Camera in OpenGL

Computer Graphics
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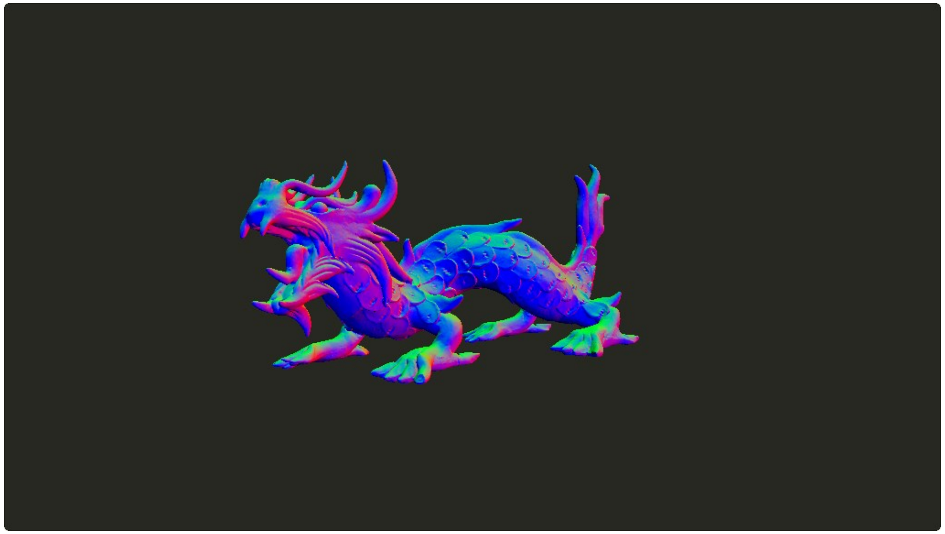
Today

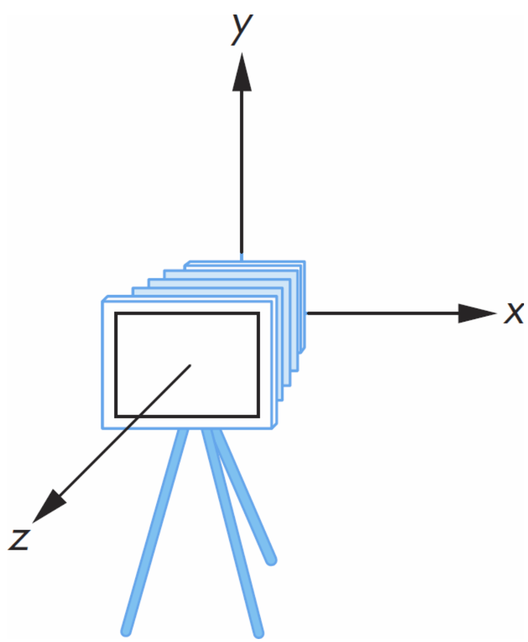
- **Viewing and Projection in OpenGL**
  - How to implement look_at() and perspective() functions.
  - The full details are covered in the theory lecture.
- **Virtual Trackball**
  - How to implement mouse-based interaction
- **Virtual Trackball Extension**
  - Hints for panning and zooming

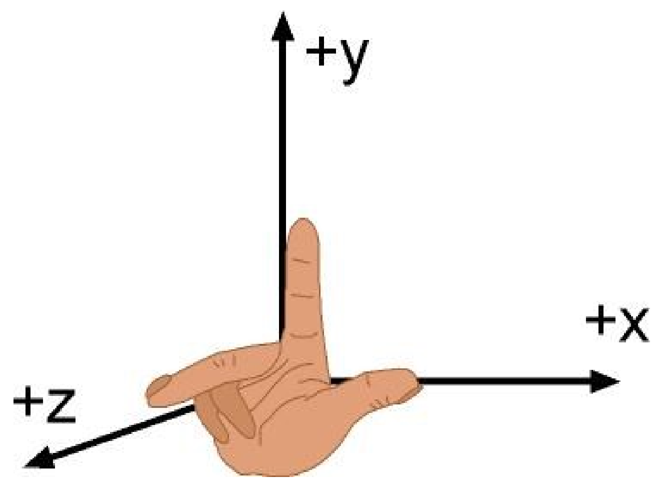


Prerequisites Revisited

Recall: OpenGL Default Camera

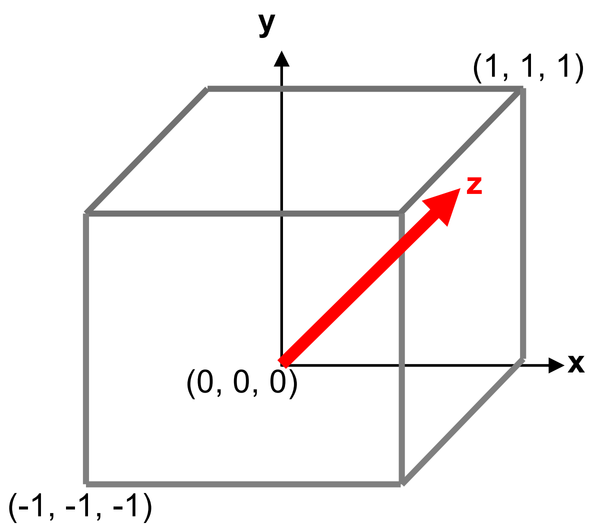
- **Located at origin and directs in the negative z direction.**
  - camera coordinate systems (frames) use RHS convention.
  - Initially the object and camera frames are identical.
  - Default model-view matrix is an identity.





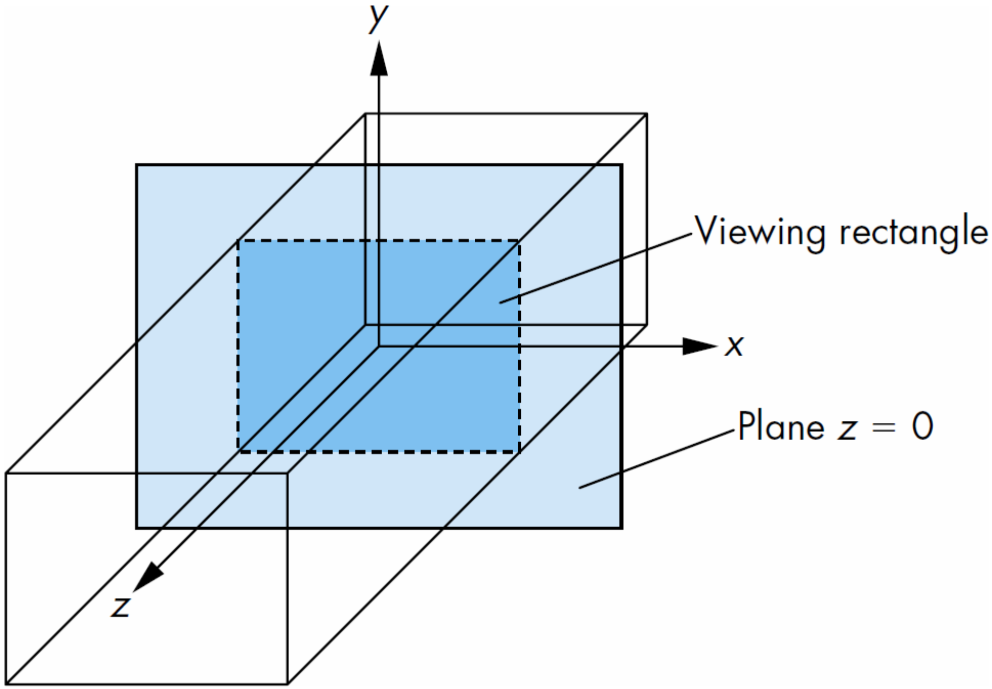
Recall: Canonical View Volume in NDC

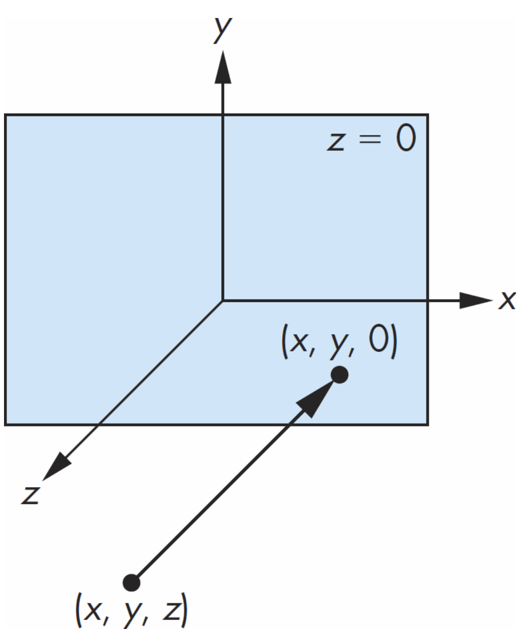
- **Canonical view volume in normalized device coordinates:**
  - Default view volume: cube with sides of length 2 centered at the origin
    - $right = top = far = 1$
    - $left = bottom = near = -1$
  - Default projection matrix is an identity matrix.
    - However, we need to negate z for correct depth test.



OpenGL Default Camera

- **Default projection:**
  - ***orthographic projection*** to $z = 0$ (but, actually we don't set z=0)
  - Objects outside the default view volume get invisible (clipped out).





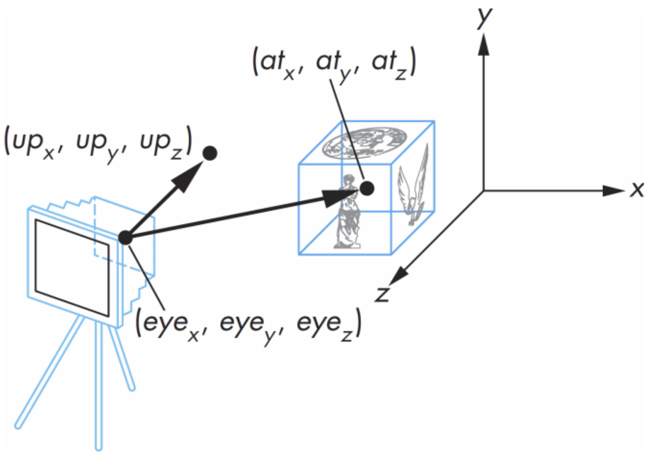
Viewing in OpenGL

Recall: look_at() Method

- **look_at () method**

```
mat4 look_at(eye, at, up)
```

- **Viewing specification with (eye, at, up)**
  - eye: a camera's location
  - at: the center of the destination position to be viewed
  - up: upward direction of the camera frame



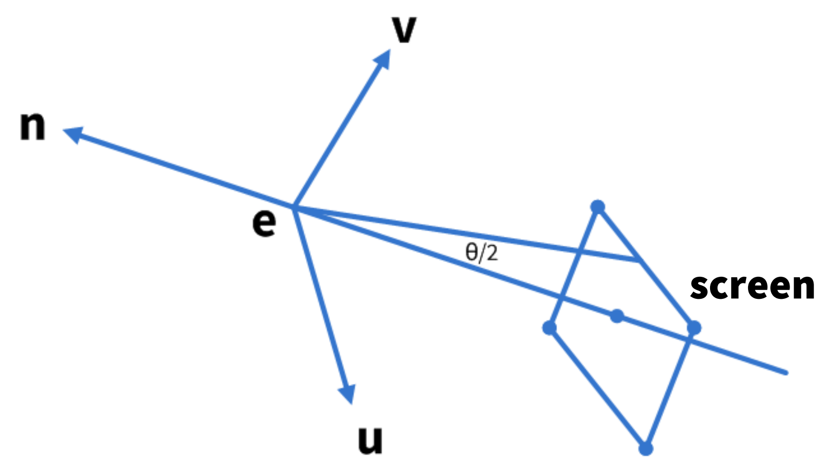
Recall: look_at() Method

- **eye, at, and up can define a camera *frame*, which has**
  - the origin at eye
  - three basis vectors, $\boldsymbol{n}$, $\boldsymbol{u}$, and $\boldsymbol{v}$, defined as:
- **Thus, the viewing transformation can be a *change of frame*,**
  - which changes from a world frame to a camera frame.
  - We can do the view transformation with $\mathbf{4 \times 4}$ **lookat matrix**.

$\boldsymbol{n}$ = normalize($\boldsymbol{eye} - \boldsymbol{at}$)

$\boldsymbol{u}$ = normalize($\boldsymbol{up} \times \boldsymbol{n}$)

$\boldsymbol{v}$ = normalize($\boldsymbol{n} \times \boldsymbol{u}$)



look_at() implementation

$$\mathbf{RT}(-eye) = \begin{bmatrix} u1 & u2 & u3 & 0 \\ v1 & v2 & v3 & 0 \\ n1 & n2 & n3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -eye.x \\ 0 & 1 & 0 & -eye.y \\ 0 & 0 & 1 & -eye.z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

```
static mat4 look_at( const vec3& eye, const vec3& at, const vec3& up )
{
    return mat4().set_look_at(eye, at, up);
}

mat4& set_look_at(vec3 eye, vec3 at, vec3 up)
{
    set_identity();
    // define camera frame.
    vec3 n = (eye - at).normalize();
    vec3 u = up.cross(n).normalize();
    vec3 v = n.cross(u).normalize();
    // calculate lookAt matrix: a combined form of RT(-eye)
    _11 = u.x;  _12 = u.y;  _13 = u.z;  _14 = -u.dot(eye);
    _21 = v.x;  _22 = v.y;  _23 = v.z;  _24 = -v.dot(eye);
    _31 = n.x;  _32 = n.y;  _33 = n.z;  _34 = -n.dot(eye);
    return *this;
};
```

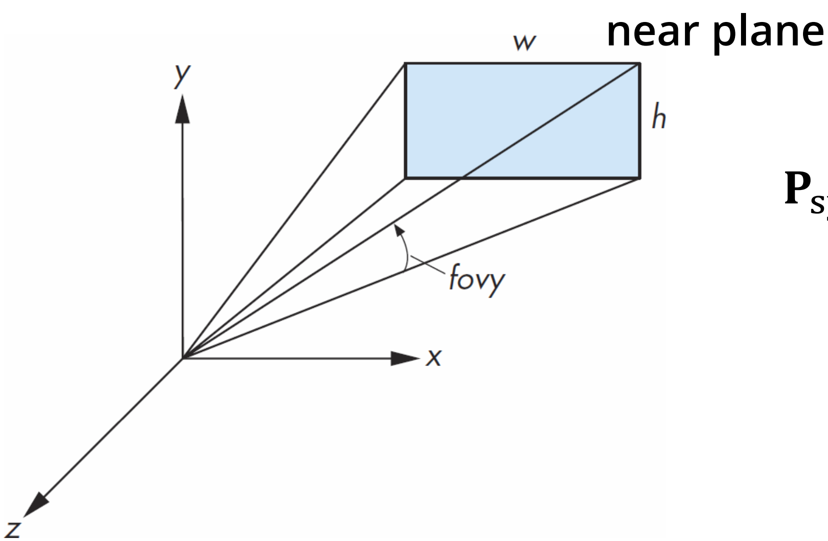
Perspective Projection in OpenGL

Perspective Projection in OpenGL

- **We can apply projection using matrix multiplication.**

```
mat4 perspective(fovy, aspect_ratio, near, far)
```

  - perspective() returns a matrix for symmetric perspective projection.
  - $fovy$ (field of view) and $aspect\_ratio$ (width/height of sensor/window):



$$\mathbf{P}_{\text{sym}} = \begin{bmatrix} \cot\left(\frac{fovx}{2}\right) & 0 & 0 & 0 \\ 0 & \cot(\frac{fovy}{2}) & 0 & 0 \\ 0 & 0 & \frac{n+f}{n-f} & \frac{2nf}{n-f} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

$$t = n * \tan(\frac{fovy}{2}) \qquad r = t * aspect\_ratio \qquad \cot\left(\frac{fovx}{2}\right) = \cot\left(\frac{fovy}{2}\right) / aspect\_ratio$$

perspective()

- **Note:**
  - We cannot use reserved ‘near’ and ‘far’ for variable names in C++.

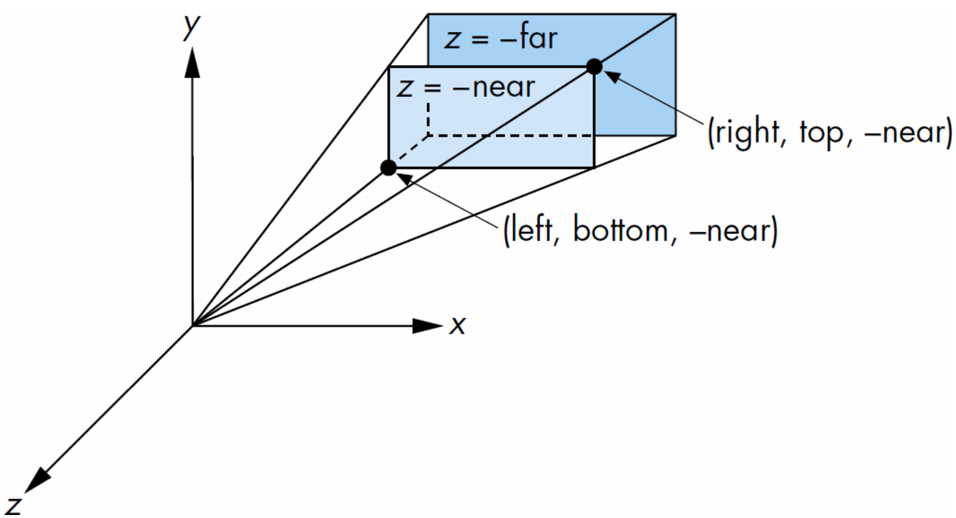
```
static mat4 perspective(float fovy, float aspect, float dnear, float dfar)
{
    return mat4().set_perspective(fovy, aspect, dNear, dFar);
}

mat4& set_perspective(float fovy, float aspect, float dnear, float dfar)
{
    set_identity();
    _22 = 1 / tan(fovy / 2.0f);
    _11 = _22 / aspect;
    _33 = (dnear + dfar) / (dnear - dfar);
    _34 = (2 * dnear * dfar) / (dnear - dfar);
    _43 = -1;
    _44 = 0;
    return *this;
}
```

frustum() for General Perspective Projection

- **The general perspective projection matrix**

```
mat4 frustum(left, right, bottom, top, near, far)
```

  - Parameters: r(right), l(left), b(bottom), t(top), n(near), f(far)



$$\mathbf{P} = \begin{bmatrix} \frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\ 0 & \frac{2n}{t-b} & \frac{t+b}{t-b} & 0 \\ 0 & 0 & \frac{n+f}{n-f} & \frac{2nf}{n-f} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

Camera in OpenGL: Programming Example

Example of Camera Structure

- **Structure for camera**

```
struct camera
{
    vec3 eye = vec3( 0, 30, 300 );  // position of camera.
    vec3 at = vec3( 0, 0, 0 );      // position where the camera looks at
    vec3 up = vec3( 0, 1, 0 );
    mat4 view_matrix;               // result of look_at function.

    float fovy = PI/4.0f;           // in radian
    float aspect_ratio;             // window_size.x / window_size.y
    float dnear = 1.0f;
    float dfar = 1000.0f;
    mat4  projection_matrix;
};
```

Update()

```
void update()
{
   // update projection matrix
   cam.aspect_ratio = window_size.x/float(window_size.y);
   cam.projection_matrix = mat4::perspective(
      cam.fovy, cam.aspect_ratio, cam.dnear, cam.dfar );
   camera.fovy = PI/6.0f;

   ...

   // update uniform variables in vertex/fragment shaders
   GLint uloc;
   uloc = glGetUniformLocation( program, "view_matrix" );
   if(uloc>-1) glUniformMatrix4fv( uloc,1,GL_TRUE, cam.view_matrix );
   uloc = glGetUniformLocation( program, "projection_matrix" );
   if(uloc>-1) glUniformMatrix4fv( uloc,1,GL_TRUE, cam.projection_matrix
);
}
```

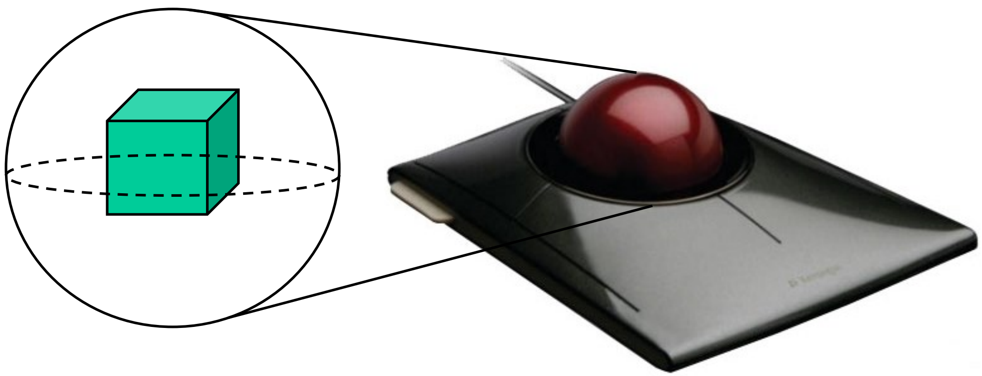
Vertex Shader: trackball.vert

```
// vertex attributes and output
in vec3 position;
in vec3 normal;
in vec2 texcoord;
out vec3 norm;

// matrices
uniform mat4 model_matrix;
uniform mat4 view_matrix;
uniform mat4 projection_matrix;

void main()
{
   vec4 wpos = model_matrix * vec4(position,1); // w: world
   vec4 epos = view_matrix * wpos; // e: eye or camera
   gl_Position = projection_matrix * epos;

   // pass eye-space normal to fragment shader
   norm = normalize(mat3(view_matrix*model_matrix)*normal);
}
```

Virtual Trackball

Physical Trackball

- **Trackball is an “upside down” mouse.**
  - Imagine the objects are rotated along with an imaginary sphere.

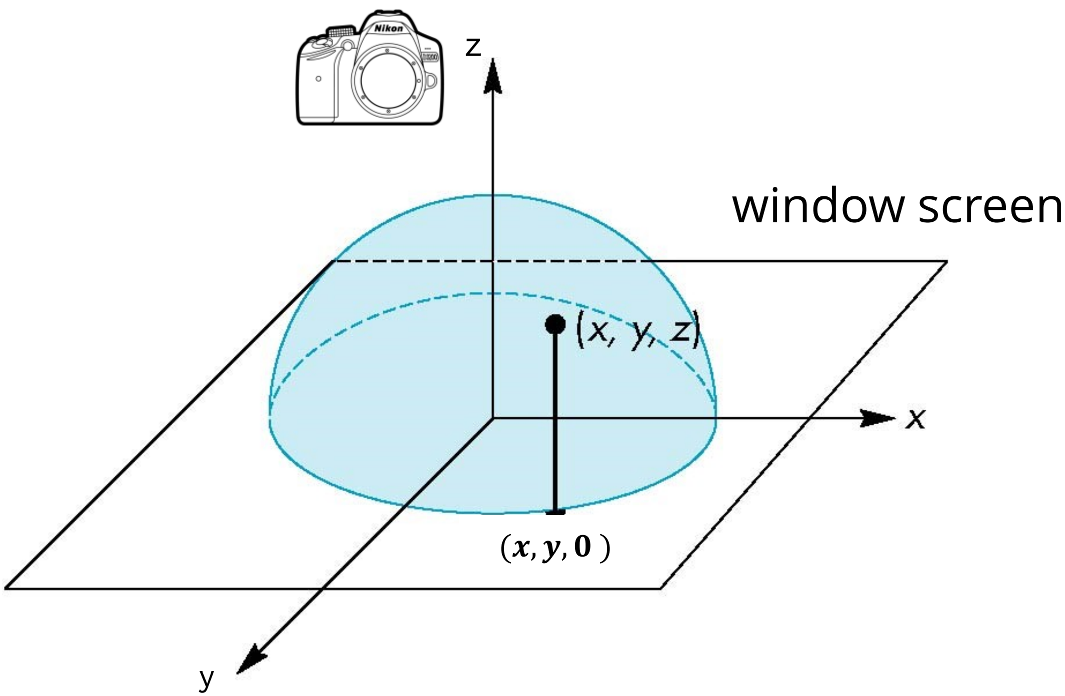


  - Allow a user to define 3D rotation using touch (mouse clicks) in window.
    - When the input occurs, the camera location is changed.

Virtual Trackball

- **A 2D point (x, y) on the window corresponds to:**
  - the 3D point (x, y, z) on the upper hemisphere where

$$r^2 = x^2 + y^2 + z^2$$
$$z = \sqrt{r^2 - x^2 - y^2}, \quad \text{if} \quad r \geq |x|, |y| \geq 0$$



Virtual Trackball Source Code

- **Class for virtual trackball**
  - Here's an interface for trackball class.

```
struct trackball
{
   bool    b_tracking = false;
   float   scale;         // controls how much rotation is applied
   mat4    view_matrix0; // initial view matrix
   vec2    m0;            // the last mouse position

    trackball( float rot_scale=1.0f ):scale(rot_scale){}
    bool is_tracking() const { return b_tracking; }

    void begin( const mat4& view_matrix, vec2 m );
    void end();
    void update( vec2 m );
}
```

Callback: mouse()

- **mouse():**
  - When the button is pressed, call begin(). Otherwise call end().
  - Retrieve a mouse position, and pass to tb.begin() with view matrix.

```
void mouse( GLFWwindow* window, int button, int action, int mods )
{
    if(button==GLFW_MOUSE_BUTTON_LEFT)
    {
        dvec2 pos; glfwGetCursorPos(window,&pos.x,&pos.y);
        vec2 npos = cursor_to_ndc( pos, window_size );

        if(action==GLFW_PRESS) tb.begin( cam.view_matrix, npos );
        else if(action==GLFW_RELEASE) tb.end();
    }
}
```

cursor_to_ndc()

- **cursor_to_ndc():**
  - Converts a position in window coordinates to normalized coordinates.
  - Here, we first normalize to $[0,1]^2$

```
vec2 cursor_to_ndc( dvec2 cursor, ivec2 window_size )
{
    // normalize window pos to [0,1]^2
    vec2 npos = vec2( float(cursor.x)/float(window_size.x-1),
                      float(cursor.y)/float(window_size.y-1) );
    ...
```

cursor_to_ndc()

- **cursor_to_ndc():**
  - Vertical flipping is applied while normalizing to [-1,1]^2
    - Window/GLFW systems define y from top to bottom, while our virtual trackball (and OpenGL) defines y from bottom to top

```
vec2 cursor_to_ndc( dvec2 cursor, ivec2 window_size )
{
    ...

    // normalize window pos to [-1,1]^2 with vertical flipping
    // vertical flipping: window coordinate system defines y from
    // top to bottom, while the trackball from bottom to top
    return vec2(npos.x*2.0f-1.0f,1.0f-npos.y*2.0f);
}
```

Virtual Trackball Source Code

- **Methods for trackball class**
  - At `begin()`, we mark we are tracking the mouse movements.
  - Also, we record the initial mouse position and view matrix.

```
void begin( const mat4& view_matrix, vec2 m )
{
    b_tracking = true;              // enable trackball tracking
    m0 = m;                         // save current mouse position
    view_matrix0 = view_matrix;     // save current view matrix
}
```

  - At `end()`, we just disable tracking, and do not need to touch others.

```
void end(){ b_tracking = false; }
```

Callback: `motion()`

- **motion():**
  - if not tracking, return
  - otherwise, calls update() when tracking

```
void motion( GLFWwindow* window, double x, double y )
{
   if(!tb.is_tracking()) return;
   vec2 npos = cursor_to_ndc( dvec2(x,y), window_size );
   cam.view_matrix = tb.update( npos );
}
```

Virtual Trackball Source Code

- **update():**

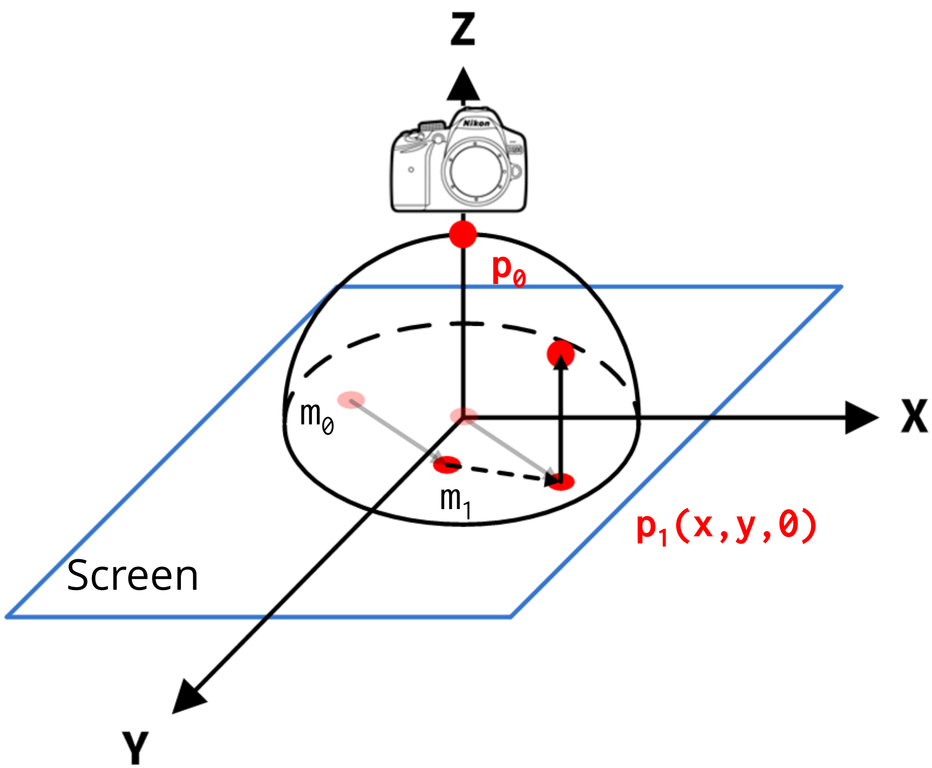
```
mat4 update( vec2 m )
{
   // project a 2D mouse position to a unit sphere
   vec3 p0 = vec3(0,0,1.0f);  // reference position on sphere
   vec3 p1 = vec3(m-m0,0);    // displacement
```

  - We then define the reference point `p0` on the virtual sphere.
  - Then, define `p1` as a displacement of mouse position.

Virtual Trackball Source Code

- **update():**
  - Visualization of p0 and p1 on the unit sphere

```
vec3 p0 = vec3(0,0,1.0f);   // reference position on sphere
vec3 p1 = vec3(m-m0,0);     // displacement
```



Virtual Trackball Source Code

- **update():**
  - Then, we detect a subtle/trivial movement, and ignore it.

```
// ignore subtle movement
if( !b_tracking || length(p1)<0.001f ) return view_matrix0;
...
```

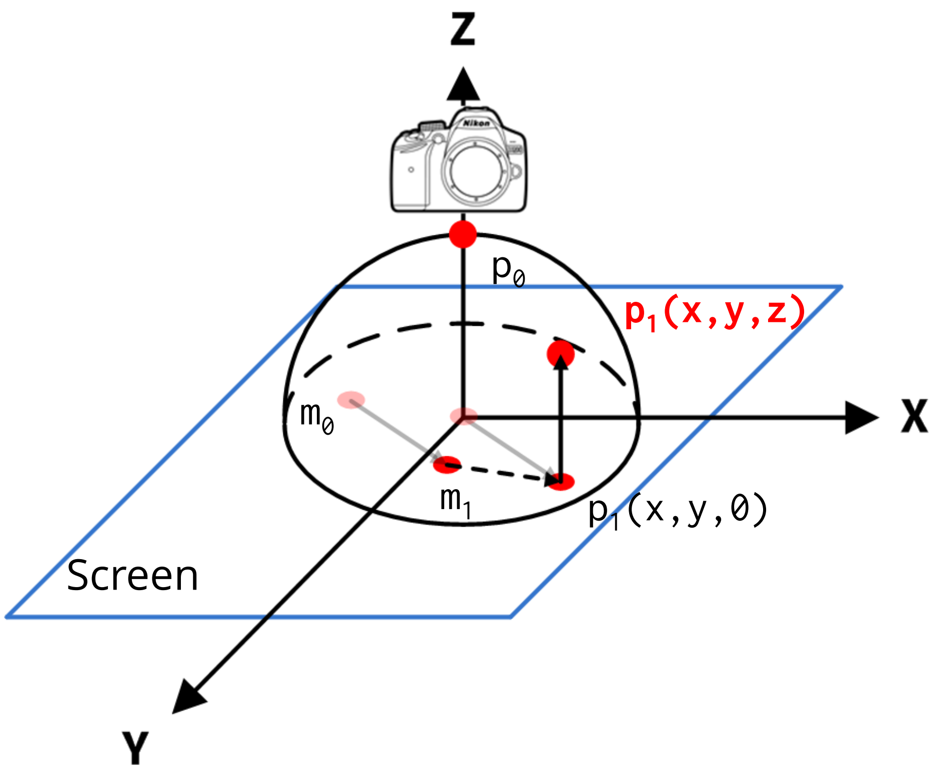
  - Then, apply rotational scale

```
// apply rotation scale
p1 *= scale;
```

Virtual Trackball Source Code

- **update():**
  - Then, back-project z=0 to the unit sphere.

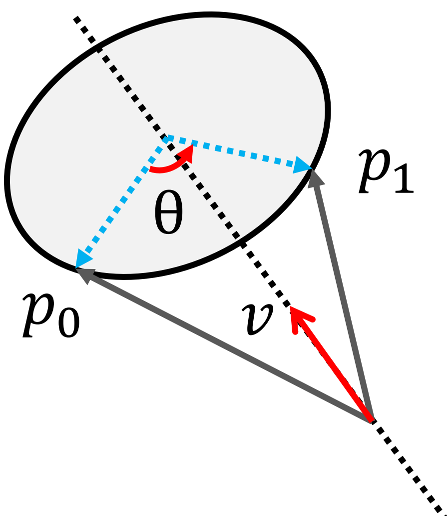
```
// back-project z=0 onto the unit sphere: z^2 = 1 - (x^2 + y^2)
p1.z = sqrtf(max(0,1.0f-length2(p1)));
p1 = p1.normalize();
```



Virtual Trackball Source Code

- **update():**
  - Find the rotation axis and angle

```
// find rotation axis and angle in world space
// - trackball self-rotation should be done at first in the world space
// - mat3(view_matrix0): rotation-only view matrix
// - mat3(view_matrix0).transpose(): inverse view-to-world matrix

vec3 v = mat3(view_matrix0).transpose()*p0.cross(p1);
float theta = asin( min(v.length(),1.0f) );
```



Virtual Trackball Source Code

- **update():**
  - Return the rotation with the initial view transformation

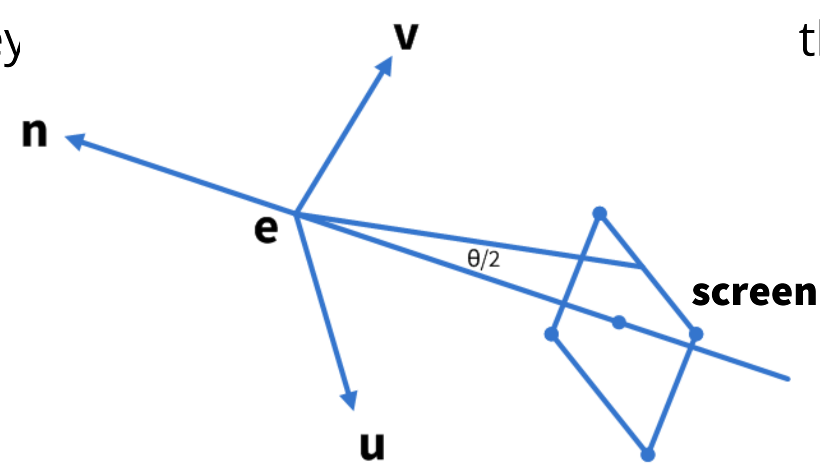
```
mat4 update( float x, float y )
{
    ...

    // resulting view matrix, which first applies
    // trackball rotation in the world space
    return view_matrix0 * mat4::rotate(v.normalize(),theta);
}
```

Virtual Trackball Extension

Extending Virtual Trackball: Hints!

- **How to implement panning**
  - The mouse displacement is mapped to translation along *uv* plane.
  - Then, move eye and at using the displacement, and rebuild your view matrix using look_at().
  - It is good to scale the amount of eye's panning based on distance to the scene center (or at).

- **How to implement zooming**
  - The mouse displacement is mapped to translation along *n* axis.
  - Displace only ey the view matrix.



Extending Virtual Trackball: Hints!

- **Changes in your mouse and motion():**

```
void mouse( GLFWwindow* window, int button, int action, int mods ){
{
    ...
    tb.button = button;
    tb.mods = mods;
}

void motion( GLFWwindow* window, double x, double y )
{
    ...
    if(button==GLFW_MOUSE_BUTTON_LEFT&&mods==0)
        tb.update(npos);
    else if(button==GLFW_MOUSE_BUTTON_MIDDLE||
            (button==GLFW_MOUSE_BUTTON_LEFT&&(mods&GLFW_MOD_CONTROL)))
        tb.update_pan(npos);
    else if(button==GLFW_MOUSE_BUTTON_RIGHT||
            (button==GLFW_MOUSE_BUTTON_LEFT&&(mods&GLFW_MOD_SHIFT)))
        tb.update_zoom(npos);
}
```