Creating great 3D figures with minimal effort

Jean Feydy
HeKA team, Inria Paris
Inserm, Université Paris-Cité

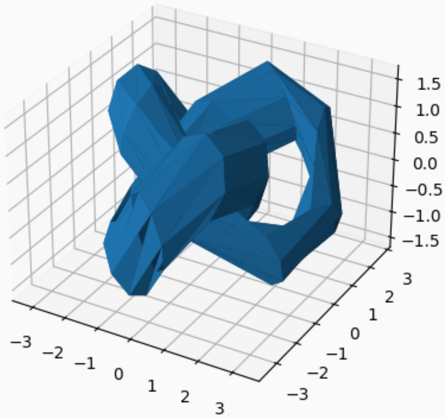
6th of November, 2024
Shape Seminar
MAP5, Paris

Who do you want to trust?

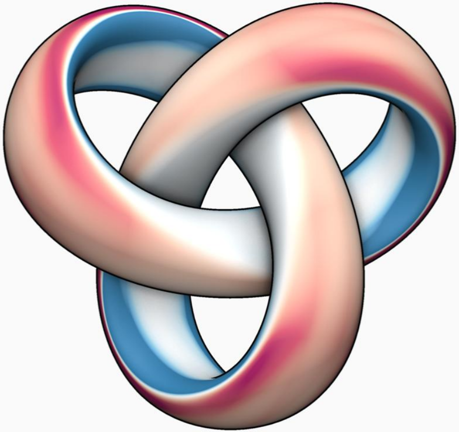
A triangle sandwich,
with soulless packaging.

A fresh sandouiche,
are you salivating yet?

Who do you want to trust?



A trefoil knot,
with default Matplotlib settings.



The same data,
with 10 lines of PyVista code.

But Jean… I'm just a mathematician!

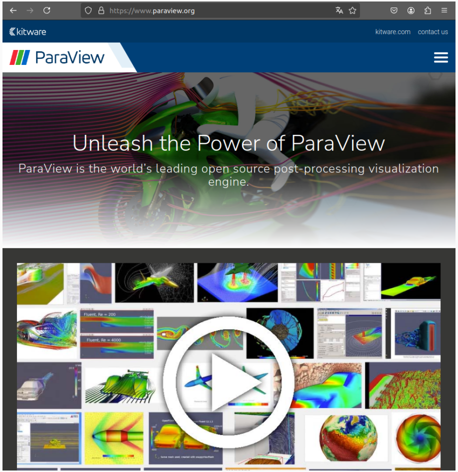
Creating great 3D figures takes some time but:

- **Can now be done in minutes** with PyVista, a transparent Matplotlib replacement.
- **Demonstrates** a familiarity with the **state-of-the-art** in geometry processing.
- **Sets you apart** from the **low-effort papers** that are flooding reviewers' mail boxes.

Keenan Crane **signals competence** with every single figure.

The Visualization ToolKit (VTK) – going strong since 1993.

PyVista – the pythonic API.



Paraview – the interactive GUI.

Today's talk – demystifying the graphics toolbox

1. Tips and tricks with **PyVista**.
   Subdivision? Culling? SSAO? PBR?

2. Links to **advanced resources**.
   The maths behind the simple functions.

3. Interactive **Paraview** demo.
   With real data :-)

Opening a PyVista window – import pyvista as pv

```python
pl = pv.Plotter(window_size=[800, 800])

S = pv.PolyData(
    [[x1, y1, z1], [x2, y2, z2], ...],
    faces=[3, a, b, c, 3, d, e, f, ...],
)
pl.add_mesh(S)

pl.camera_position = "xy"
pl.camera.zoom(1.4)
pl.enable_anti_aliasing("ssaa")
pl.enable_parallel_projection()

pl.show()
pl.screenshot("knot.jpg")
```

A **"flat"** 3D rendering of our trefoil knot.

Anti-aliasing matters, especially for small screenshots – 200x200 below

`pl.disable_anti_aliasing()`

One sample per pixel.

`pl.enable_anti_aliasing()`

Multiple samples per pixel.

Parallel projection – a bit better for scientific visualization?

Default 3D perspective.

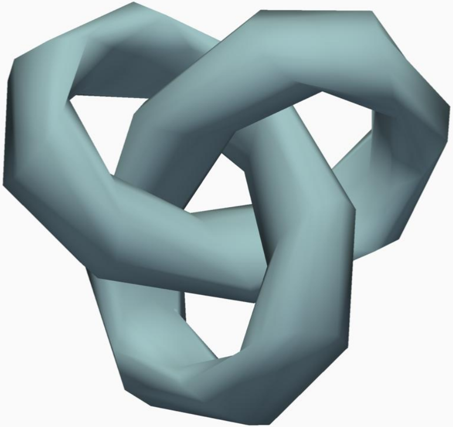
`pl.enable_parallel_projection()`

Smoothness

From flat to Gouraud shading with point normals

`pl.add_mesh(S)`

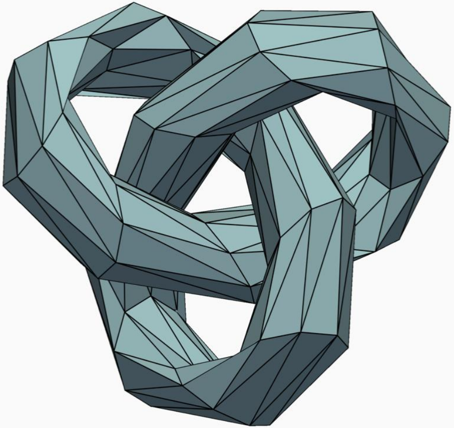
Raw data with flat shading.

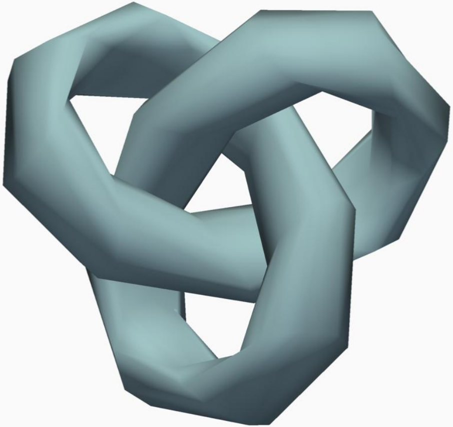


`pl.add_mesh(S, smooth_shading=True)`

Interpolate point normals.

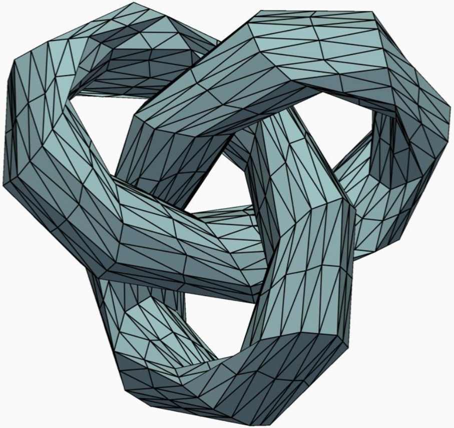
Getting smoother geometry: with linear subdivision?

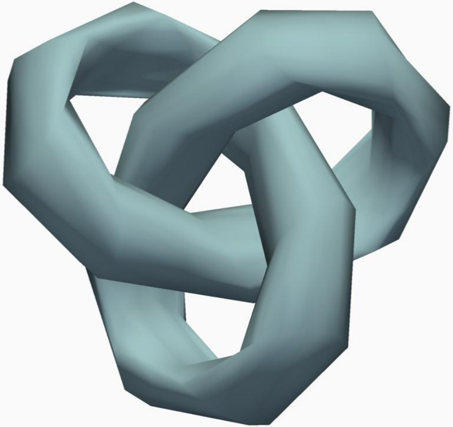




```
S = S.subdivide(subfilter="linear", nsub=0)
```

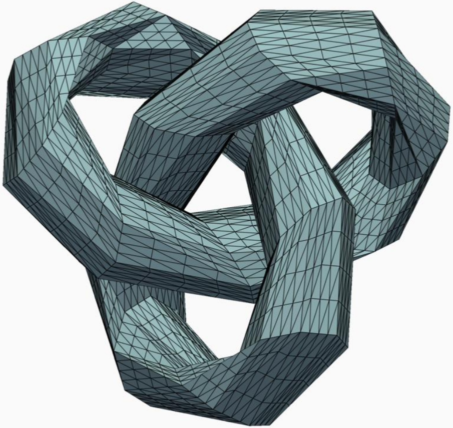
Getting smoother geometry: with linear subdivision?

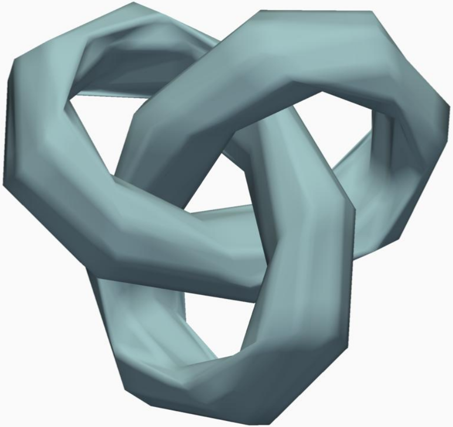




```
S = S.subdivide(subfilter="linear", nsub=1)
```

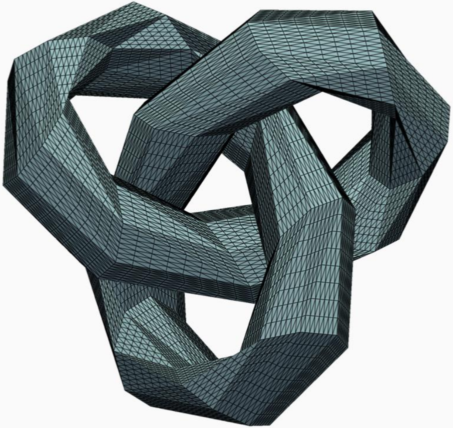
Getting smoother geometry: with linear subdivision?





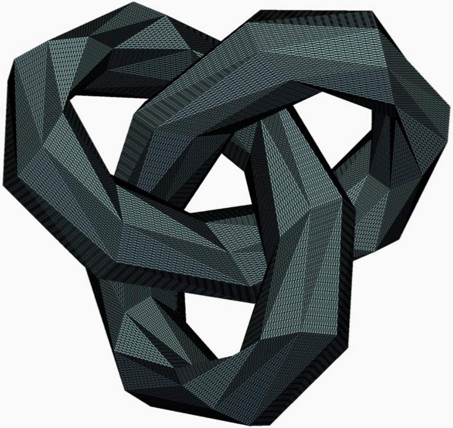
```
S = S.subdivide(subfilter="linear", nsub=2)
```

Getting smoother geometry: with linear subdivision?



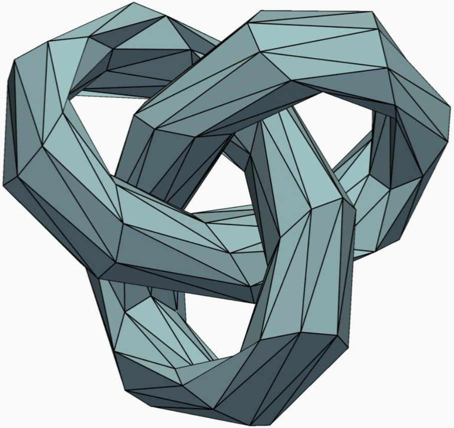
```
S = S.subdivide(subfilter="linear", nsub=3)
```

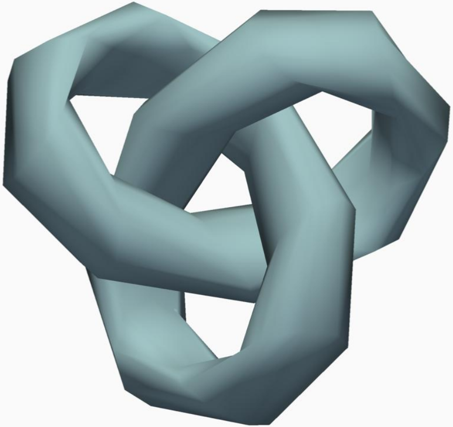
Getting smoother geometry: with linear subdivision?



```
S = S.subdivide(subfilter="linear", nsub=4)
```

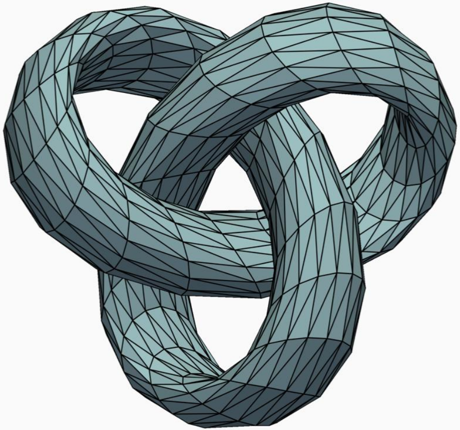
Getting smoother geometry: with loop subdivision!

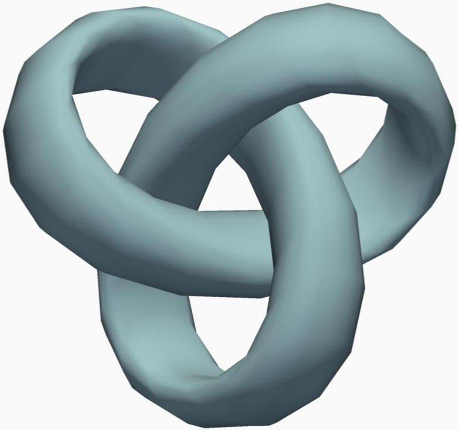




```
S = S.subdivide(subfilter="loop", nsub=0)
```

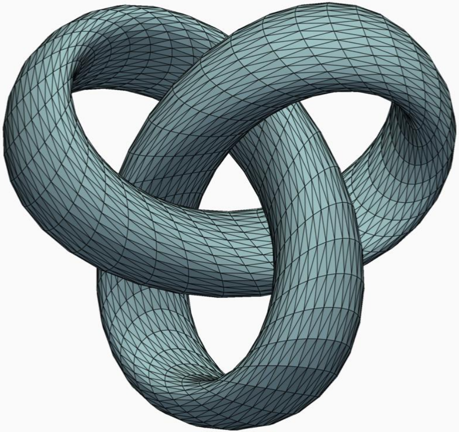
Getting smoother geometry: with loop subdivision!

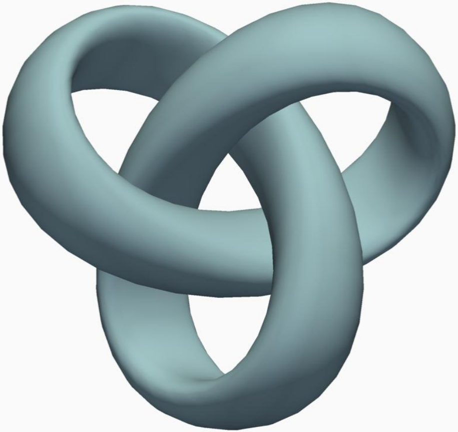




```
S = S.subdivide(subfilter="loop", nsub=1)
```

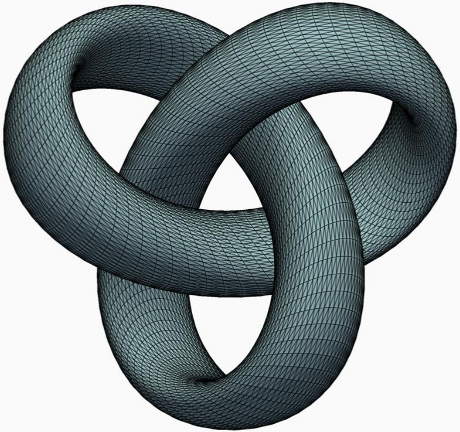
Getting smoother geometry: with loop subdivision!

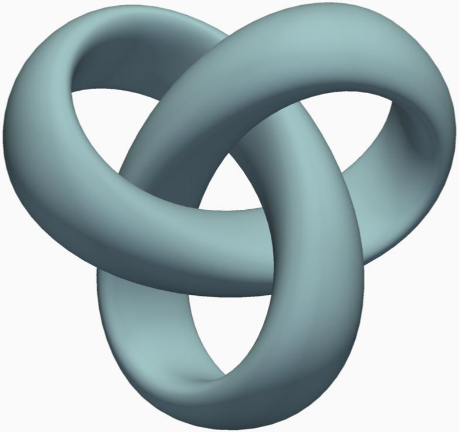




```
S = S.subdivide(subfilter="loop", nsub=2)
```

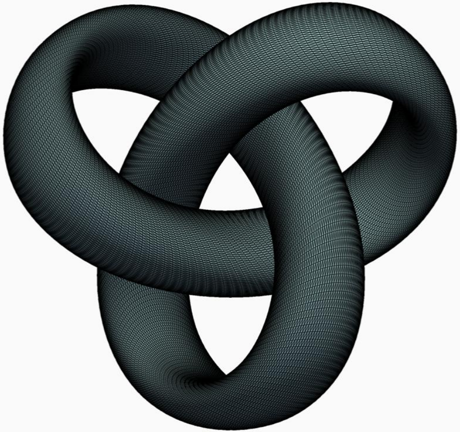
Getting smoother geometry: with loop subdivision!

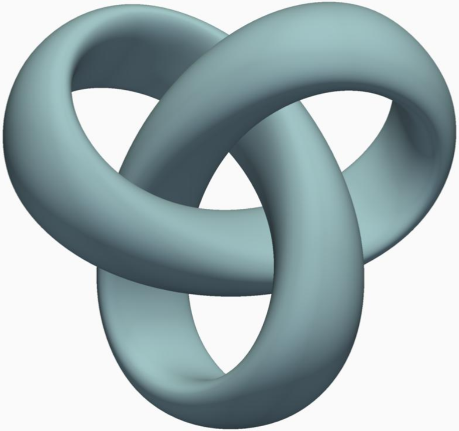




```
S = S.subdivide(subfilter="loop", nsub=3)
```

Getting smoother geometry: with loop subdivision!

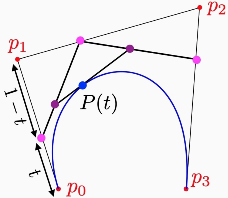




```
S = S.subdivide(subfilter="loop", nsub=4)
```

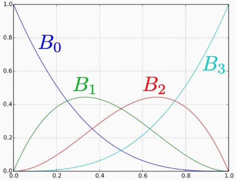
This is not "cheating" – why stick to linear interpolation for smooth data?

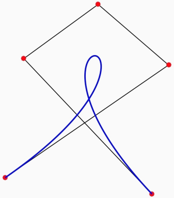
Interesting mathematics behind subdivision surfaces



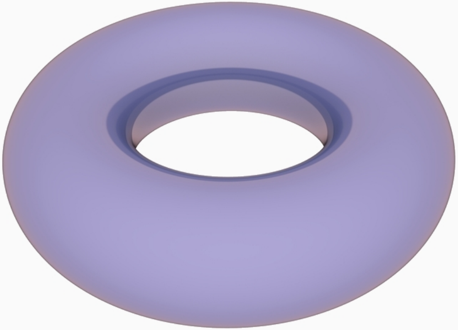
$P(t) = \sum_i P_i B_i(t)$

Bernstein polynomials:



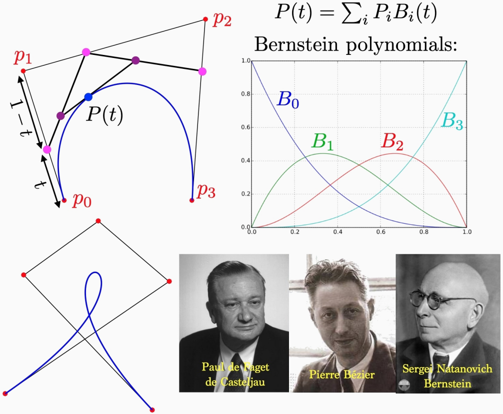


De Casteljau's algorithm,
courtesy of Gabriel Peyré.



The **flat torus** embedded in $\mathbb{R}^3$
by the Hevea project.

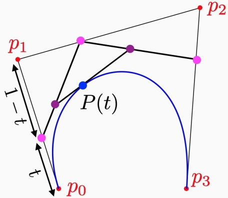
Interesting mathematics behind subdivision surfaces



De Casteljau's algorithm,
courtesy of Gabriel Peyré.

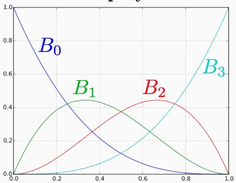
The **flat torus** embedded in $\mathbb{R}^3$
by the Hevea project.

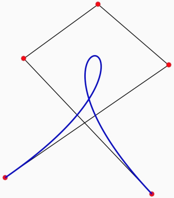
Interesting mathematics behind subdivision surfaces



$P(t) = \sum_i P_i B_i(t)$

Bernstein polynomials:

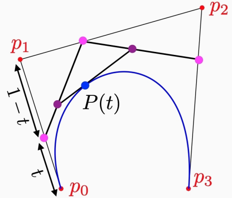




De Casteljau's algorithm,
courtesy of Gabriel Peyré.

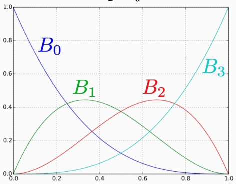
The **flat torus** embedded in $\mathbb{R}^3$
by the Hevea project.

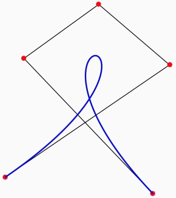
Interesting mathematics behind subdivision surfaces



$$P(t) = \sum_i P_i B_i(t)$$

Bernstein polynomials:

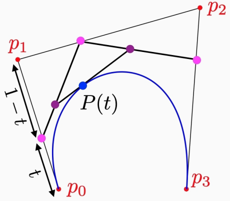




De Casteljau's algorithm,
courtesy of Gabriel Peyré.

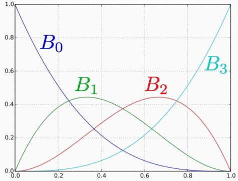
The **flat torus** embedded in $\mathbb{R}^3$
by the Hevea project.

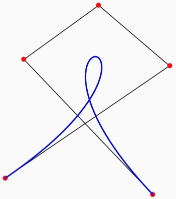
Interesting mathematics behind subdivision surfaces



$$P(t) = \sum_i P_i B_i(t)$$

Bernstein polynomials:



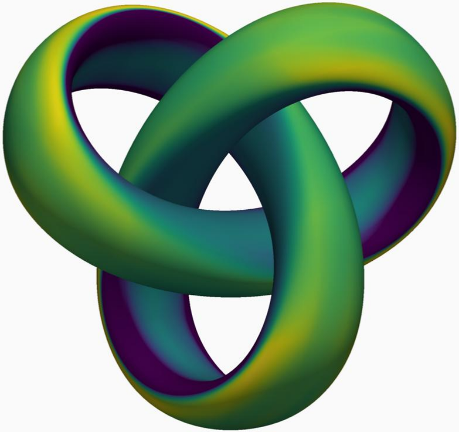


De Casteljau's algorithm,
courtesy of Gabriel Peyré.

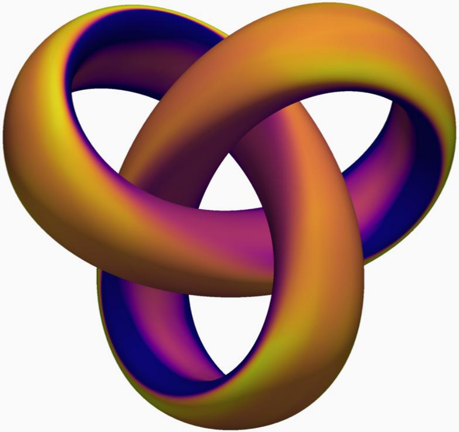
The **flat torus** embedded in $\mathbb{R}^3$
by the Hevea project.

Colors

Adding some colors



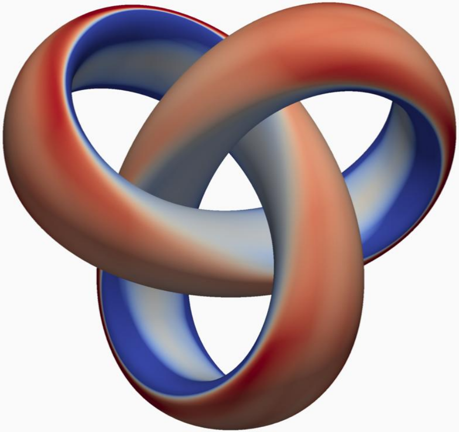
`cmap="viridis"`



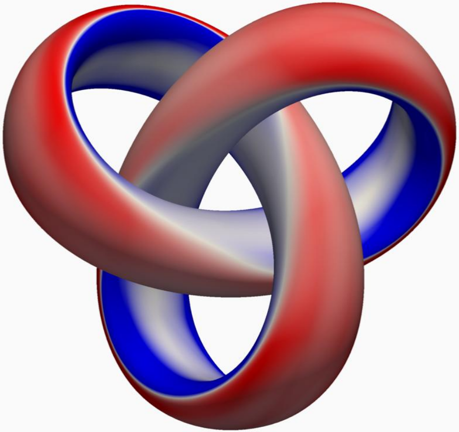
`cmap="plasma"`

```
pl.add_mesh(S, scalars=S.curvature("gaussian"), cmap=cmap, clim=(-1, 1))
```

Adding some colors: beware of perceptual artifacts



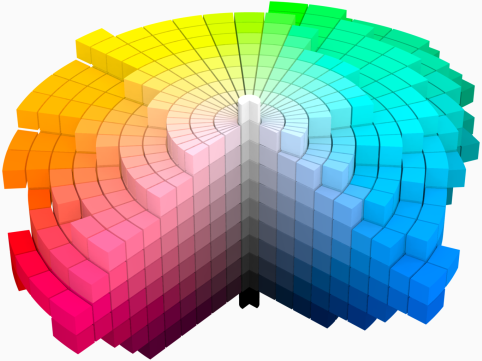
`cmap="coolwarm"`



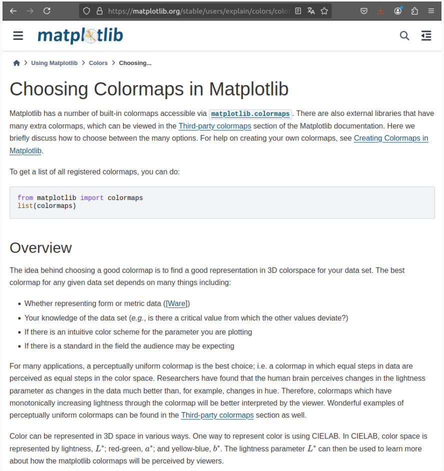
`cmap="bwr"`

```
pl.add_mesh(S, scalars=S.curvature("gaussian"), cmap=cmap, clim=(-1, 1))
```

Choosing a colormap



The Munsell **perceptual** color space, from the Chromatone center.



https://matplotlib.org/stable/users/explain/colors/colo

Using Matplotlib > Colors > Choosing...

Choosing Colormaps in Matplotlib

Matplotlib has a number of built-in colormaps accessible via `matplotlib.colormaps`. There are also external libraries that have many extra colormaps, which can be viewed in the Third-party colormaps section of the Matplotlib documentation. Here we briefly discuss how to choose between the many options. For help on creating your own colormaps, see Creating Colormaps in Matplotlib.

To get a list of all registered colormaps, you can do:

```
from matplotlib import colormaps
list(colormaps)
```

Overview

The idea behind choosing a good colormap is to find a good representation in 3D colorspace for your data set. The best colormap for any given data set depends on many things including:

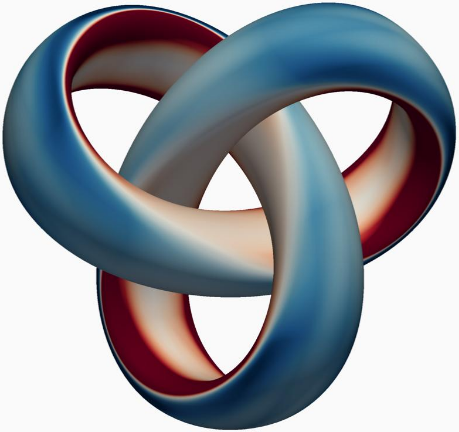
- Whether representing form or metric data ([Ware])
- Your knowledge of the data set (*e.g.*, is there a critical value from which the other values deviate?)
- If there is an intuitive color scheme for the parameter you are plotting
- If there is a standard in the field the audience may be expecting

For many applications, a perceptually uniform colormap is the best choice; i.e. a colormap in which equal steps in data are perceived as equal steps in the color space. Researchers have found that the human brain perceives changes in the lightness parameter as changes in the data much better than, for example, changes in hue. Therefore, colormaps which have monotonically increasing lightness through the colormap will be better interpreted by the viewer. Wonderful examples of perceptually uniform colormaps can be found in the Third-party colormaps section as well.

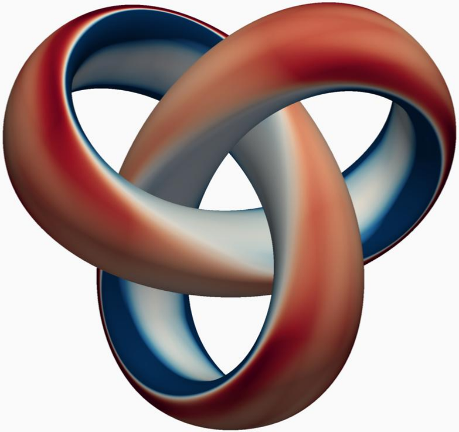
Color can be represented in 3D space in various ways. One way to represent color is using CIELAB. In CIELAB, color space is represented by lightness, L^*; red-green, a^*; and yellow-blue, b^*. The lightness parameter L^* can then be used to learn more about how the matplotlib colormaps will be perceived by viewers.

The **Matplotlib tutorial** on the subject.

Adding some colors: append "_r" to reverse colormaps



`cmap="RdBu"`

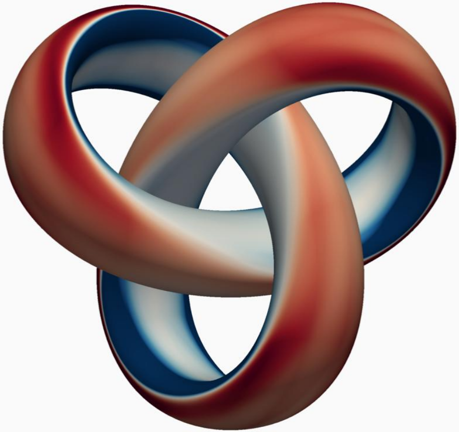


`cmap="RdBu_r"`

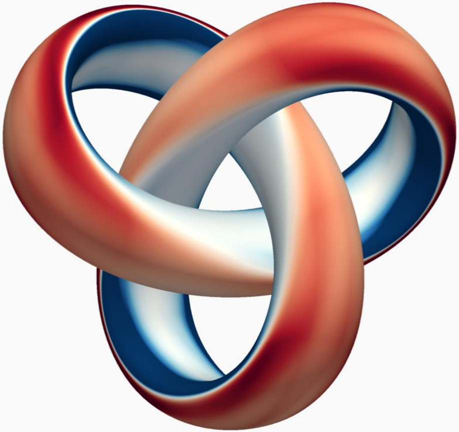
```
pl.add_mesh(S, scalars=S.curvature("gaussian"), cmap=cmap, clim=(-1, 1))
```

Lighting and material models

Adjust lighting: ambient glow



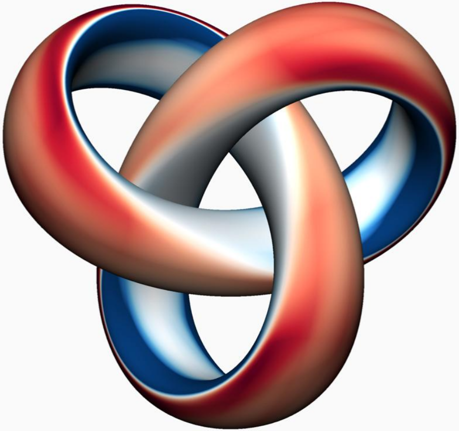
```
pl.add_mesh(S, ambient=0., ...)
```



```
pl.add_mesh(S, ambient=0.2, ...)
```

Adjust lighting: custom set with pv.Light(...)

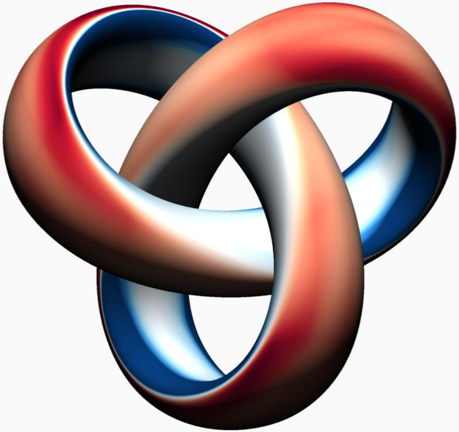
```
pl = pv.Plotter(
    window_size=[800, 800],
    lighting="none"
)
pl.add_mesh(S)

light = pv.Light(intensity=0.7)
light.set_direction_angle(40, 90)
pl.add_light(light)

light = pv.Light(
    light_type="headlight",
    intensity=0.7
)
pl.add_light(light)
```



Our light kit.

Adjust lighting: custom set with pv.Light(...)

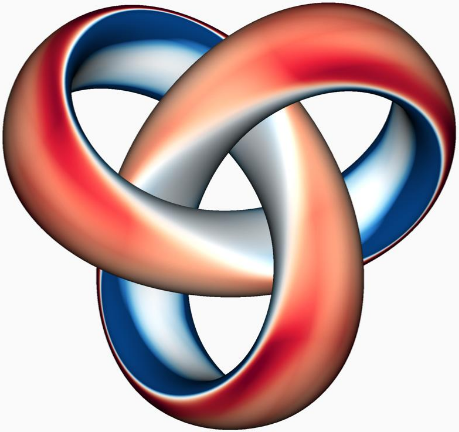
```
pl = pv.Plotter(
    window_size=[800, 800],
    lighting="none"
)
pl.add_mesh(S)

light = pv.Light(intensity=1.2)
light.set_direction_angle(40, 90)
pl.add_light(light)

light = pv.Light(
    light_type="headlight",
    intensity=0.2
)
pl.add_light(light)
```



Less headlight.

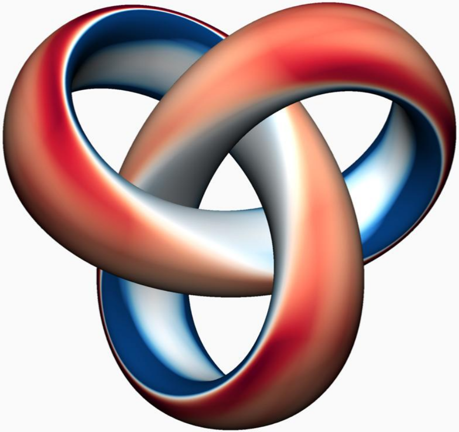
Adjust lighting: custom set with pv.Light(...)

```
pl = pv.Plotter(
    window_size=[800, 800],
    lighting="none"
)
pl.add_mesh(S)

light = pv.Light(intensity=0.2)
light.set_direction_angle(40, 90)
pl.add_light(light)

light = pv.Light(
    light_type="headlight",
    intensity=1.2
)
pl.add_light(light)
```



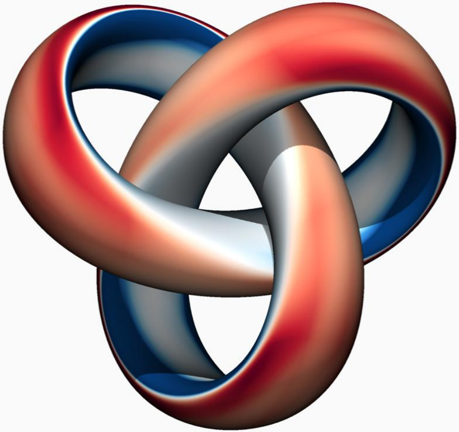
More headlight.

Adjust lighting: include shadows!



Default rendering.

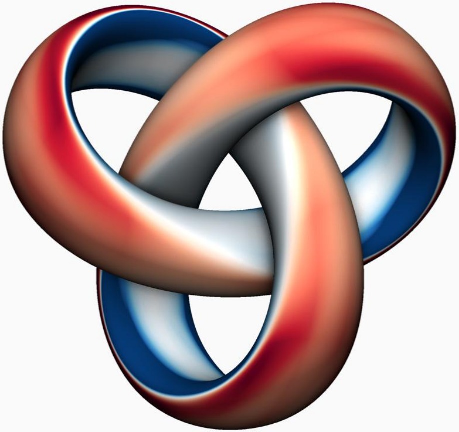
Hard to read.



`pl.enable_shadows()`

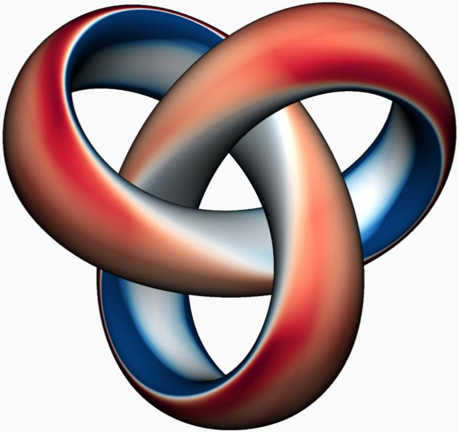
Realistic shadow casting.

Adjust lighting: pseudo-shadows



`pl.enable_ssao(radius=1)`

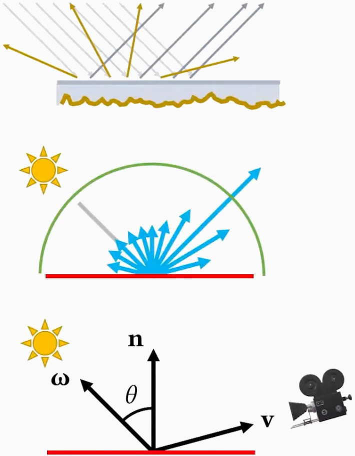
Screen Space Ambient Occlusion.



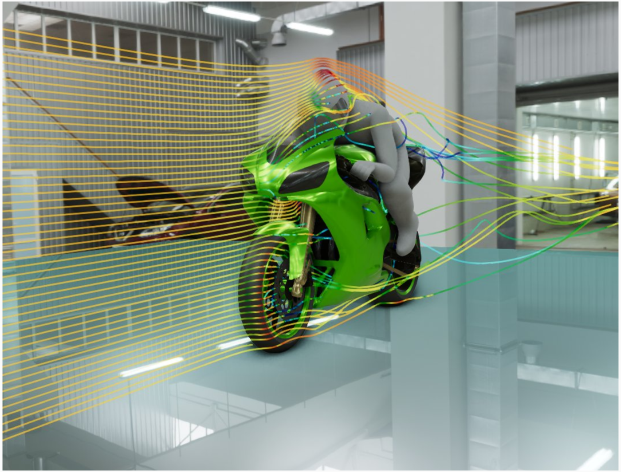
`pl.enable_eye_dome_lighting()`

Highlighting contours from the inside.

Adjust the material model with Physics Based Rendering (PBR)

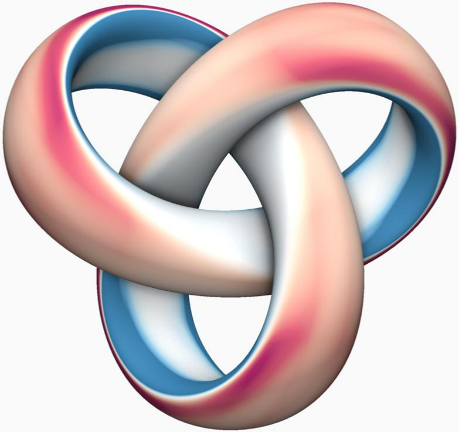


Microfacets and the rendering equation, by **Cem Yuksel**.

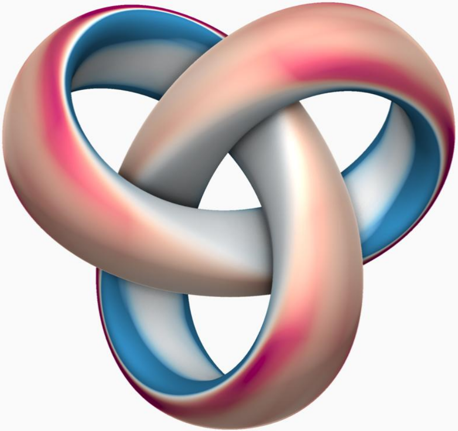


VTK supports PBR since 2019. Made in **Lyon**!

Adjust the material model with Physics Based Rendering (PBR)



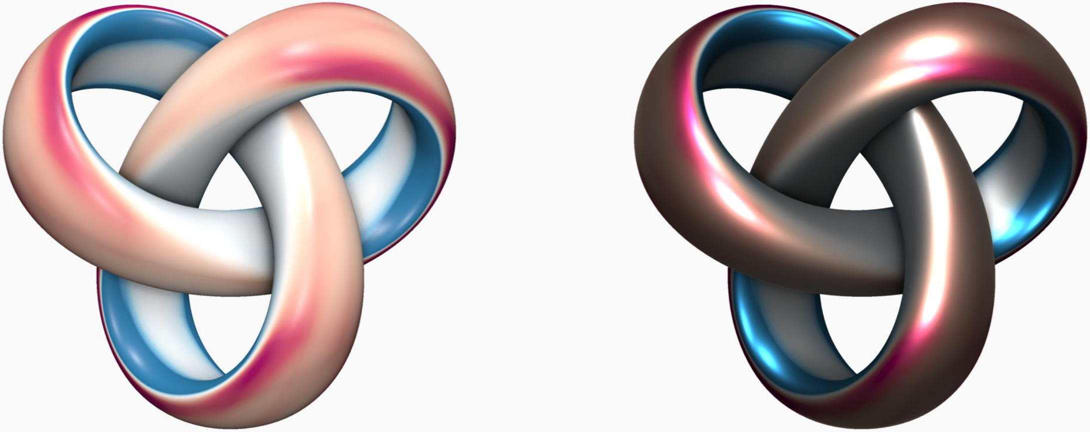
`metallic=0, roughness=0.8`



`metallic=1, roughness=0.8`

```
pl.add_mesh(S, pbr=True, metallic=m, roughness=r, ...)
```

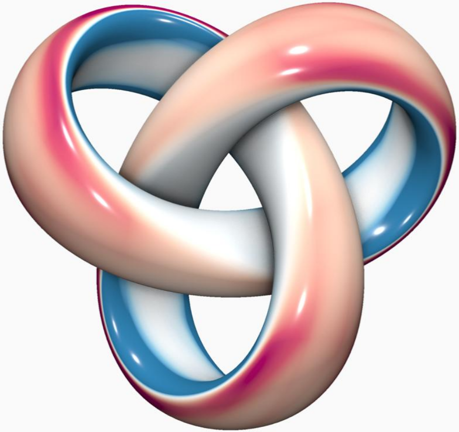
Adjust the material model with Physics Based Rendering (PBR)



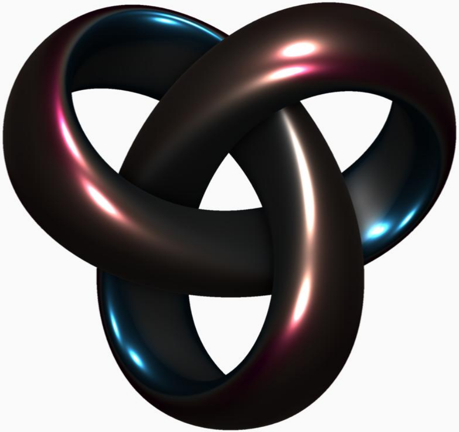
`metallic=0, roughness=0.4` `metallic=1, roughness=0.4`

```
pl.add_mesh(S, pbr=True, metallic=m, roughness=r, ...)
```

Adjust the material model with Physics Based Rendering (PBR)



`metallic=0, roughness=0.2`

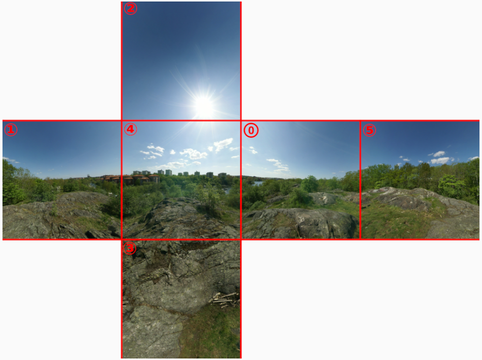


`metallic=1, roughness=0.2`

```
pl.add_mesh(S, pbr=True, metallic=m, roughness=r, ...)
```

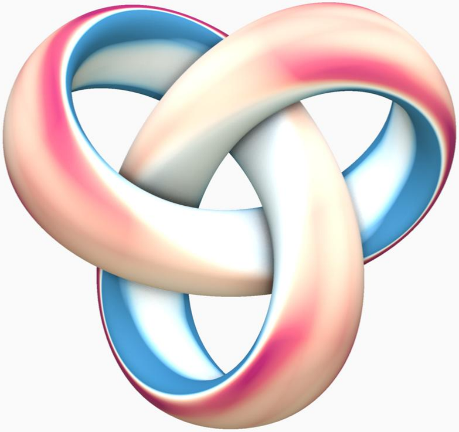
Add a cubemap – and some more lights

```python
cubemap =
pv.examples.download_sky_box_cube_map()
pl.set_environment_texture(cubemap)

if show_background:
    pl.add_actor(cubemap.to_skybox())

light = pv.Light(intensity=1.0)
light.set_direction_angle(40, 90)
for _ in range(3):
    pl.add_light(light)

...
pl.show()
```

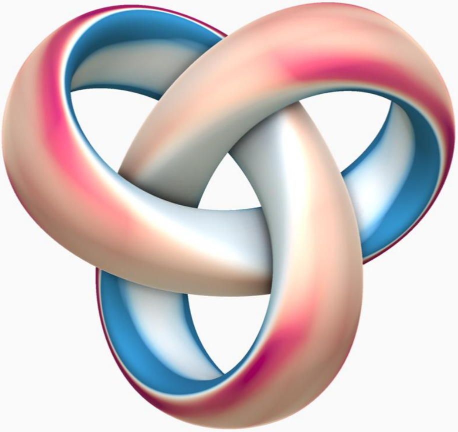


A **cubemap** encodes the **environment** lighting using **6 square images**.

Adjust the material model with Physics Based Rendering (PBR)



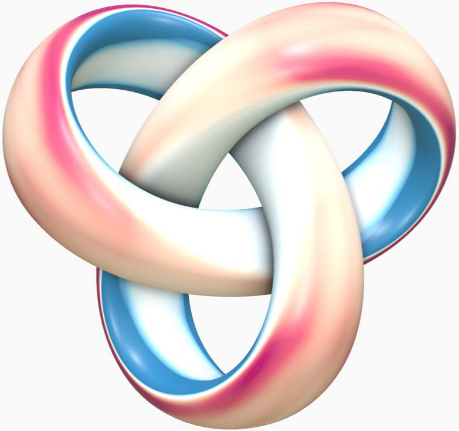
`metallic=0.5, roughness=0.8`



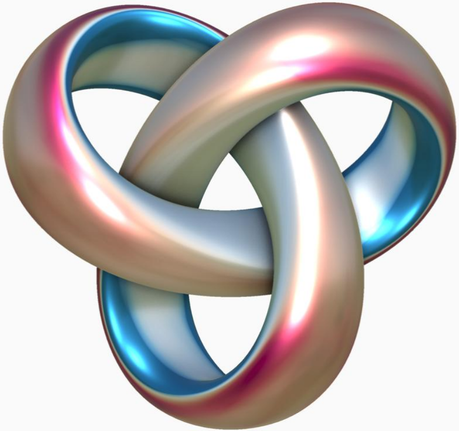
`metallic=1, roughness=0.8`

```
pl.add_mesh(S, pbr=True, metallic=m, roughness=r, ...)
```

Adjust the material model with Physics Based Rendering (PBR)



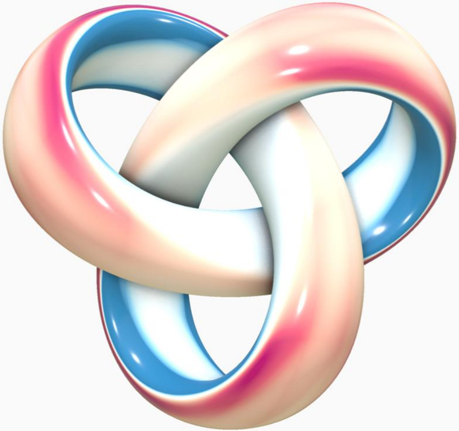
metallic=0.5, **roughness**=0.4



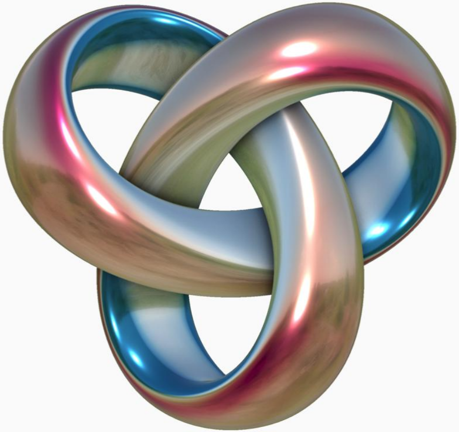
metallic=1, **roughness**=0.4

`pl.add_mesh(S, pbr=True, metallic=m, roughness=r, ...)`

Adjust the material model with Physics Based Rendering (PBR)



metallic=0.5, **roughness**=0.2



metallic=1, **roughness**=0.2

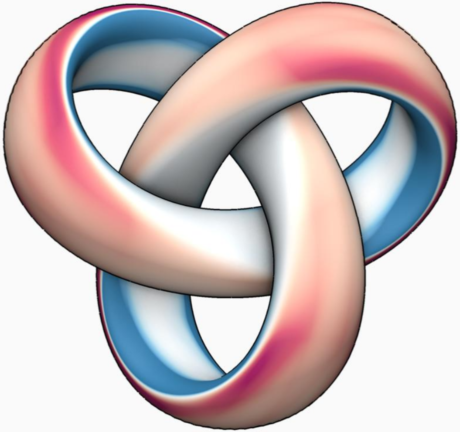
`pl.add_mesh(S, pbr=True, metallic=m, roughness=r, ...)`

Silhouettes and animations

Highlight the silhouette with a simple filtering step

Extract the **mesh edges** that look “tangent” and draw them with a **bold marker**.

```
pl.add_mesh(
    S,
    silhouette=dict(
        color="black",
        line_width=10.0,
    ),
    ...
)
```

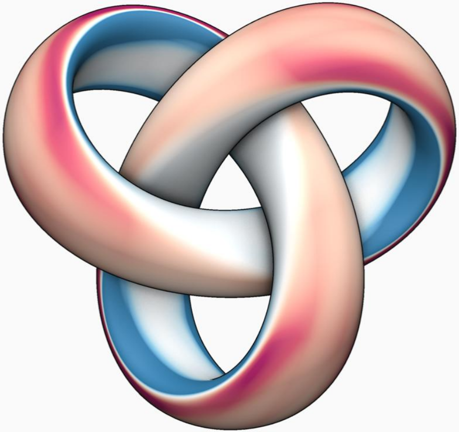


Fast and simple, but crenelated.

Highlight the silhouette with a black shell

Inflate the mesh, paint it black,
and **cull the triangles** facing the camera.

```
S["sw"] = w * np.ones(surface.n_points)
shell = S.warp_by_scalar(scalars="sw")

pl.add_mesh(S, ...)
pl.add_mesh(
    shell,
    color="black",
    culling="front",
    interpolation="pbr",
    roughness=1,
)
```

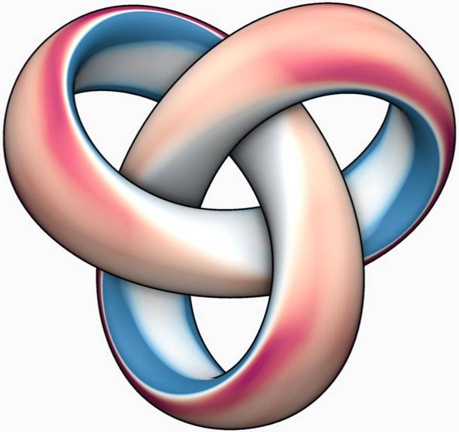


`w = 0.01`

Highlight the silhouette with a black shell

Inflate the mesh, paint it black,
and **cull the triangles** facing the camera.

```
S["sw"] = w * np.ones(surface.n_points)
shell = S.warp_by_scalar(scalars="sw")

pl.add_mesh(S, ...)
pl.add_mesh(
    shell,
    color="black",
    culling="front",
    interpolation="pbr",
    roughness=1,
)
```

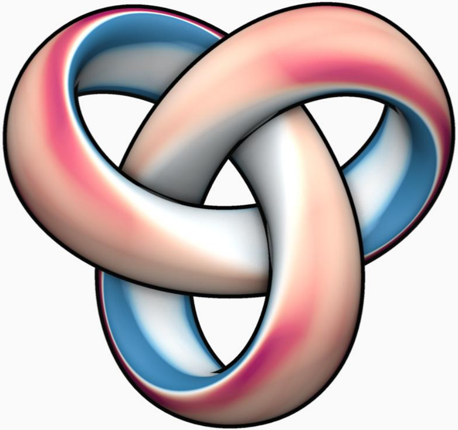


`w = 0.02`

Highlight the silhouette with a black shell

Inflate the mesh, paint it black,
and **cull the triangles** facing the camera.

```
S["sw"] = w * np.ones(surface.n_points)
shell = S.warp_by_scalar(scalars="sw")

pl.add_mesh(S, ...)
pl.add_mesh(
    shell,
    color="black",
    culling="front",
    interpolation="pbr",
    roughness=1,
)
```

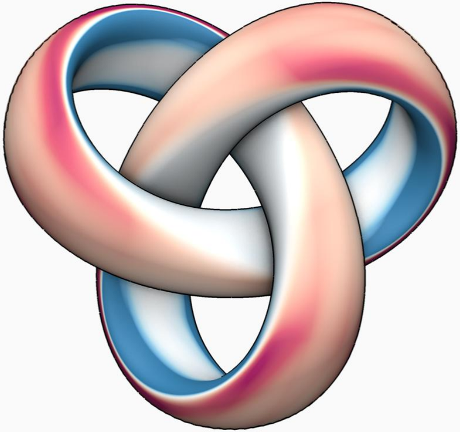


`w = 0.05`

Create movies!

Save screenshots and fuse them with **ffmpeg**
or update point features and **write frames**.

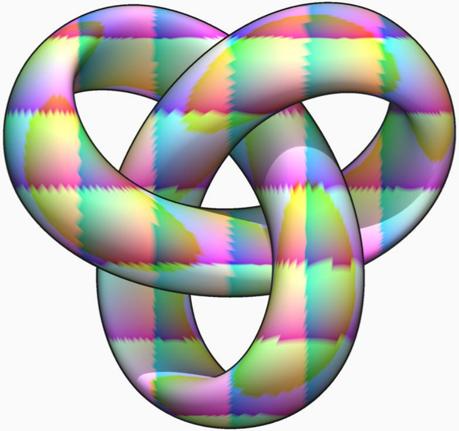
```
pl.open_movie("flow.mp4", quality=10)

for frame in range(1000):
    S.points += ...
    S["signal"] = ...
    pl.write_frame()

pl.close()
```



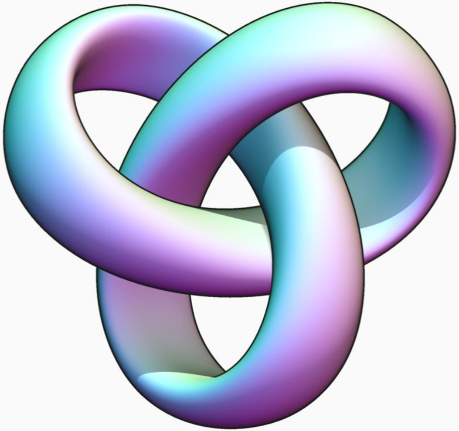
Mean curvature flow.

Textures

Define custom RGB(A) vertex colors



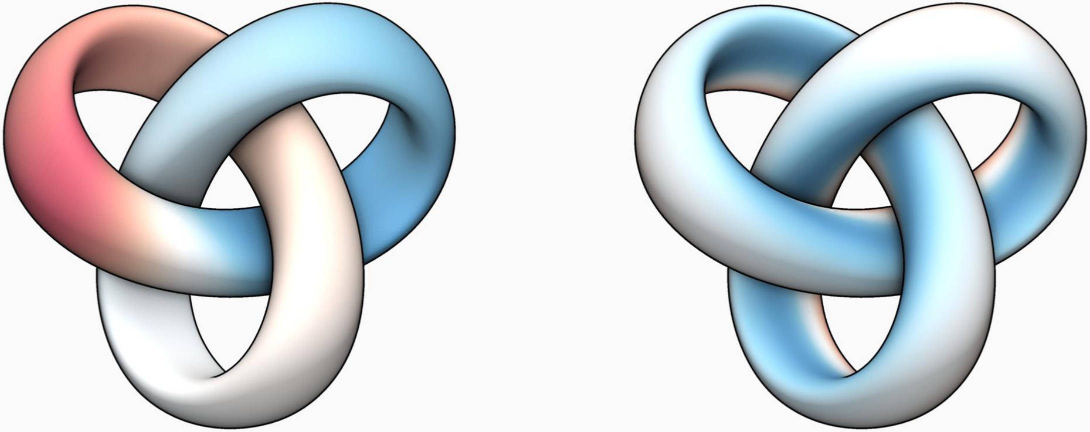
`RGB = S.points`



`RGB = (S.point_normals + 1) / 2`

```
pl.add_mesh(S, rgb=True, scalars=RGB, ...)
```

Define custom UV coordinates in [0,1] and fetch RGBA from a texture image

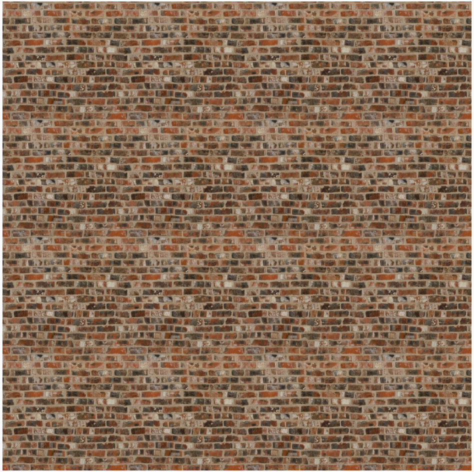


U coordinates.

V coordinates.

```
S.active_texture_coordinates = UV.reshape(S.n_points, 2)
```

Define custom UV coordinates in [0,1] and fetch RGBA from a texture image

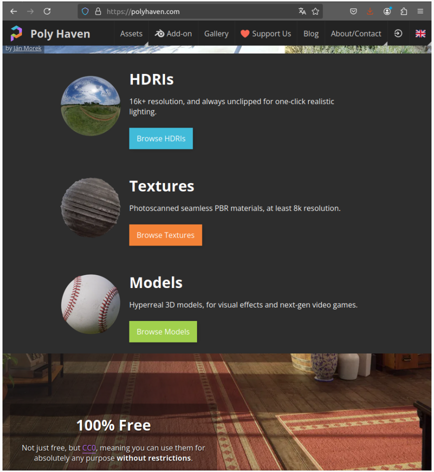


Texture image.

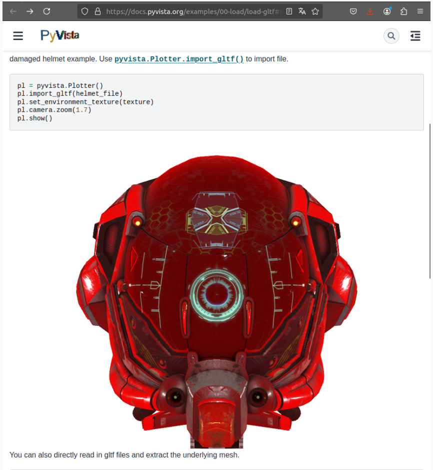
Textured mesh.

```
pl.add_mesh(S, texture=pv.read_texture("bricks.jpg"), ...)
```

Going further with glTF models – use textures for material properties



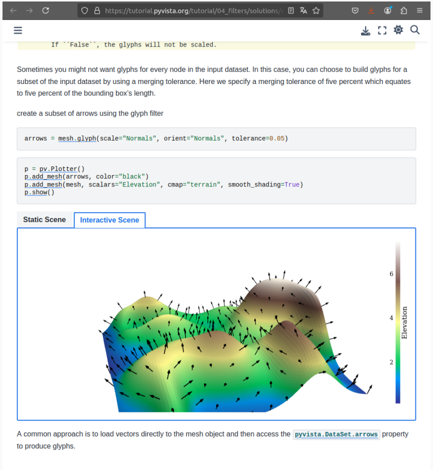
Download assets from e.g. **PolyHaven**.



Use them with PyVista!

`pl.import_gltf(...)`

Going further – the PyVista documentation is great



https://tutorial.pyvista.org/tutorial/04_filters/solutions/

```
If ``False``, the glyphs will not be scaled.
```

Sometimes you might not want glyphs for every node in the input dataset. In this case, you can choose to build glyphs for a subset of the input dataset by using a merging tolerance. Here we specify a merging tolerance of five percent which equates to five percent of the bounding box's length.

create a subset of arrows using the glyph filter

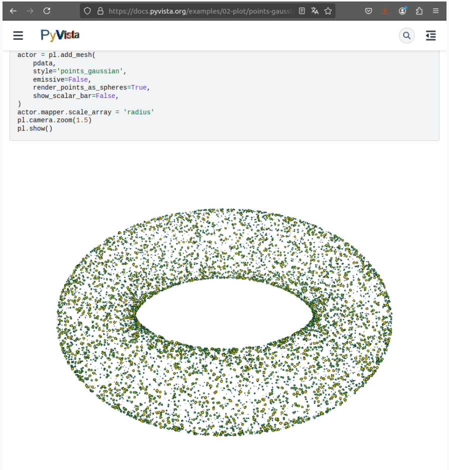
```
arrows = mesh.glyph(scale="Normals", orient="Normals", tolerance=0.05)
```

```
p = pv.Plotter()
p.add_mesh(arrows, color="black")
p.add_mesh(mesh, scalars="Elevation", cmap="terrain", smooth_shading=True)
p.show()
```

Static Scene | Interactive Scene

A common approach is to load vectors directly to the mesh object and then access the `pyvista.DataSet.arrows` property to produce glyphs.

Use **glyphs** to display **arrows**.



https://docs.pyvista.org/examples/02-plot/points-gauss...

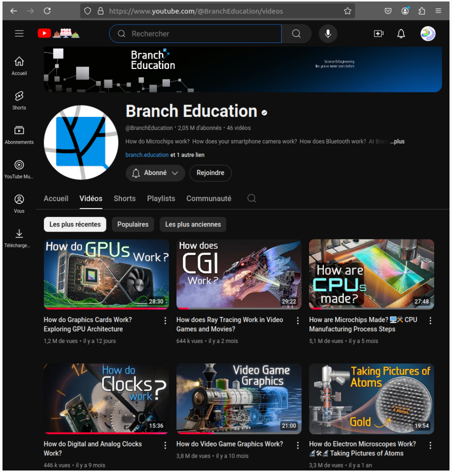
PyVista

```
actor = pl.add_mesh(
    pdata,
    style='points_gaussian',
    emissive=False,
    render_points_as_spheres=True,
    show_scalar_bar=False,
)
actor.mapper.scale_array = 'radius'
pl.camera.zoom(1.5)
pl.show()
```

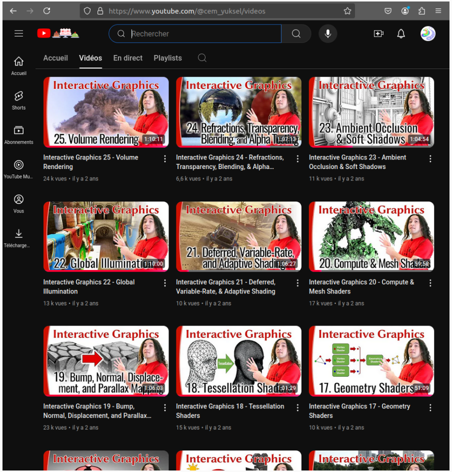
Use **point Gaussians**

for **non-uniform** point clouds.

Going further – two fantastic YouTube channels



Branch Education’s deep dives into **modern hardware**.



Cem Yuksel’s lectures about (interactive) **computer graphics**.

Time for a Paraview demo?

References i