



## PROJECT REPORT

GEOMETRY-BASED SHADING FOR SHAPE DEPICTION ENHANCEMENT  
AN IMPLEMENTATION

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# Real-Time Graphics Programming Project

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## Executive Summary

This project report describes the realization and implementation decisions of the shading technique proposed in [1].

The paper's goal is to describe an approach for **enhancing shape depiction** of 3D objects on **Non-Photorealistic Rendering (NPR) shading models** using *local geometry*.

The approach described provides **time-efficiency**, to make it usable in *interactive application*, without any constraints on the choice of material or illumination model.

The proposed method is inspired by **Normal Enhancement** and **Radiance Scaling** Shading approach and it tries to combine the advantages of both techniques while, also, relaxing their constraints.

The overall goal of my project is to implement one of the newest techniques in NPR as well as coding some of the most famous ones.

## 1 Introduction

The advent of Computer Graphic technologies has **not replaced artists**. Many non-photorealistic rendering techniques have focused on depicting shape through shading that *mimic hand-drawn illustration* but NPR models still **lack in expressive power**.

The proposed technique should *correlate* the enhancement functionalities to **surface feature variations**. To achieve this result, the paper [1] starts from analyzing two existing techniques that either perturbates the surface normal as in **Normal enhancement** or alters reflected radiance based on local surface information as in **Radiance scaling**.

However, both of those methods have some limitations:

Normal enhancement operators are *restricted* on specific types of material and illumination models, and they are **not able to enhance** some important geometry features such as **concavities** and **convexities**. In contrary, Radiance scaling overcomes those limitations but (especially in NPR shading) tends to mask subtle shading variations and hence **reduce effectiveness** of the overall technique.

The proposed technique's goal is to *reformulate* NPR shading models with respect to **geometry surface features** combining the advantages of Normal enhancement and Radiance scaling while also **relaxing their constraints**.

The enhancement is achieved in two ways. First, by *modifying the surface normal* using a simple high-frequency enhancement operation. Second, by correlating reflected lighting intensity to **surface curvature** using a new scaling function.

In this way, we can achieve enhancement in different extent, allowing users to produce more desirable enhancement results.

### 1.1 Project Overview

In this project I implemented all the shading models used in [1] :

**Blinn-Phong**, **Cartoon** and **Gooch** as well as their **enhanced version**, following the reformulation of the *reflectance radiance equation* described in paragraphs 6.1, 6.2 and 6.3 of [1].

Contextually, I realized also all the needed **helping operators**, such as *normal smoothing*, *sharpening* and *curvature* calculation. Lastly, I realized other *subroutines* to better visualize the differences between normal and enhanced normal, as well as curvature and enhanced curvature (that uses enhanced normal).

A list of all the usable subroutine in the project can be seen in **Figure 1**.

```
Subroutine Uniform: 0 - name: Illumination_Model
Compatible Subroutines:
  0 - BlinnPhong
  1 - EnhancedBlinnPhong
  2 - ToonShading
  3 - EnhancedToonShading
  4 - GoochShading
  5 - EnhancedGoochShading
  6 - VisualizeCurvature
  7 - VisualizeEnhancedCurvature
  8 - VisualizeNormal
  9 - VisualizeEnhancedNormal
  10 - Lambert
Current shader subroutine: BlinnPhong
```

Figure 1: All subroutines available in the project

## 2 Geometry-based shading Approach

The key of this approach is *incorporating surface curvature* information into shape depiction enhancement technique. This is done with multiple steps:

1. **3D Shape Descriptor:** 3D Object surface shape is analyzed using the shape descriptor. **Curvature computation** extracts salient surface features. Tts contribution can be controlled using some parameters.
2. **Geometry-based Shading:** the surface normals are *smoothed* or *sharpened* to attenuate or exaggerate the surface depiction; Then, the **reflected lightning intensity** is scaled using also surface curvature previously calculated.
3. **Rendering:** This shading technique is applied to various **non-photorealistic rendering styles**, reformulating the reflected radiance equation in a way that takes the enhanced shading into account.

In **Figure 2** the rendering pipeline is graphically illustrated.

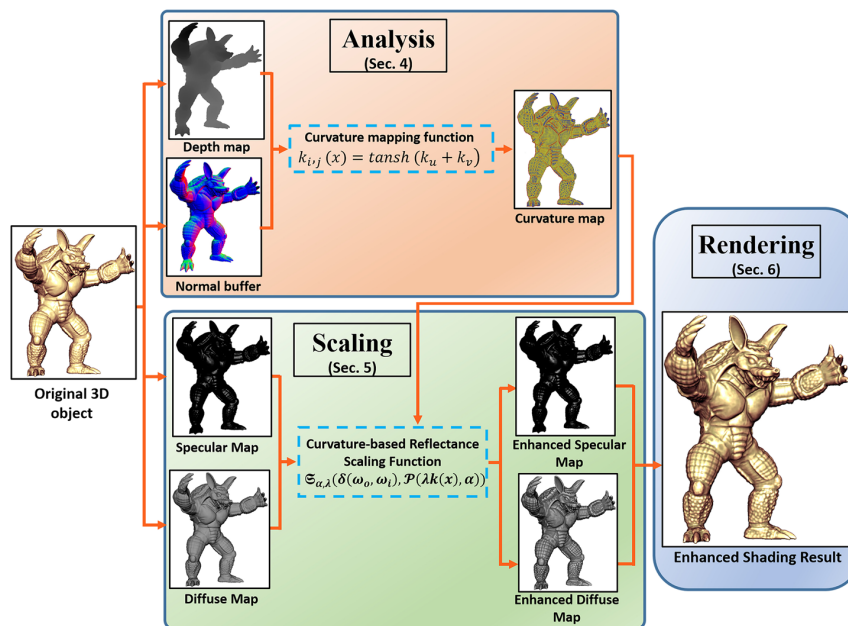


Figure 2: The rendering pipeline of the paper’s approach. It combines estimating the surface curvature, scaling the reflected lighting and rendering the NPR result

### 3 Design and Implementation

In this chapter, I will cover all the implementation choices that I made during the realization of the project. Some of the operations described in the paper [1] were not clearly specified so I was forced to take some implementation decisions and use the paper as a guideline. Moreover, some operations were too general and customizable so I tried to simplify it to make the project simpler.

Code-wise, My project started from the code version **lecture03a** that we saw during lectures. I also used 3 standard models in Computer Graphics for testing, downloaded from **Stanford** website<sup>1</sup>: *Bunny*, *Armadillo* and *Dragon*.

#### 3.1 Normal Enhancement Operators

In the paper [1] are described two types of normal variations: *smoothing* and *sharpening*. Those two kind of enhancement operators work on the high-frequency components of the surface normal. Smoothing reduces those components, while Sharpening increases them.

##### 3.1.1 Normal Smoothing Operator Implementation

To calculate smoothed surface normal I started from this idea<sup>2</sup>. The implementation of normal smoothing operator was done in `model_v1` file, while *processing the Assimp mesh* in order to obtain an *OpenGL mesh*. I created a **new position in the vertex attribute**, that stores smoothed normal.

In this way, data can be loaded in vertex shader by simply add the lines in **Code 1**.

The smoothing normal computation is done for each vertex. I **initialized** it to vector zero. Then, I **computed face normal** for each face of the mesh and I **added** it to each vertex of the face. Finally, for each vertex, I **normalized the result** of this sum.

By doing so, I implicitly consider the *kernel* of convolution as the *smallest one*, considering as **neighbourhood** only the faces that share the same vertex. I also implicitly defined the  $\sigma$  parameter, found in Equation 5 of 4.2.1 chapter of [1] that *weights* this operation as 1. This greatly **simplifies** computation and code while maintaining the same *intent* as the original paper. The added lines of code are showed in **Code 2**.

```
1 layout (location = 2) in vec3 sm_normal;
```

**Code 1:** Smoothed normal loaded in vertex shader

```
1  for(GLuint i = 0; i < mesh->mNumVertices; i++)
2  {
3      Vertex vertex;
4      ...
5      vertex.Sm_Normal = glm::vec3();
6      ...
7  }
8  // For each face, I calculate the face normal and I add to the vertices' normal used
   // by the face. Finally, I normalize the normal to obtain the smoothed surface normal.
9  for ( int i = 0; i < indices.size(); i += 3 )
10 {
11     // I Compute the face normal using triangleNormal method, that computes normal
   // starting from triangle points
12     glm::vec3 faceNormal = glm::triangleNormal(
13         vertices[indices[i]].Position,
14         vertices[indices[i+1]].Position,
15         vertices[indices[i+2]].Position);
16 }
```

<sup>1</sup><http://graphics.stanford.edu/data/3Dscanrep/>

<sup>2</sup>[https://www.reddit.com/r/opengl/comments/6976lc/smoothing\\_function\\_for\\_normals/](https://www.reddit.com/r/opengl/comments/6976lc/smoothing_function_for_normals/)

```

17
18
19 // I add face normal to each of the 3 vertex normal of the face
20 for ( int j = 0; j < 3; j++ )
21 {
22     vertices[indices[i+j]].Sm_Normal += faceNormal;
23 }
24 }
25 for (auto &v : vertices)
26 {
27     // Normalizing the vectors accumulating face normals to obtain the smoothed surface
    normal
28     // NOTE: Sigma parameter, found in Equation 5 of 4.2.1 chapter of the reference
    paper ( to control the quantity of convolution kernel used ) is implicitly 1.
29     v.Sm_Normal = glm::normalize(v.Sm_Normal);
30 }

```

**Code 2:** Smoothed normal computations added in processMesh method

### 3.1.2 Normal Sharpening Operator Implementation

Normal Sharpening operator is implemented in **fragment shader** and uses the smoothed normal previously described and passed to the *vertex shader*.

In vertex shader, I apply *normal Matrix transformation* before passing them to the fragment shader as showed in **Code 3**.

In fragment shader, I calculate the **mask** by subtracting the original normal vector with its smoothed version. Then, I add the mask multiplied by a **scaling factor**  $\lambda$  to the normal vector, with a typical process called **unsharp masking** as described in Equation 6 of 4.2.2 chapter of [1]. Finally, I normalize the result.

The **Code 4** is added to the fragment shader to implement this process.

```

1 vSMNormal = normalize( normalMatrix * sm_normal );

```

**Code 3:** Transformation applied to smoothed normal in vertex shader

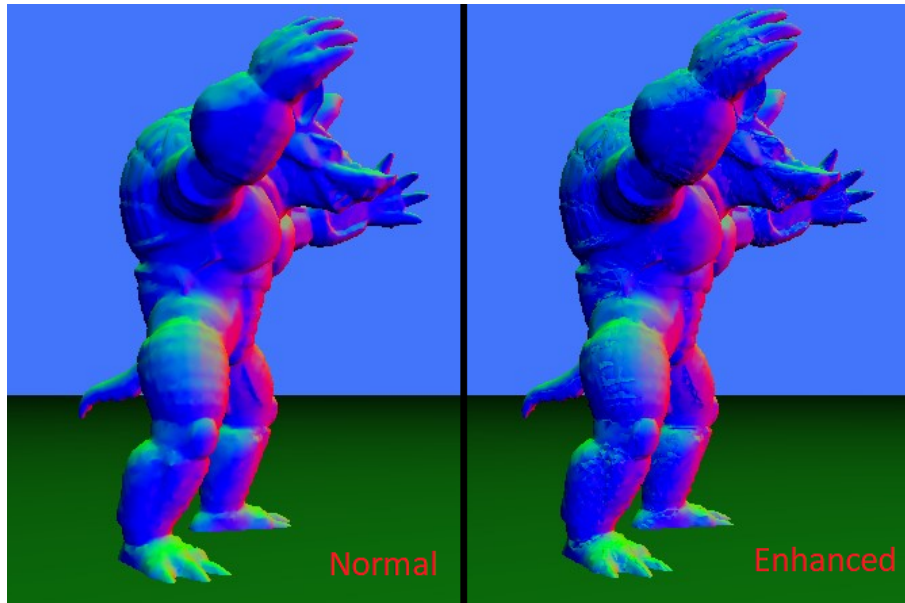
```

1 // Computing the mask for Unsharp Masking
2 vec3 mask = vNormal - vSMNormal;
3 // calculating enhanced Normal using the Unsharp Masking technique. This is defined,
  in the reference paper, in equation 6 of chapter 4.2.2
4 vec3 eNormal = vNormal + lambda * mask;
5 // normalization of the per-fragment enhanced normal
6 vec3 N_I = normalize(eNormal);

```

**Code 4:** Calculation of normal sharpening operator in fragment shader

A Comparison between normal vector and enhanced normal vector (through sharpening) is showed in **Figure 3** that shows two subroutines created in the project.



**Figure 3:** Comparison between normal and enhanced normal vector (through sharpening)

### 3.2 Curvature Analysis

Curvature analysis is another key point of the technique described in [1].

However, curvature calculation was not so clear and straightforward in the paper because they introduced the **second fundamental tensor** and the computation of **Hessian of depth field** by differentiating the gradient with a *Sobel filter*.

The approach implemented in my project, instead, is simpler. It starts from here<sup>3</sup> and considers **screen-space normals of neighbouring** fragments as well as **depth of the current fragment** to compute a curvature value.

#### 3.2.1 Screen Space Surface Curvature Implementation

Surface curvature is computed in screen space, using OpenGL *partial derivatives functions* of the normal **dFdx**, **dFdy** and the *depth* of the current fragment. However, we cannot use **z-values** directly, but we need to *linearize* them as it is specified in OpenGL documentation<sup>4</sup>. Because of projection properties, a non-linear depth equation is used and it is proportional to  $1/z$ . For this reason, we have good precision when  $z$  is small, so the object is *close to the camera*, and much less precision when it is far away.

As a result, we need to **transform** non-linear depth values of fragments back to its linear form in order to use them in *surface curvature* calculation. To achieve this, we need to *revert* the process of projection, re-transforming the values to textbfnormalized device coordinates (NDC) and applying the inverse equation, using far and near planes.

Surface Curvature and Linearized Depth functions are visible in **Code 5**.

```

1  float LinearizeDepth(float depth)
2  {
3      float z = depth * 2.0 - 1.0; // back to NDC
4      return (2.0 * near * far) / (far + near - z * (far - near));
5  }
6
7
8

```

<sup>3</sup><https://madebyevan.com/shaders/curvature/>

<sup>4</sup><https://learnopengl.com/Advanced-OpenGL/Depth-testing>



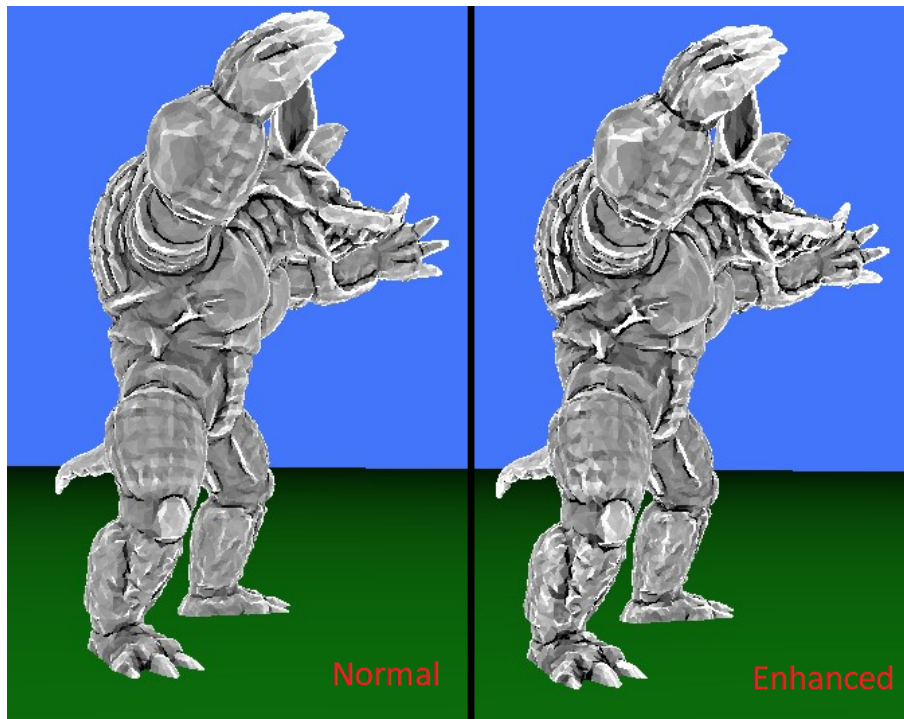
```

9  float curvature(vec3 N_I)
10 {
11     // We compute curvature exploiting partial derivatives of the Enhanced Surface
    Normal
12     vec3 dx = dFdx(N_I);
13     vec3 dy = dFdy(N_I);
14     float depth = LinearizeDepth(gl_FragCoord.z);
15     float curvature_value = (cross(N_I - dx, N_I + dx).y - cross(N_I - dy, N_I + dy).x)
        * 4.0 / depth;
16     return clamp(curvature_value, -1, 1);
17 }

```

**Code 5:** Curvature and LinearizeDepth functions in fragment shader

A Comparison between curvature computation using normal vector or enhanced normal vector (through sharpening) is showed in **Figure 4** that shows two subroutines created in the project.



**Figure 4:** Comparison between curvature computation using normal vector or enhanced normal vector (through sharpening)

### 3.3 Non-Photorealistic Rendering shading styles

As previously said, the goal of [1] is to render 3D objects *without any constraint* on the choice of material or illumination, while taking into consideration the way of Geometry-based Shading technique that *enhances the lighting* at each surface point.

To achieve this, the authors of [1] demonstrated their approach with three different **non-photorealistic shading styles**: *Blinn-Phong Shading*, *Cartoon shading* and *Gooch Shading*. For each of those styles, they **adapted** their technique by choosing properly an **intensity mapping** function  $\delta$  to be used in the reflected radiance equation.



### 3.3.1 Enhanced Blinn-Phong Shading implementation

In the context of non-photorealistic rendering, it is common to make use of *simple shading models* such as Blinn-Phong shading model.

Geometry-based shading technique can alter surface shading to enhance surface fine-scale **geometric details** in a non-photorealistic manner. This process is performed by incorporating enhanced surface normal and surface curvature measure into Blinn-Phong. As **intensity mapping** function [1] choosed  $\delta_j = \rho_j$ , where  $j \in \{a, d, s\}$  iterates over the components of Blinn-Phong's shading models: ambient, diffuse and specular.

With this approach, using a single light, the lightning equation becomes:

$$L_r(x, \omega_o) = \sum_j \rho_j(\omega_o, l) \mathcal{G}_j(x, \omega_o, l) L_j(l) \quad (1)$$

In this equation,  $l$  is the direction of the light source at point  $x$ ,  $L_j$  corresponds to the light intensity of each component,  $\rho_a = 1$ ,  $\rho_d(l) = (n' \cdot l)$ ,  $\rho_d(s) = (n' \cdot r)^f$ ;  $n'(x)$  is the **enhanced surface normal**,  $r$  is the reflection direction,  $f$  is the shininess parameter and  $\mathcal{G}_j(x, \omega_o, l)$  corresponds to the **Curvature-based Reflectance Scaling Function**.

In particular,  $\mathcal{G}_j$  is computed as:

$$\mathcal{G}_j(\delta, P) = \frac{\delta}{e^P(1 - \delta) + \delta} \quad \text{where} \quad P_{\lambda, \alpha}(k) = \text{pow}(\lambda|k|, \alpha) \quad (2)$$

In this equation,  $P_{\lambda, \alpha}$  is the **curvature mapping** function; its magnitude and strength are controlled using two parameters  $(\lambda, \alpha)$ ;  $\delta$  corresponds to the previously declared **intensity mapping** function.

Code-wise, I started from Blinn-Phong implementation, already present in **lecture03a** repository, and modified it as we can see in **Code 6**, introducing all the previously listed functions.

```

1
2
3
4 // Curvature-Based Reflectance Scaling Function
5 float Lr(float curvature_value, float delta)
6 {
7     // We apply the curvature mapping function that uses lambda and alpha parameters to
8     // apply non-linear mapping
9     float P = pow (lambda * abs(curvature_value), alpha);
10    // Uses as intensity mapping function the second parameter, delta
11    // This function maps intensity mapping and curvature mapping functions in the
12    // reflectance radiance equation
13    // This aims to correlate the reflected lightning intensity to surface curvature
14    float G = delta / ( exp(P) * ( 1 - delta ) + delta );
15    return G;
16 }
17
18
19
20
21
22
23
24
25
26

```

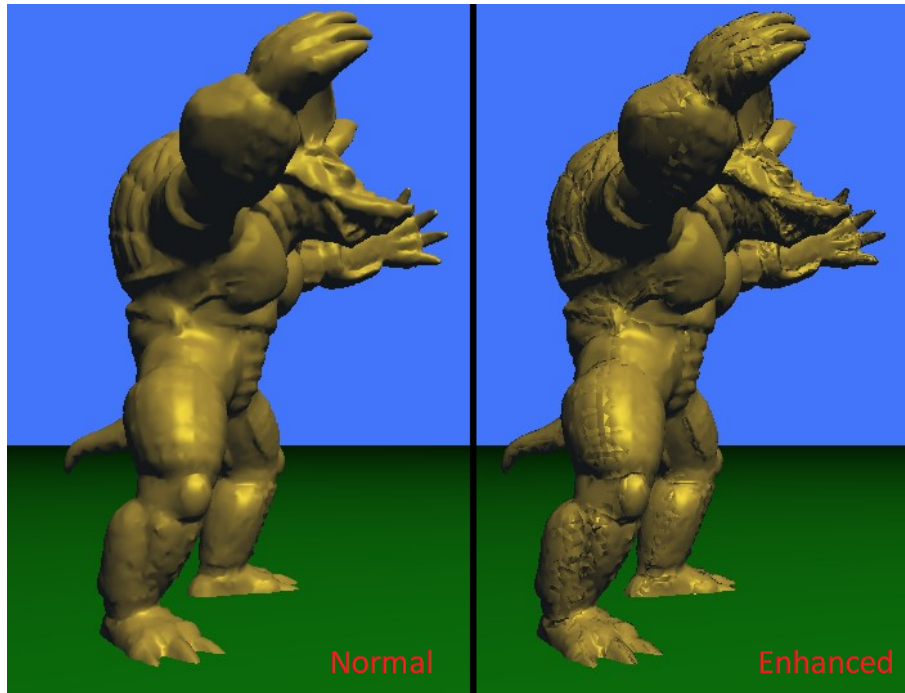
```

27
28 // a subroutine for the Enhanced Blinn-Phong model using Shape Depiction Enhancement
    based on local Geometry
29 subroutine(ill_model)
30 vec3 EnhancedBlinnPhong()
31 {
32     // Computing the mask for Unsharp Masking
33     vec3 mask = vNormal - vSMNormal;
34     // calculating enhanced Normal using the Unsharp Masking technique. This is defined
    , in the reference paper, in equation 6 of chapter 4.2.2
35     vec3 eNormal = vNormal + lambda * mask;
36     // normalization of the per-fragment enhanced normal
37     vec3 N_I = normalize(eNormal);
38     // calculating curvature value using enhanced normal
39     float curvature_value = curvature(N_I);
40     // Implementing equation 12 of chapter 6.1 of the reference paper. I calculate the
    Curvature-Based Reflectance Scaling factor for each of the Blinn-Phong components.
    NOTE: Reference paper use the constant 1 as rho_a component for ambient
41     float rhoA = 1;
42     float G_a = Lr(curvature_value, rhoA);
43     // ambient component can be calculated at this point
44     vec3 color = Ka * G_a * ambientColor;
45     // normalization of the per-fragment light incidence direction
46     vec3 L = normalize(lightDir.xyz);
47     // Lambert coefficient
48     float rhoD = max(dot(L, N_I), 0.0);
49     // if the lambert coefficient is positive, then I can calculate the specular
    component
50     if(rhoD > 0.0)
51     {
52         // This is the Curvature-Based Reflectance Scaling factor for the diffuse
        component. NOTE: Reference paper use the lambertian coefficient as rho_d for
        diffuse
53         float G_d = Lr(curvature_value, rhoD);
54         // the view vector has been calculated in the vertex shader, already negated to
        have direction from the mesh to the camera
55         vec3 V = normalize( vViewPosition );
56         // in the Blinn-Phong model we do not use the reflection vector, but the half
        vector
57         vec3 H = normalize(L + V);
58         // we use H to calculate the specular component
59         float specAngle = max(dot(H, N_I), 0.0);
60         // shininess application to the specular component
61         float rhoS = pow(specAngle, shininess);
62         // This is the Curvature-Based Reflectance Scaling factor for the specular
        component. NOTE: Reference paper use the lambertian coefficient as rho_s for
        specular
63         float G_s = Lr(curvature_value, rhoS);
64         // We add diffusive and specular components to the final color using our
        Curvature-Based factors
65         color += vec3( Kd * G_d * diffuseColor +
66             Ks * G_s * specularColor);
67     }
68     return color;
69 }

```

**Code 6:** Enhanced Blinn-Phong subroutine and Curvature-Based Reflectance scaling function implemented in fragment shader

A Comparison between standard Blinn-Phong and Enhanced Blinn-Phong using Geometry-based shading is showed in **Figure 5** that use two subroutines created in the project.



**Figure 5:** Comparison between standard Blinn-Phong and Enhanced Blinn-Phong using Geometry-based shading

### 3.3.2 Enhanced Cartoon/Cel Shading implementation

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### 3.3.3 Enhanced Gooch Shading implementation

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## 4 Conclusions

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## References

- [1] Riyadh Al-Rousan, Mohd Shahrizal Sunar, Hoshang Kolivand (2017) *Geometry-based shading for shape depiction enhancement*