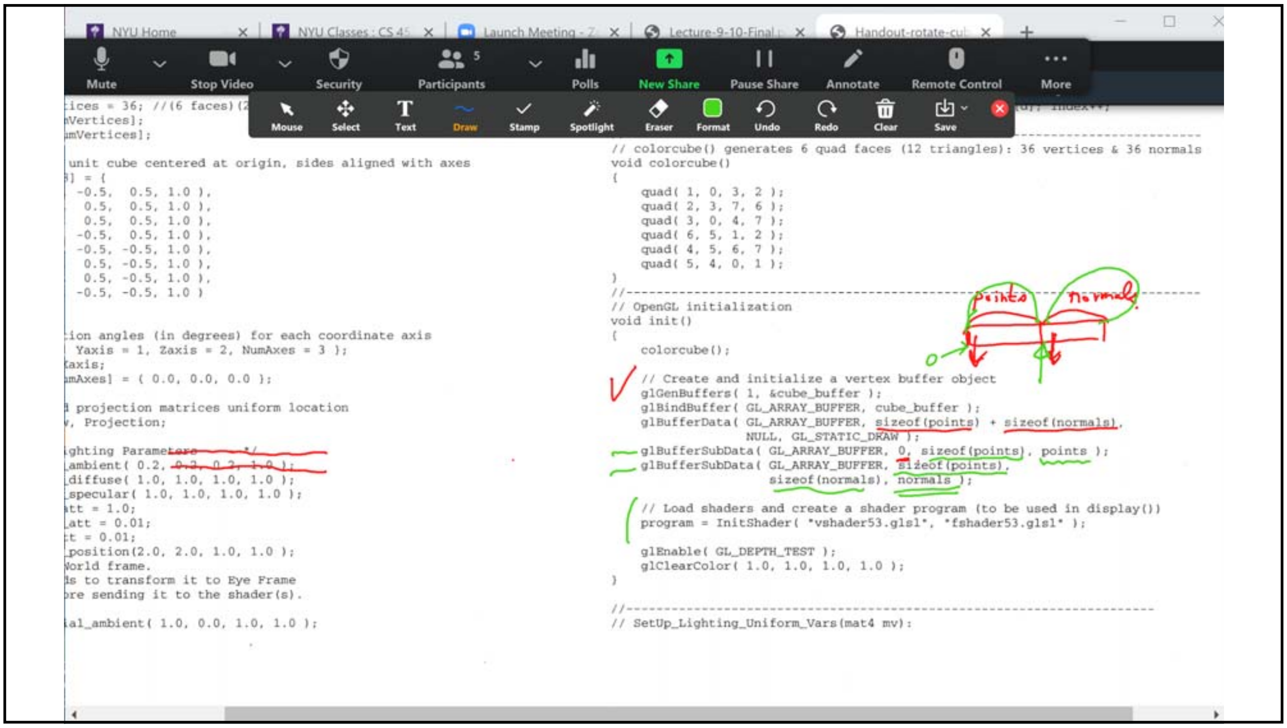



```
//         to the vertices
void quad( int a, int b, int c, int d )
{
    // Initialize temporary vectors along the quad's edges tc
    //   compute its face normal
    vec4 u = vertices[b] - vertices[a];
    vec4 v = vertices[d] - vertices[a];

    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 );
```

```
 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;
ta] = { 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++;  )
    normals[Index] = normal; points[Index] = vertices[b]; Index++;  ) △abc
    normals[Index] = normal; points[Index] = vertices[c]; Index++;  )
    normals[Index] = normal; points[Index] = vertices[a]; Index++;  )
    normals[Index] = normal; points[Index] = vertices[c]; Index++;  ) △acd
    normals[Index] = normal; points[Index] = vertices[d]; Index++;  )
}
//-----------------------------------------------------------------
// colorcube() generates 6 quad faces (12 triangles): 36 vertices & 36 normals
void colorcube()
{                                 ccw
    quad( 1, 0, 3, 2 );                     normal vector is
    quad( 2, 3, 7, 6 );   as before.      pointing outward.
    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
```

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ices = 36; //(6 faces)(2
nVertices];
mVertices];
unit 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 ),
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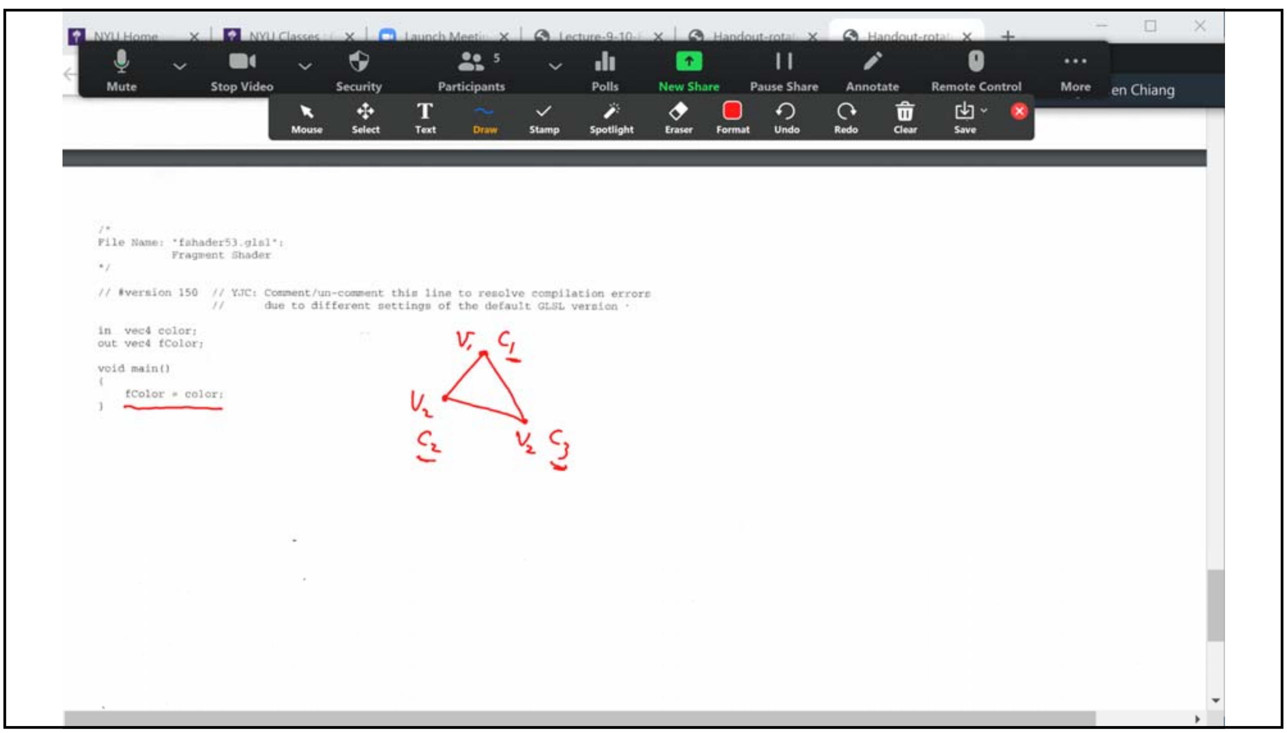
-0.5, -0.5, 1.0 ),
0.5, -0.5, 1.0 ),
0.5, -0.5, 1.0 ),
-0.5, -0.5, 1.0 )
ion angles (in degrees) for each coordinate axis
Yaxis = 1, Zaxis = 2, NumAxes = 3 };
axis;
mAxes] = { 0.0, 0.0, 0.0 };
projection matrices uniform location
, Projection;
ghting Parameters */
ambient( 0.2, 0.2, 0.2, 1.0 );
diffuse( 1.0, 1.0, 1.0, 1.0 );
specular( 1.0, 1.0, 1.0, 1.0 );
tt = 1.0;
att = 0.01;
t = 0.01;
position(2.0, 2.0, 1.0, 1.0 );
World frame.
s to transform it to Eye Frame
re sending it to the shader(s).
al_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):
points
normals
0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Pause Share
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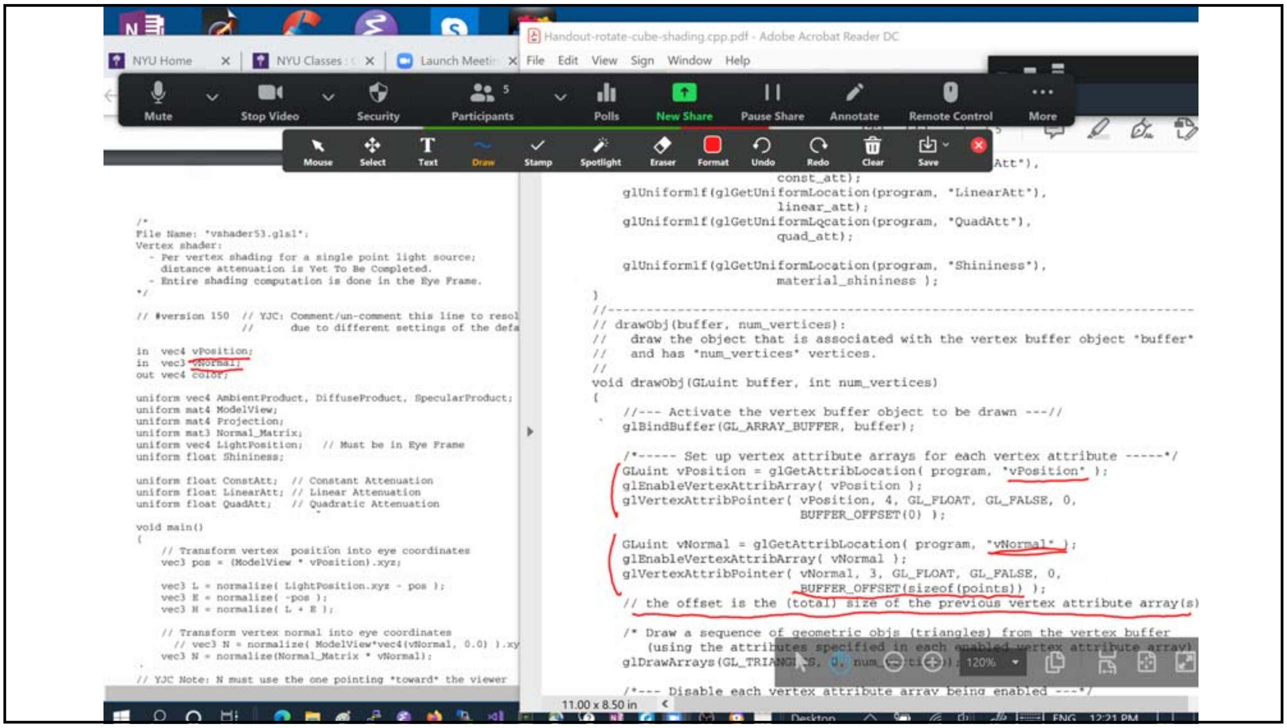
en Chiang
Mouse
Select
Text
Draw
Stamp
Spotlight
Eraser
Format
Undo
Redo
Clear
Save
/*
File Name: "fshader53.glsl":
Fragment Shader
*/
// #version 150 // YJC: Comment/un-comment this line to resolve compilation errors
// due to different settings of the default GLSL version
in vec4 color;
out vec4 fColor;
void main()
{
fColor = color;
}
V1 C1
V2 C2
V3 C3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Remote Control
More
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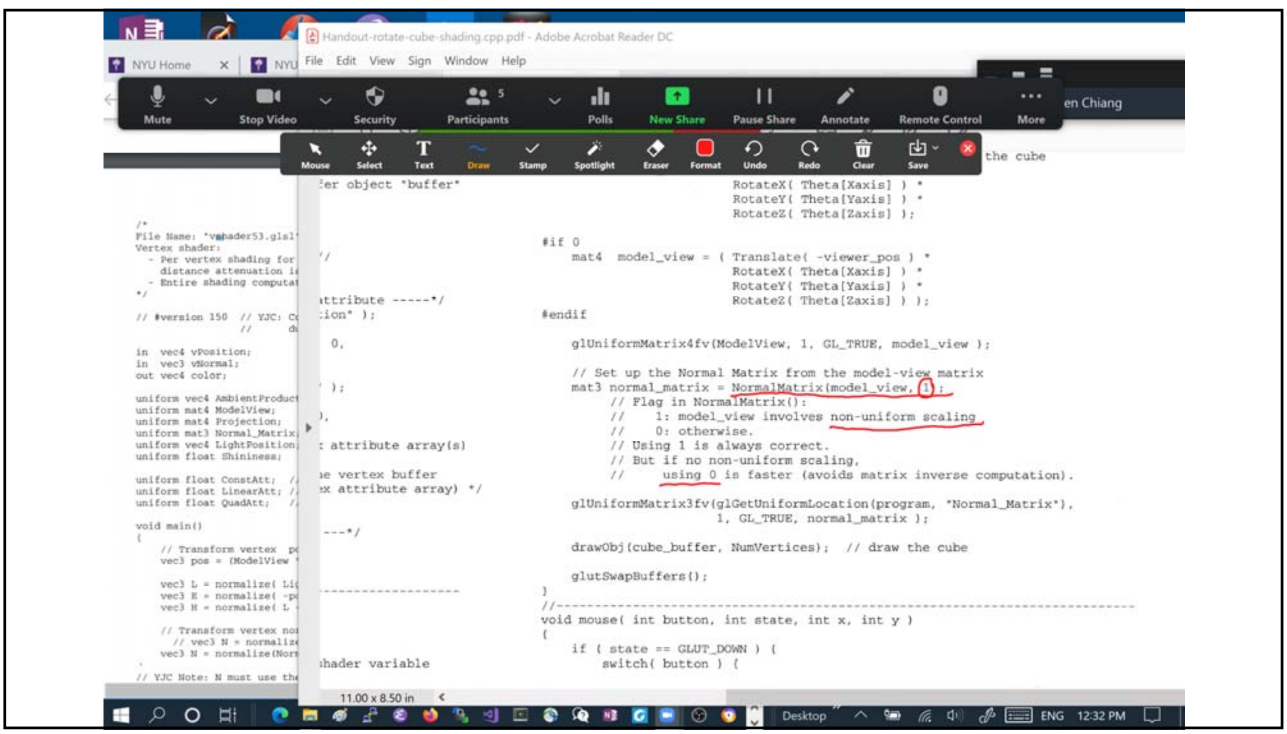
Select
Text
Draw
Stamp
Spotlight
Eraser
Format
Undo
Redo
Clear
Save
/*
File Name: "vshader53.glsl":
Vertex shader:
- Per vertex shading for a single point light source;
distance attenuation is Yet To Be Completed.
- Entire shading computation is done in the Eye Frame.
*/
// #version 150 // YJC: Comment/un-comment this line to resol
// due to different settings of the defa
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( ModelView*vec4(vNormal, 0.0) ).xy
vec3 N = normalize(Normal_Matrix * vNormal);
// YJC Note: N must use the one pointing *toward* the viewer
const_att);
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
(using the attributes specified in each enabled vertex attribute array)
/*--- Disable each vertex attribute array being enabled ---*/
11.00 x 8.50 in
120%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Stamp
Spotlight
Eraser
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Redo
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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

## * Normal Matrix

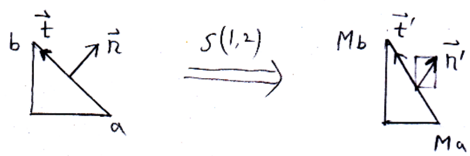
* Typically we perform shading computation in the (eye frame) (i.e. the right-handed eye frame where the eye/camera is at the origin looking at the $-z$ direction. This is the frame obtained by applying LookAt() to the world frame)

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




$$\vec{t'} = Mb - Ma = M(b-a) = M\vec{t}$$ 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 $\vec{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \\ 0 \end{bmatrix}$ $\quad \vec{n} \cdot \vec{t} = 0$

The dot product can be expressed as matrix multiplication:

$$\vec{n} \cdot \vec{t} = [\quad][\quad] = (\vec{n})^t \vec{t} \text{ ---- } (*)$$
$$= 0$$

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

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

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 $(\divideontimes)$ we can use $\ell$ to replace $M$:

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

$(\vec{x})^t$ 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 $N \overset{\vec{n}}{\begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}}$ where the $3 \times 3$ matrix $N$ (normal matrix) is $\left((\ell^{-1})^t\right)$

## 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 $\ell$
LookAt( ) has translation and rotation
$\Rightarrow$ $\ell$ only involves rotations and uniform scaling

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

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

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

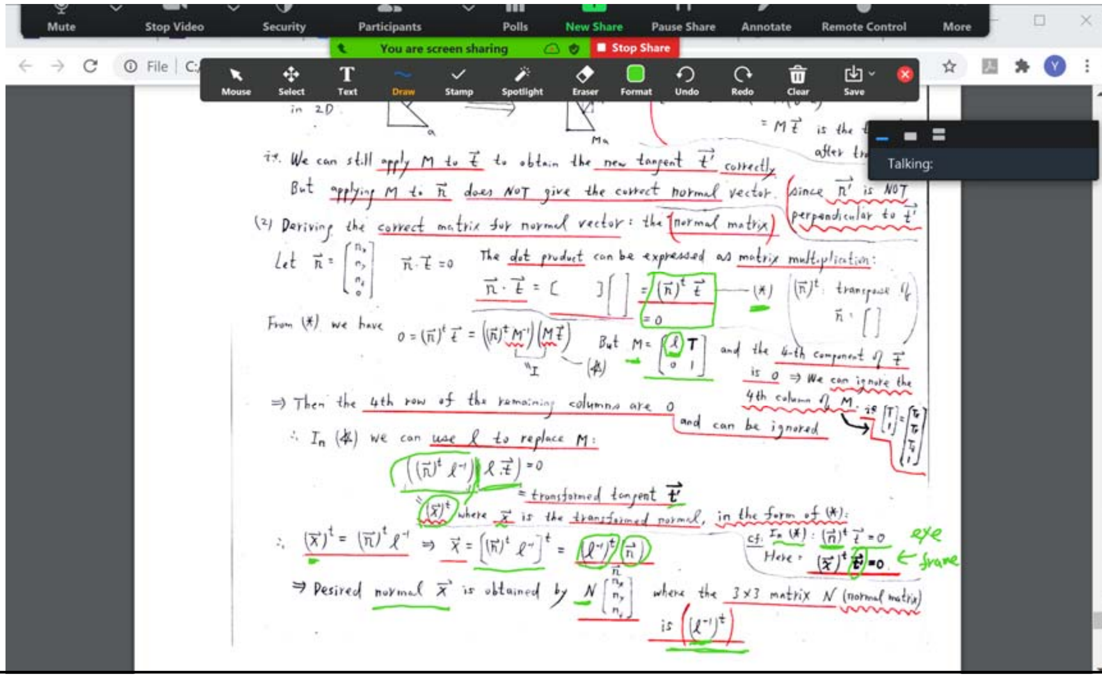
ie ① We can use ($\ell$) to replace $(\ell^{-1})^t$

4 components

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

① ≡ ②

**Screenshot for Elaboration:**



# 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, $\alpha$-blending

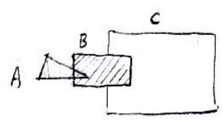
  * How do we model transparent objects? — the alpha channel

    RGBA (RGB$\alpha$) color : $(r, g, b, \alpha)$ → opacity : 1 opaque ↕ 0 transparent

    (transparency $= 1-\alpha$)

  * $\alpha$ value controls how the RGB values are written to the frame buffer

    e.g.




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 $b = [b_r \ b_g \ b_b \ b_a]$

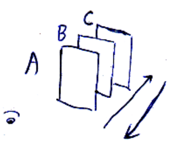
destination ": $d = [d_r \ d_g \ d_b \ d_a]$, destination ": $c = [c_r \ c_g \ c_b \ c_a]$

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

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.



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

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 is posted at NYU Classes:
``Resources -> 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 $[0,1]$)

Plugging $f$ into (*)

$\Rightarrow$ $C_f$ has more weight

i.e. when object is farther ($z \uparrow$)

we see more of the fog color ($C_f$)