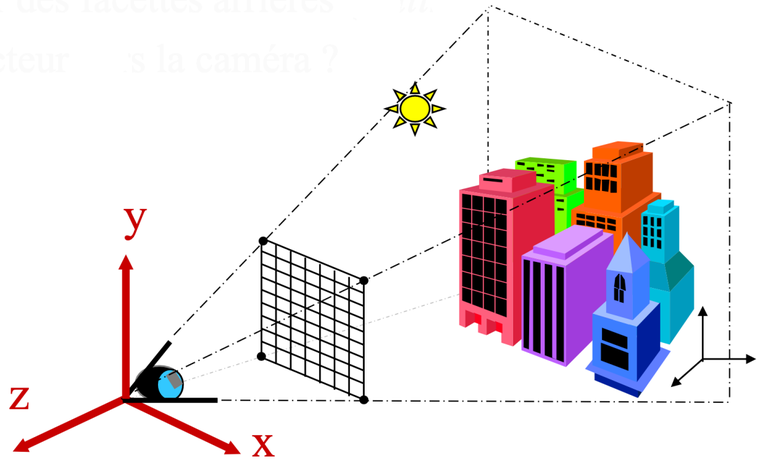
Pipeline de Rendu et Illumination

Principes d'une scène 3D - Concepts

Description

- Modèle 3D: Une surface ou un volume
- Source de lumière
- Caméra

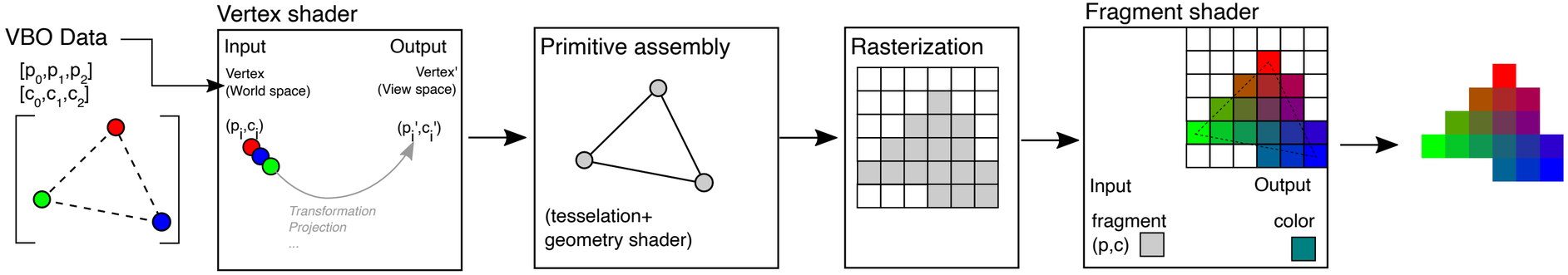


Sortie

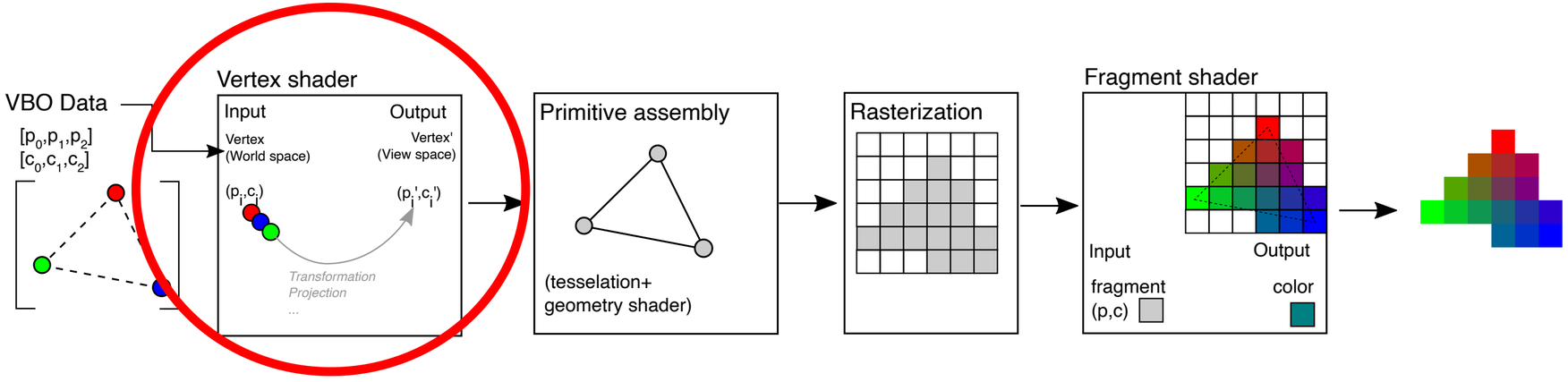
- Image vue de la caméra

OpenGL/GPU

- Pas de notion de caméra, de lumière
- Notion de sommets et d'attributs: entrée du vertex shaders
- Notion de pixels/fragments coloré: sortie du fragment shaders



Transformation des sommets
Projection et perspective



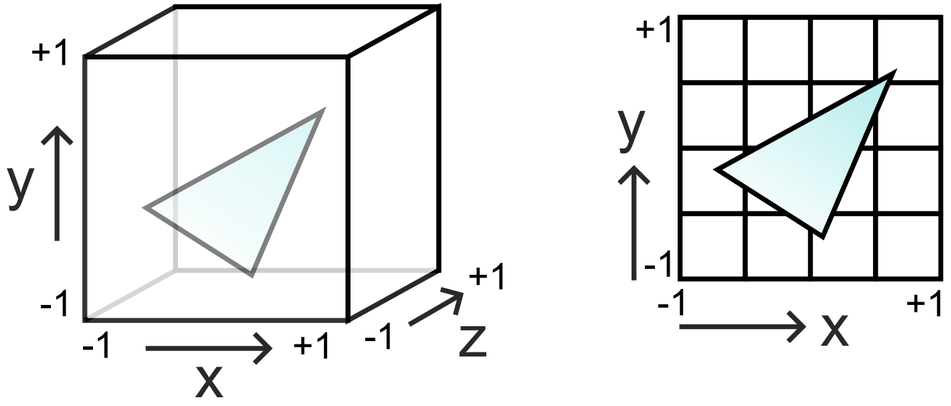
Principe de projection

OpenGL n'affiche que les triangles dans le cube $[-1, 1]^3$

Normalized Device Coordinates (NDC)

(x, y) $\rightarrow$: coordonnées de l'écran

z: profondeur



Objectif de la projection

Convertir les coordonnées globales (World space coordinates) en Normalized Device Coordinates

Décider d'un modèle de caméra

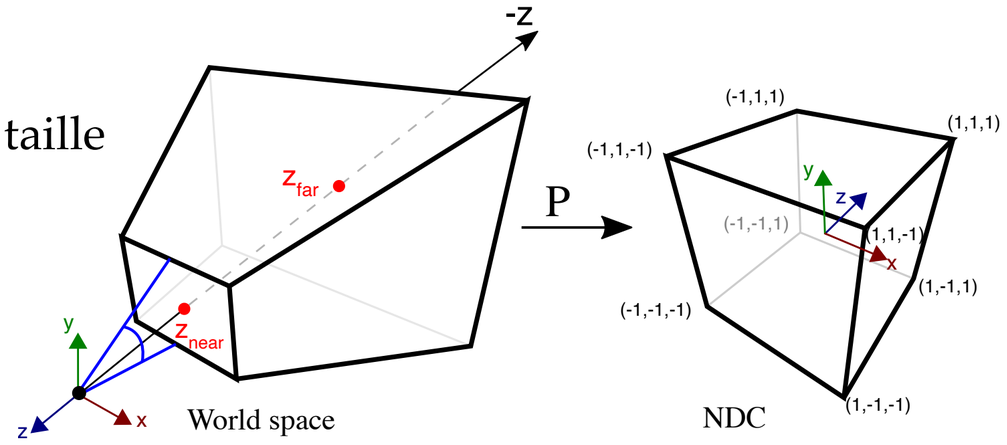
Partie visible de l'espace

Appliquer une perspective: éloignement $\rightarrow$ réduction de taille

Perspective la plus courante:

Visibilité dans un cone rectangulaire tronqué: Frustum

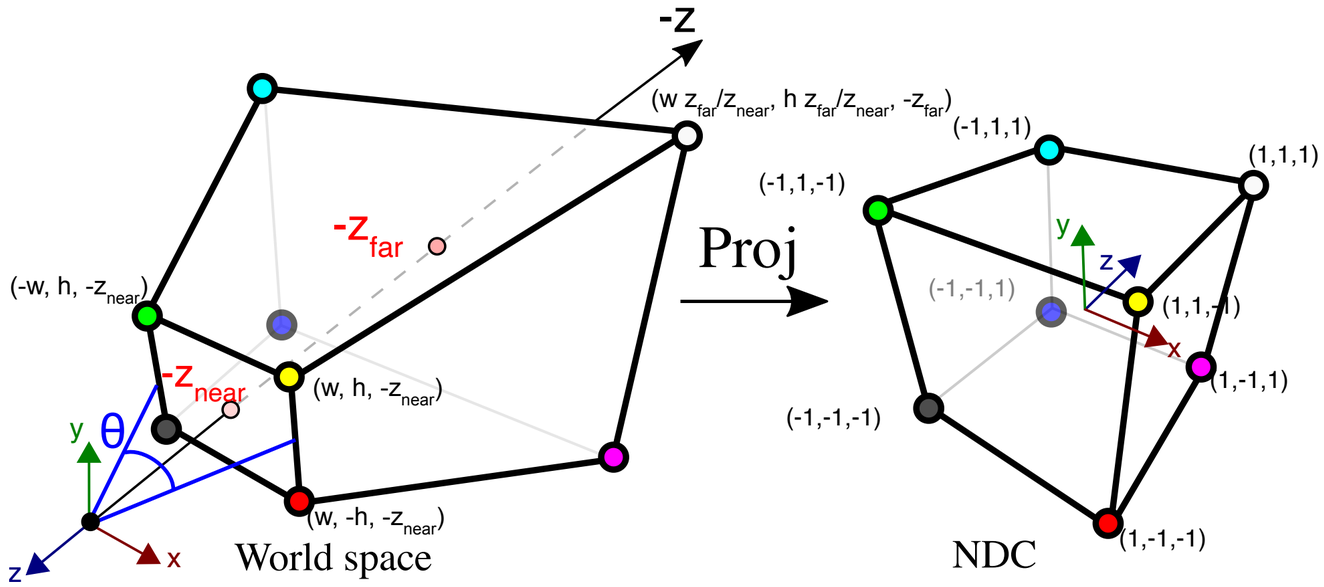
Perspective en "1/z"



Projection formulation

World space: (x, y, z), NDC: $(x_{ndc}, y_{ndc}, z_{ndc})$

$(x_{ndc}, y_{ndc}, z_{ndc}) = \text{Proj}(x, y, z)$



Mapping

$(w, h, -z_{near}) \to (1, 1, -1)$

$\left(w\frac{z_{far}}{z_{near}}, h\frac{z_{far}}{z_{near}}, -z_{far}\right) \to (1, 1, 1)$

etc.

Rem: $-z$ pour garder un repère droit

Formulation

- $\boxed{x_{ndc} = \frac{z_{near}}{-z} x/w}$

  ou, avec un champ de vision (field of view) d'angle θ: $\boxed{x_{ndc} = 1/\tan(\theta/2)\ x/(-z)}$

- $\boxed{y_{ndc} = \frac{z_{near}}{-z} y/h}$

  ou, avec un champ de vision (field of view) d'angle θ: $\boxed{y_{ndc} = r/\tan(\theta/2)\ y/(-z), \quad r = h/w}$

- z_{ndc}: variation linéaire divisée par $1/z$: $z_{ndc} = (\alpha z + \beta)/(-z)$

  Division par $1/z \Rightarrow$ précision plus fine proche de la caméra, grossier plus loin.

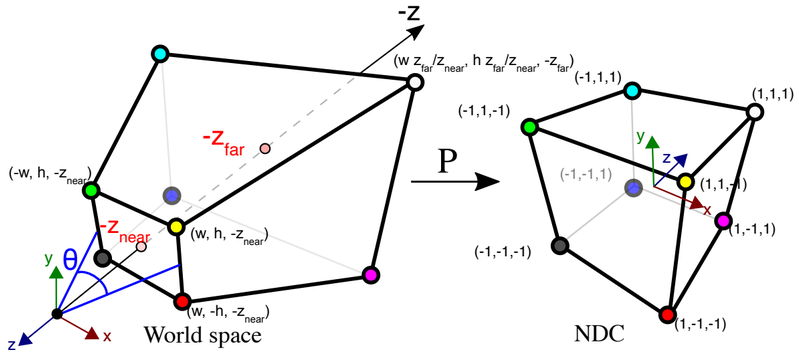
  Mapping $(0, 0, -z_{far}) \to (0, 0, 1)$, et $(0, 0, -z_{near}) \to (0, 0, -1)$

  $$\Rightarrow \begin{cases} (-\alpha\, z_{far} + \beta)/z_{far} = 1 \\ (-\alpha\, z_{near} + \beta)/z_{near} = -1 \end{cases} \Rightarrow \begin{cases} \alpha = -(z_{far} + z_{near})/(z_{far} - z_{near}) \\ \beta = -2\, z_{near} z_{far}/(z_{far} - z_{near}) \end{cases}$$

  $$\boxed{\Rightarrow z_{ndc} = \frac{1}{z}\left(\frac{z_{far} + z_{near}}{z_{far} - z_{near}} z + 2\frac{z_{near} z_{far}}{z_{far} - z_{near}}\right)}$$

Projection matrix

Formulation matricielle en coordonnées généralisées: $p_{ndc} = \text{Proj}\ p$

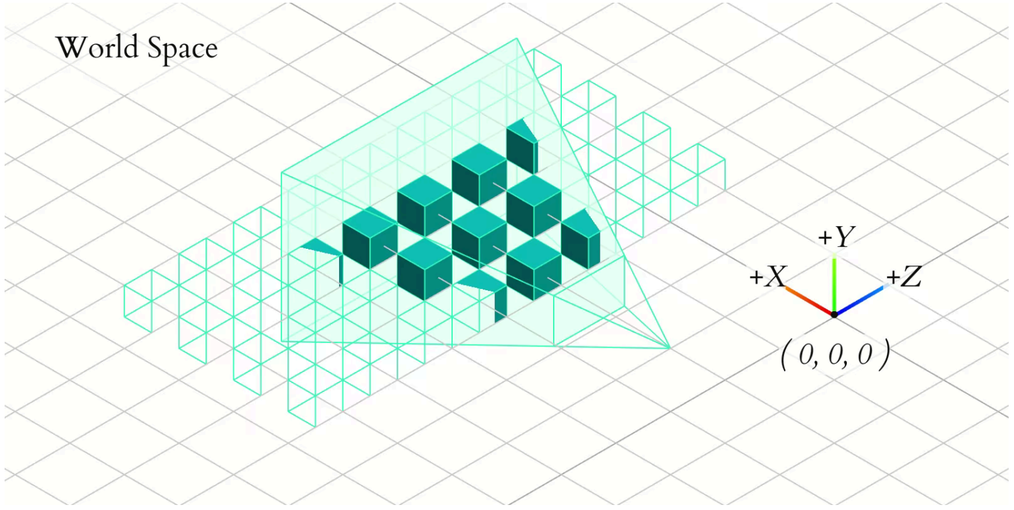


$$(x_{ndc}, y_{ndc}, z_{ndc}) = \frac{1}{-z}\left(\frac{1}{\tan(\theta/2)}x,\ \frac{r}{\tan(\theta/2)}y,\ -\frac{z_{far}+z_{near}}{z_{far}-z_{near}}\ z - 2\frac{z_{near}z_{far}}{z_{far}-z_{near}}\right)$$

$$\Rightarrow p_{ndc} = \begin{pmatrix} 1/\tan(\theta/2)\,x \\ r/\tan(\theta/2)\,y \\ -\frac{z_{far}+z_{near}}{z_{far}-z_{near}}\ z - 2\frac{z_{near}z_{far}}{z_{far}-z_{near}} \\ -z \end{pmatrix} = \underbrace{\begin{pmatrix} 1/\tan(\theta/2) & 0 & 0 & 0 \\ 0 & r/\tan(\theta/2) & 0 & 0 \\ 0 & 0 & -\frac{z_{far}+z_{near}}{z_{far}-z_{near}} & -2\frac{z_{near}z_{far}}{z_{far}-z_{near}} \\ 0 & 0 & -1 & 0 \end{pmatrix}}_{\text{Proj}} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \text{Proj}\ p$$

Normalized Device Coordinates:

- Espace déformé dans le cube $[-1, -1]$
  + déformation perspective
- Image = Vue (x,y) du cube
- z_{ndc} = profondeur vue de la caméra dans l'espace image.



Credit: Jordan Santell

Z-Fighting

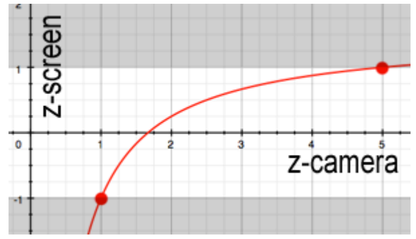
Plus de précision proche de z_{near} que de z_{far}

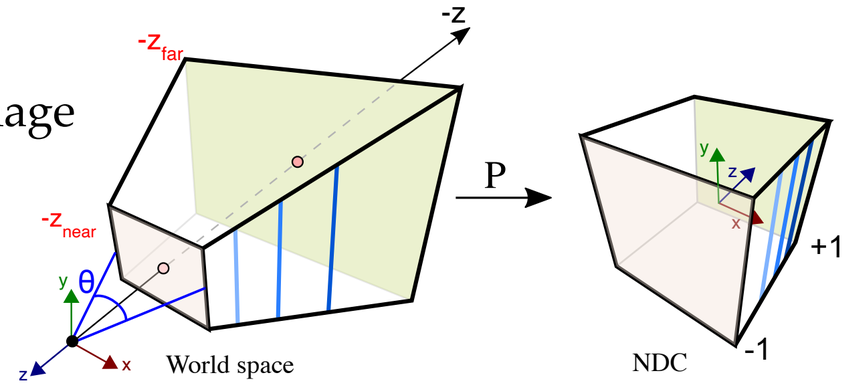
Si z_{near} trop proche de 0

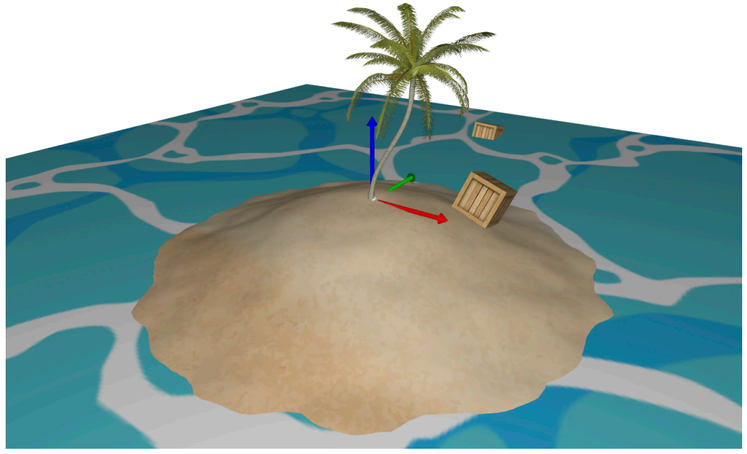
Toute la précision est concentrée sur z_{near}

Profondeur éléments éloignés = même valeur après échantillonnage

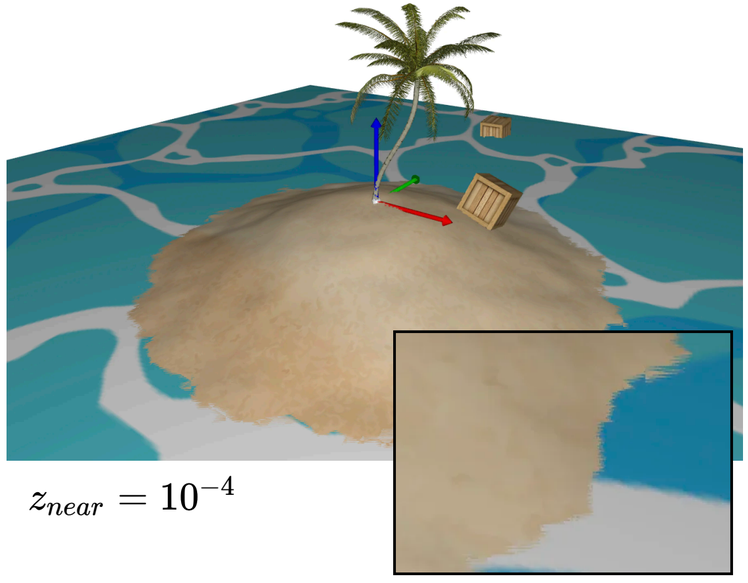
$\Rightarrow$ Z-fighting / Depth-fighting



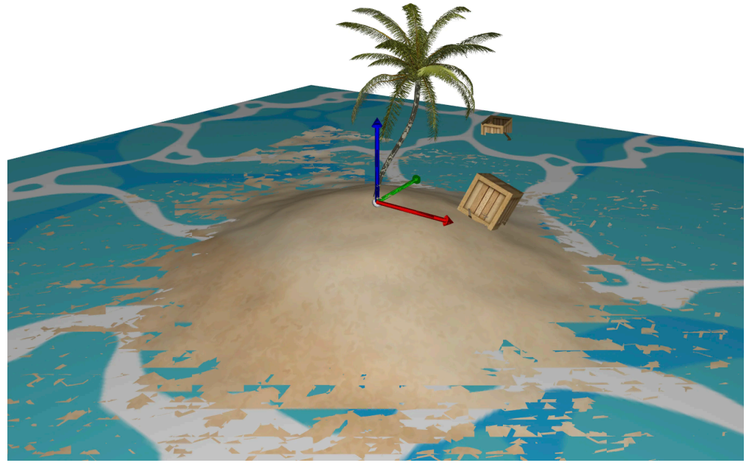




$z_{near} = 10^{-2}$



$z_{near} = 10^{-4}$



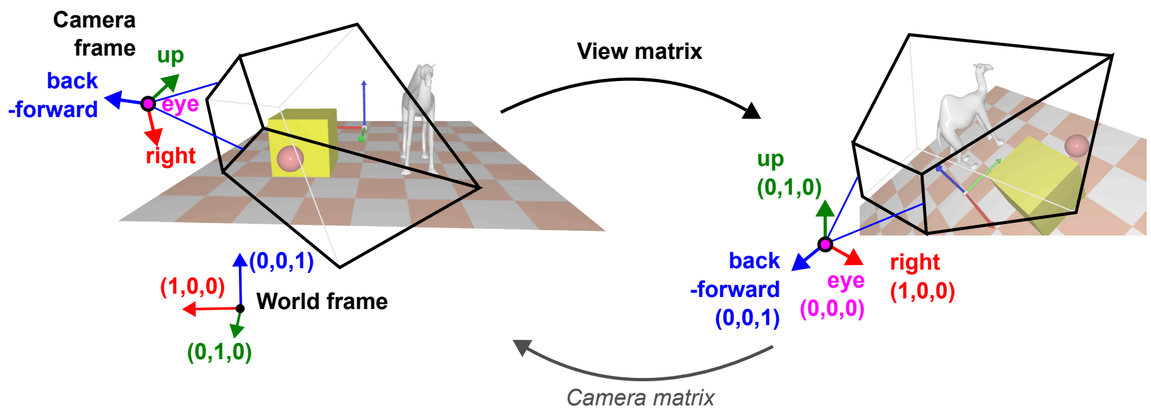
$z_{near} = 10^{-5}$

Z-Fighting Demo

View matrix - Formulation

Matrice **View**:

Transforme *World space coords.* $\rightarrow$ *View space coords.*



Coordonnées de la caméra: Cam

$\text{Cam} \times (1,0,0,0) = right$

$\text{Cam} \times (0,1,0,0) = up$

$\text{Cam} \times (0,0,1,0) = back$

$\text{Cam} \times (0,0,0,1) = eye$

$$\text{Cam} = \begin{pmatrix} | & | & | & | \\ right & up & back & eye \\ | & | & | & | \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} O & eye \\ 0 & 1 \end{pmatrix}$$

View matrix: View

$\text{View} \times right = (1,0,0,0)$

$\text{View} \times up = (0,1,0,0)$

$\text{View} \times back = (0,0,1,0)$

$\text{View} \times eye = (0,0,0,1)$

$$\text{View} = \begin{pmatrix} (\cdots & right & \cdots) & -right \cdot eye \\ (\ldots & up & \cdots) & -up \cdot eye \\ (\cdots & back & \cdots) & -back \cdot eye \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} O^T & -O^T\, eye \\ 0 & 1 \end{pmatrix}$$

$$\boxed{\text{View} = \text{Cam}^{-1}}$$

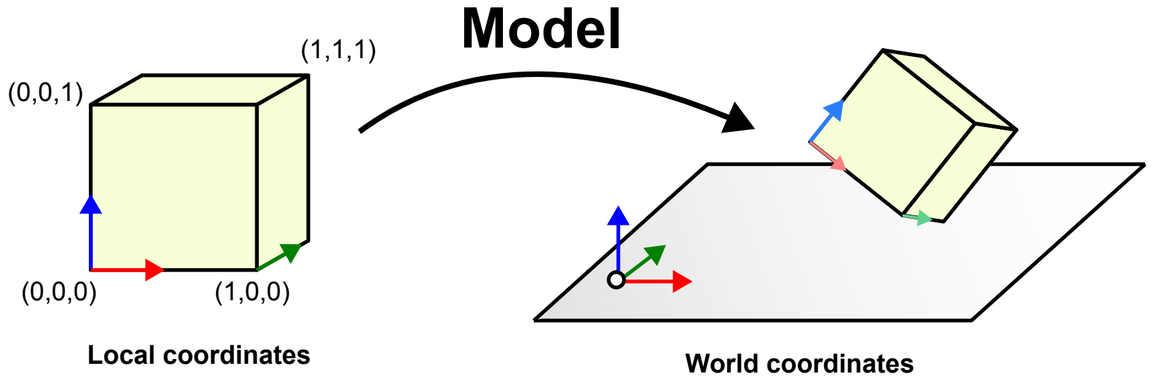
Model matrix

Positionne l'objet dans le monde

Model: coords. locales objet $\rightarrow$ world coords.

Intêret:

- Charge une unique fois les coordonnées géométriques de l'objet dans un repère locale.
- Place/déplace en changeant uniquement la matrice Model.



$$\text{Model} = \begin{pmatrix} \text{rotation} & \text{translation} \\ 0 & 1 \end{pmatrix}$$

Synthèse matrices - Formulation

Entrée: Coordonnées $p = (x, y, z, 1)$ dans l'espace objet

- Coordonnées dans l'espace du monde $p_{ws} = \text{Model } p$
- Coordonnées dans l'espace caméra $p_{view} = \text{View } p_{ws}$
- Coordonnées dans le NDC - Normalized Device Coordinates $p_{ndc} = \text{Proj } p_{view}$

Sortie en espace image: NDC homogénéisée $p_{out} = (x_{ndc}/w_{ndc},\ y_{ndc}/w_{ndc},\ z_{ndc}/w_{ndc},\ 1)$

Formulation globale: $\boxed{p_{ndc} = \text{Proj} \times \text{View} \times \text{Model} \ \ p}$

1ère étape du pipeline graphique: **Vertex shader**

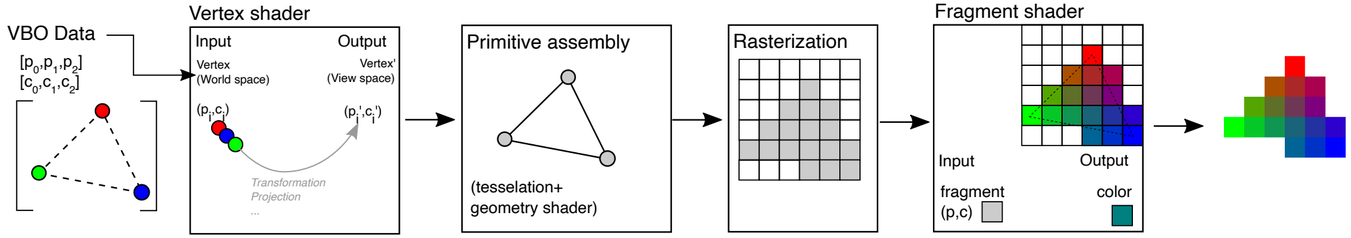
```
#version 330 core

// vertex position in local space (x,y,z)
layout (location = 0) in vec3 vertex_position;

// uniform = parameters send from C++ code
uniform mat4 model;
uniform mat4 view;
uniform mat4 projection;

void main() {
    // gl_Position: Output position from Vertex Shader (NDC)
    gl_Position = projection * view * model * (position,1.0);

    // normalization automatically performed by the GPU
}
```



Synthèse matrices - Demo

$$p_{ndc} = \text{Proj} \times \text{View} \times \text{Model} \;\; p$$

Matrices: C++ / paramètres uniformes

Changement de coordonnées en C++:

- Principalement mono-thread
  - Calcul des nouvelles positions
  - Copies coordonnées sur mémoire GPU
- Possible, mais lent

```
std::vector<vec3> apply(mat4 Model, mat4 View, mat4 Projection,
                        std::vector<vec3> const& position_in) {
    std::vector<vec3> position_out;
    for (auto const& p : p_in) {
        vec4 p_homog{p, 1.0f};
        vec4 p_ndc_homog = Projection * View * Model * v_homog;
        vec3 p_ndc = vec3{v_clip} / v_clip.w;
        position_out.push_back(p_ndc);
    }
    return position_out;
}

void main_loop() {
    std::vector<vec3> new_position;
    // Update Model, View, Projection, ...

    // N-operations - monothread
    new_position = apply(Model, View, Projection, mesh.position);

    // N-copy to the GPU
    mesh_drawable.position.update(new_position);

    draw(mesh_drawable);
}
```

Matrices: C++ / paramètres uniformes

Changement de coordonnées via Uniforms:

- Simple copie de matrices
- Pas de calcul supplémentaire en C++
- Calcul des nouvelles positions en parallèle sur le GPU, surcout négligeable

```cpp
void main_loop() {
    // Update Model, View, Perspective, ...

    // Copy three 4x4 matrices
    glUniform(shader, Model);
    glUniform(shader, View);
    glUniform(shader, Projection);

    draw(mesh_drawable);
}
```

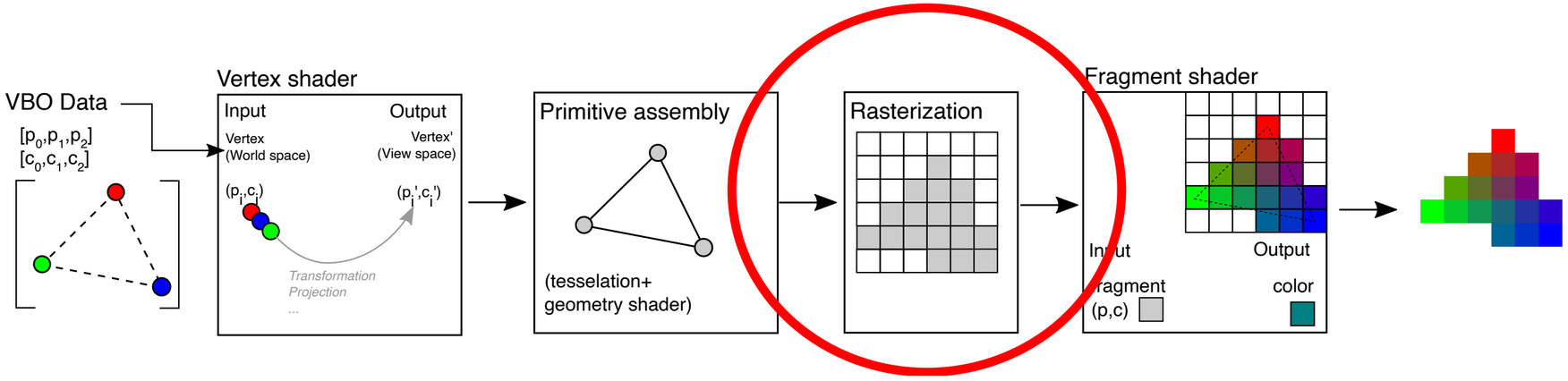
C++

```
in vec3 vertex_position;
uniform mat4 Model;
uniform mat4 View;
uniform mat4 Projection;
void main() {
    gl_Position = Projection * View * Model * (position,1.0);
}
```

In parallel on all vertices

Vertex shader

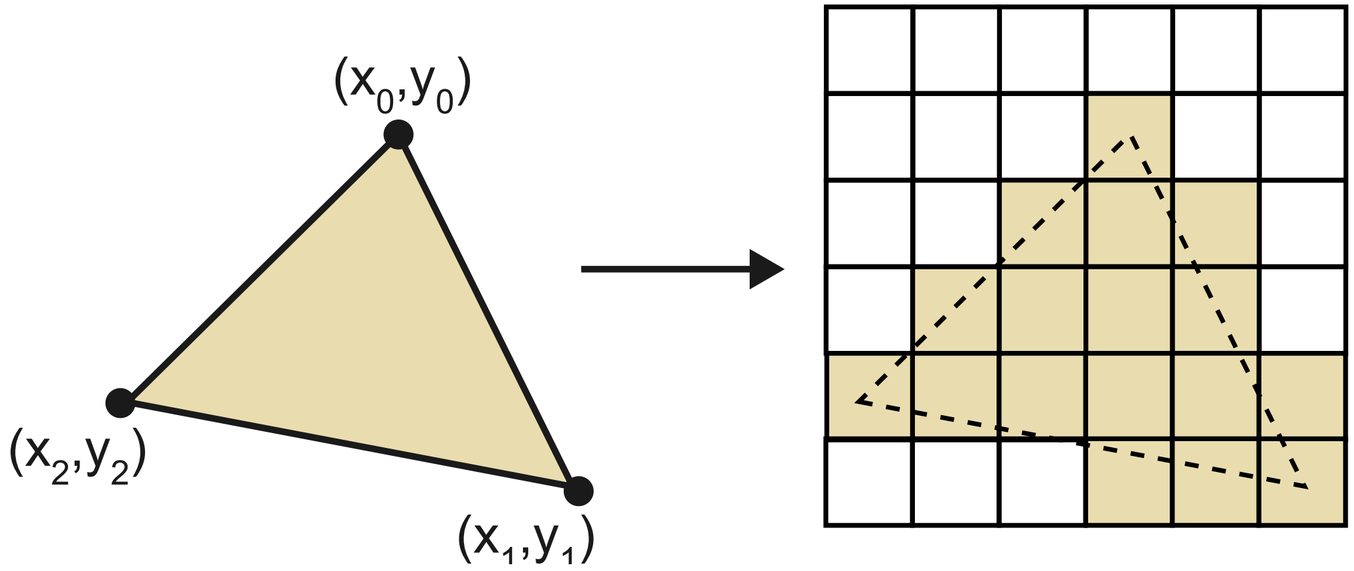
Rasterization



Rasterization

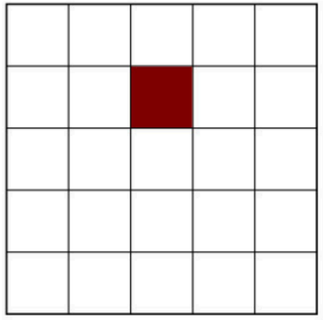
Rasterization/facetisation = conversion de données vectorielles en éléments unitaires: pixels/fragments.
Automatique en OpenGL, non programmable.

Triangle définis par 3 points 2D $\Rightarrow$ Ensemble de coordonnées de pixels



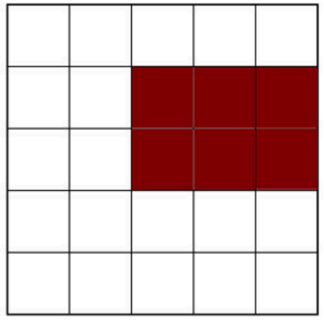
Rasterization de primitives

Point



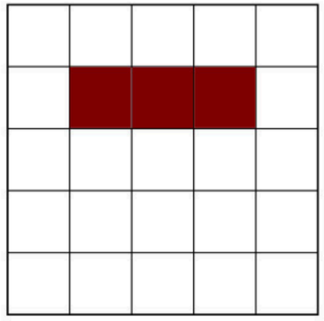
```
im(x0, y0) = c;
```

Rectangle



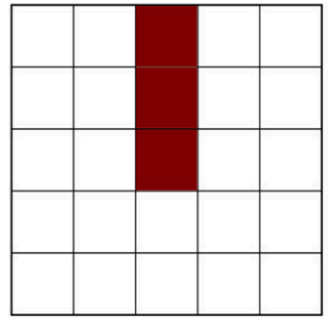
```
for(int kx=x0; kx<x1; kx++)
  for(int ky=y0; ky<y1; ky++)
    im(kx, ky) = c;
```

Segment horizontal



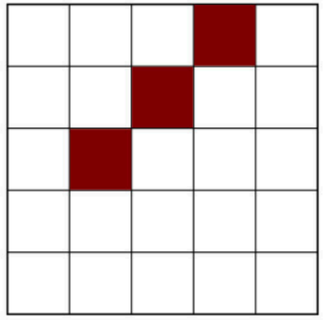
```
for(int kx=x0; kx<x1; kx++)
    im(kx, y0) = c;
```

Segment vertical



```
for(int ky=y0; ky<y1; ky++)
    im(x0, ky) = c;
```

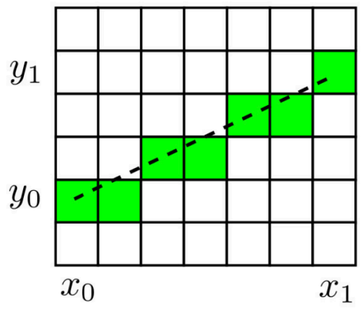
Segment diagonal

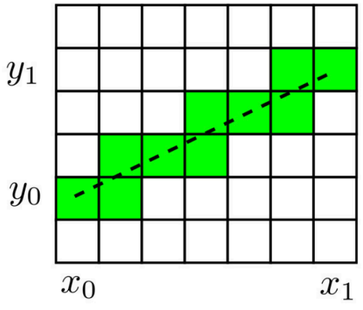


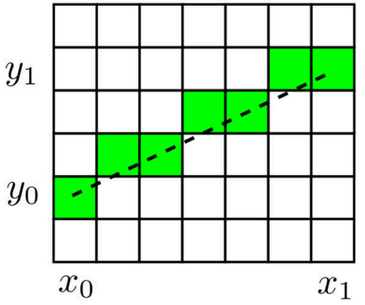
```
for(int ky=y0; ky<y1; ky++)
    im(x0, ky) = c;
```

Segment quelconque

Plusieurs possibilitées ?





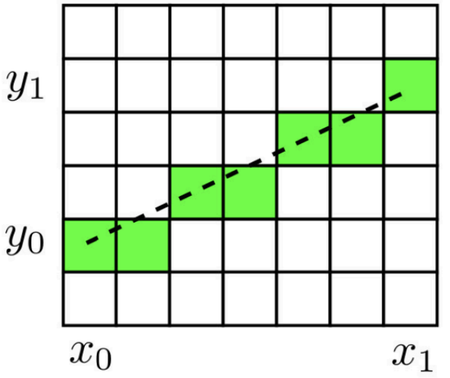


Segment discret

Algorithme efficace: Algorithme de **Bresenham**

$y = a(x - x_0) + y_0$

Valeur exacte (x, y) supposée au centre du pixel

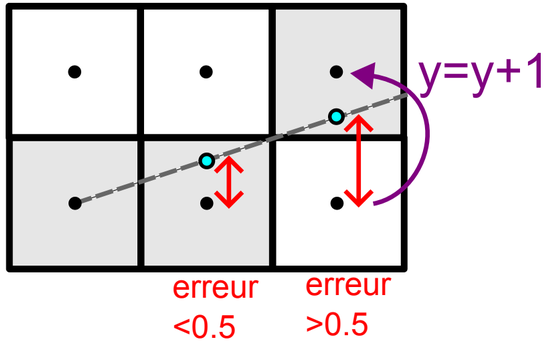


Principe:

Avance suivant x de 1 pixel

Evalue si erreur en $y > 0.5$

Si oui: augment y de 1, et corrige erreur




```
int dx=x1-x0, dy=y1-y0;
float a = float(dy)/float(dx);
float erreur = 0.0f;

int y=y0;
for(int x=x0; x<=x1; x++)
{
    im(x, y) = c;
    erreur += a;
    if( erreur >= 0.5f )
    {
        y = y+1;
        erreur = erreur - 1.0f;
    }
}
```

Rem.

- Calcul entièrement sur entier possible en multipliant par $2dx$.

- Version symmétrique en fonction des quadrants

Triangle: algorithme scanline

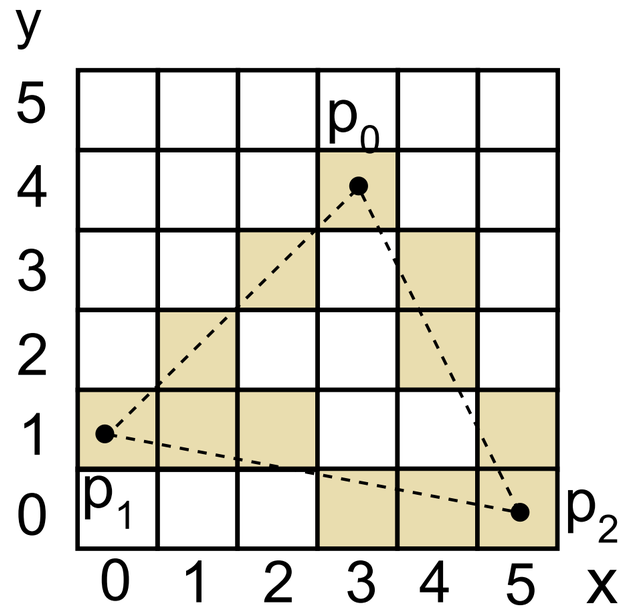
Triangle p_0, p_1, p_2

Parcours les arêtes (p_0, p_1), (p_1, p_2), (p_2, p_0)

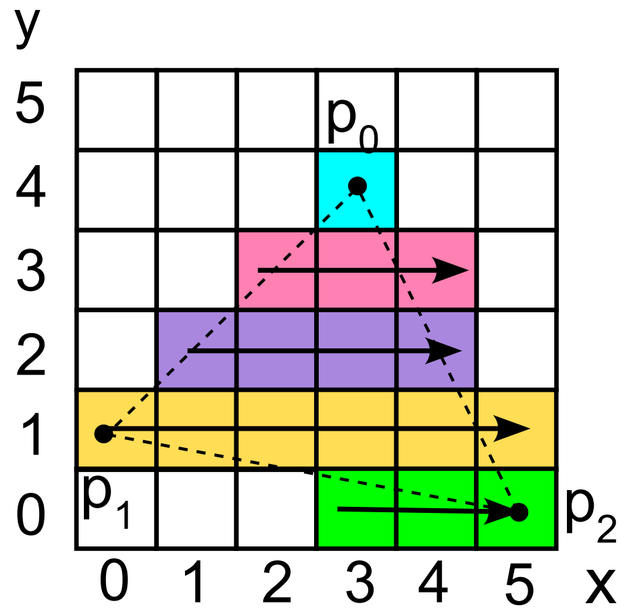
Stocke $\{y, (x_{\min}, x_{\max})\}$

Pour chaque ligne y

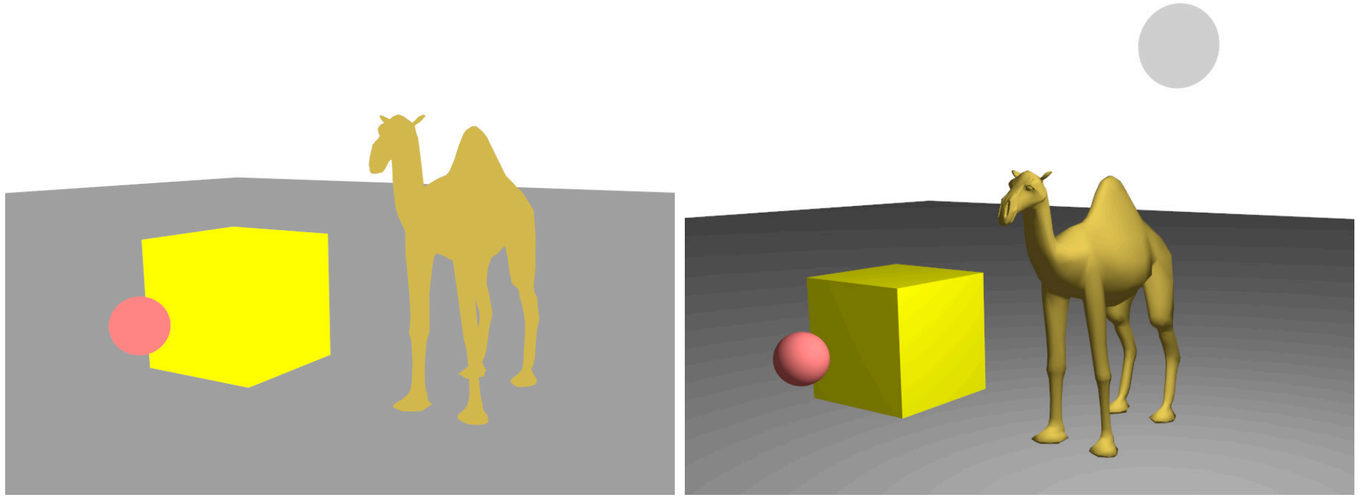
Affiche les segments horizontaux $(x_{\min}, x_{\max})$

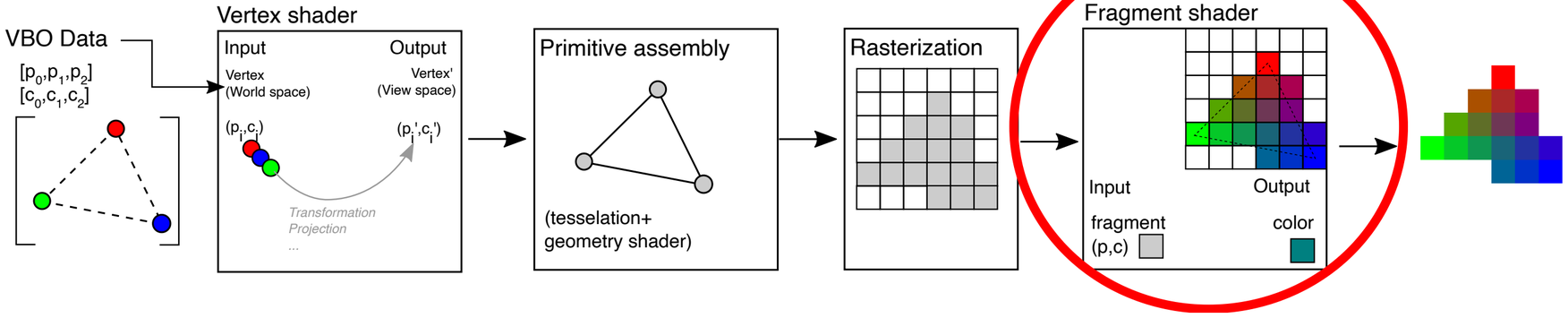


y	$x_{\min}$	$x_{\max}$
0	3	5
1	0	5
2	1	4
3	2	4
4	3	3



Shading / Illumination





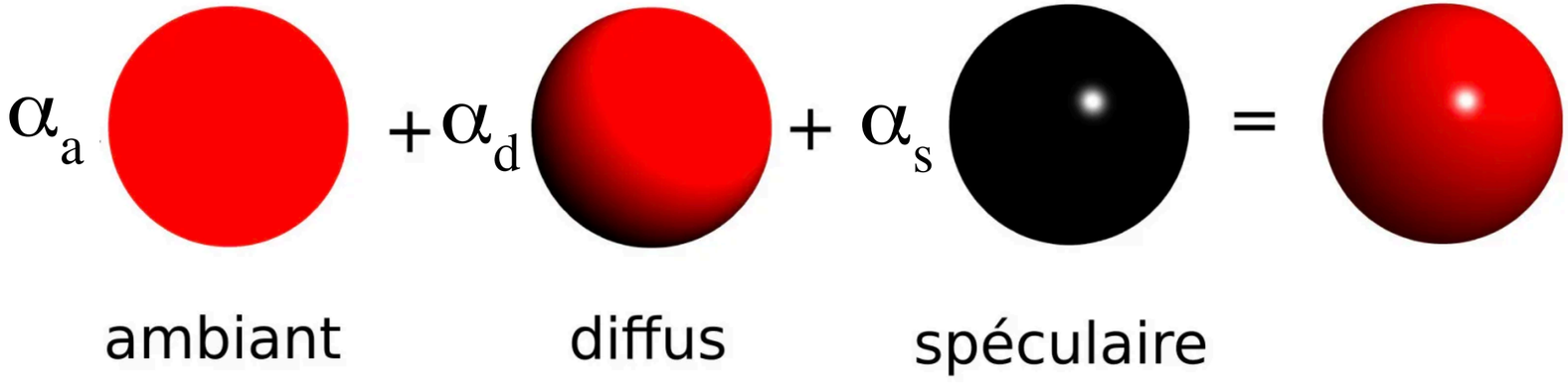
Modèle d'illumination de Phong

Trois composantes:

- **Ambiante/Ambiant**: Couleur générale
- **Diffuse/Diffus**: Orientation locale
- **Spéculaire/Specular**: Reflexion, brillance

Dependance de la couleur:

- Couleur de la source lumineuse $C_\ell = (r_\ell, g_\ell, b_\ell) \in [0,1]^3$
- Couleur de la surface $C_o = (r_o, g_o, b_o) \in [0,1]^3$



Illumination

Couleur ambiante

$$C_a = \alpha_a \, C_\ell \, C_0$$

$\alpha_a \in [0,1]$: Coefficient ambiant

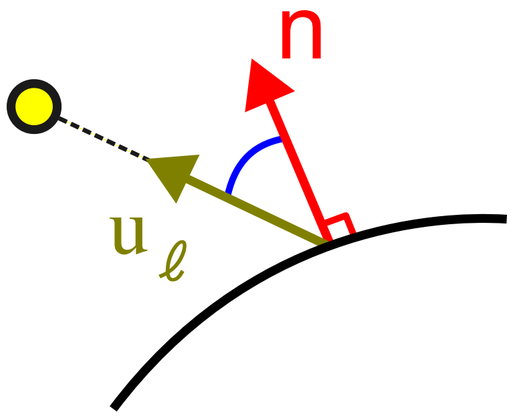
Couleur diffuse

Orientation locale de la surface / source de lumière

$$C_d = \alpha_d \, (n \cdot \, u_\ell)_+ \, C_\ell \, C_0$$

$\alpha_d \in [0,1]$: Coefficient diffus

$(n \cdot \, u_\ell)_+ = \max(n \cdot \, u_\ell, 0) \in [0,1]$: Composante diffuse



Illumination: Speculaire

Couleur speculaire

Réflection source lumineuse sur la camera

$$C_s = \alpha_s \left(u_r \cdot \ u_v\right)_+^{s_{exp}} \ C_\ell$$

$\alpha_s \in [0,1]$: Coefficient speculaire

$s_{exp} \simeq 64 - 256$: Hardness / Glossiness

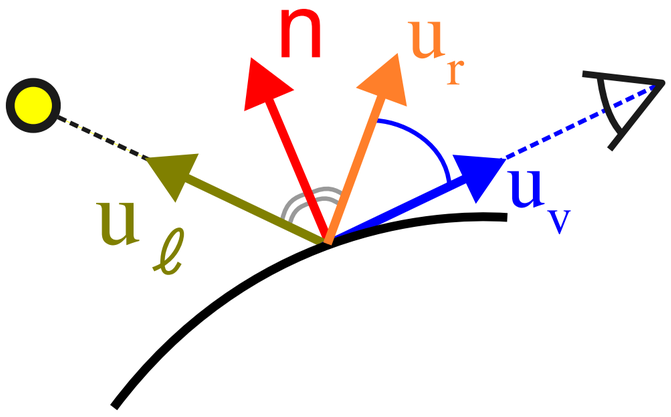
u_r: reflexion de la source lumineuse / normale

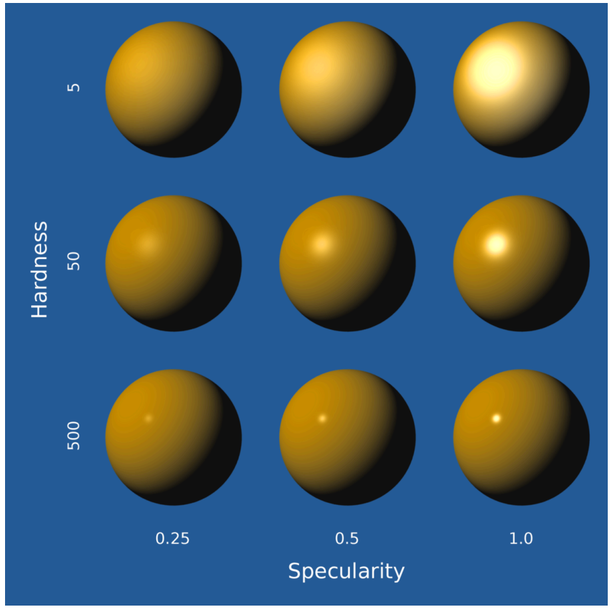
$u_r = 2(u_\ell \cdot n)n - u_\ell$

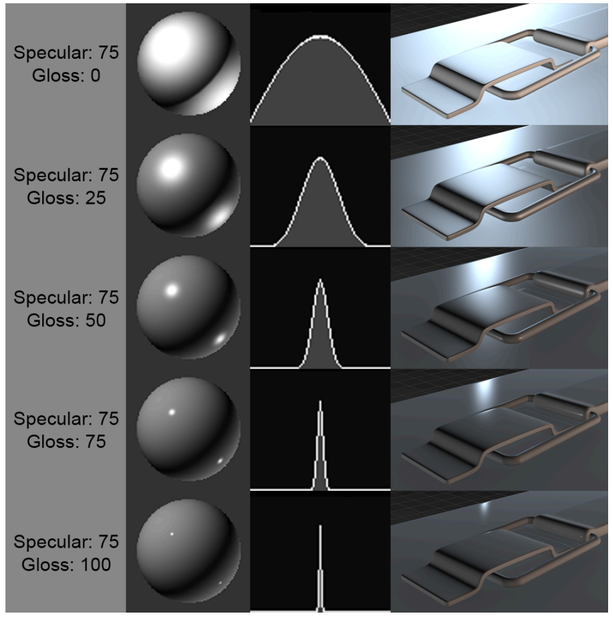
En glsl: $u_r = \text{reflect}(-u_\ell, n)$

u_v: direction position-caméra

Ne dépend que de la couleur de la source lumineuse

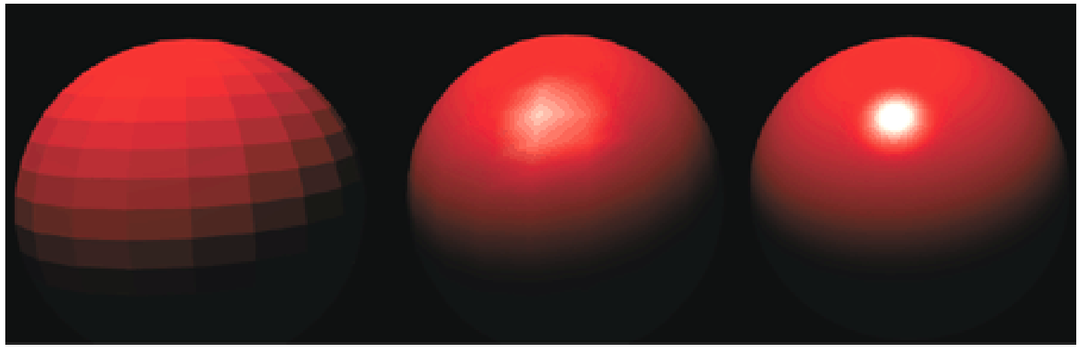






Interpolation de l'illumination: Flat, Gouraud, Phong

- **Flat**: Couleur uniforme par triangle
- **Gouraud**: Calcul illumination par sommet, interpolation linéaire de la couleur dans le triangle.
  Calcul illumination dans vertex shader
- **Phong**: Calcul illumination pour chaque fragment
  Calcul illumination dans le fragment shader



Effets d'illumination

Sources multiples

$$C = \sum_i \alpha_a \, C_{\ell_i} C_s + \alpha_d \, (n \cdot u_{\ell_i})_+ \, C_{\ell_i} C_s + \alpha_s \, (u_{r_i} \cdot u_v)_+^{s_{exp}} \, C_{\ell_i}$$

Atténuation d'intensité fonction de la distance

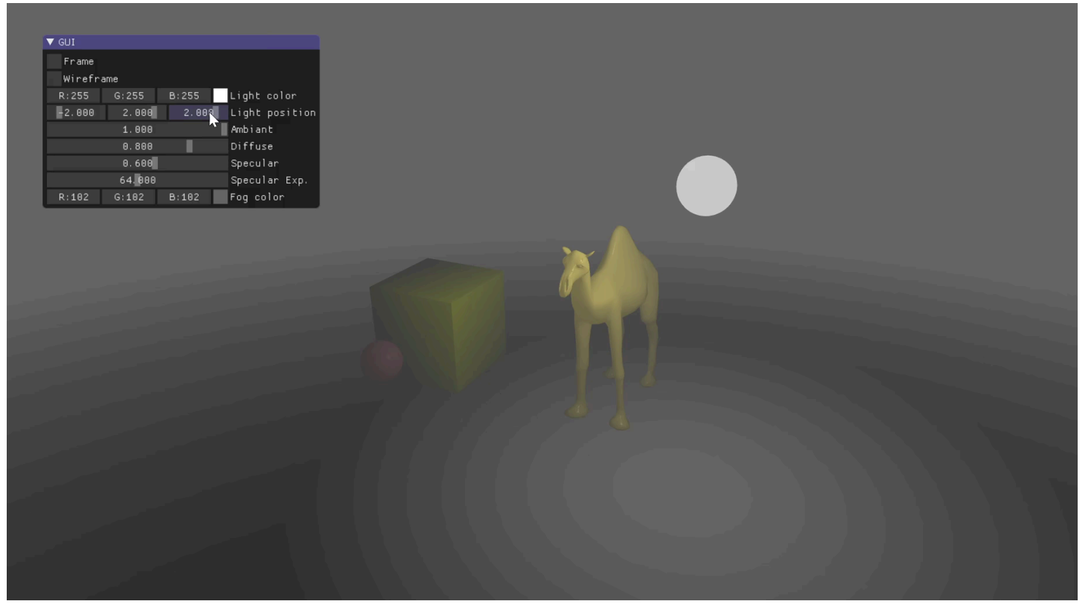
$$C_\ell(p) = \left(1 - \min\left(\frac{\|p - p_\ell\|}{d^0_{att}}, 1\right)\right) \, C^0_\ell$$

$p \in \mathbb{R}^3$: position sur la surface

$p_\ell \in \mathbb{R}^3$: centre de la lumière

d^0_{att}: distance caractéristique d'attenuation

C^0_ℓ: couleur de la lumière à la source



Effet de brume/fog

Mélange de couleur en fonction de la distance à la caméra

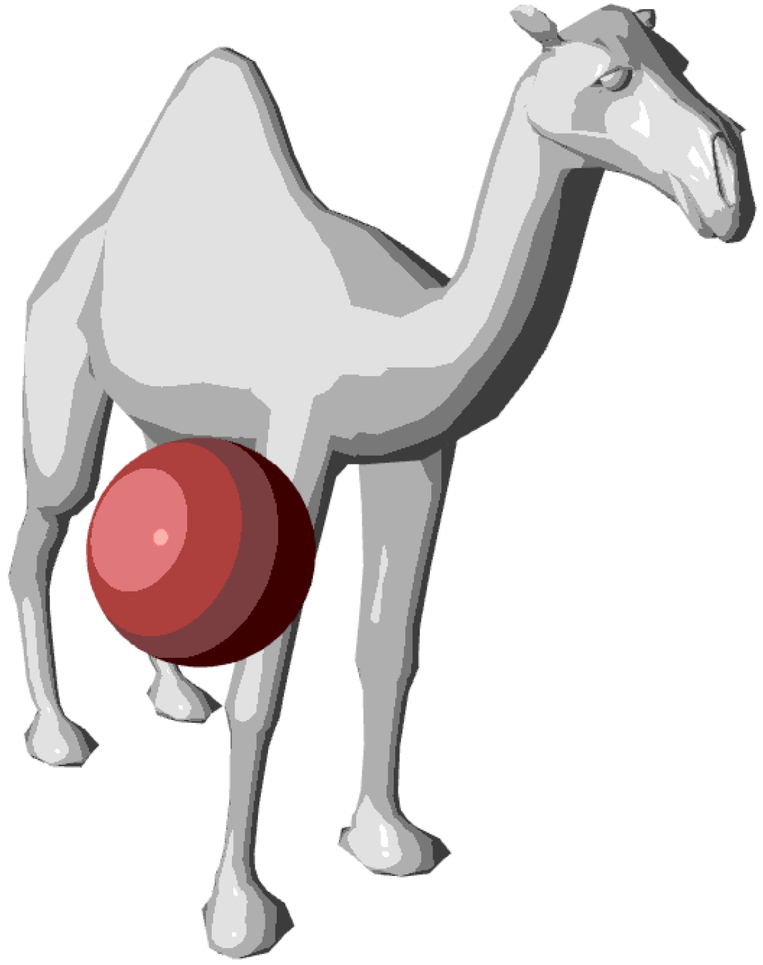
$$C = (1 - \gamma(p)) \, C_s C_\ell + \gamma(p) \, C_{fog}$$

$$\gamma(p) = \min(\|p - p_{eye}\| / d_{fog}, 1)$$

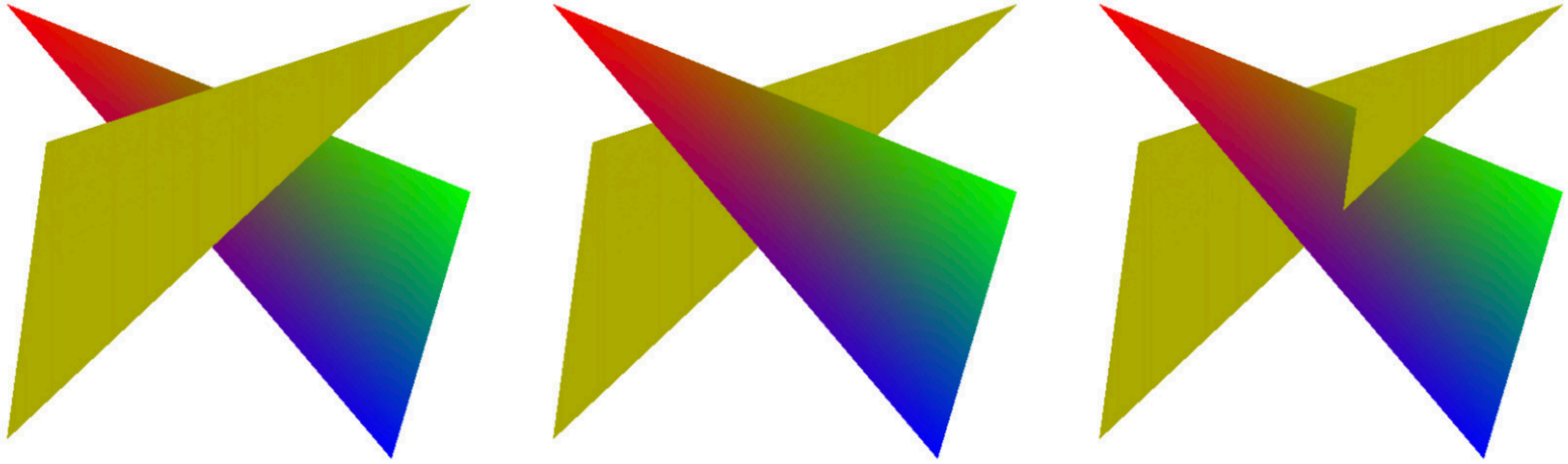
Example effet: Toon Shading

Sous échantillonne les valeurs de couleurs

$C_{toon} = float(N\, int(C/N))$



Buffer de profondeur / Depth Buffer

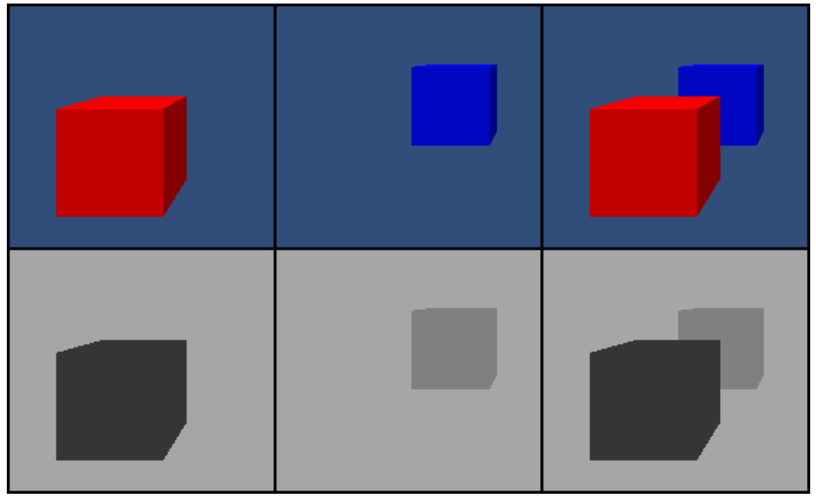


Buffer de profondeur / Depth Buffer

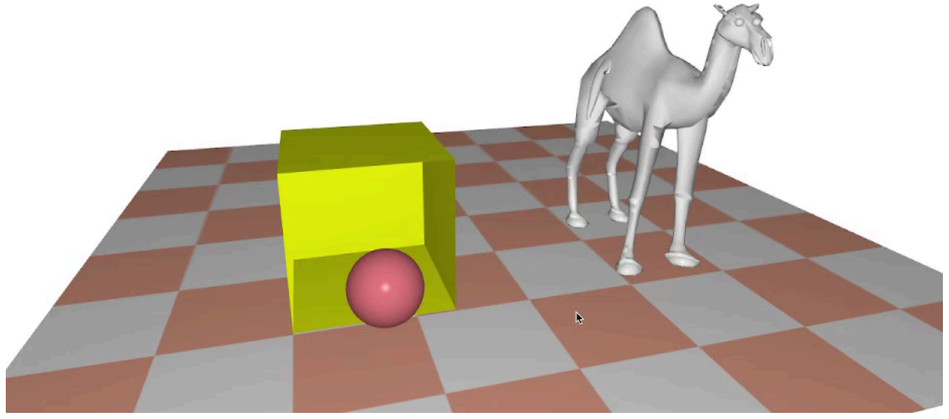
- Gestion d'un buffer/image de profondeur
  - Depth-buffer / Z-buffer
  - Stocke la valeur z_{ndc} pour chaque pixel

Algorithme

```
def Draw(position, couleur, z, image, Zbuffer):
    if Zbuffer(position) < z:
        image(position) = couleur
    # else draw nothing
```

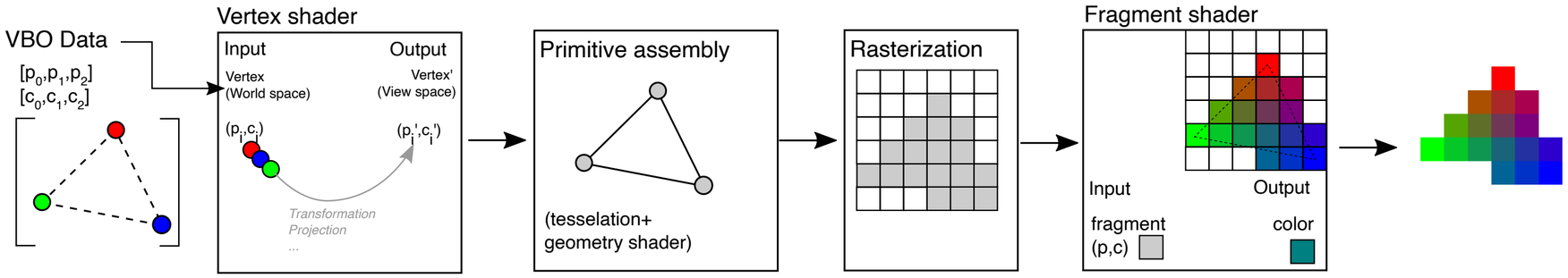


Depth buffer

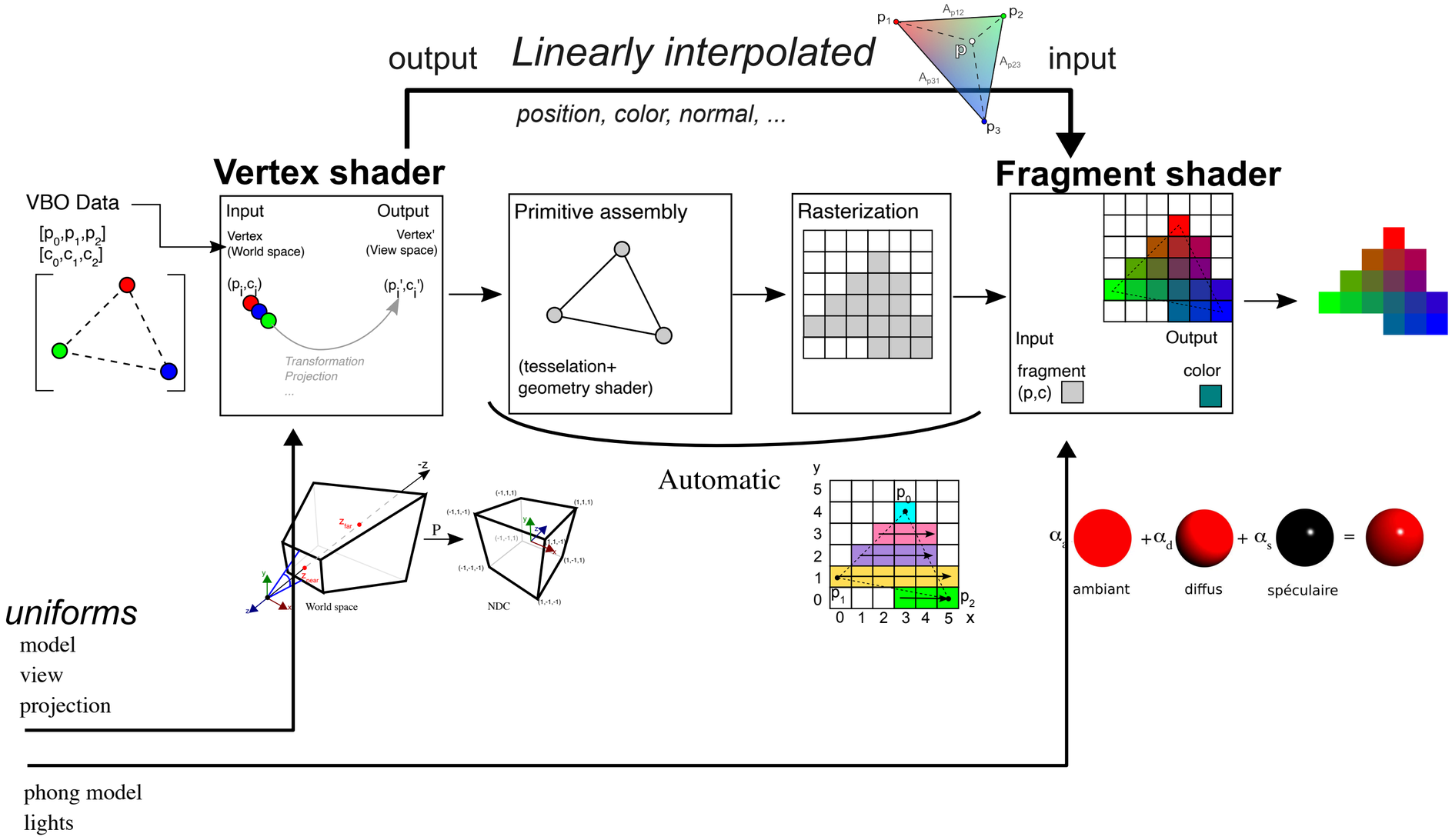


Without Depth Buffer

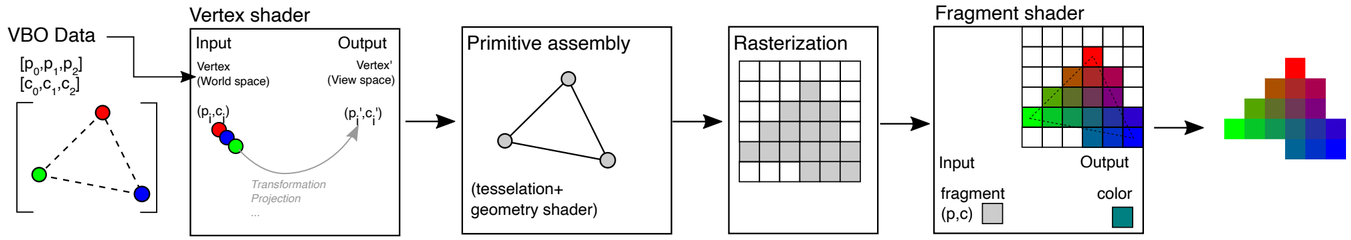
Shaders: résumé



Shaders Résumé



Shaders Résumé: Exemple de code




```glsl
layout (location = 0) in vec3 vertex_position;
layout (location = 1) in vec3 vertex_normal;
layout (location = 2) in vec3 vertex_color;

out struct fragment_data {
    vec3 position;
    vec3 normal;
    vec3 color;
} fragment;

uniform mat4 model;
uniform mat4 view;
uniform mat4 projection;

void main() {
    vec4 position = model * vec4(vertex_position, 1.0);

    mat4 modelNormal = transpose(inverse(model));
    vec4 normal = modelNormal * vec4(vertex_normal, 0.0);

    fragment.position = position.xyz;
    fragment.normal   = normal.xyz;
    fragment.color = vertex_color;

    gl_Position = projection * view * position;
}
```

```glsl
// Interpolated values on the fragment
in struct fragment_data {
    vec3 position;
    vec3 normal;
    vec3 color;
} fragment;

uniform vec3 light_position;
uniform vec3 light_color;

layout(location=0) out vec4 FragColor;

uniform mat4 model;
uniform mat4 view;
uniform mat4 projection;

void main() {

    vec3 N = normalize(fragment.normal);
    vec3 L = normalize(light_position-fragment.position);

    float diffuse_magnitude = max(dot(N,L),0.0);
    // ...

    vec3 c = a_ambient * fragment.color*light_color;
    c = c + a_diffuse*diffuse_magnitude*fragment.color*light_color;
    c = c + a_specular*specular_magnitude*light_color;

    FragColor = vec4(c,1.0);
}
```