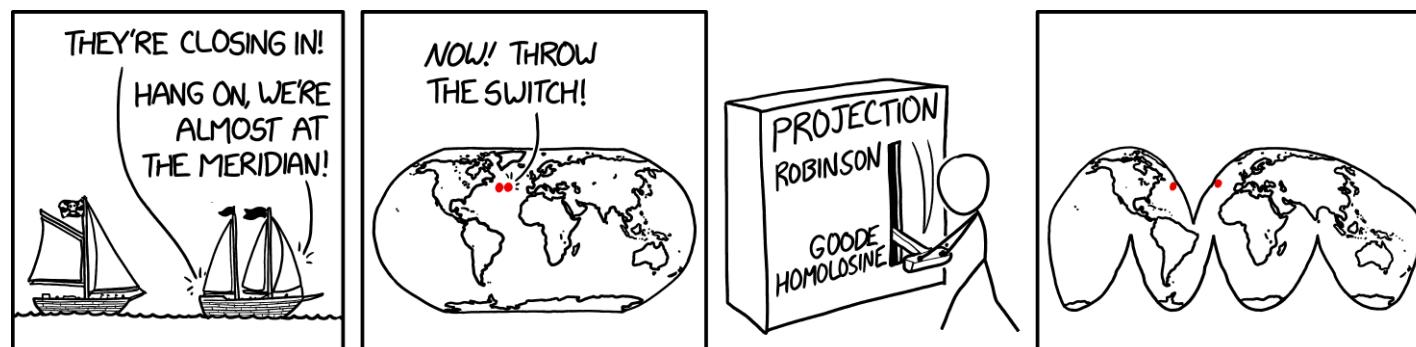


# Projection cartographique de la pseudosphère sur le plan

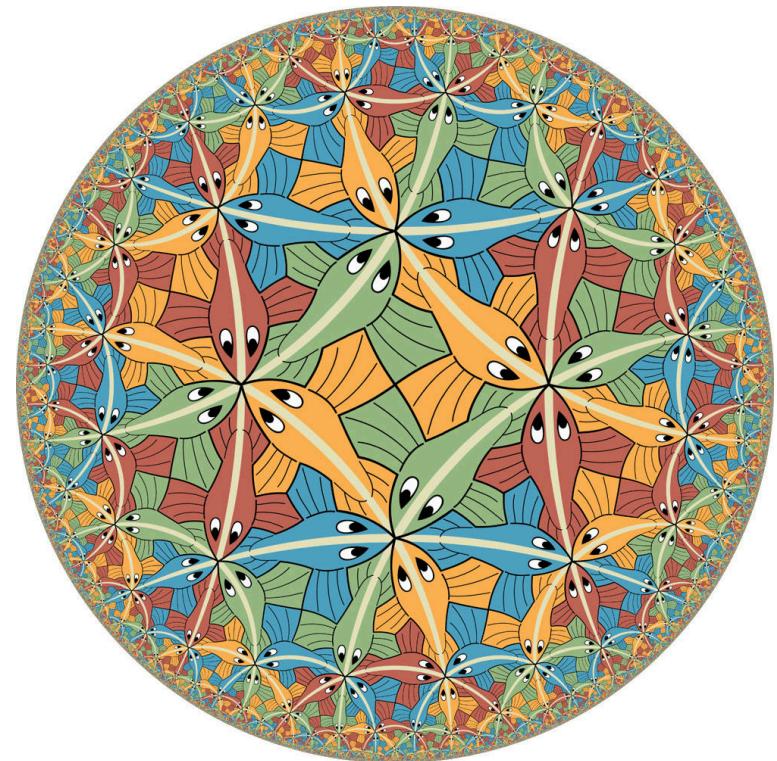
Gaspar Daguet, n°= 21528



Sea Chase - Xkcd

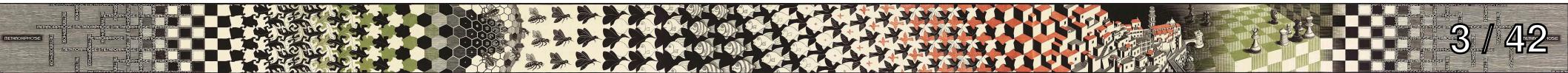


- 1) Introduction et problématique
- 2) La pseudosphère
- 3) La projection
- 4) Projection des droites



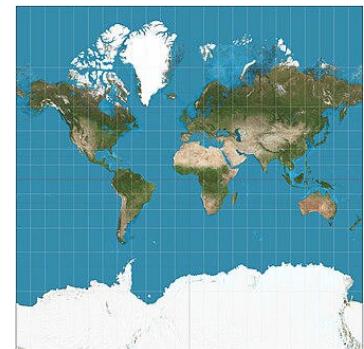
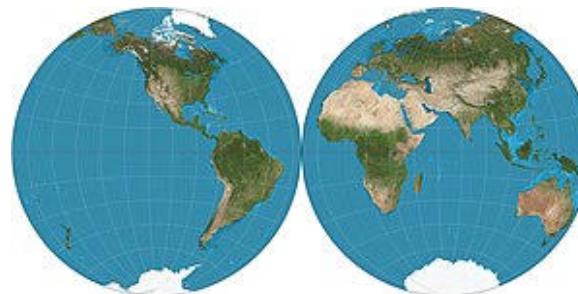
Cercle Limite III – M.C. Escher

# 1) Introduction et problématique



# 1) Introduction et problématique

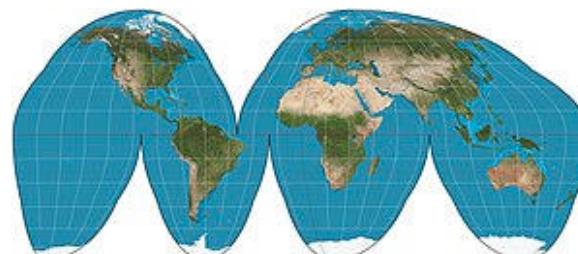
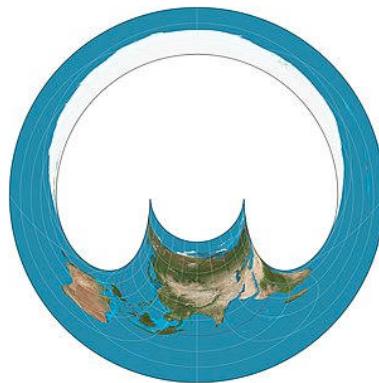
Gaspar Daguet, n°=21528



Stéréographique :  
~200 av J.C.  
conforme

Globulaire de  
Nicolosi : ~1000  
compromise

Mercator : 1569  
conforme



Rétro-azimutale de  
Hammer : 1910  
équivalente

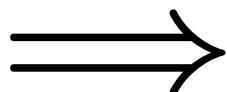
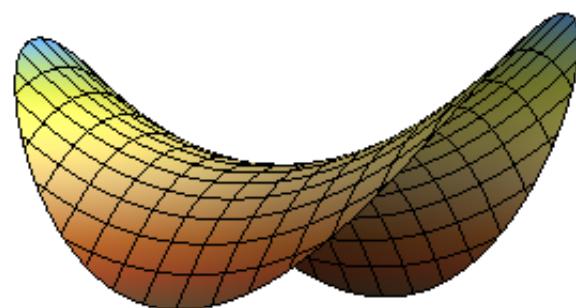
Goode : 1923  
équivalente

Cahill-Keyes : 1975  
compromis



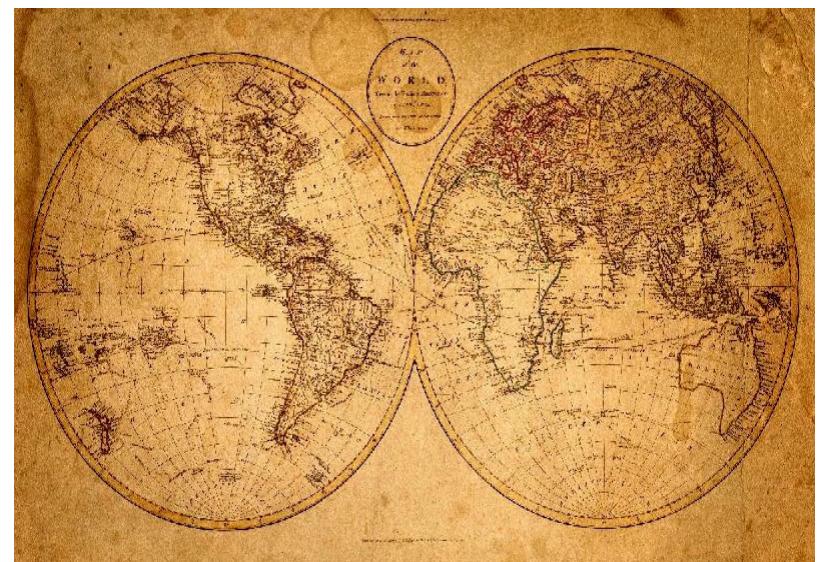
## Problématique :

Comment projeter une surface hyperbolique  
sur le plan ?

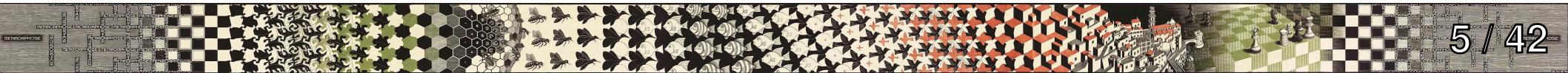


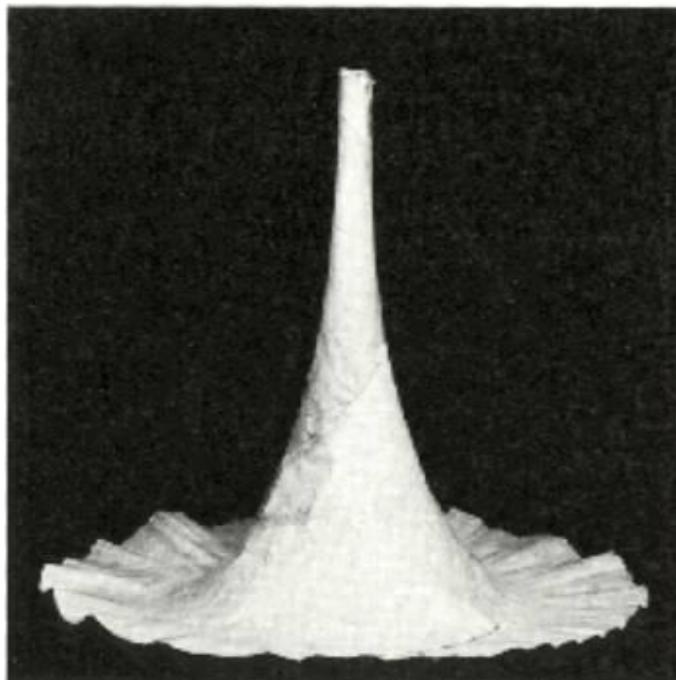
$$z = \frac{x^2}{a^2} - \frac{y^2}{b^2}, \quad \frac{x^2}{a^2} + \frac{y^2}{b^2} < 1$$

Paraboloïde hyperbolique  
(une chips)

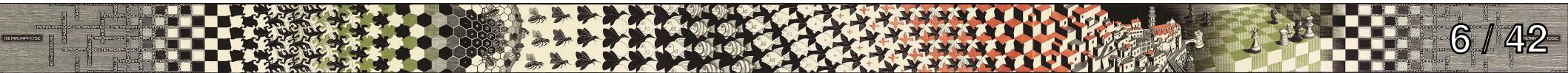


une carte





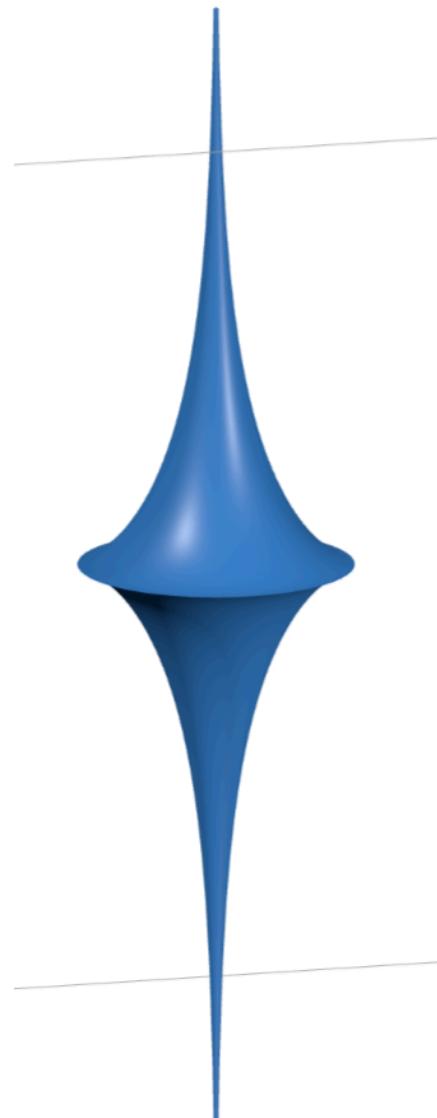
## 2) La pseudosphère



## 2) La pseudosphère

Gaspar Daguet, n°=21528

$$P : \left\{ \begin{array}{ccc} [0; 2\pi] \times \mathbb{R}_+ & \longrightarrow & \mathbb{R}^3 \\ (u, v) & \longmapsto & \left( \begin{array}{c} \frac{\cos(u)}{\operatorname{ch}(v)} \\ \frac{\sin(u)}{\operatorname{ch}(v)} \\ v - \operatorname{th}(v) \end{array} \right) \end{array} \right.$$



## 2) La pseudosphère

Gaspar Daguet, n°=21528

On note  $\frac{\partial P}{\partial u} = P_u$

$$E(p) = \|P_u\|^2$$

$$F(p) = \langle P_u \mid P_v \rangle$$

$$G(p) = \|P_v\|^2$$

$$\mathcal{L}(p) = \langle P_{uu} \mid N \rangle$$

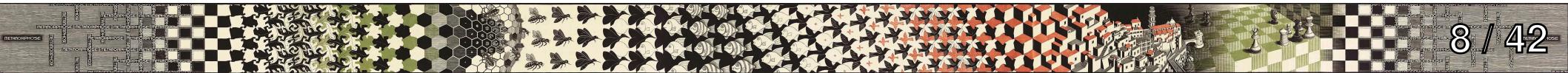
$$\mathcal{M}(p) = \langle P_{uv} \mid N \rangle$$

$$\mathcal{N}(p) = \langle P_{vv} \mid N \rangle$$

L'application Normale :

$$N : [0; 2\pi] \times \mathbb{R}_+ \longrightarrow \mathbb{R}^3$$

$$p \longmapsto \frac{P_u(p) \wedge P_v(p)}{\|P_u(p) \wedge P_v(p)\|}$$

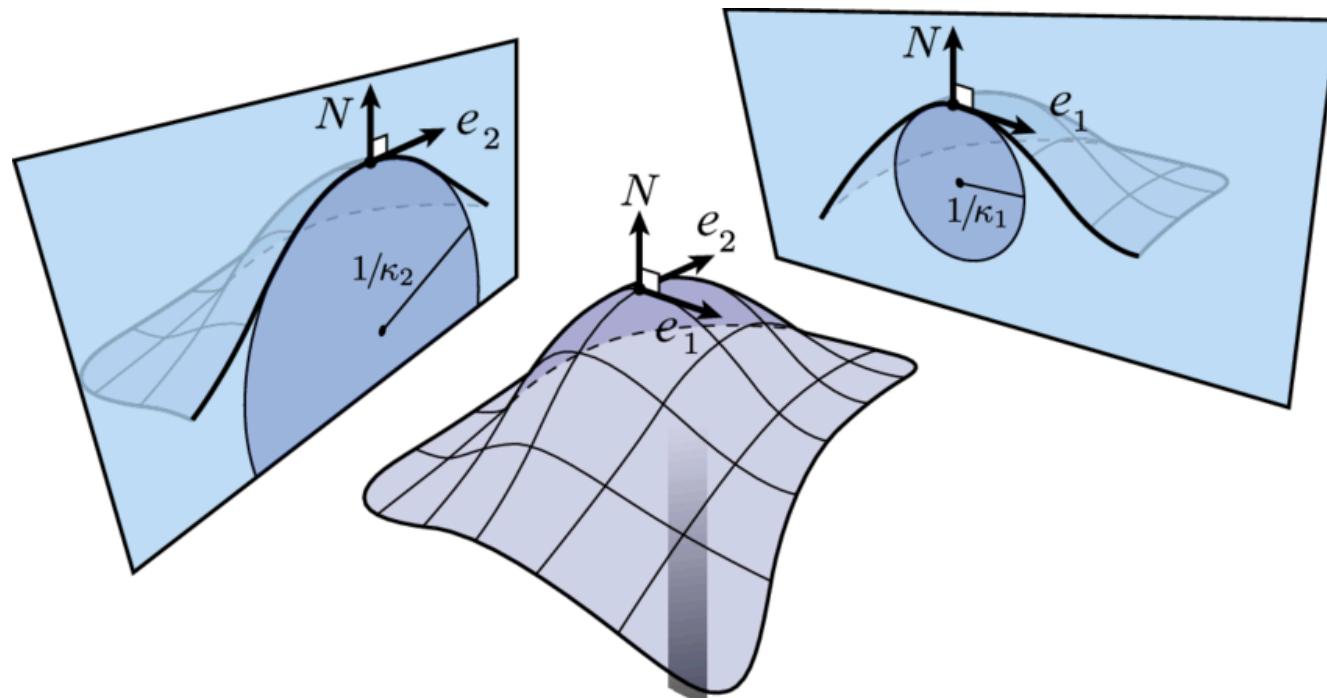


## 2) La pseudosphère

Gaspar Daguet, n°=21528

La courbure en  $p \in [0; 2\pi] \times \mathbb{R}_+$

$$K(p) = \frac{\mathcal{L}(p)\mathcal{N}(p) - \mathcal{M}(p)^2}{E(p)G(p) - F(p)^2}$$



source : Localisation d'objets 3D industriels à l'aide d'un algorithme de SLAM contraint au modèle

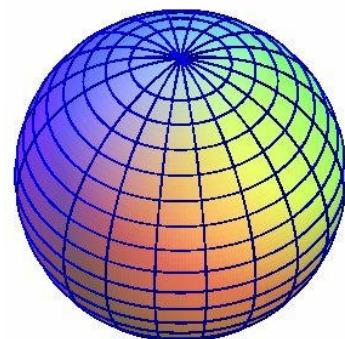


## 2) La pseudosphère

Gaspar Daguet, n°=21528

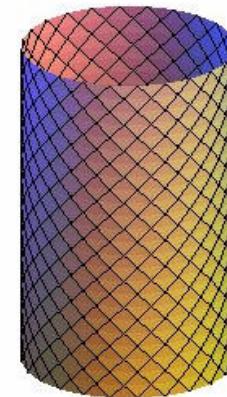
Sphérique:  $K > 0$

Sphère:  $K = \frac{1}{R}$



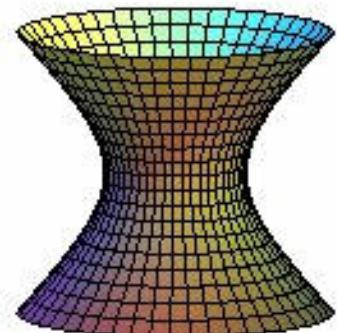
Planne:  $K = 0$

Cylindre, Plan



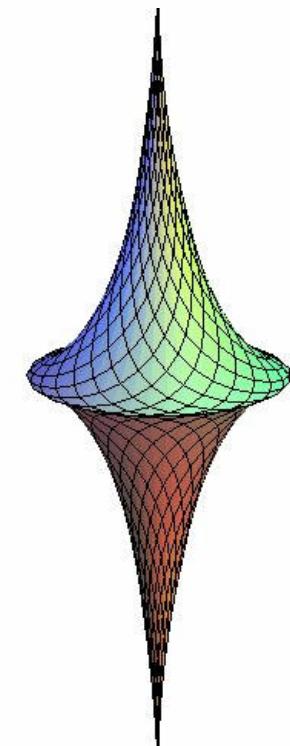
Hyperbolique:

$K < 0$



Pseudosphère:

$K = -\frac{1}{R}$

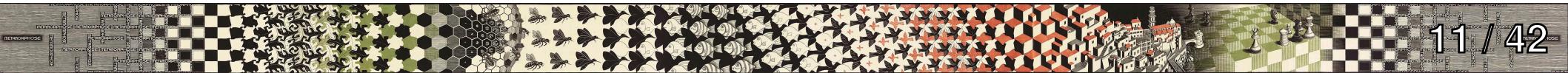


Paraboloïde hyperbolique

$$K = -\frac{4a^2b^2}{\left(4\left(\frac{b^2}{a^2}x^2 + \frac{a^2}{b^2}y^2\right) + a^2b^2\right)} < 0$$

source: <https://mathcurve.com>

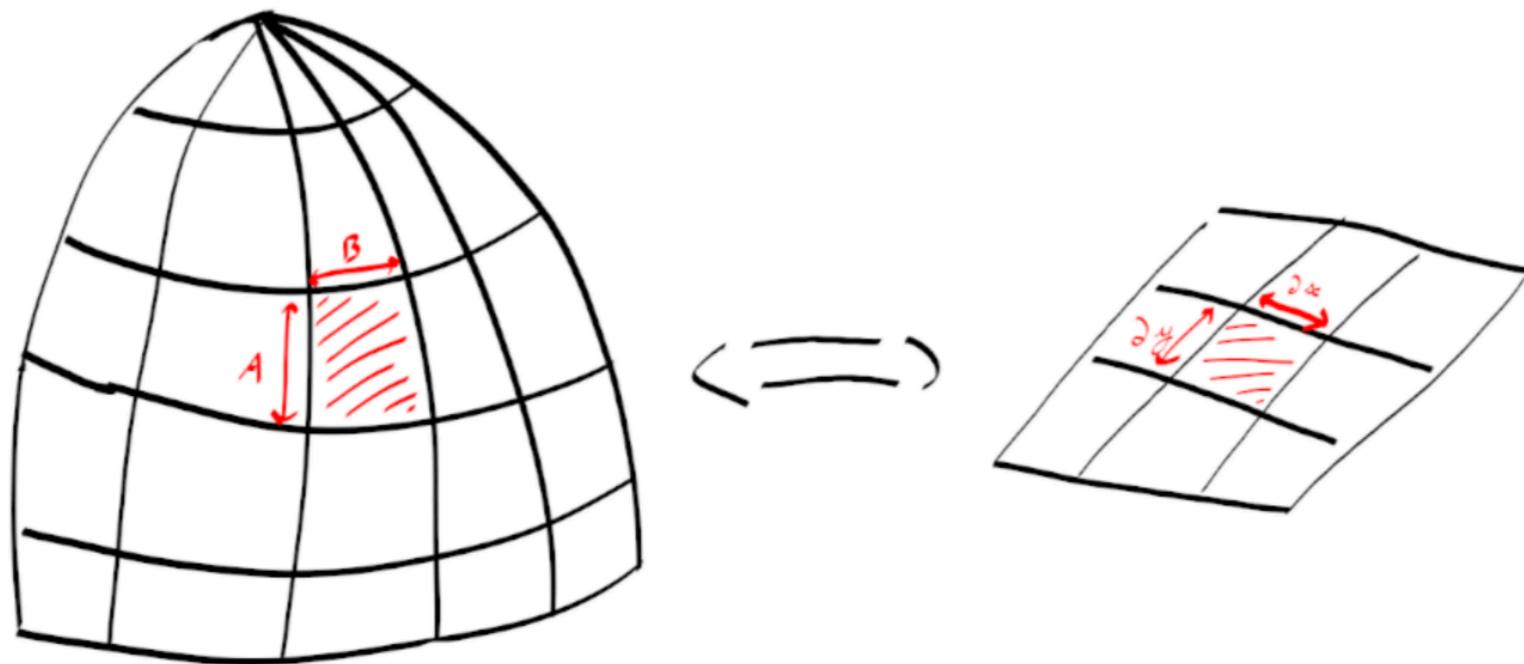
### 3) La projection



### 3) La projection

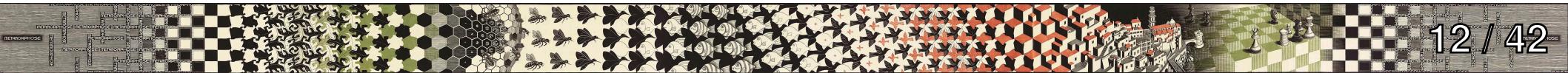
Gaspar Daguet, n°=21528

Idée de la projection de Mercator :



$$\frac{\partial y}{\partial x} = \frac{A}{B}$$

-1

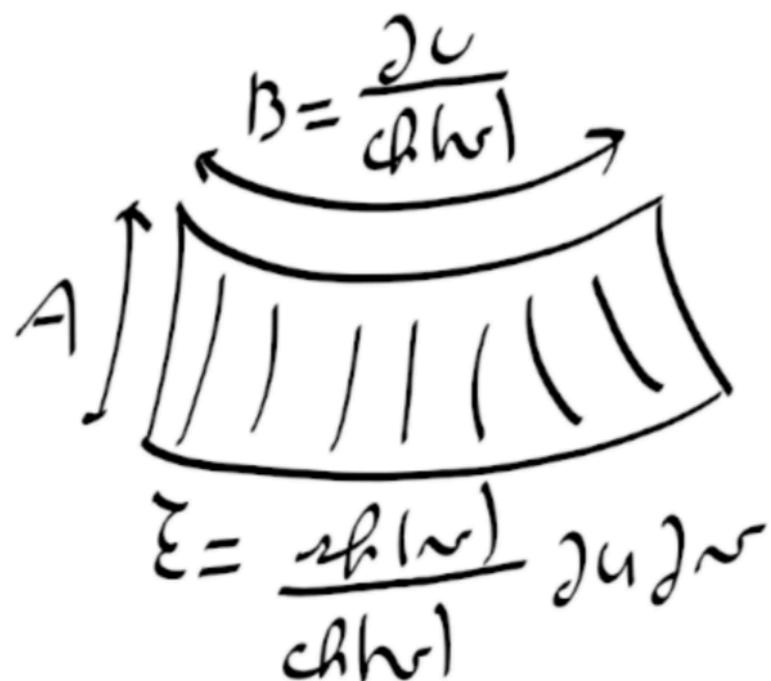


### 3) La projection

Gaspar Daguet, n°=21528

Surface élémentaire :

$$\mathcal{E} = \|P_u \wedge P_v\| \partial u \partial v$$



Pour la pseudosphère :

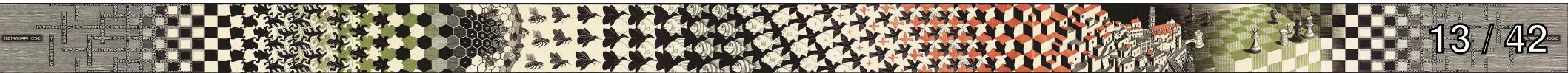
$$\mathcal{E} = \frac{\text{sh}(v)}{\text{ch}^2(v)} \partial u \partial v$$

Or :

$$B = \frac{\partial u}{\text{ch}(v)}$$

Donc :

$$\frac{A}{B} = \frac{\mathcal{E}}{B^2} = \frac{\text{sh}(v) \partial v}{\partial u}$$



La projection :

$$C : \begin{cases} [0; 2\pi] \times \mathbb{R}_+ \longrightarrow \mathbb{R}^2 \\ p = (u, v) \longmapsto \begin{pmatrix} u \\ \operatorname{ch}(v) \end{pmatrix} \end{cases}$$

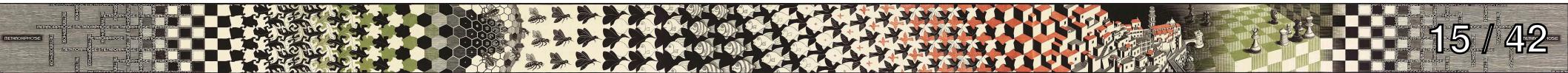
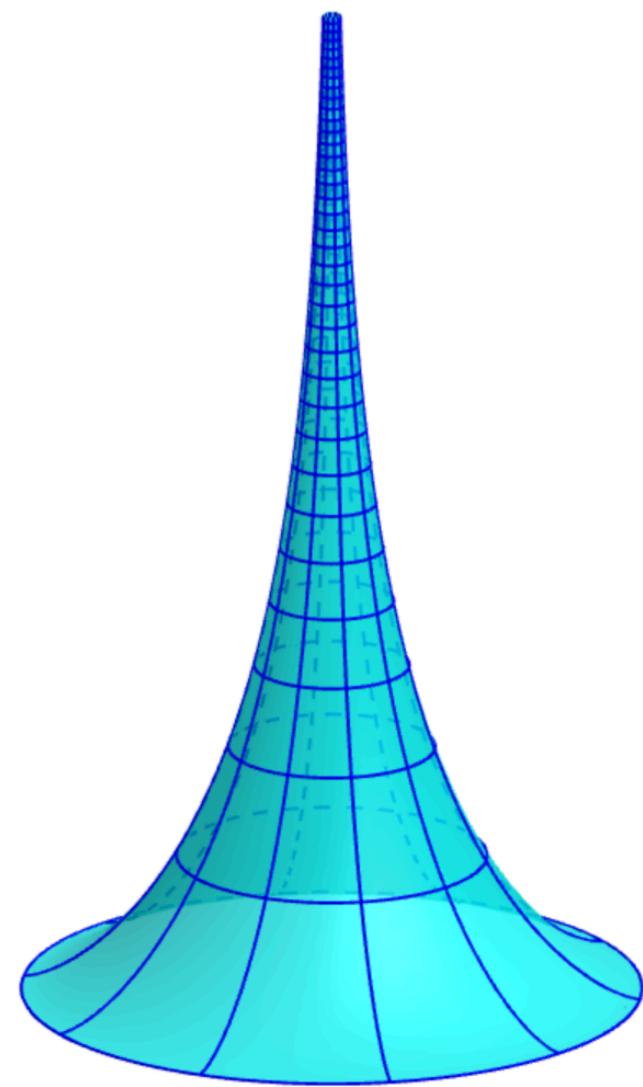
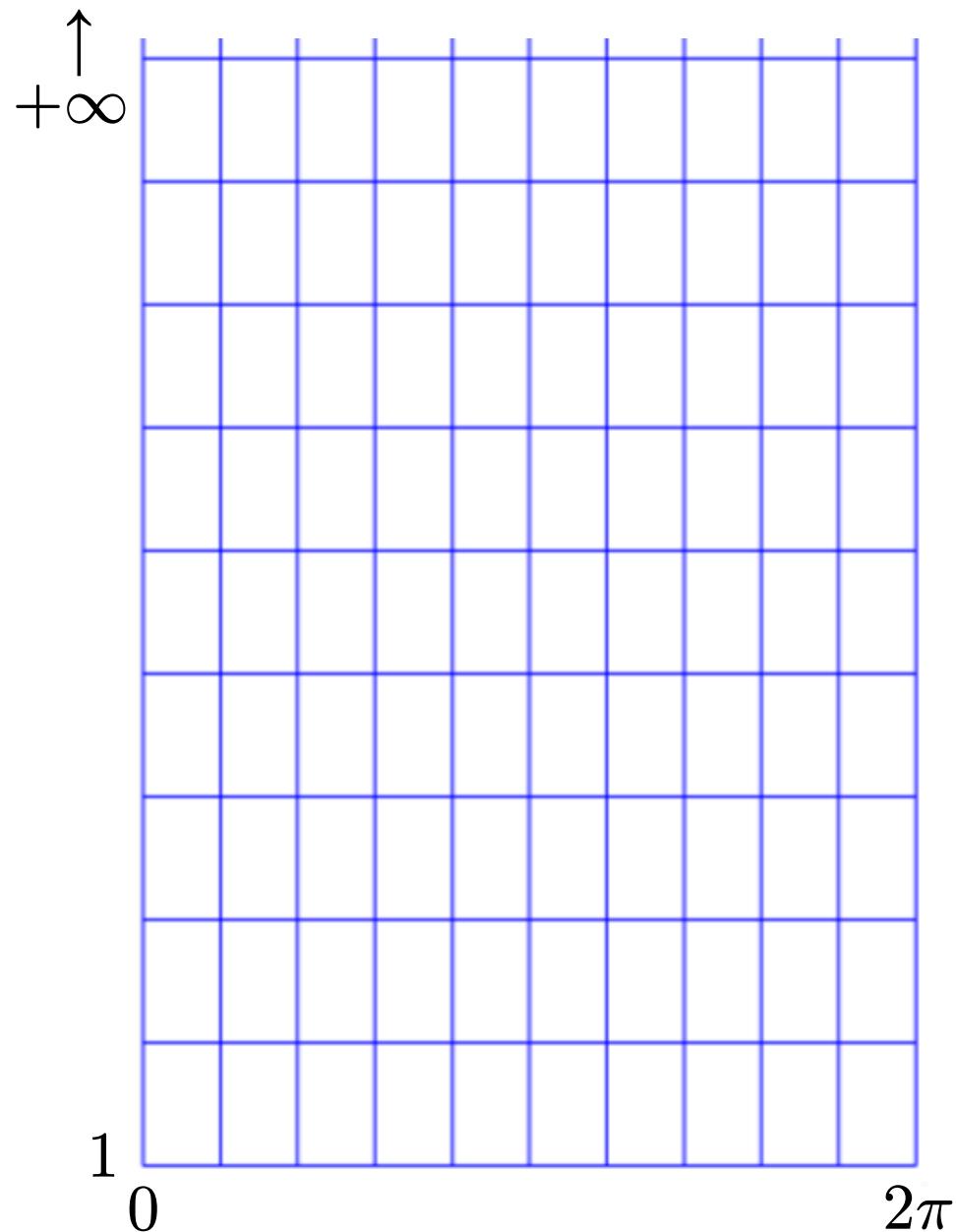
Celle de Mercator:

$$M : \begin{cases} [0; 2\pi] \times [-\pi; \pi] \longrightarrow \mathbb{R}^2 \\ p = (u, v) \longmapsto \begin{pmatrix} u \\ \ln(\tan(\frac{v}{2} + \frac{\pi}{4})) \end{pmatrix} \end{cases}$$



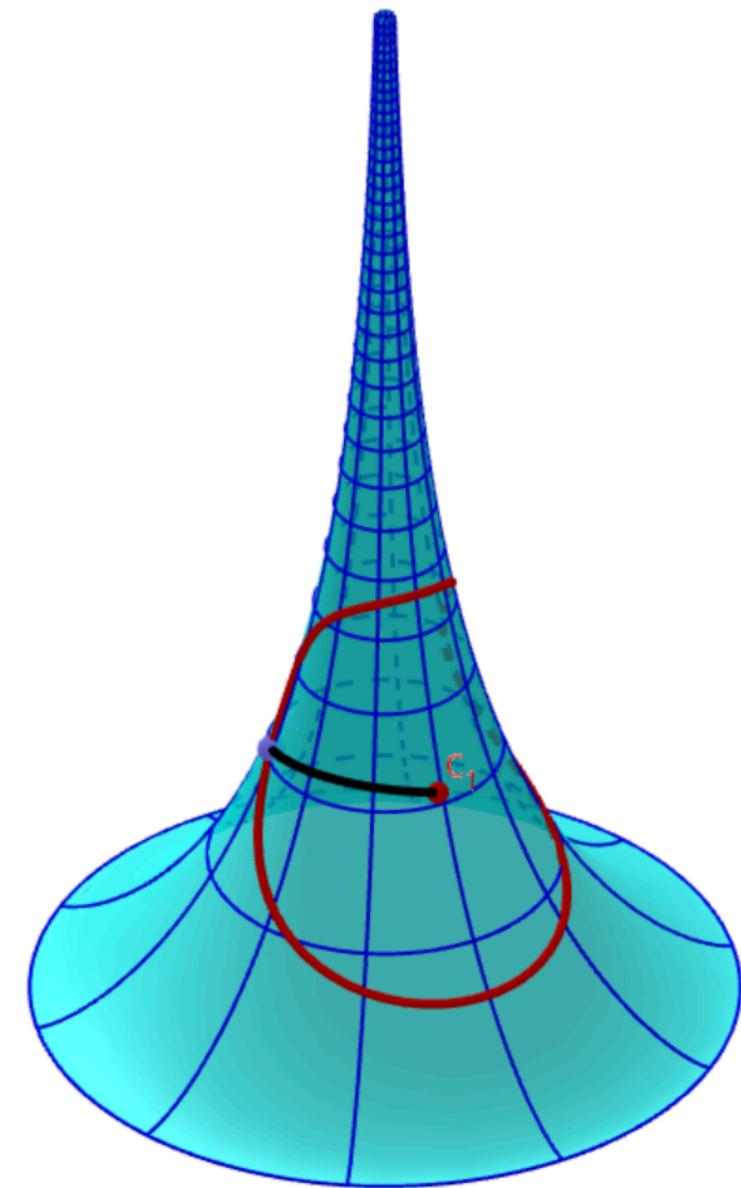
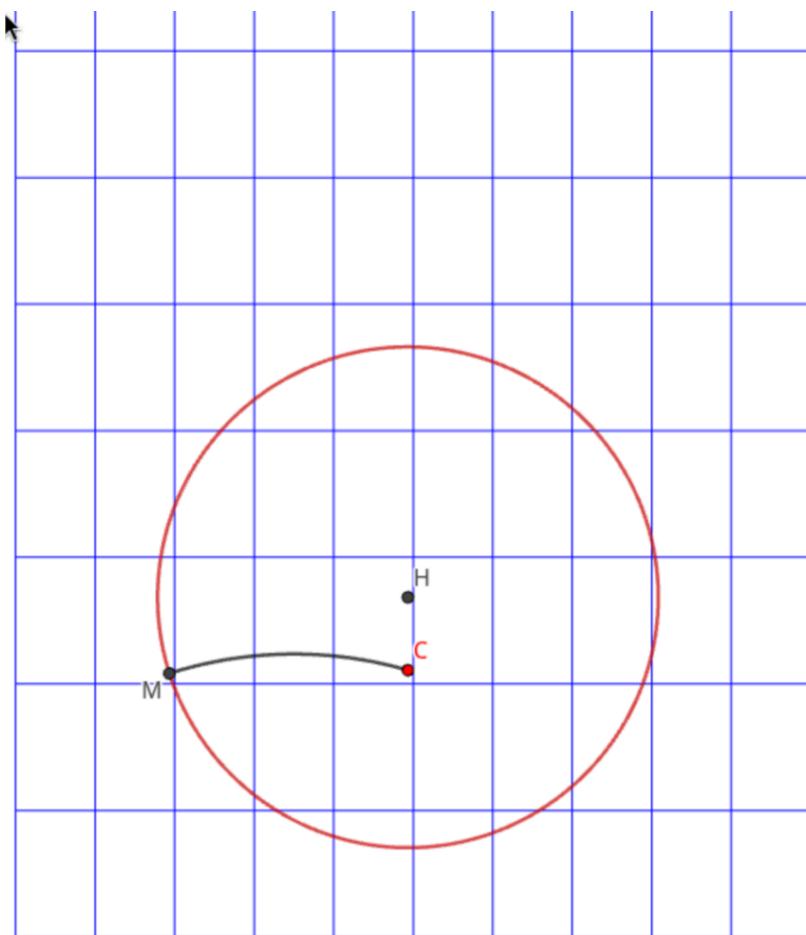
### 3) La projection

Gaspar Daguet, n°=21528



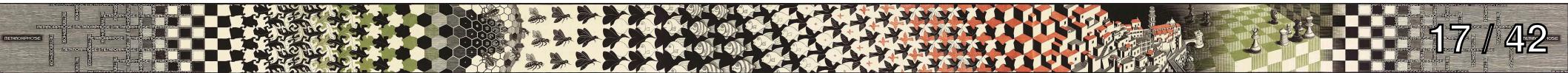
### 3) La projection

Gaspar Daguet, n°=21528



Cercle sur la pseudosphère, avec un de ses rayons

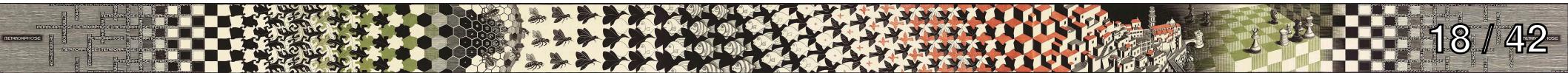
## 4) Projection des droites



Équation des droites (géodésique):

- Méridiens:  $g : t \mapsto P(u, t)$
- Autres droites:

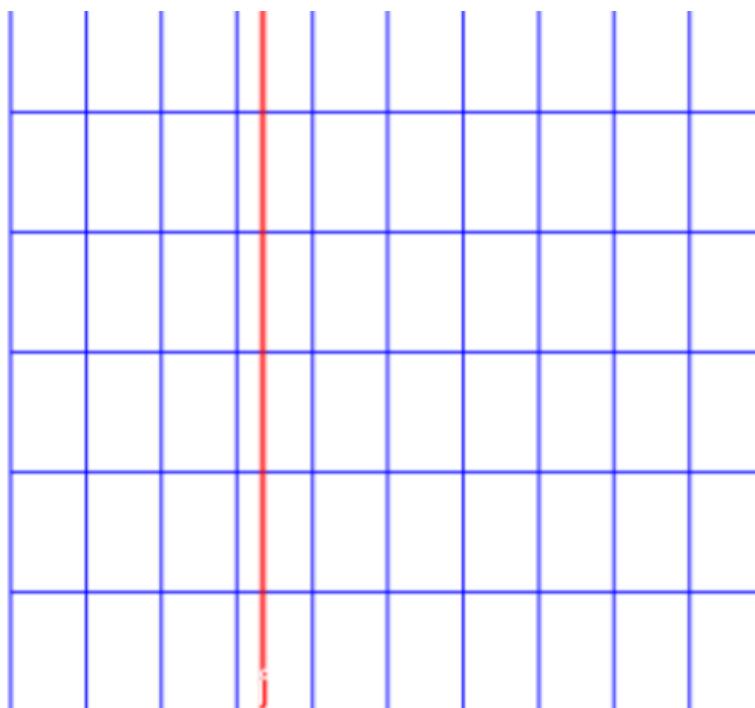
$$g : t \mapsto P\left(t, \operatorname{arcch}\left(\sqrt{k^2 - (t + c)^2}\right)\right)$$



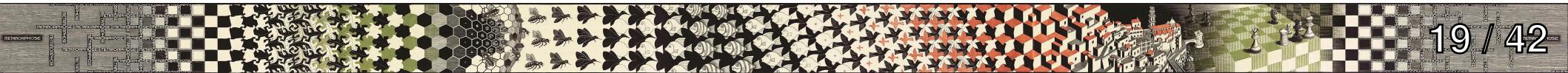
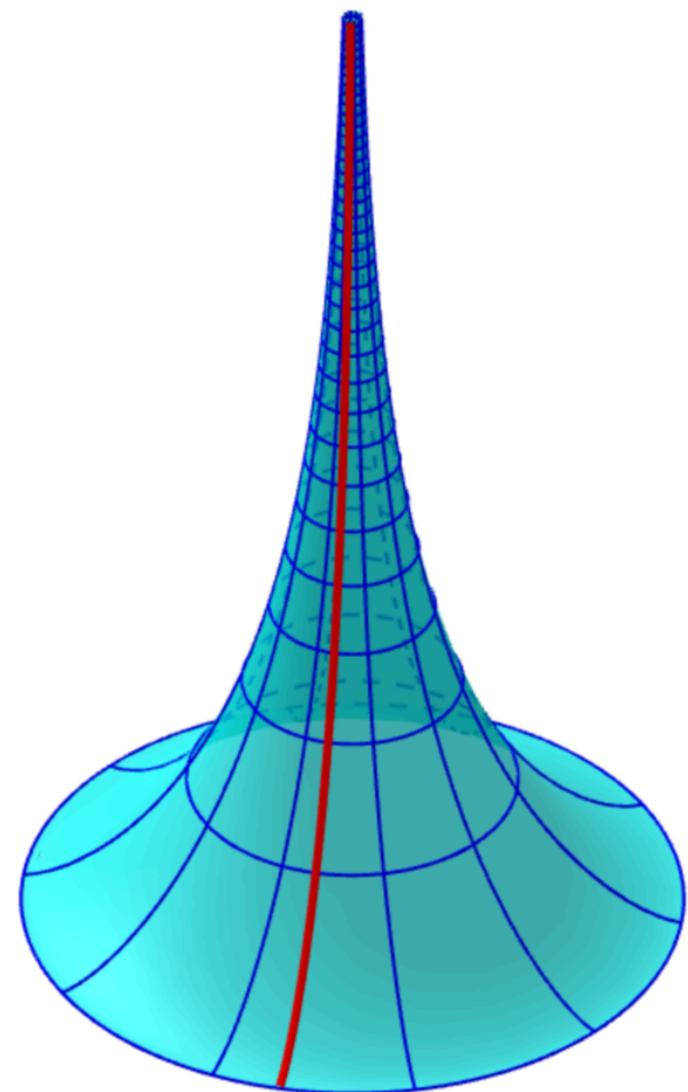
# 4) Projection des droites

Gaspar Daguet, n°=21528

Méridiens :



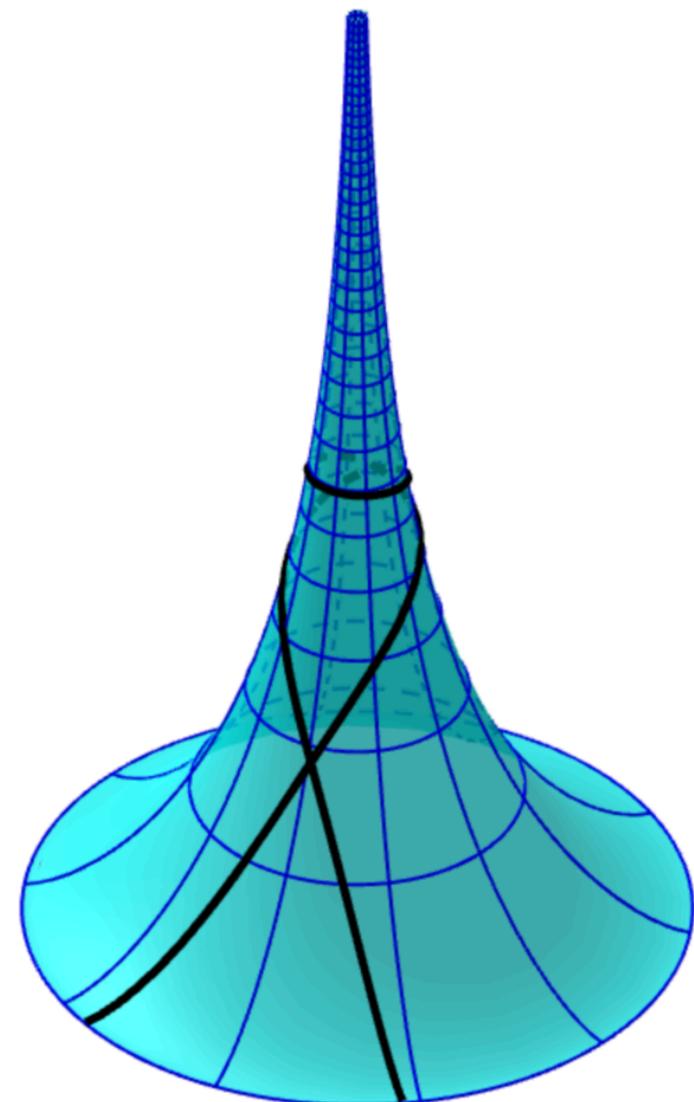
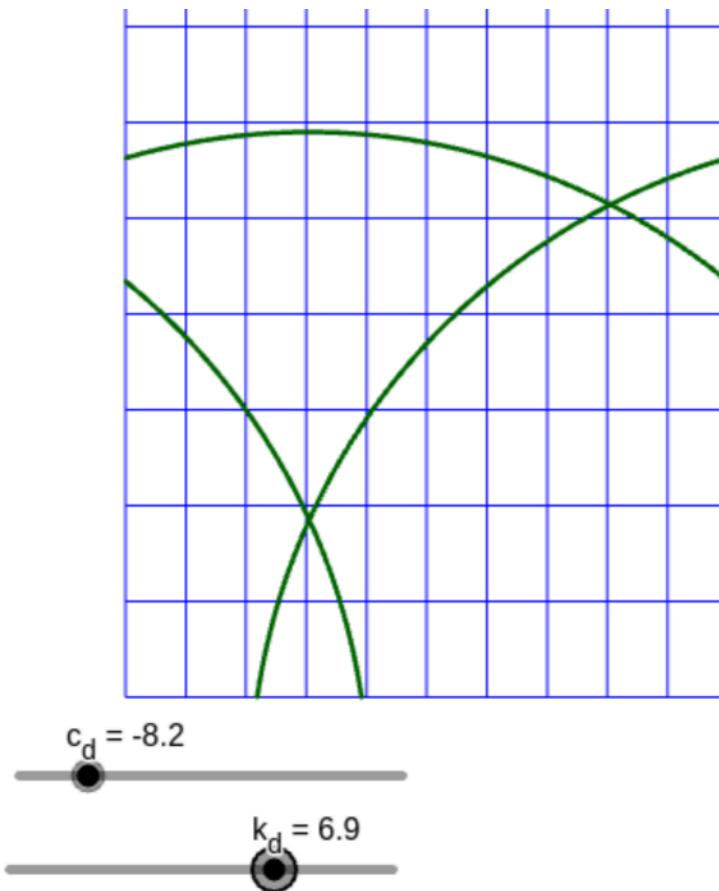
$$u = 2.1$$



## 4) Projection des droites

Gaspar Daguet, n°=21528

Droites quelconques :



# 4) Projection des droites

Gaspar Daguet, n°=21528

Sur les méridiens ( $v_A = v_B$ ):

Sur la pseudosphère :

$$d(A, B) = \ln\left(\frac{\operatorname{ch}(u_B)}{\operatorname{ch}(u_A)}\right)$$

Longueur d'arc :

$$d(A, B) = \int_{t_A}^{t_B} \|g'(t)\| dt \neq$$

Sur la carte :

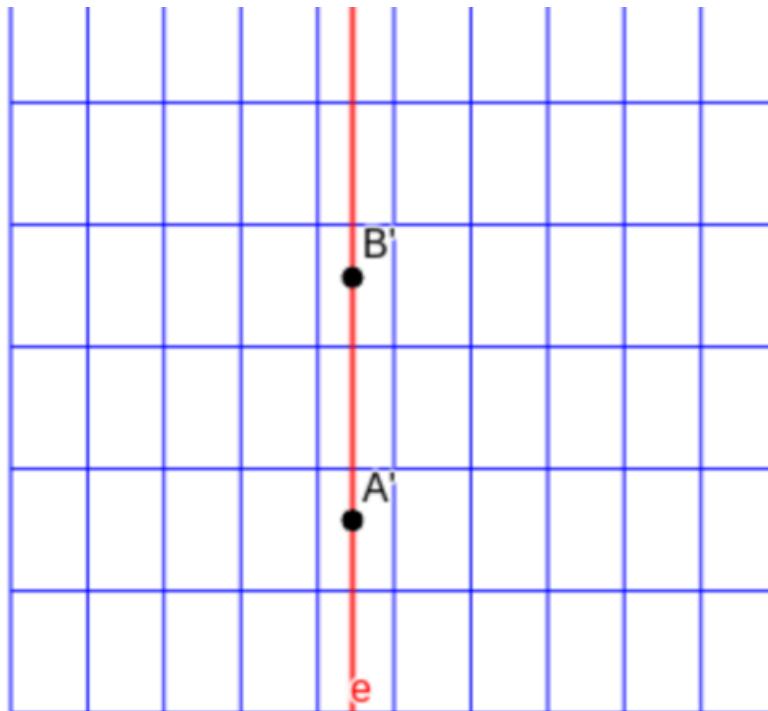
$$d(A, B) = \operatorname{ch}(u_B) - \operatorname{ch}(u_A)$$

Donc la projection n'est pas équivalente

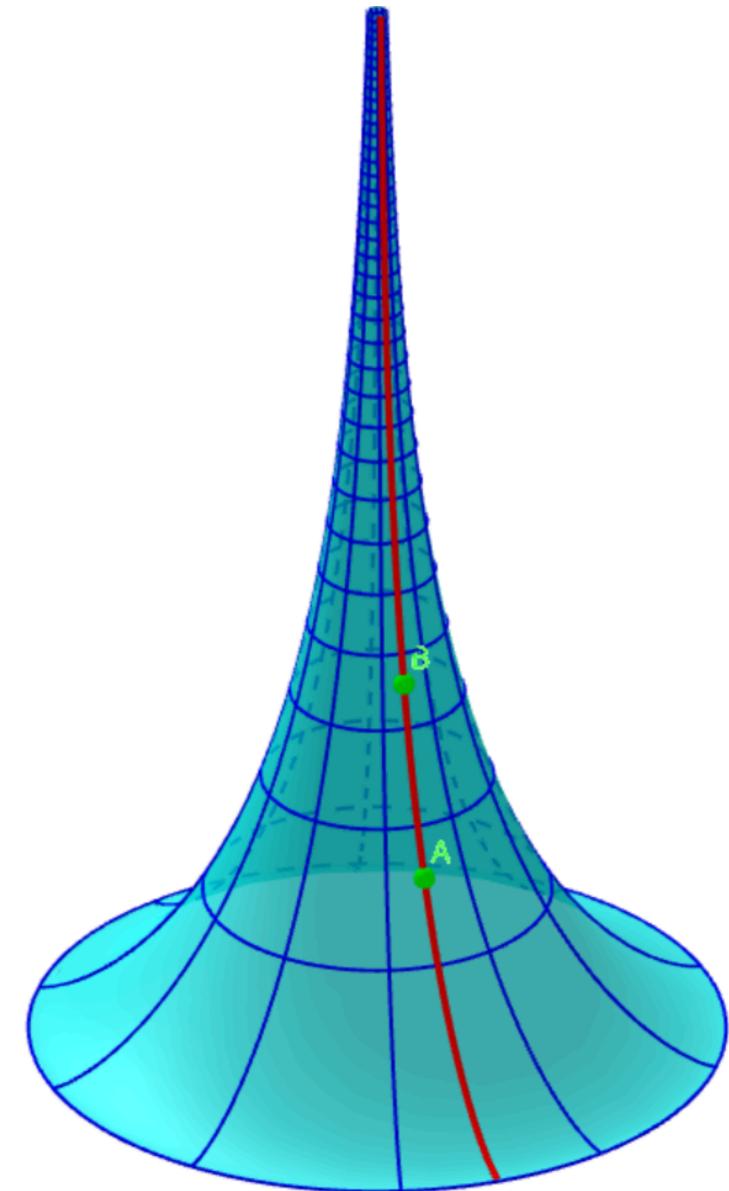


#### 4) Projection des droites

Gaspar Daguet, n°=21528



$$d(A, B) = 1,99$$

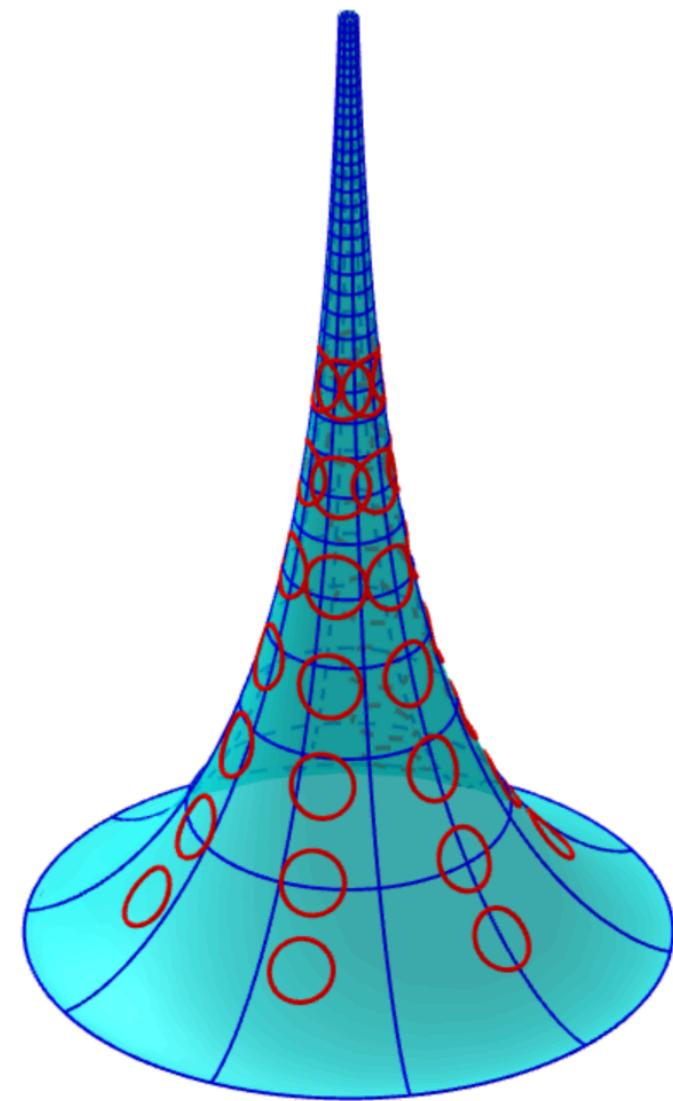
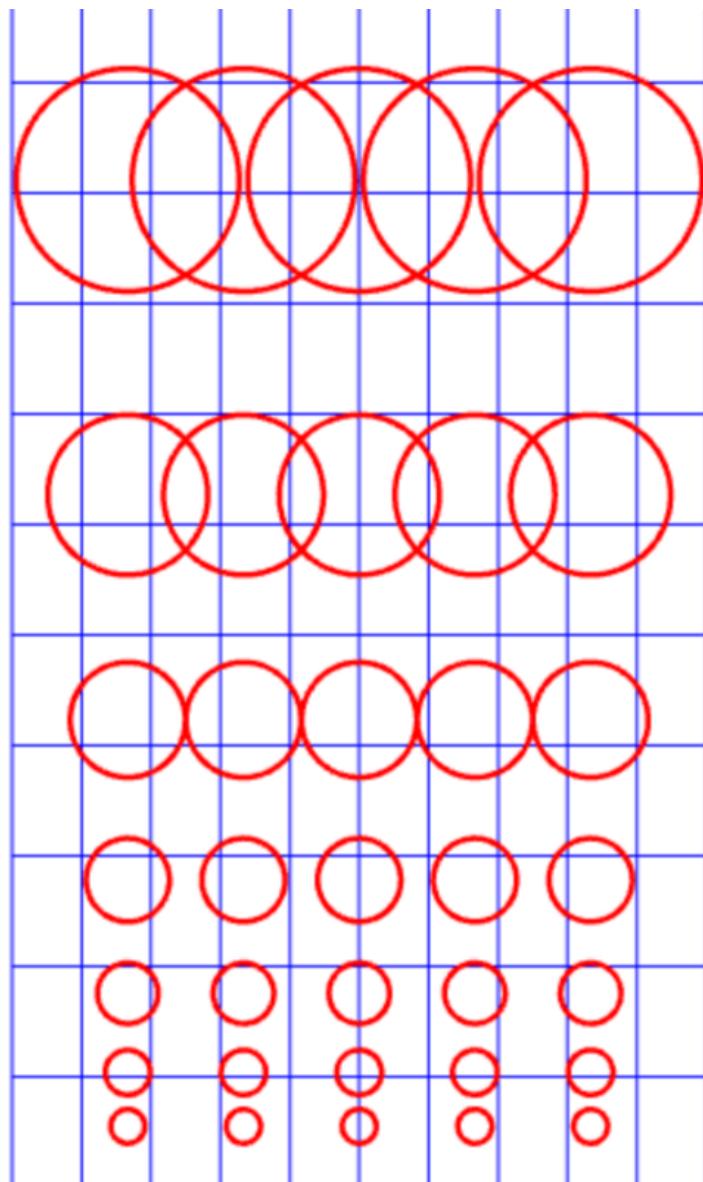


$$d(A, B) = 0,57$$



## 4) Projection des droites

Gaspar Daguet, n°=21528

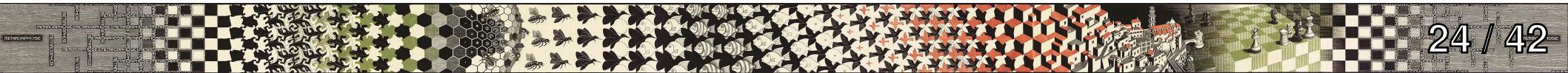


Indicatrice de Tissot sur la pseudosphère

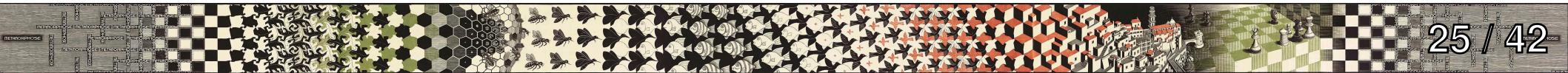


Merci de votre attention

Gaspar Daguet, n°=21528



# Annexes



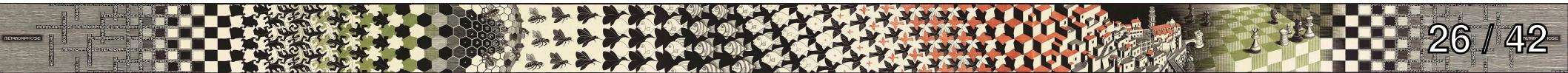
La première forme fondamentale est l'écriture formelle du produit scalaire dans le plan tangent au point  $p$  de la surface  $S$

Or le produit scalaire entre deux vecteur du plan tangent peut s'écrire comme la combinaison linéaire entre  $P_u(p)$  et  $P_v(p)$ , donc le produit scalaire peut s'écrire :

$$\begin{aligned} I(aP_u + bP_v, cP_u + dP_v) &= \langle aP_u + bP_v \mid cP_u + dP_v \rangle \\ &= \underbrace{ac(P_u)^2}_{=E} + \underbrace{(ad + bc)\langle P_u \mid P_v \rangle}_{=F} + \underbrace{bd\|P_v\|^2}_{=G} \end{aligned}$$

Ainsi sous forme matricielle pour les vecteur  $x$  et  $y$  du plan tangent :

$$I(x, y) = x^T \begin{pmatrix} E & F \\ F & G \end{pmatrix} y$$



Dans le repère  $(P_{u(p)}, P_{v(p)}, N(p))$ , on peut faire un développement limité de la surface de la forme :

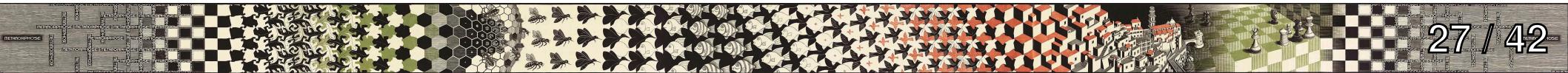
$$z = \underbrace{\langle P_{uu} \mid N \rangle}_{= \mathcal{L}} \frac{x^2}{2} + \underbrace{\langle P_{uv} \mid N \rangle}_{= \mathcal{M}} + \underbrace{\langle P_{vv} \mid N \rangle}_{= \mathcal{N}} \frac{x^2}{2}$$

Ainsi on définit la seconde forme fondamentale par :

$$\text{II} = L \, dx^2 + 2M \, dx \, dy + N \, dy^2$$

Et donc sous forme matricielle :

$$\text{II} = \begin{pmatrix} \mathcal{L} & \mathcal{M} \\ \mathcal{M} & \mathcal{N} \end{pmatrix}$$



L'endomorphisme de Weingarten (ou opérateur de forme) est défini par :

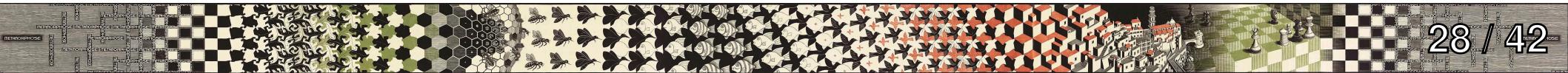
$$W = dN$$

De plus, ses valeurs propres sont les courbures principales au point  $p$ , et ses vecteurs propres sont la direction des courbures principales

Comme l'on définit la courbure de Gauss par le produit des valeurs propres, alors le déterminant de l'endomorphisme de Weingarten est la courbure de Gauss

$$K(p) = \det(W)$$

Nous avons également que la seconde forme fondamentale est la forme quadratique associée à l'endomorphisme de Weingarten

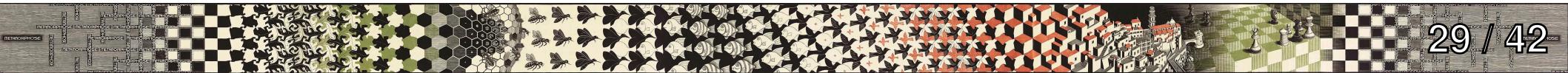


Soit  $\vec{x}, \vec{y}$  deux vecteurs du plan tangent au point  $p$  sur notre surface  $P$  tel que  $\vec{y}$  soit un vecteur propre de  $W$  associé à la valeur propre  $\lambda$ . Ainsi la première forme fondamentale nous donne le produit scalaire entre ces deux vecteurs :

$$\langle \vec{x} \mid \vec{y} \rangle = X^T \begin{pmatrix} E & F \\ F & G \end{pmatrix} Y$$

Et comme la seconde forme fondamentale est la quadratique associée à l'endomorphisme de Weingarten :

$$\langle \vec{x} \mid W(\vec{y}) \rangle = X^T \begin{pmatrix} \mathcal{L} & \mathcal{M} \\ \mathcal{M} & \mathcal{N} \end{pmatrix} Y$$



Donc comme  $\vec{y}$  est vecteur propre:

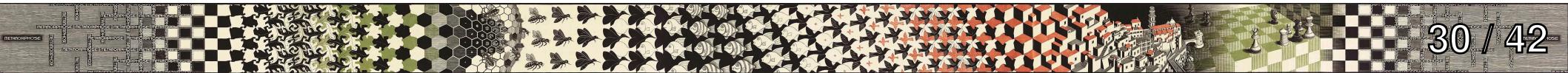
$$X^T \begin{pmatrix} \mathcal{L} & \mathcal{M} \\ \mathcal{M} & \mathcal{N} \end{pmatrix} Y = \langle \vec{x} \mid W(\vec{y}) \rangle = \lambda \langle \vec{x} \mid \vec{y} \rangle = \lambda X^T \begin{pmatrix} E & F \\ F & G \end{pmatrix} Y$$

Comme ceci est vrai pour tout  $\vec{x}$ , on a:

$$\begin{pmatrix} \mathcal{L} & \mathcal{M} \\ \mathcal{M} & \mathcal{N} \end{pmatrix} Y = \lambda \begin{pmatrix} E & F \\ F & G \end{pmatrix} Y$$

Donc

$$\left( \begin{pmatrix} \mathcal{L} & \mathcal{M} \\ \mathcal{M} & \mathcal{N} \end{pmatrix} - \lambda \begin{pmatrix} E & F \\ F & G \end{pmatrix} \right) Y = 0$$



Donc  $\begin{pmatrix} \mathcal{L} & \mathcal{M} \\ \mathcal{M} & \mathcal{N} \end{pmatrix} - \lambda \begin{pmatrix} E & F \\ F & G \end{pmatrix} = \begin{pmatrix} \mathcal{L}-\lambda E & \mathcal{M}-\lambda F \\ \mathcal{M}-\lambda F & \mathcal{N}-\lambda G \end{pmatrix}$  est non inversible

Et donc  $\begin{pmatrix} \mathcal{L}-\lambda E & \mathcal{M}-\lambda F \\ \mathcal{M}-\lambda F & \mathcal{N}-\lambda G \end{pmatrix} = 0$

Soit  $(EG - F^2)\lambda^2 + (E \mathcal{N} + G \mathcal{L} - 2 \mathcal{M}F)\lambda + \mathcal{L}\mathcal{N} - \mathcal{M}^2 = 0$

Ainsi le terme  $\frac{\mathcal{L}\mathcal{N}-\mathcal{M}^2}{EG-F^2}$  vaut le produit des valeurs propres et donc des courbures principales, donc :

$$K = \frac{\mathcal{L}\mathcal{N}-\mathcal{M}^2}{EG-F^2}$$



# Annexes - Géogébra

Gaspar Daguet, n°=21528

$$S = \text{Surface}\left(\frac{\cos(u)}{\cosh(v)}, \frac{\sin(u)}{\cosh(v)}, v - \text{th}(v), u, 0, 2\pi, v, 0, 100\right)$$

$$= \begin{pmatrix} \frac{\cos(u)}{\cosh(v)} \\ \frac{\sin(u)}{\cosh(v)} \\ v - \text{th}(v) \end{pmatrix}$$

$S_x(x, y) = \frac{\cos(x)}{\cosh(y)}$

$S_y(x, y) = \frac{\sin(x)}{\cosh(y)}$

$S_z(x, y) = y - \text{th}(y)$

Sur = 1

-5  5

c = 1

0  2

h<sub>n</sub> = 100

1  100

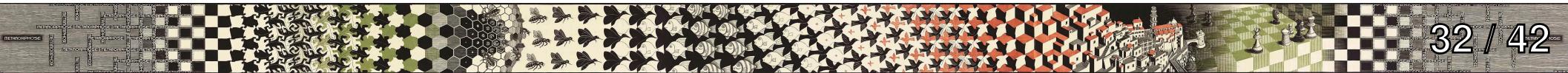
$$l1 = \text{Séquence}\left(\text{Courbe}\left(\frac{2\pi}{n}k, t, t, 1, c h_n + 1\right), k, 0, n\right)$$

$$= \left\{ \left(\frac{2\pi}{10} \cdot 0, t\right), \left(\frac{2\pi}{10} \cdot 1, t\right), \left(\frac{2\pi}{10} \cdot 2, t\right), \left(\frac{2\pi}{10} \cdot 3, t\right), \left(\frac{2\pi}{10} \cdot 4, t\right), \left(\frac{2\pi}{10} \cdot 5, t\right), \left(\frac{2\pi}{10} \cdot 6, t\right), \left(\frac{2\pi}{10} \cdot 7, t\right), \left(\frac{2\pi}{10} \cdot 8, t\right), \left(\frac{2\pi}{10} \cdot 9, t\right), \left(\frac{2\pi}{10} \cdot 10, t\right) \right\}$$

$$l2 = \text{Séquence}\left(\text{Courbe}(S_x(t, \cosh^{-1}(c k + 1)), S_y(t, \cosh^{-1}(c k + 1)), S_z(t, \cosh^{-1}(c k + 1)), t, 0, 2\pi), k, 0, h_n - 1\right)$$

$$= \left\{ \left(\frac{\cos(t)}{\cosh(\cosh^{-1}(1 \cdot 0 + 1))}, \frac{\sin(t)}{\cosh(\cosh^{-1}(1 \cdot 0 + 1))}, \cosh^{-1}(1 \cdot 0 + 1) - \text{th}(\cosh^{-1}(1 \cdot 0 + 1))\right), \left(\frac{\cos(t)}{\cosh(\cosh^{-1}(1 \cdot 1 + 1))}, \frac{\sin(t)}{\cosh(\cosh^{-1}(1 \cdot 1 + 1))}, \cosh^{-1}(1 \cdot 1 + 1) - \text{th}(\cosh^{-1}(1 \cdot 1 + 1))\right), \left(\frac{\cos(t)}{\cosh(\cosh^{-1}(1 \cdot 2 + 1))}, \frac{\sin(t)}{\cosh(\cosh^{-1}(1 \cdot 2 + 1))}, \cosh^{-1}(1 \cdot 2 + 1) - \text{th}(\cosh^{-1}(1 \cdot 2 + 1))\right) \right\}$$

$$l3 = \text{Séquence}\left(\text{Courbe}\left(S_x\left(\frac{2\pi}{n}k, \cosh^{-1}(t)\right), S_y\left(\frac{2\pi}{n}k, \cosh^{-1}(t)\right), S_z\left(\frac{2\pi}{n}k, \cosh^{-1}(t)\right), t, 1, h_n - 1\right), k, 0, n\right)$$



Donc on a :

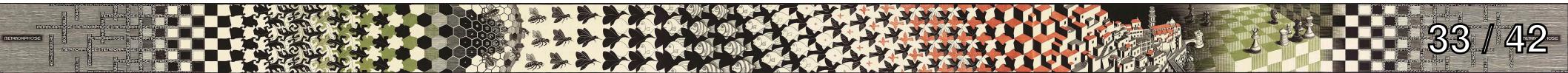
$$\frac{\partial y}{\partial x} = \frac{A}{B} = \frac{\operatorname{sh}(v)\partial v}{\partial u}$$

Ainsi en posant  $x(u) = u \Leftrightarrow \frac{\partial x}{\partial u} = 1$ ,

$$\frac{\partial y}{\partial v} = \operatorname{sh}(v) \underbrace{\frac{\partial x}{\partial u}}_{=1}$$

Donc

$$y(v) = \operatorname{ch}(v)$$



# Annexes - Calculs des Dérivés

Gaspar Daguet, n°=21528

$$P_u(u, v) = \begin{pmatrix} -\frac{\sin(u)}{\operatorname{ch}(v)} \\ \frac{\cos(u)}{\operatorname{ch}(v)} \\ 0 \end{pmatrix}$$

$$P_v(u, v) = \begin{pmatrix} -\cos(u) \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^2} \\ -\sin(u) \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^2} \\ \operatorname{th}(v)^2 \end{pmatrix}$$

$$P_{uu}(u, v) = \begin{pmatrix} -\frac{\cos(u)}{\operatorname{ch}(v)} \\ -\frac{\sin(u)}{\operatorname{ch}(v)} \\ 0 \end{pmatrix}$$

$$P_{vv}(u, v) = \begin{pmatrix} \cos(u) \frac{2\operatorname{sh}(v)^2 - \operatorname{ch}(v)^2}{\operatorname{ch}(v)^3} \\ \sin(u) \frac{2\operatorname{sh}(v)^2 - \operatorname{ch}(v)^2}{\operatorname{ch}(v)^3} \\ 2 \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^3} \end{pmatrix}$$

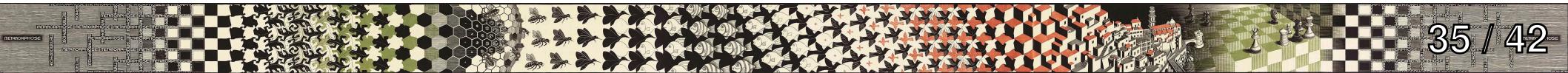
$$P_{uv} = \begin{pmatrix} \sin(u) \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^2} \\ -\cos(u) \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^2} \\ 0 \end{pmatrix}$$



$$E = \|P_u\|^2 = \frac{1}{\text{ch}(v)^2}$$

$$F = \langle P_u \mid P_v \rangle = \cos(u) \sin(u) \frac{\text{sh}(v)}{\text{ch}(v)^3} - \cos(u) \sin(u) \frac{\text{sh}(v)}{\text{ch}(v)^3} = 0$$

$$G = \|P_v\|^2 = \frac{\text{sh}(v)^2}{\text{ch}(v)^4} + \frac{\text{sh}(v)^4}{\text{ch}(v)^4} = \frac{\text{sh}(v)^2}{\text{ch}(v)^4} \underbrace{\left(1 + \text{sh}(v)^2\right)}_{=\text{ch}(v)^2} = \frac{\text{sh}(v)^2}{\text{ch}(v)^2}$$



Tout d'abord:

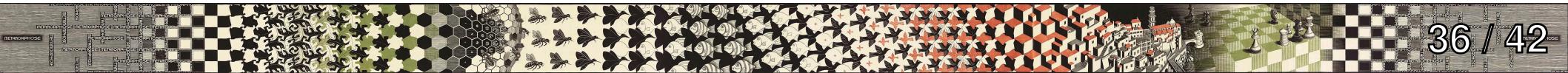
$$P_u \wedge P_v = \begin{pmatrix} \cos(u) \frac{\operatorname{sh}(v)^2}{\operatorname{ch}(v)^3} \\ \sin(u) \frac{\operatorname{sh}(v)^2}{\operatorname{ch}(v)^3} \\ \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^3} \end{pmatrix}$$

Donc:

$$\begin{aligned} \|P_u \wedge P_v\| &= \sqrt{\frac{\operatorname{sh}(v)^4}{\operatorname{ch}(v)^6} + \frac{\operatorname{sh}(v)^2}{\operatorname{ch}(v)^6}} \\ &= \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^3} \underbrace{\sqrt{\operatorname{sh}(v)^2 + 1}}_{=\operatorname{ch}(v)} = \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^2} \end{aligned}$$

Donc:

$$N = \frac{P_u \wedge P_v}{\|P_u \wedge P_v\|} = \begin{pmatrix} \cos(u) \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)} \\ \sin(u) \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)} \\ \frac{1}{\operatorname{ch}(v)} \end{pmatrix}$$



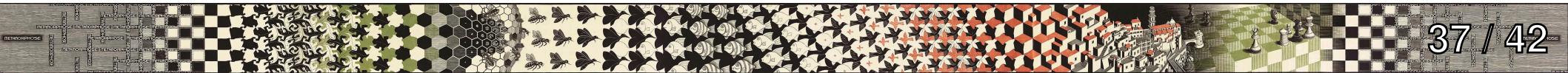
$$\mathcal{L} = \langle P_{uu} \mid N \rangle = -\frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^2}$$

$$\mathcal{M} = \langle P_{uv} \mid N \rangle = \frac{\operatorname{sh}(v)^2}{\operatorname{ch}(v)^3} (\cos(u) \sin(u) - \cos(u) \sin(u)) = 0$$

$$\mathcal{N} = \langle P_{vv} \mid N \rangle = \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^4} (2\operatorname{sh}(v)^2 - \operatorname{ch}(v)^2 + 2)$$

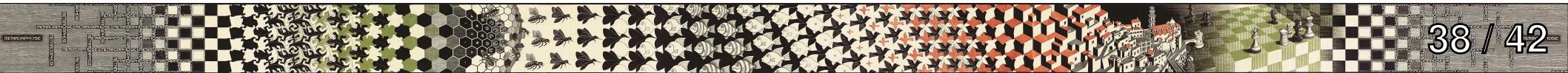
$$= \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^4} (2(\operatorname{ch}(v)^2 - 1) - \operatorname{ch}(v)^2 + 2)$$

$$= \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^4} \operatorname{ch}(v)^2 = \frac{\operatorname{sh}(v)}{\operatorname{ch}(v)^2}$$



On a :

$$\begin{aligned} K &= \frac{\mathcal{L}\mathcal{N}-\mathcal{M}^2}{EG-F^2} = -\frac{\operatorname{sh}(v)^2}{\operatorname{ch}(v)^4} \times \frac{1}{\frac{\operatorname{sh}(v)^2}{\operatorname{ch}(v)^4}} \\ &= -\frac{\operatorname{sh}(v)^2}{\operatorname{ch}(v)^4} \times \frac{\operatorname{ch}(v)^4}{\operatorname{sh}(v)^2} = -1 \end{aligned}$$



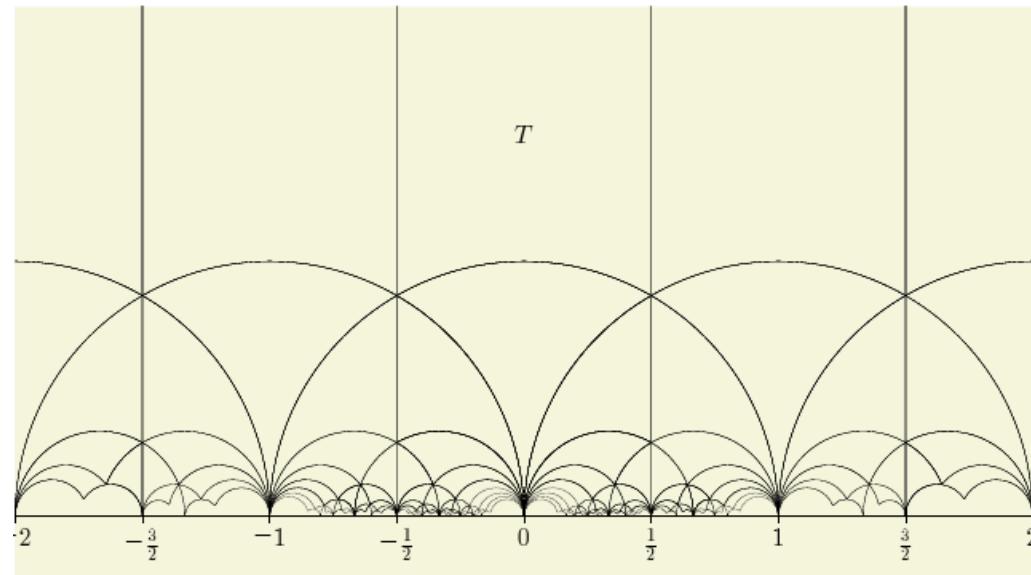
Le demi plan de Poincaré est un modèle de géométrie hyperbolique

Il est défini par :

$$\mathfrak{H}_2 = \{x + iy \in \mathbb{C}, y > 0\}$$

munis de la métrique :

$$ds^2 = \frac{dx^2 + dy^2}{y^2}$$



**NB:** Une métrique est une application  $g$  qui permet de définir le produit scalaire entre deux vecteurs, dans notre cas on note  $ds^2 = g_{ij} dx_i dx_j$  où  $g_{ij}$  sont les composante de la matrice associé et où  $ds^2$  est la longueur d'arc infinitésimal

Tout d'abord on peut définir la métrique sur notre surface par :

$$ds^2 = E dx^2 + 2F dx dy + G dy^2$$

Donc sur notre surface, la métrique s'écrit :

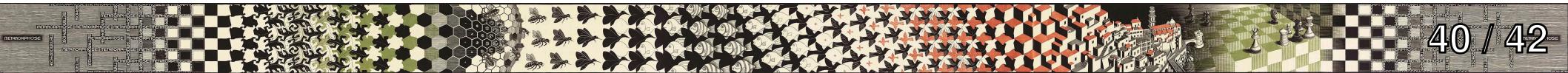
$$ds^2 = \frac{du^2}{\operatorname{ch}(v)^2} + \frac{\operatorname{sh}(v)^2}{\operatorname{ch}(v)^2} dv^2 = \frac{du^2 + \operatorname{sh}(v)^2 dv^2}{\operatorname{ch}(v)^2}$$

En appliquant notre porjection sur la métrique :

$$\begin{cases} x = u \\ y = \operatorname{ch}(v) \end{cases} \Leftrightarrow \begin{cases} dx = du \\ dy = \operatorname{sh}(v) dv \end{cases}$$

donc :

$$ds^2 = \frac{dx^2 + dy^2}{y^2}$$

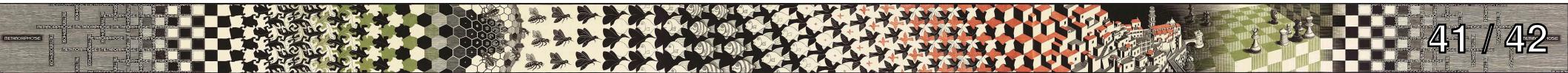


```
import matplotlib.pyplot as plt
import numpy as np
from mpl_toolkits.mplot3d import Axes3D

def dec(v):
    if v < 0:
        return -np.arccosh(1 - v)
    else:
        return np.arccosh(v + 1)

# Surface 3D (exemple : une sphère)
theta = np.linspace(0, 2 * np.pi, 500)
phi = np.linspace(-7, 7, 500)
for i in range(len(phi)):
    phi[i] = dec(phi[i])
print(phi)
theta, phi = np.meshgrid(theta, phi)
r = 1
x = r * np.cos(theta) / np.cosh(phi)
y = r * np.sin(theta) / np.cosh(phi)
z = phi - np.tanh(phi)

# Projection personnalisée (exemple : projection cylindrique)
image = plt.imread("/home/jvj/Telechargements/merci.jpg")
u = (theta - np.min(theta)) / (np.max(theta) - np.min(theta)) # Normalisation
v = (phi - np.min(phi)) / (np.max(phi) - np.min(phi))
image = image[::-1]
texture = image[
    (v * (image.shape[0] - 1)).astype(int), (u * (image.shape[1] - 1)).astype(int)
]
```



```
# Affichage
fig = plt.figure()
ax: Axes3D = fig.add_subplot(111, projection="3d")
ax.set_axis_off()
ax.view_init(elev=4, azim=-180, roll=0)
ax.set_xlim(-3, 3)
ax.set_ylim(-3, 3)
ax.plot_surface(x, y, z, facecolors=texture / 255.0, rstride=1, cstride=1)

plt.savefig("result.png", format="png", dpi=1000)
#plt.show()
```