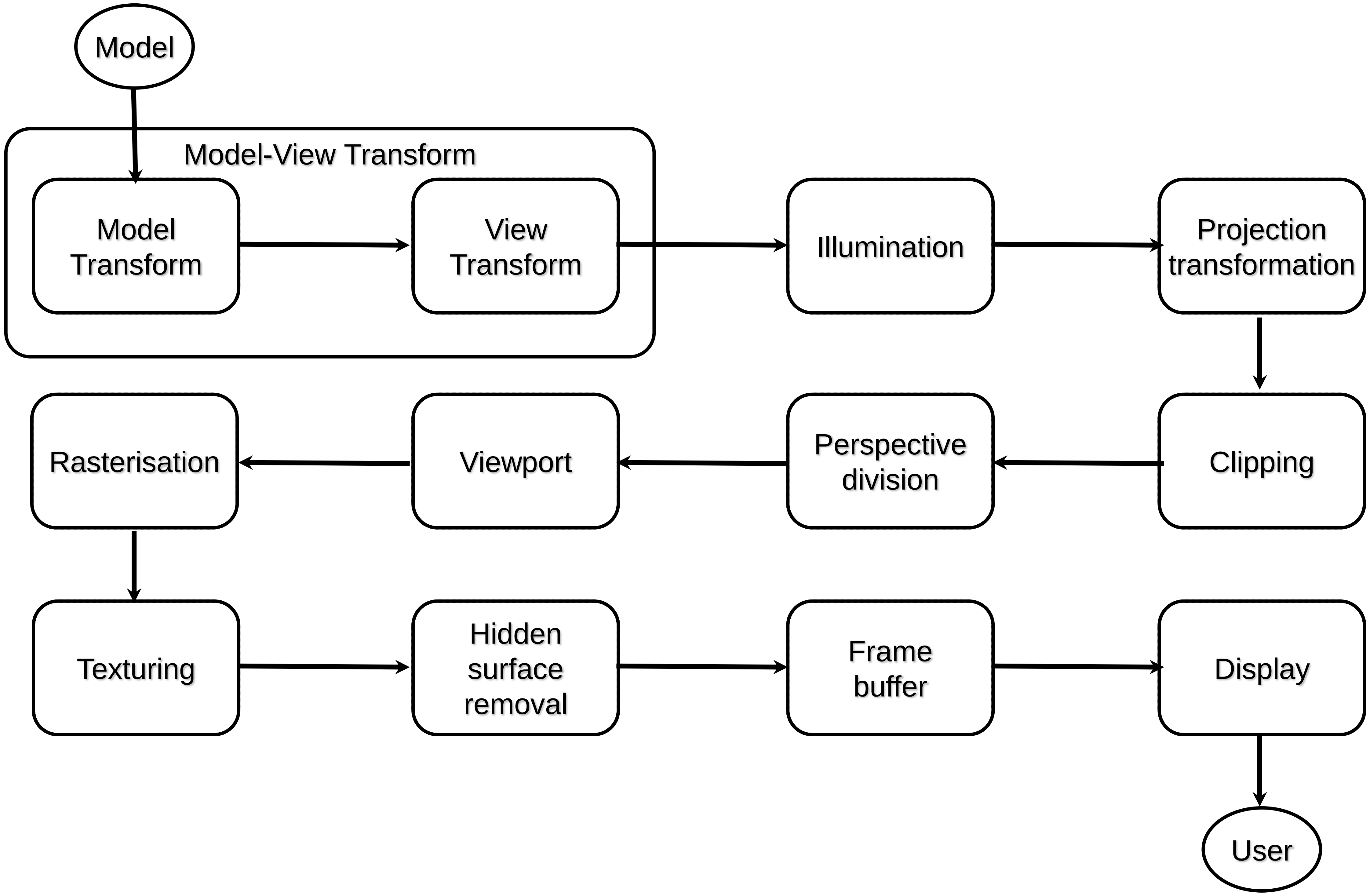
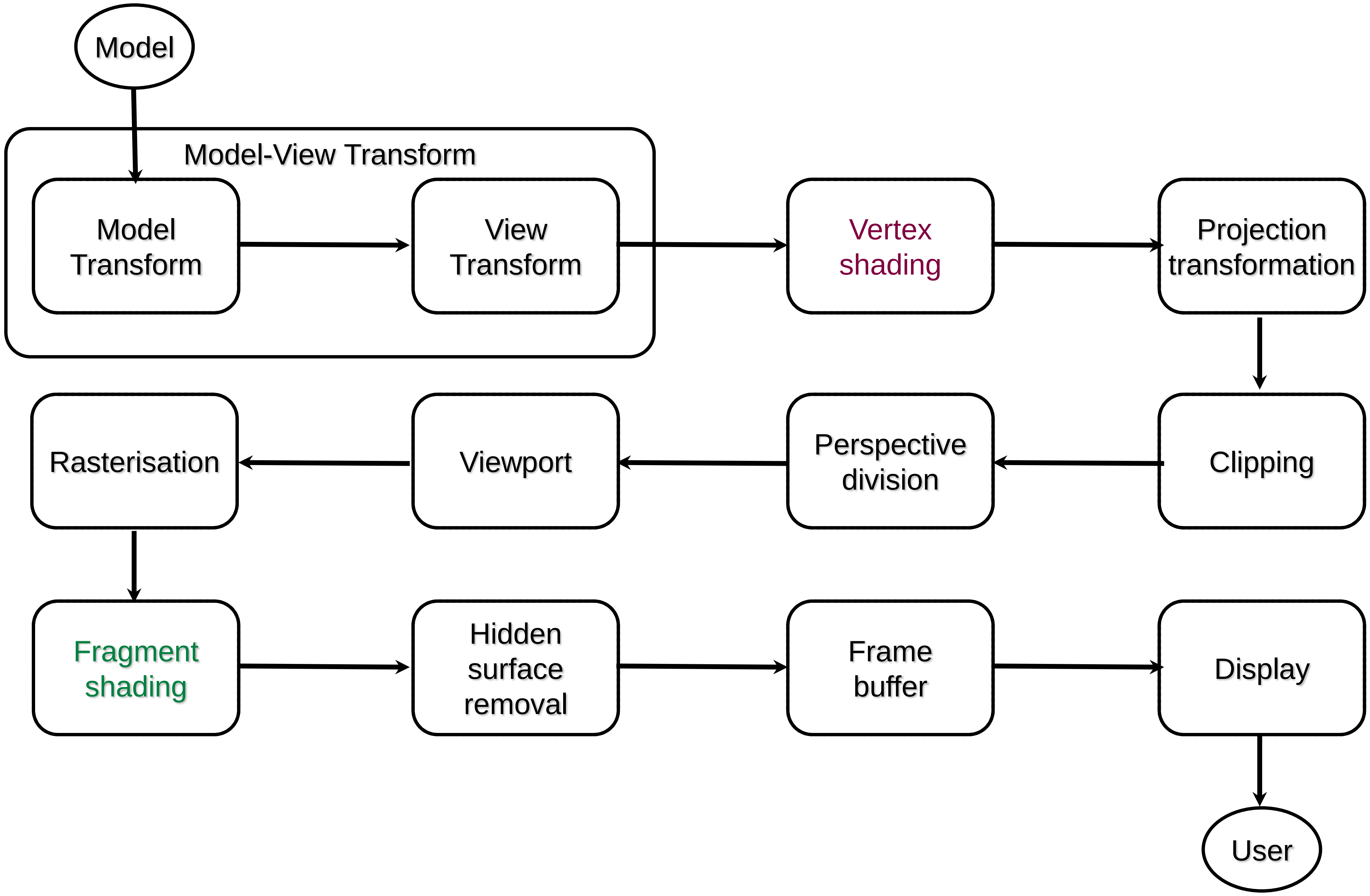
COMP3421

The programmable pipeline and Shaders

The graphics pipeline



The graphics pipeline



Shading

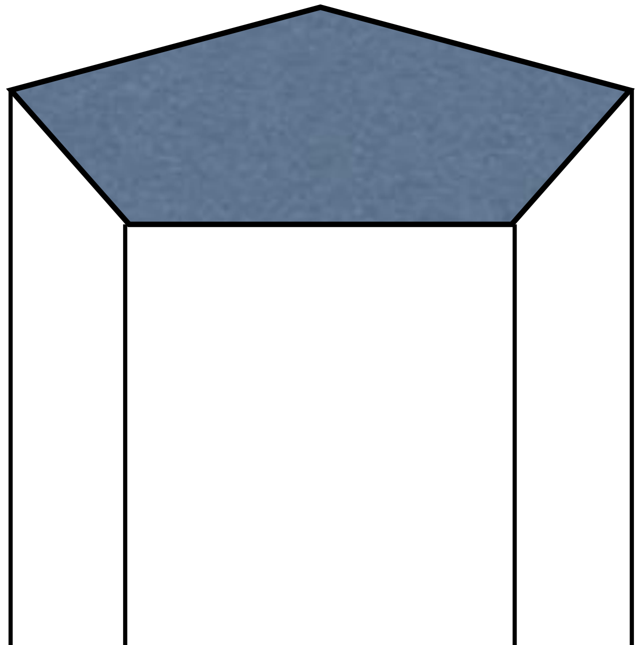
Illumination (a.k.a shading) is done at two points in the fixed function pipeline:

- Vertices in the model are shaded before projection.
- Pixels (fragments) are shaded in the image after rasterisation.
- Doing more work at the vertex level is more efficient. Doing more work at the pixel level can give better results.

Vertex shading

The built-in lighting in OpenGL is mostly done as vertex shading.

The lighting equations are calculated for each vertex in the image using the associated vertex normal.

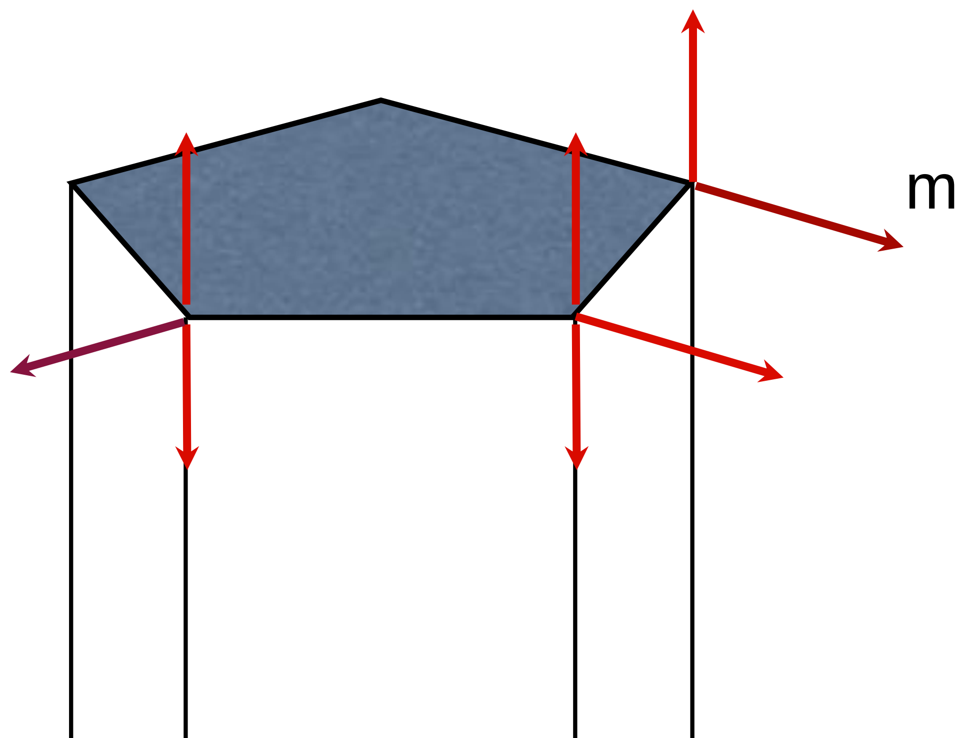


Illumination
is calculated at
each of these
vertices.

Vertex shading

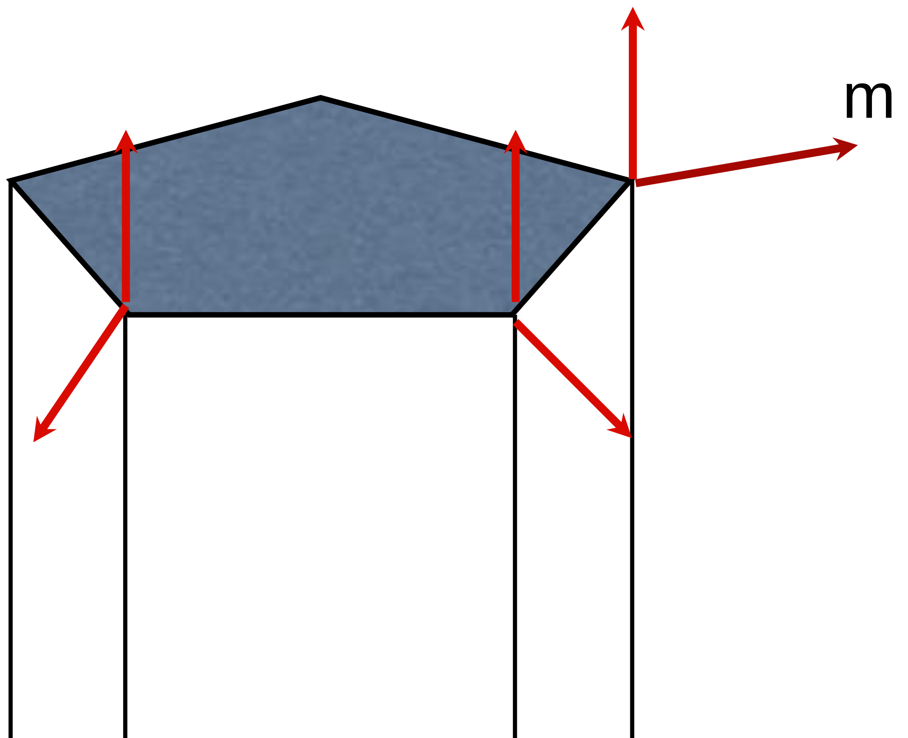
The normal vector **m** used to compute the lighting equation is the normal we specified when creating the vertex using

```
gl.glNormal3d(mx, my, mz);
```



Vertex shading

This is why we use different normals on curved vs flat surfaces, so the vertex may be lit properly.



Vertex shading

Illumination values are attached to each vertex and carried down the pipeline until we reach the fragment shading stage.

```
struct vert {

  float[4] pos;   // vertex coords
  float[4] light; // rgba colour
                  // other info...

}
```

Fragment shading

Knowing the vertex properties, we need calculate appropriate colours for every pixel that makes up the polygon.

There are three common options:

- Flat shading
- Gouraud shading
- Phong shading

In OpenGL

```
// Flat shading :
gl.glShadeModel(GL2.GL_FLAT);
// Gouraud shading (default):
gl.glShadeModel(GL2.GL_SMOOTH);
// Phong shading:
// No built-in implementation
```

Flat shading

The simplest option is to shade the entire face the same colour:

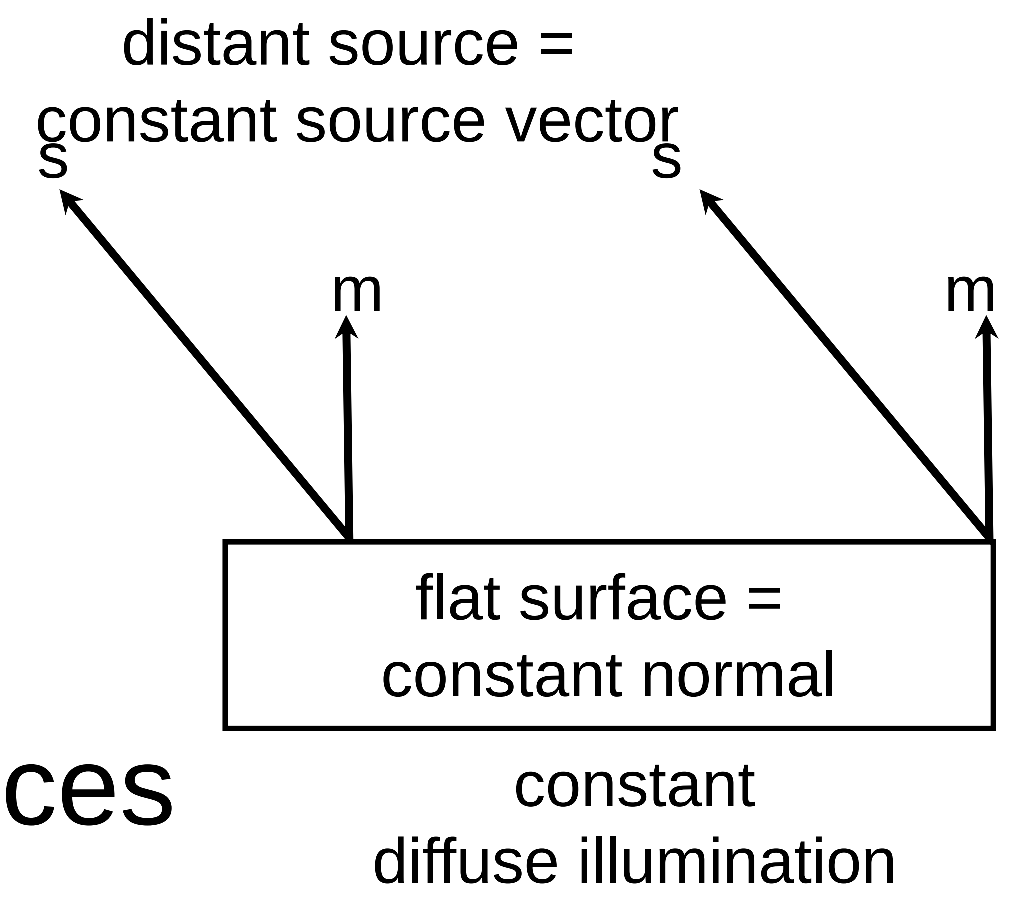
- Choose one vertex (arbitrarily chosen by OpenGL…)
- Take the illumination of that vertex
- Set every pixel to that value.

Flat shading

Flat shading is good for:

- Diffuse illumination
- for flat surfaces
- with distant light sources

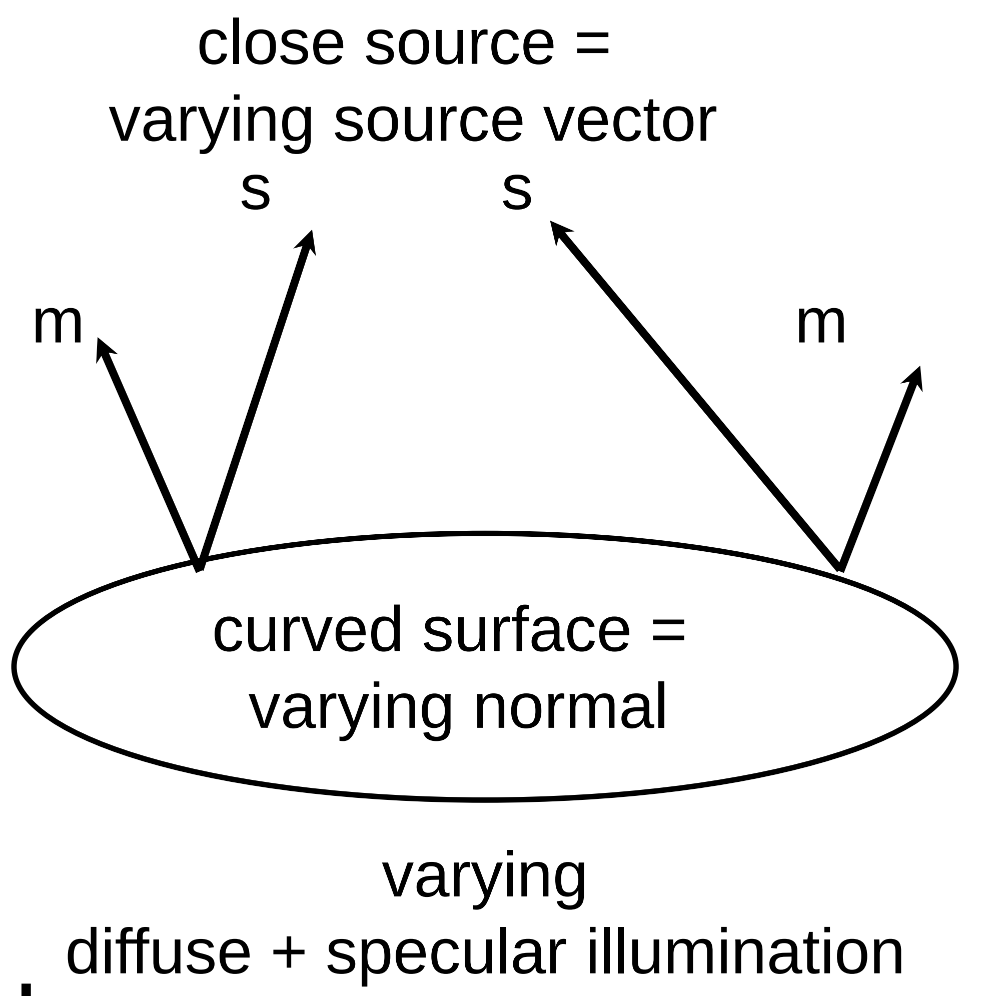
It is the fastest shading option.



Flat shading

Flat shading is bad for:

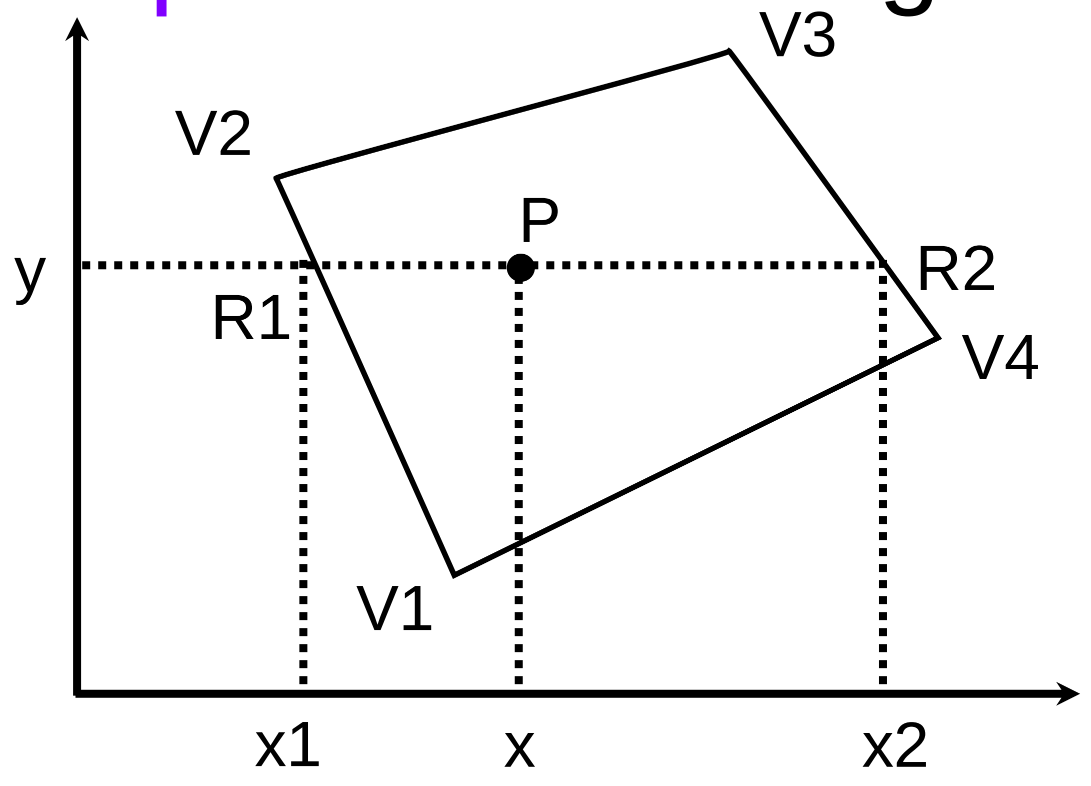
- close light sources
- specular shading
- curved surfaces
  - Edges between faces become more pronounced than they actually are (Mach banding)



Gouraud shading

Gouraud shading is a simple smooth shading model.

We calculate fragment colours by bilinear interpolation on neighbouring vertices.

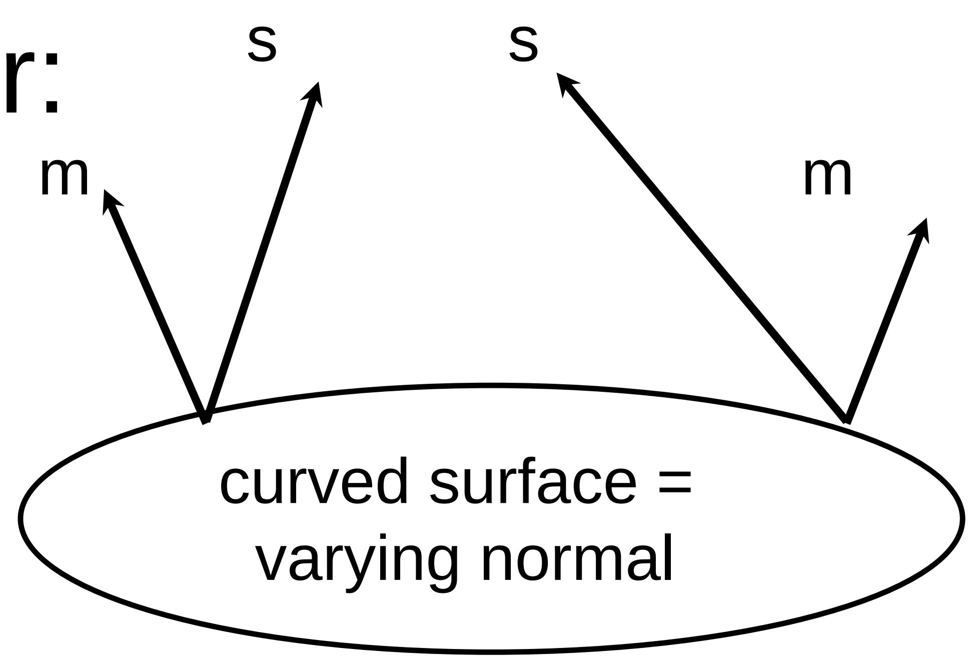


$$\begin{aligned} colour(R_1) &= lerp(V_1, V_2, \tfrac{y-y_1}{y_2-y_1}) \\ colour(R_2) &= lerp(V_3, V_4, \tfrac{y-y_3}{y_4-y_3}) \\ colour(P) &= lerp(R_1, R_2, \tfrac{x-x_1}{x_2-x_1}) \end{aligned}$$

Gouraud shading

Gouraud shading is good for:

- curved surfaces
- close light sources
- diffuse shading



varying
diffuse illumination

Gouraud shading

Gouraud shading is only slightly more expensive than flat shading.

It handles specular highlights poorly.

- It works if the highlight occurs at a vertex.
- If the highlight would appear in the middle of a polygon it disappears.
- Highlights can appear to jump around from vertex to vertex with light/camera/object movement

Phong shading

Phong shading is designed to handle specular lighting better than Gouraud. It also handles diffuse better as well.

It works by deferring the illumination calculation until the fragment shading step.

So illumination values are calculated per fragment rather than per vertex.

Not implemented on the fixed function pipeline. Need to use the programmable pipeline.

Phong shading

For each fragment we need to know:

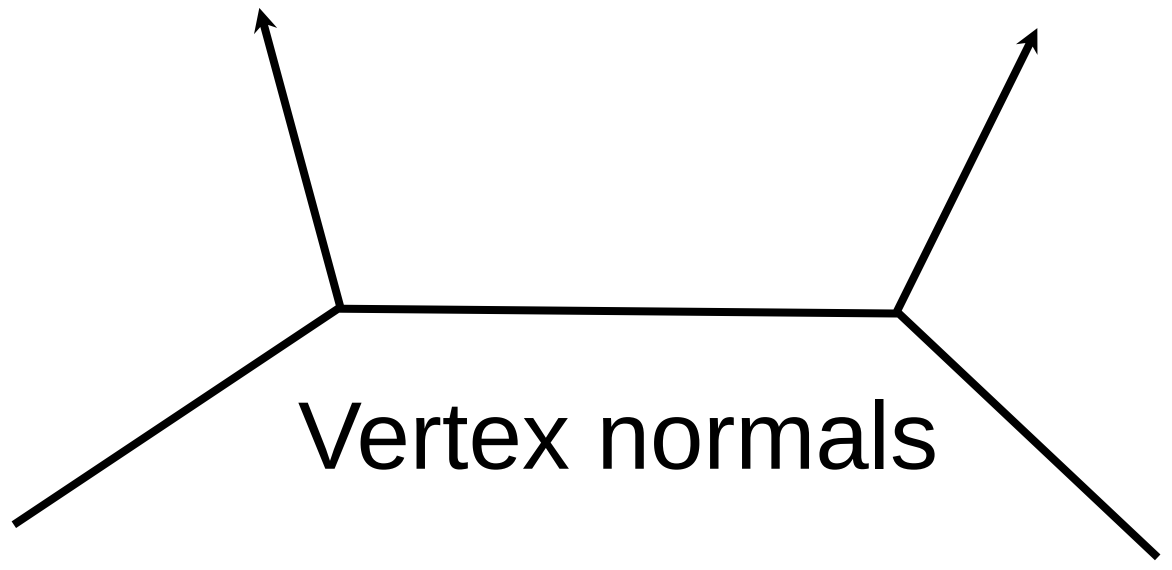
- source vector **s**
- eye vector **v**
- normal vector **m**

Knowing the source location, camera location and fragment location we can compute **s** and **v**.

What about **m**?

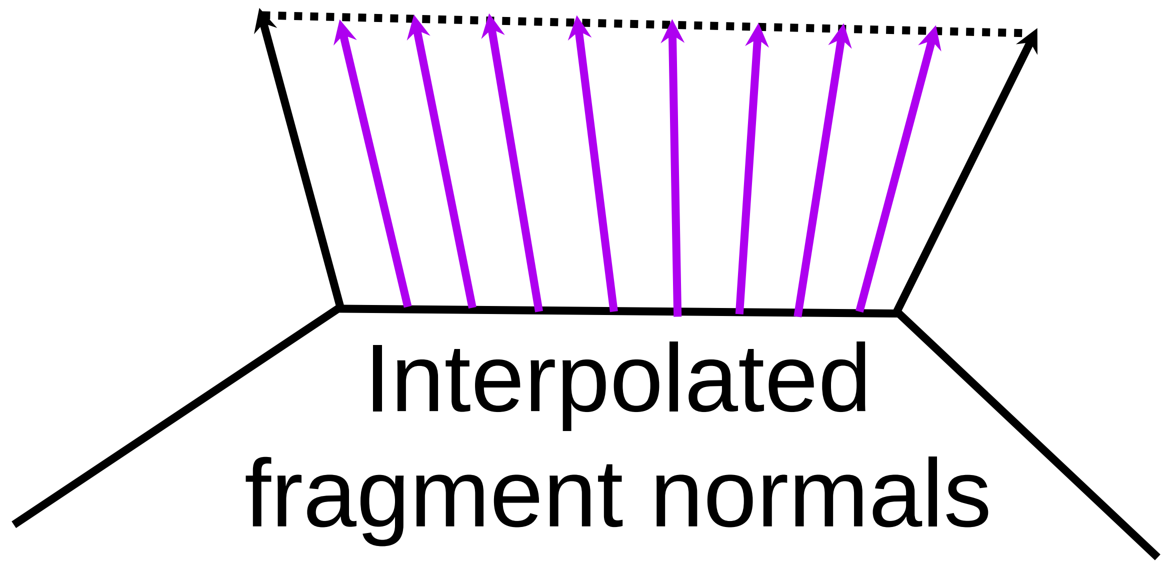
Normal interpolation

Phong shading approximates **m** by interpolating the normals of the polygon.



Normal interpolation

Phong shading approximates **m** by interpolating the normals of the polygon.



Normal interpolation

In a 2D polygon we do this using (once again) bilinear interpolation.

However the interpolated normals will vary in length, so they need to be normalised (set length = 1) before being used in the lighting equation.

Phong shading

Pros:

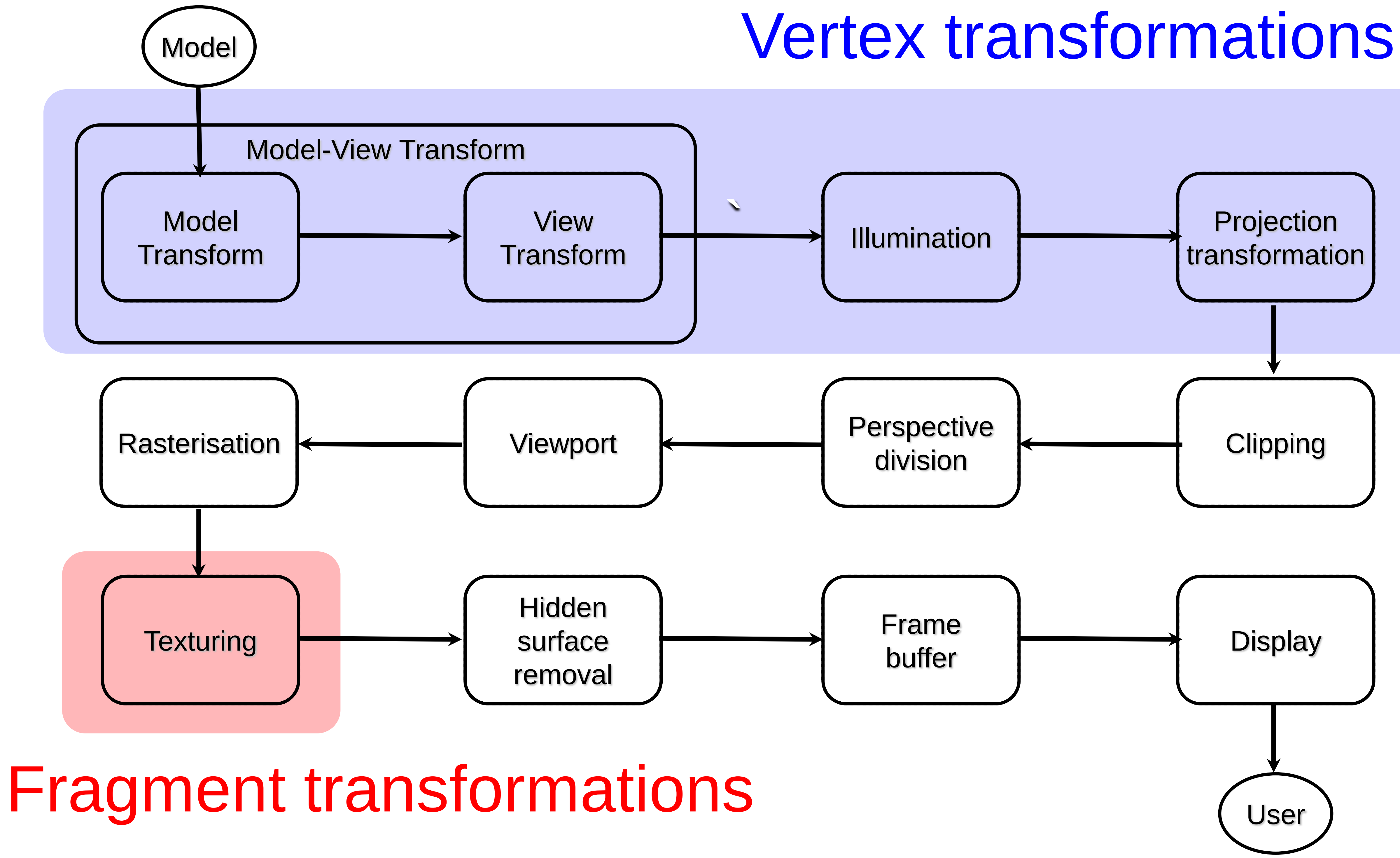
- Handles specular lighting well.
- Improves diffuse shading
- More physically accurate

Phong shading

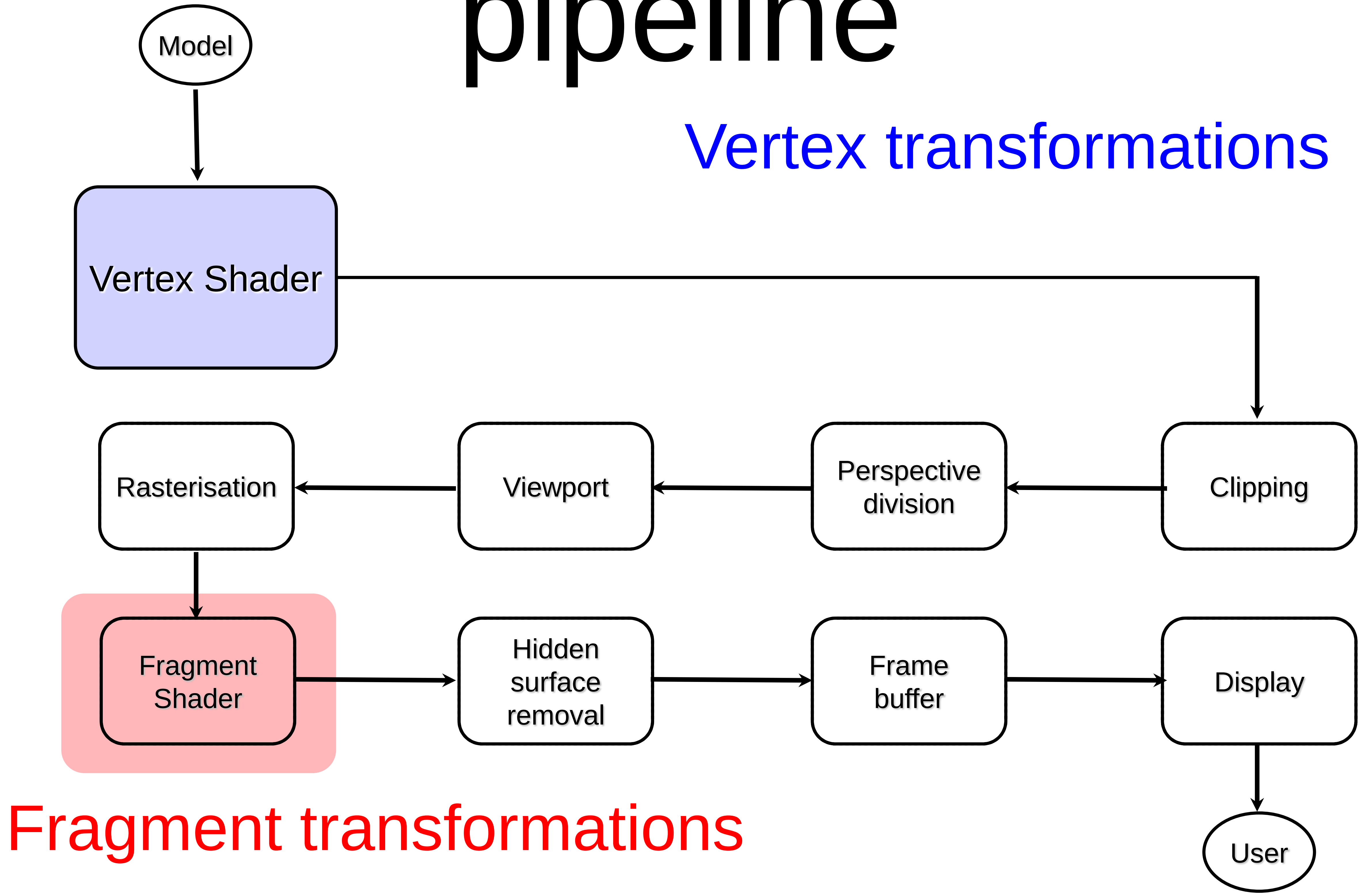
Cons:

- Slower than Gouraud as normals and illumination values have to be calculated per pixel rather than per vertex. In the old days this was a BIG issue. Now it is usually ok.

Fixed function pipeline



Programmable pipeline



Shaders

The programmable pipeline allows us to write shaders to perform arbitrary vertex and fragment transformations. (There are also optional tessellation and geometry shaders.)

Shaders are written in a special language called GLSL (GL Shader Language) suitable for specifying functions on the GPU.

Basic Vertex Shader

```
/* This does the bare minimum. It
transforms the input gl_Vertex and
outputs the gl_Position value in
4DCVV coordinates */

void main(void) {

    gl_Position =

    gl_ModelViewProjectionMatrix *

                            gl_Vertex;

}
```

Basic Fragment Shader

```
/* Make every fragment red */
void main (void) {
   gl_FragColor =vec4(1.0,0.0,0.0,1.0);
}
```

GPU

The graphics pipeline performs the same transformations to thousands of millions of vertices and fragments.

These transformations are highly parallelisable.

The GPU is a large array of SIMD (single instruction, multiple data) processors.

Vertex Shaders

Replaces fixed function

- vertex transformation
- normal transformation, normalization
- vertex illumination
- Has access to OpenGL states such as model view transforms, colors etc (in later versions these must be explicitly passed in). These variables start with gl_ (eg gl_Color)

Vertex Shaders

Input: individual vertex in model coordinates

Output: individual vertex in clip (4Dcvv) coordinates

They may also be sent other inputs from the application program and output color,lighting and other values for the fragment shader

They operate on individual vertices and results can’t be shared with other vertices.

They can’t create or destroy a vertex

Fragment Shaders

Replaces fixed function

- texturing and colouring the fragment.

Enables lighting to be done at the fragment stage (such as phong shading) which could not be done in fixed function pipeline

Has access to OpenGL states (in later versions this must be explicitly passed in)

Fragment Shaders

Input: individual fragment in window coordinates

Output: individual fragment in window coordinates (with color set)

May receive inputs (that may be interpolated) from the vertex shader and inputs from the application program.

They can’t share results with other fragments.

Can access and apply textures.

Fragment Shaders

The fragment shader does not replace the fixed functionality graphics operations that occur at the back end of the OpenGL pixel processing pipeline such as

- depth testing
- alpha blending.

Setting up Shaders

1. Create one or more empty *shader objects* with **glCreateShader**.
2. Load source code, in text, into the shader with **glShaderSource**.
3. Compile the shader with **glCompileShader**.
4. Create an empty *program object* with **glCreateProgram**. This returns an int ID.
5. Bind your shaders to the program with **glAttachShader**.
6. Link the program with **glLinkProgram**.
7. See Shader.java for details

Setting up Shaders in OpenGL code

```
// create shader objects and

// reserve shader IDs

int vertShader =
gl.glCreateShader(GL2.GL_VERTEX_
SHADER);

int fragShader =
gl.glCreateShader(GL2.GL_FRAGMEN
T_SHADER);
```

OpenGL

```
// compile shader which is just
// a string (do once for vertex
// and then for fragment)

gl.glShaderSource(
    vertShader,
    vShaderSrc.length,
    vShaderSrc, vLengths, 0);
gl.glCompileShader(vertShader);
```

OpenGL

```
// check compilation

int[] compiled = new int[1];

gl.glGetShaderiv(vertShader,
       GL2ES2.GL_COMPILE_STATUS,
       compiled, 0);

if (compiled[0] == 0) {
    // compilation error!
}
```

OpenGL

```
// program = vertex shader + frag shader

int shaderprogram =
gl.glCreateProgram();

gl.glAttachShader(shaderprogram,
                           vertShader);
gl.glAttachShader(shaderprogram,
                           fragShader);
gl.glLinkProgram(shaderprogram);
gl.glValidateProgram(shaderprogram);
```

Using Shaders

After your shaders have been set up you need to tell OpenGL what shaders to use.

OpenGL uses the current shader program.

To set the current shader use:

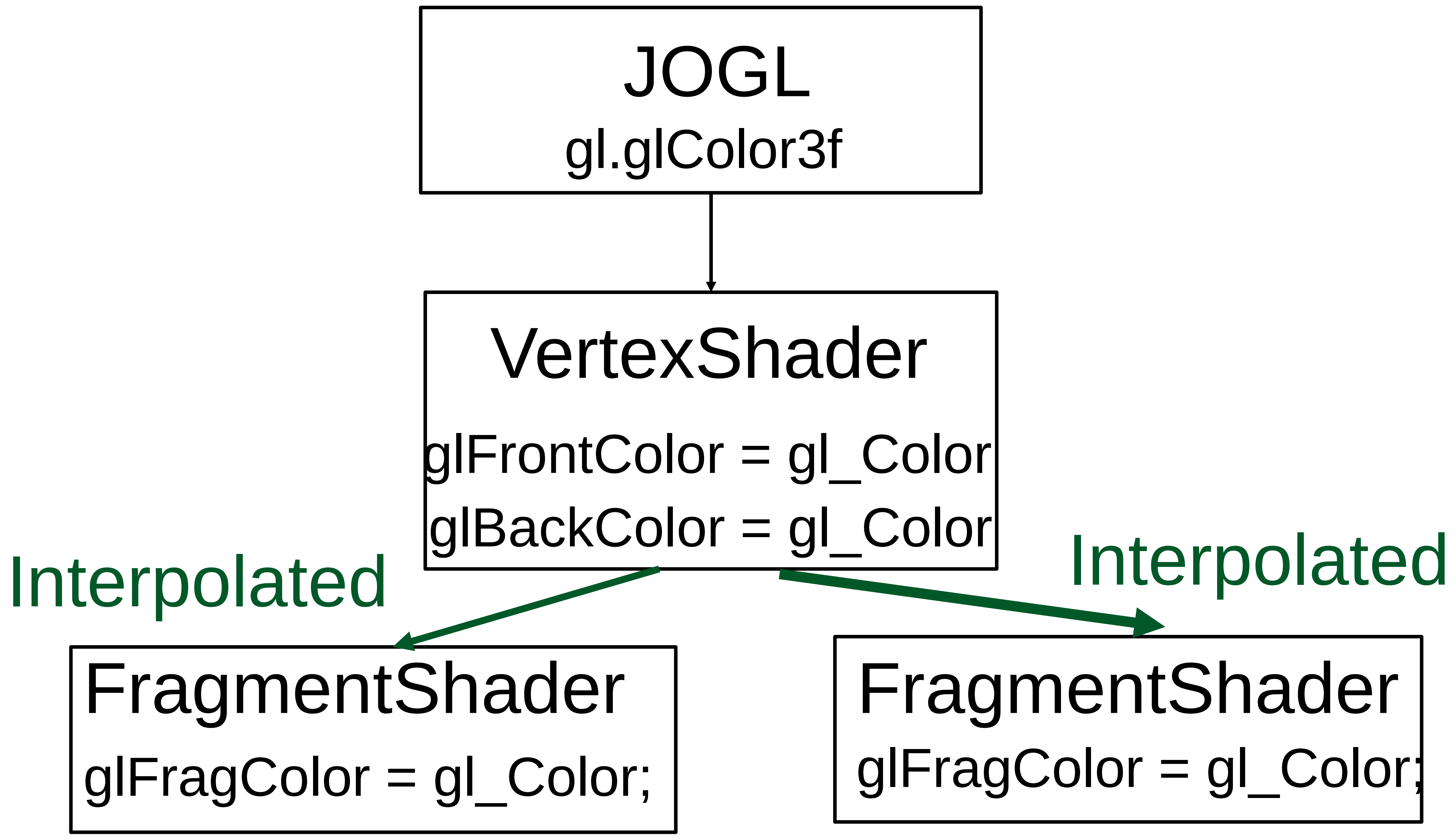
```
gl.glUseProgram(shaderProgramID);
```

Using Shaders

Can set multiple shaders within a program.

```
gl.glUseProgram(shaderProgram1);

//render an object with shaderprogram1

gl.glUseProgram(shaderProgram2);

//render an object with shaderprogram2

gl.glUseProgram(0);

//render an object with fixed function
pipeline
```

Color Data


JOGL
gl.glColor3f
VertexShader
glFrontColor = gl_Color
glBackColor = gl_Color
Interpolated
Interpolated
FragmentShader
glFragColor = gl_Color;
FragmentShader
glFragColor = gl_Color;

Passthrough Vertex Shader

```
void main(void) {
     gl_Position =
    gl_ModelViewProjectionMatrix *
                         gl_Vertex;
    gl_FrontColor = gl_Color;
    gl_BackColor = gl_Color;
}
```

Passthrough Fragment Shader

```
/* fragment shader */

void main(void) {

/* gl_FrontColor and gl_BackColor are
set by each vertex in the vertex
shader and the rasteriser
interpolates the appropriate value to
get the fragment gl_Color */

   gl_FragColor = gl_Color;

}
```

Interpolation

By default the rasteriser interpolates vertex attributes such as

positions, colors, normals

across primitives to generate the right interpolated values for fragments.

We can turn on flat shading in jogl or use the keyword **flat** in our own shader variables to stop interpolation.

GLSL Syntax

C like language with

- No long term memory
- Basic types: float int bool
- Other type: sampler (textures)
- C++ Style Constructors
- Standard C/C++ arithmetic and logic operators
- if statements,loops

GLSL Syntax

Has limited support for loops

```
for(i=0; i< n; i++){

/* etc */

}
```

Conditional branching is much more expensive than on CPU!

Do not use too much – especially in fragment shader (there are usually lots of fragments!)

GLSL Syntax

Has support for 2D, 3D, 4D vectors (array like list like containers) of different types

- vec2, vec3, vec4 are float vectors.
- ivec2, ivec3, ivec4 are int vectors.

Has support for float matrix types

- mat2, mat3, mat4

Operators are overloaded for matrix and vector operations

GLSL Syntax

No characters, strings or printf

No pointers

No recursion

No double (limited support in later versions)

May not cast implicitly eg

vec3(1,0,1) may NOT work as it needs float. vec3(1.0,0.0,1.0) is correct.

Vectors

C++ Style Constructors

`vec3 a = vec3(1.0, 2.0, 3.0);`

For vectors can use [ ], xyzw, rgba

`vec3 v;`

`v[1], v.y, v.g` all refer to the same element

Swizzling: `vec3 a, b;`

`a.xy = b.yx;`

Matrix Components

Matrices are in column major order

M[i][j] is column i row j

```
mat4 m = mat4(1.0); //identity matrix
m = mat4(1.0,2.0,3.0,4.0, //first col
         5.0,6.0,7.0,8.0, //second col
         9.0,10.0,11.0 12.0,   //third col
         13.0,14.0,15.0,16.0); //fourth col
float f = m[0][1]; //Would be 2.0
```

Variable Qualifiers

uniform: read-only input variables to vertex or fragment shader. Can’t be changed for a given primitive.

Attributes: May be different for each vertex.
in : read-only input variables to vertex shader.

out, in : Outputs from the vertex shader that are passed in to the fragment shader. They are interpolated for each fragment

GLSL Compatability

Macs may not have version #130

Use #120 and change

in to attribute in your vertex shader

out to varying in your vertex shader

in to varying in your fragment shader

Built in Vertex Shader Attributes

in: gl_Vertex,
    gl_Normal,
    gl_Color
out: gl_FrontColor,
     gl_BackColor,
     gl_Position (must be written)

Built in Fragment Shader Variables

in: gl_FragCoord

gl_Color - If this is a front facing it will be the interpolated value set by the vertex shader for gl_FrontColor, (if it is back facing it will be gl_BackColor Note: gl_BackColor does not work on my computer).

out: gl_Fragment (fragment colour)

in/out: gl_depth

Built-in Uniform Variables

gl_ModelViewMatrix

gl_ModelViewProjectionMatrix,

gl_NormalMatrix

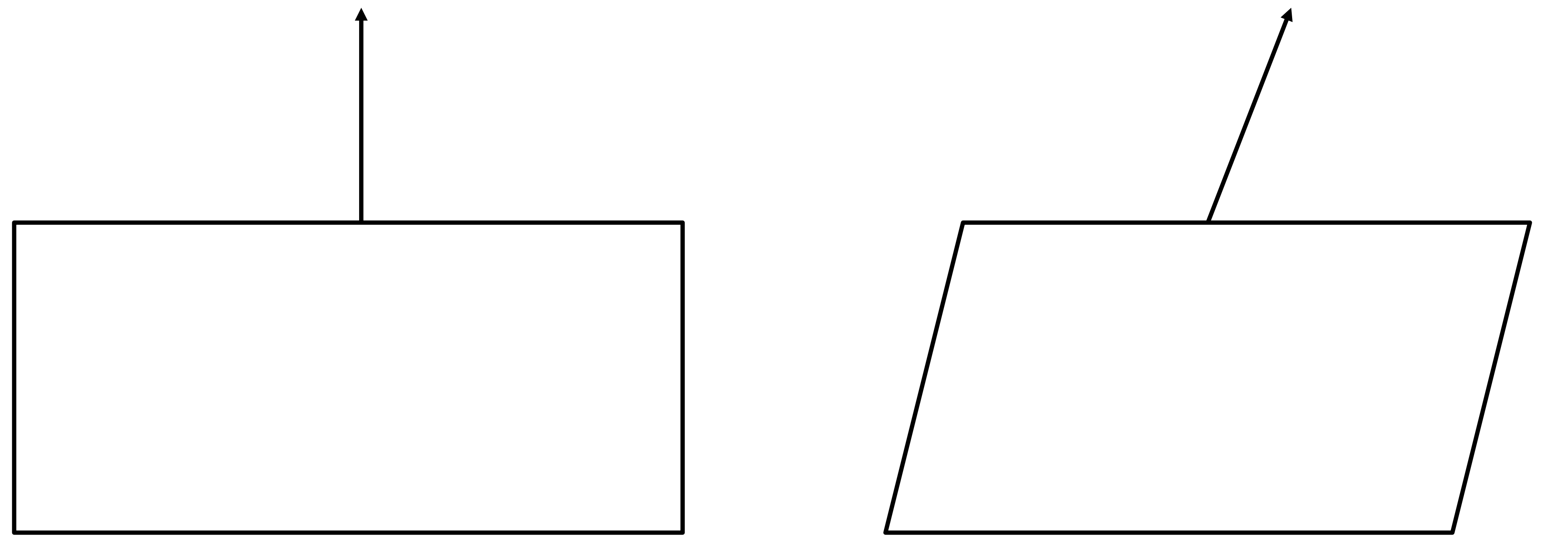
gl_LightSource[0].position (in camera coords)

gl_LightSource[0].diffuse

etc

Aside: gl_NormalMatrix

If the *modelview* matrix contains a non-uniform scale then it will not transform normals properly. It is no longer perpendicular!



gl_NormalMatrix

Instead we use the transpose of the inverse of the upper left 3*3 corner of the modelview matrix.

The fixed function pipeline has been doing this behind the scenes for us.

We can use gl_NormalMatrix

Derivation (not examinable)

Garoud vertex shader

```
void main() {
 //Ambient light calculations
 vec4 globalAmbient =
     gl_LightModel.ambient *
     gl_FrontMaterial.ambient;
 vec4 ambient =
     gl_LightSource[0].ambient *
     gl_FrontMaterial.ambient;
```

Garoud vertex shader

```
//Diffuse calculations
vec3 v, normal, lightDir;

// transform the normal into eye space and normalize
normal = normalize(gl_NormalMatrix * gl_Normal);

//transform co-ords into eye space
 v = vec3(gl_ModelViewMatrix * gl_Vertex);

// Assuming point light, get a vector TO the light

lightDir = normalize(gl_LightSource[0].position.xyz - v);

float NdotL = max(dot(normal, lightDir), 0.0);


vec4 diffuse = NdotL * gl_FrontMaterial.diffuse *
                    gl_LightSource[0].diffuse;
```

Garoud vertex shader

```
vec4 specular = vec4(0.0,0.0,0.0,1.0);
vec3 dirToView = normalize(-v);
vec3 H = normalize(dirToView+lightDir);
// compute specular term if NdotL is  larger than  zero
if (NdotL > 0.0) {
   float NdotHV = max(dot(normal, H),0.0);
   specular = gl_FrontMaterial.specular *
              gl_LightSource[0].specular *
              pow(NdotHV,gl_FrontMaterial.shininess);
}
```

Garoud vertex shader

```
gl_FrontColor = gl_FrontMaterial.emission +
                globalAmbient +
                ambient +
                diffuse +
                specular;
gl_Position = gl_ModelViewProjectionMatrix *
               gl_Vertex;
}
```

Garoud Light fragment shader

```
//gl_Color is calculated in the
vertex shader and interpolated

void main() {

   gl_FragColor = gl_Color;

}
```

Phong vertex shader

```
/* data associated with each vertex */

out vec3 N; //Send eyeCoords normal to fragment shader
out vec3 v; //Send eyeCoords position to fragment shader

void main(){

   /* send point and the normal in camera coords  to the
fragment shader - these will be interpolated */

   v = vec3(gl_ModelViewMatrix * gl_Vertex);
   N = normalize(gl_NormalMatrix * gl_Normal);

   gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;

}
```

Phong fragment shader

```
in vec3 N;  //Interpolated from vertex shader outputs
in vec3 v;  //Interpolated from vertex shader outputs

void main (void){
   vec3 lightDir =
          normalize(gl_LightSource[0].position.xyz - v);
   vec3 dirToView = normalize(-v);
   vec3 normal = normalize(N);

   //etc same calculations as done in the
   // specular vertex shader
   // except we are doing calculations on EVERY fragment
   gl_FragColor = globalAmbient + ambient + diffuse + 
specular;

}
```

Things to try

These shaders have not handled basics such as

- multiple lights
- two sided lighting
- lights being enabled/disabled
- directional lights, spotlights etc
- attenuation...

More...

There are many more shading algorithms designed to implement different lighting techniques with different levels of speed and accuracy.

For example Cook Torrance is a more realistic model than Phong or Blinn-Phong

Check out the Graphics Gems and GPU Gems books for lots of ideas.

User Defined Variables

To pass in your own uniforms or attribute ‘in’ variables into your shaders from the application program

```
int loc =
gl.glGetUniformLocation(shaderProgram,”myVal”
);
gl.glUniform1f(loc,0.5);
//Or for attributes
int loc =
glGetAttribLocation(shaderProgram,”myVal”);
gl.glVertexAttrib1f(loc, 1, 1, 0, 1);
```

Optional Shaders

In later versions on GLSL, there are optional shaders between the vertex shader and the clipping stage.

Tesselation Shaders: can create additional vertices in your geometry

Geometry Shader: can be used to add, modify, or delete geometry,

GLSL Documentation

For the version compatible with class demos and slides:

https://www.opengl.org/registry/doc/GLSLangSpec.Full.1.30.10.pdf