


Sculpting procedural noise for real-time visualization of astronomical objects

M2 MoSIG Research internship - 2023

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Context: Galaxy walkthrough

Continuation of veRTIGE: a virtual tour through our galaxy

- Real-time walkthrough through the galaxy
- Hubble-like quality

Usage in digital planetariums - RSA cosmos

Internship focus:

- Interstellar dust clouds (nebula, galaxy arm, solar flare, ...)

How to model these objects ?

No 3D groundtruth:

- 2D view from Earth
- Sparse physical knowledge

Case study: Astronomical objects

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- Sparse physical knowledge

A few observable properties:

1. Volumetric & semi-transparent

Case study: Astronomical objects

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2. Large voids
3. Clusters of high density with a macro shape (tube, spiral)

Case study: Astronomical objects

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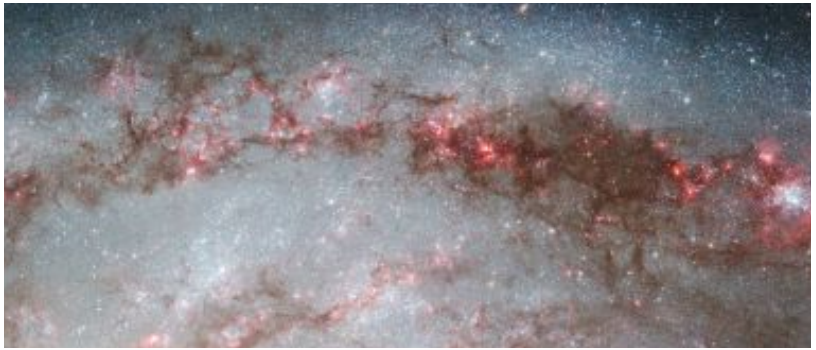
1. Volumetric & semi-transparent
2. Large voids
3. Clusters of high density with a macro shape (tube, spiral)
4. Stochastic details



Case study: Astronomical objects

No 3D groundtruth:

- 2D view from Earth
- Sparse physical knowledge

A few observable properties:

1. Volumetric & semi-transparent
2. Large voids
3. Clusters of high density with a macro shape (tube, spiral)
4. Stochastic details
5. Anisotropy caused by deformation

Goals & a priori knowledge

Data structures and **algorithms** allowing:

- **Real-time volumetric** rendering (60 fps)
- **High details** resolution (but fits in GPU memory, **4-16 GB**)
- Ease of design
- ~~Infinite scene~~

A priori knowledge:

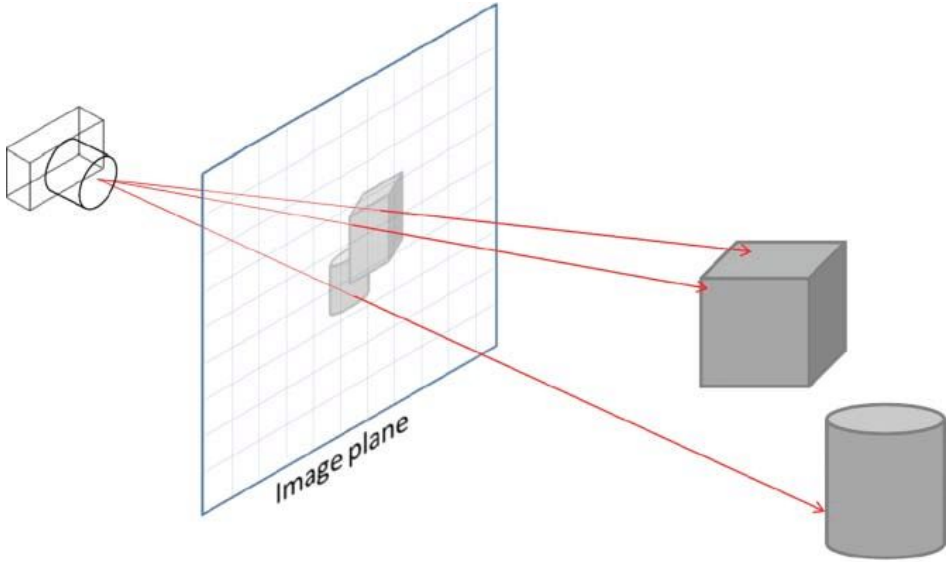
- Big empty spaces
- Medium scale: **cloud clusters** with **simple shape**
- Small scale: **anisotropic** “galactic dust cloud” **material**

2. State of the art

Method	Memory	Infinite details	Ease to design	Render time	Local anisotropy

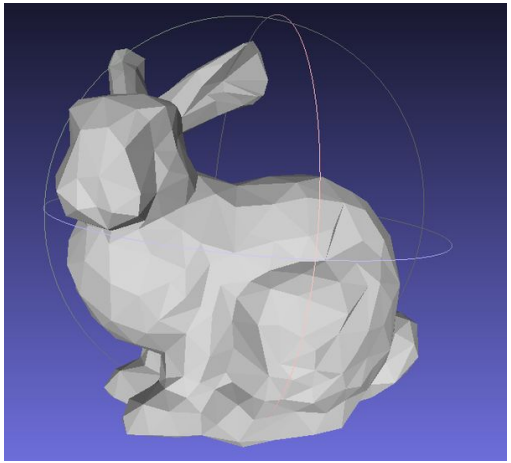
2.1. How to represent & render scenes ?

Surface ray casting:



For each **ray**:

- Compute **intersection** with **every object**
- Find **closest object**
- Compute **appearance** of object at intersection point



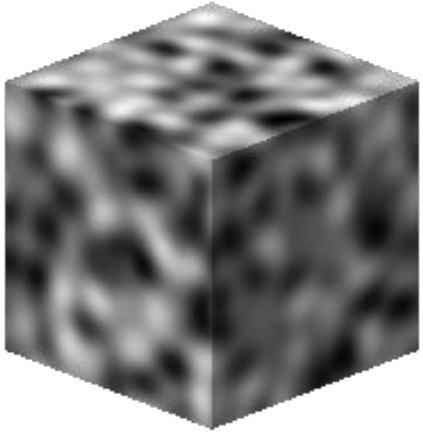
2.1. How to represent & render scenes ?

What if **no real “surface”** ?

2.1. How to represent & render scenes ?

Rendering heterogeneous participating medium
➜ **integrate density along ray**

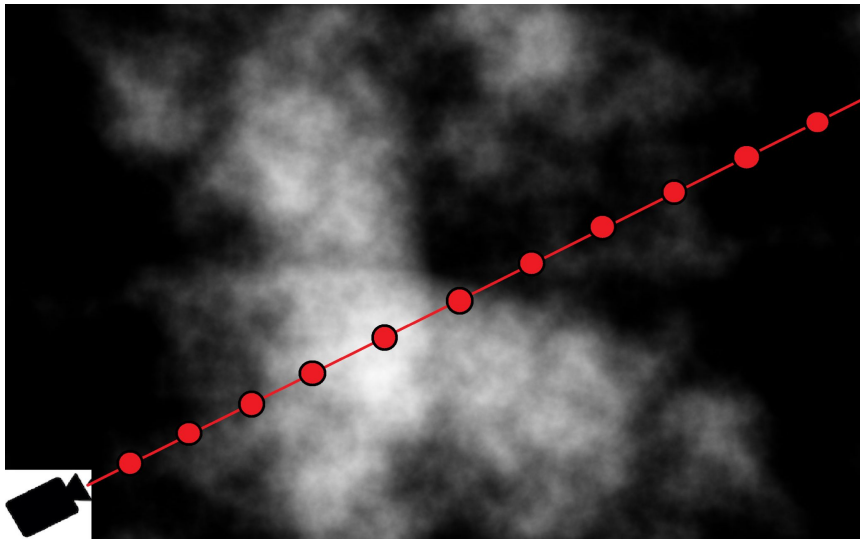
Density field:



Describe **density** at **every position** ***P*** = (x,y,z) in the scene.

$$density(P) : \mathbb{R}^3 \rightarrow \mathbb{R}$$

Volumetric ray marching:
numerical integration by **sampling**



2. State of the art - comparison

1.2. Plain RGBA volumes
1.3. Fully procedural volumes
1.4. Mesh-based volumes
1.5. Implicit volumes

Method	Memory	Infinite details	Ease to design	Render time	Local anisotropy
Plain volume					
Fully procedural					
Mesh based					
Implicit volume					

2.2. Plain RGBA volumes (ex: Ilumbra^{TM})

Orion nebula 3D image (512^3):

- Memory / quality tradeoff ($1024^3 \simeq$ 4 GB)
- Requires skilled astronomical experts and artists
- Slow to render

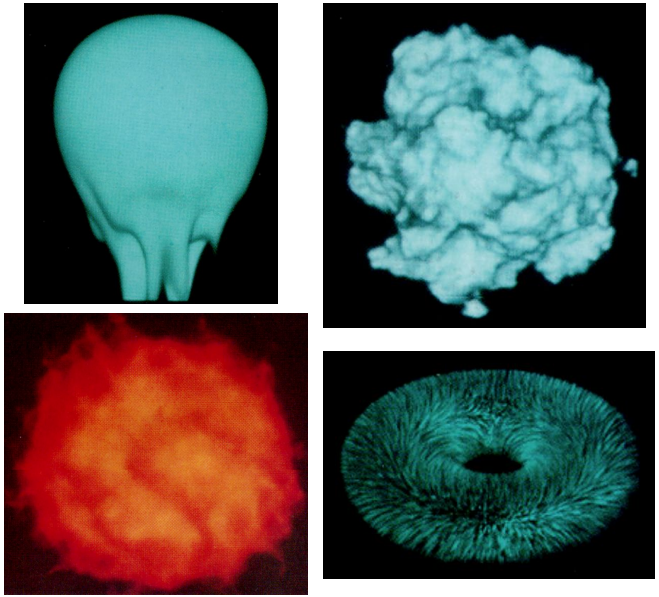
2.2. State of the art - comparison

Method	Memory	Infinite details	Ease to design	Render time	Local anisotropy
Plain volume	- -	No	- -	-	- -
Fully procedural					
Mesh based					
Implicit volume					

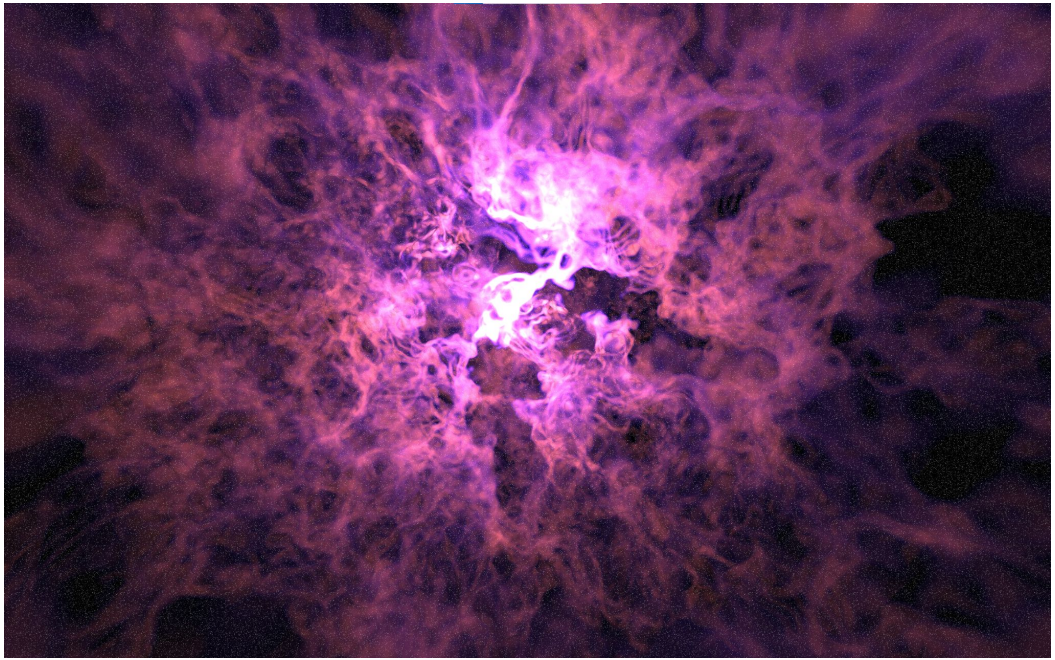
2.3. Procedural volumes

$$noise(P) : \mathbb{R}^3 \rightarrow \mathbb{R}$$
$$density(P) = noise(P)$$

“Hypertextures” [Perlin, 89]



Procedural nebula (Erwan Leria):



2.3. State of the art - comparison

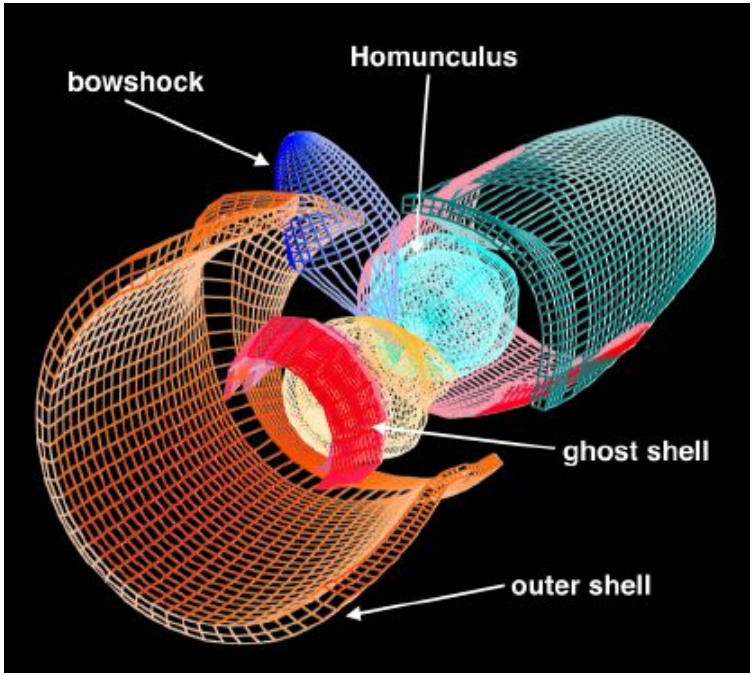
Method	Memory	Infinite details	Ease to design	Render time	Local anisotropy
Plain volume	- -	No	- -	-	- -
Fully procedural	0	Yes	- -	- -	-
Mesh based					
Implicit volume					

2.4. Mesh-based volume (ex: Shape™)

Orion nebula (Shape™):

Homunculus Nebula (Shape™):

[Mehner, et al., 2016]



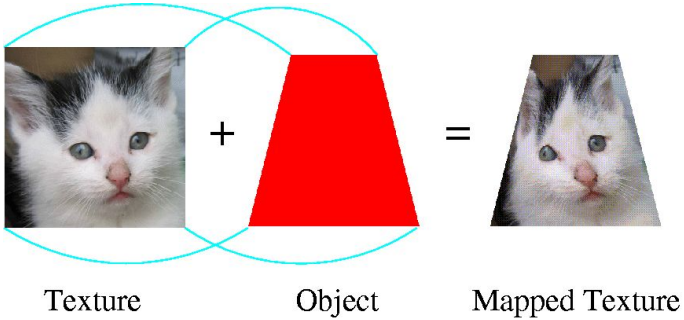
Texture mapping

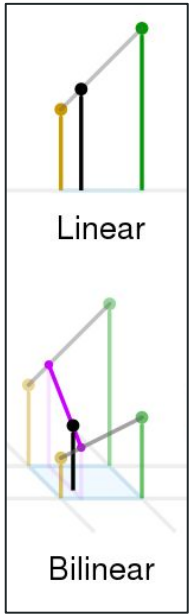
$$map(P) : \mathbb{R}^3 \rightarrow \mathbb{R}^3$$
$$density(P) = noise(map(P))$$

$noise(P)$: **Procedural material**

$map(P)$: **Material space coordinates**

Isotropic material + **anisotropic** mapping
➔ **anisotropic material**





With a mesh :

$map(P)$: computed by **linear interpolation** of map values **stored at mesh nodes**

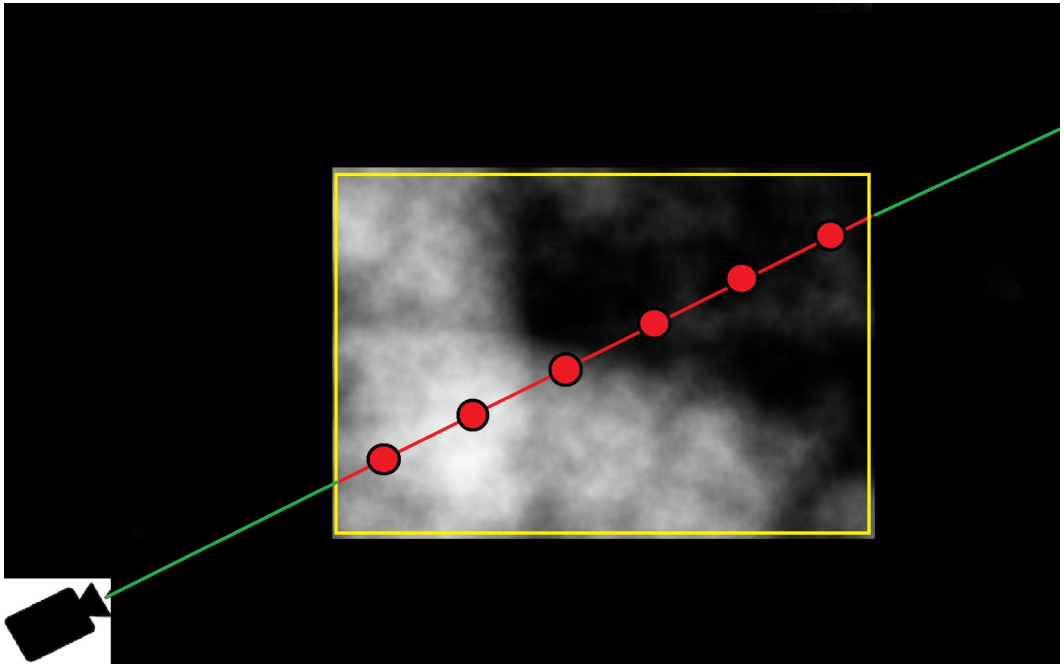
Linear interpolation:

From **2 samples**, reconstruct **linear approximation** of the function in the interval of the samples.

Intuitively: **weighted mean** between samples

2D extension : **Bilinear** interpolation
3D extension : **Trilinear** interpolation

Empty space skipping

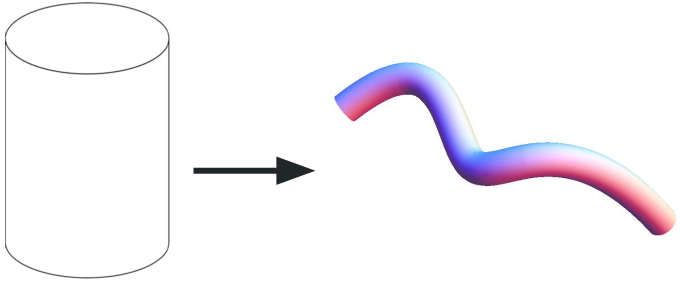


2.4. State of the art - comparison

Method	Memory	Infinite details	Ease to design	Render time	Local anisotropy
Plain volume	- -	No	- -	-	- -
Fully procedural	0	Yes	- -	- -	-
Mesh based	-	Yes	+	+	+
Implicit volume					

2.5. Implicit volume (ex: [MM22])

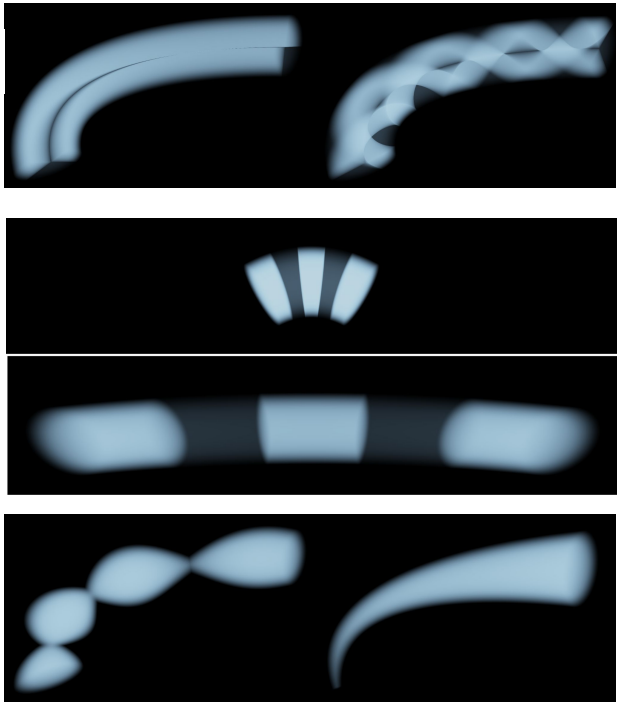
Spline tubes - Generalized cylinders:

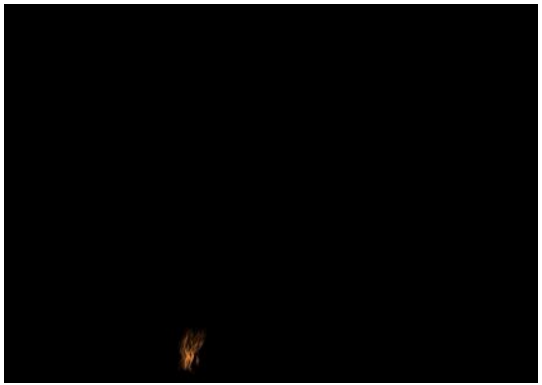


$$density(P) = noise(map(P))$$

$map(P)$ computed directly on the fly

Torsion, stretch, varying radius

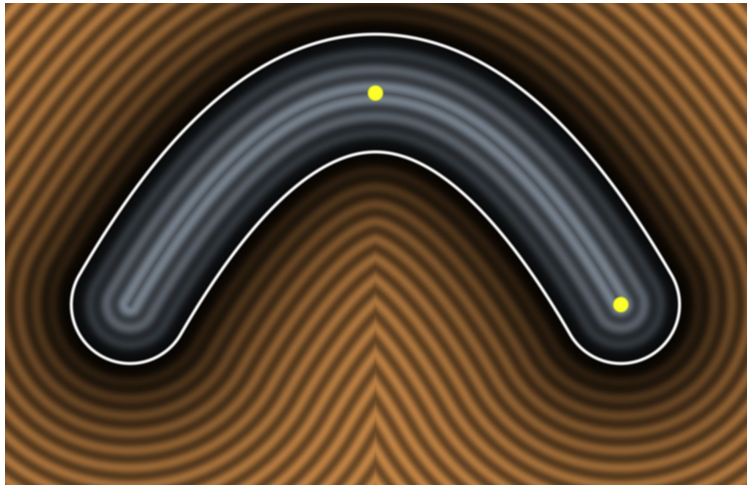




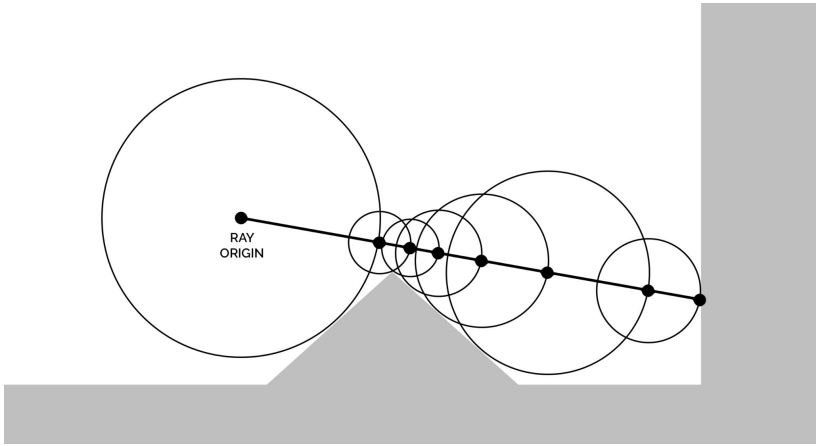
Signed Distance Field (SDF)

$$SDF(P) : \mathbb{R}^3 \rightarrow \mathbb{R}$$

$$SDF(P) = \begin{cases} distance(P), & \text{if } P \text{ outside of the object} \\ -distance(P), & \text{if } P \text{ inside of the object} \\ 0, & \text{if } P \text{ on the object} \end{cases}$$

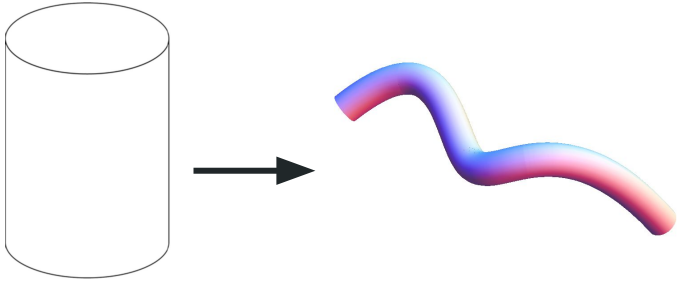


Sphere tracing [Hart, J. C. (1996)]:



2.5. Implicit volume (ex: [MM22])

Spline tubes - Generalized cylinders:



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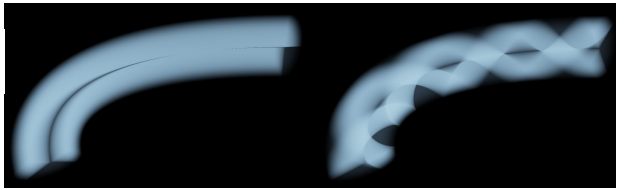
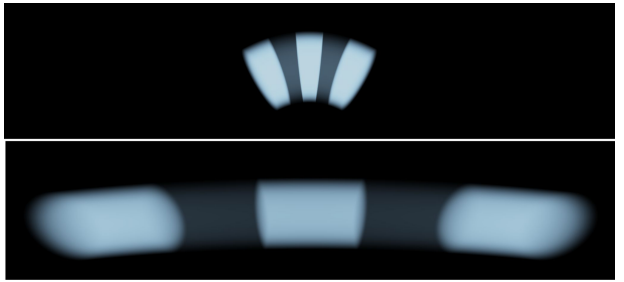
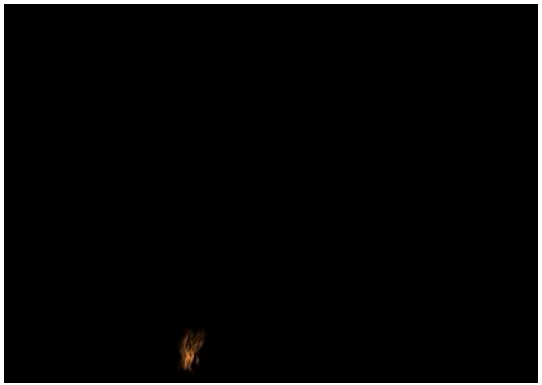
Torsion, stretch, varying radius







2.5. State of the art - comparison

Method	Memory	Infinite details	Ease to design	Render time	Local anisotropy
Plain volume	- -	No	- -	-	- -
Fully procedural	0	Yes	- -	- -	-
Mesh based	-	Yes	+	+	+
Implicit volume	0	Yes	+	+	+

State of the art: conclusions

Method	Memory	Infinite details	Ease to design	Render time	Local anisotropy
Plain volume	- -	No	- -	-	- -
Fully procedural	0	Yes	- -	- -	-
Mesh based	-	Yes	+	+	+
Implicit volume	0	Yes	+	+	+

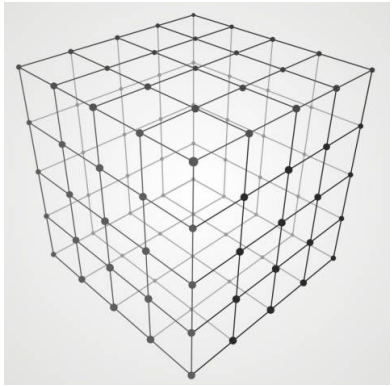
Our takeaway:

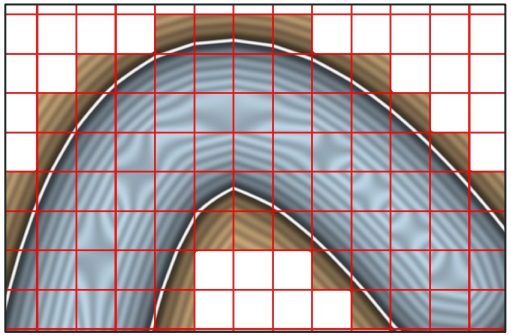
- Separate shape and material: □
- Skip empty spaces: □
- Procedural material: □
- Pre-compute mapping (small memory cost): □
- Scalable at runtime (independent from number of objects) □

Ours	-	Yes	+	++	+

3. Contribution

3. Base idea: pre-computations at 3D grid nodes

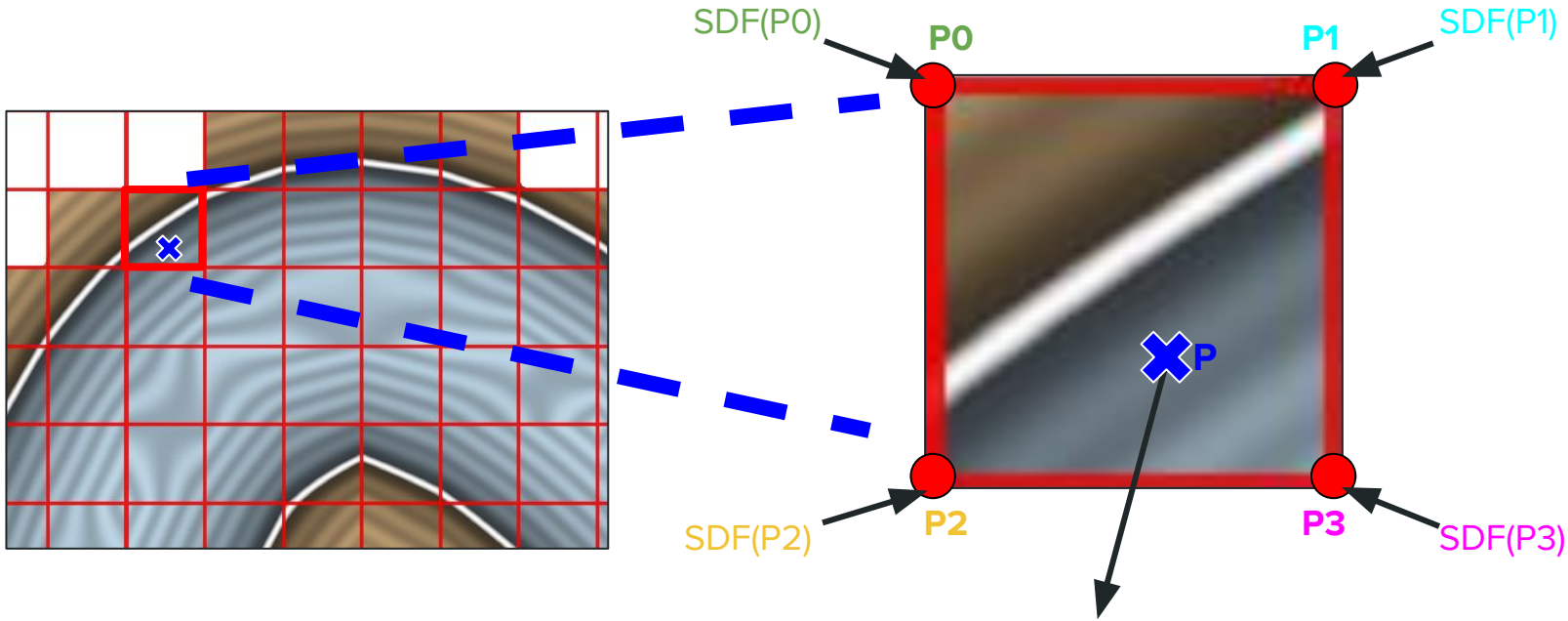




- **Pre-compute** everything expensive & **store** it at **nodes**:
  - **SDF** to retrieve the shape
  - **Mapping** to compute the density field
- Two steps:
  - Before runtime: **Pre-compute** and build structure
  - At runtime: **Reconstruct** data from structure

3. Base idea: using a 3D grid

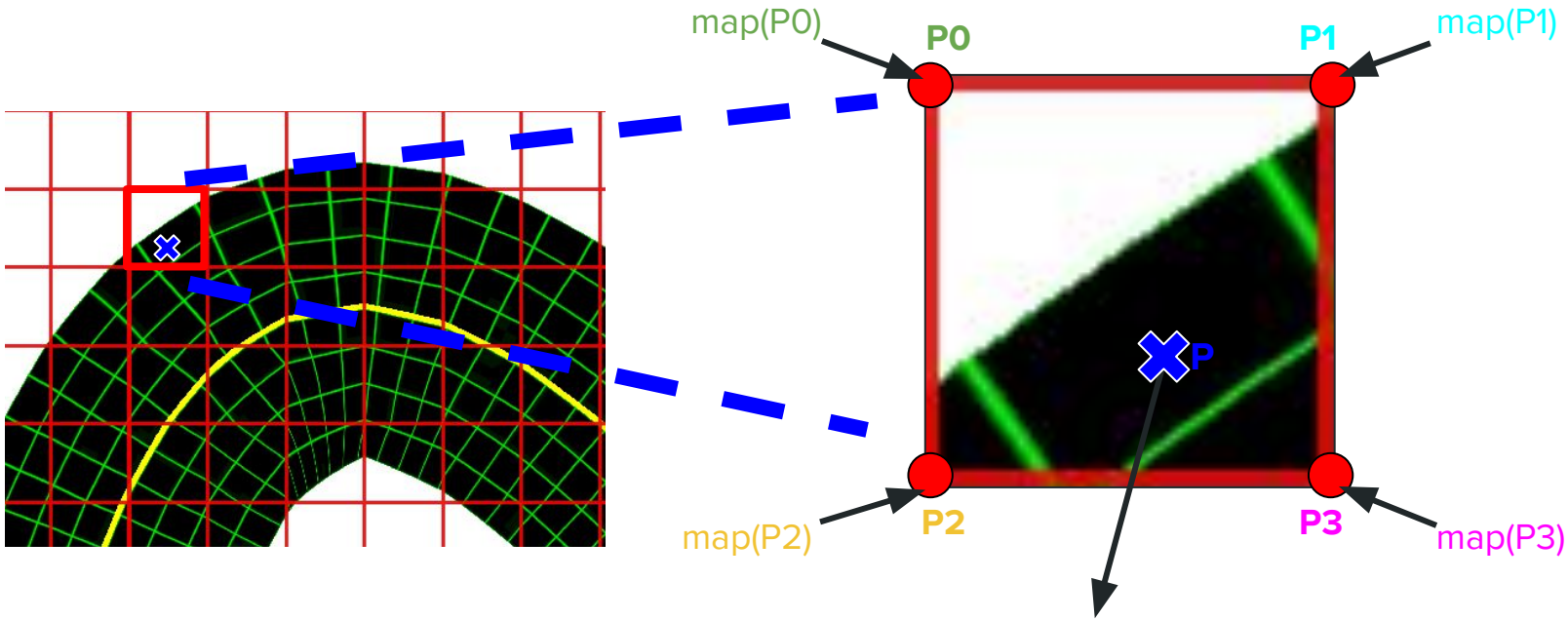
SDF reconstruction:



SDF(**P**) = Lerp (SDF(**P0**), SDF(**P1**), SDF(**P2**), SDF(**P3**), **P**)

3. Base idea: using a 3D grid

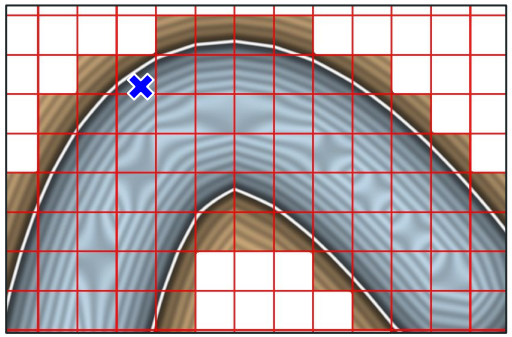
Mapping coordinates reconstruction:

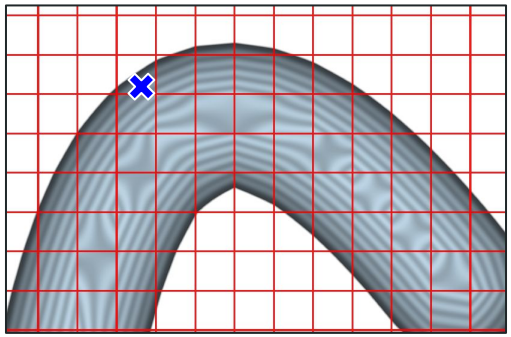


map(**P**) = Lerp (map(**P0**), map(**P1**), map(**P2**), map(**P3**), **P**)

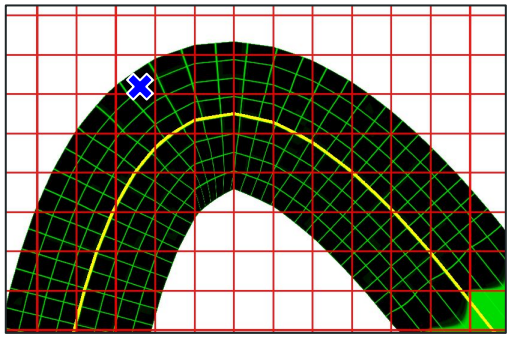
3. Base idea: using a 3D grid

SDF reconstruction: (SDF(**P**))

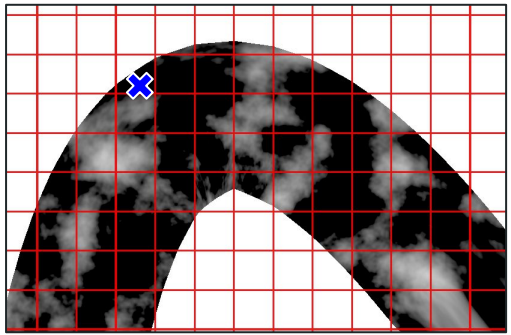


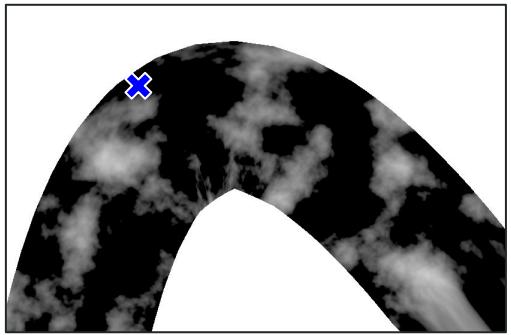


Mapping reconstruction: (map(**P**))



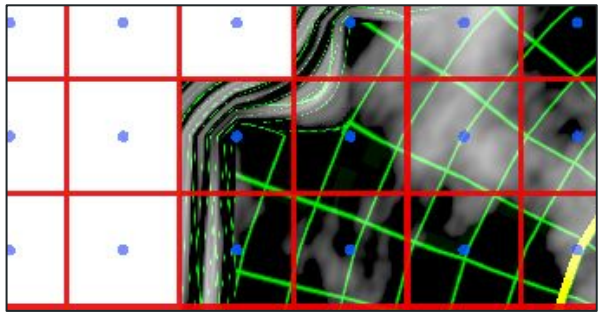
Noise evaluation: (noise(map(**P**))



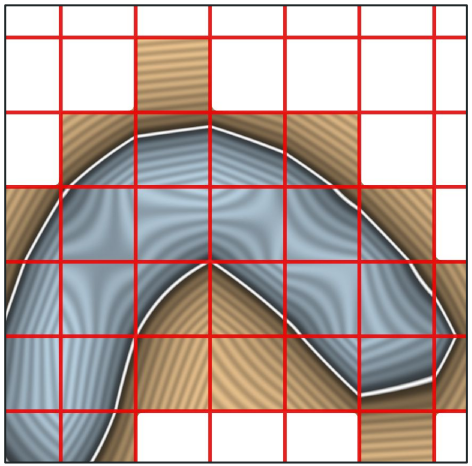


3D grid associated challenges

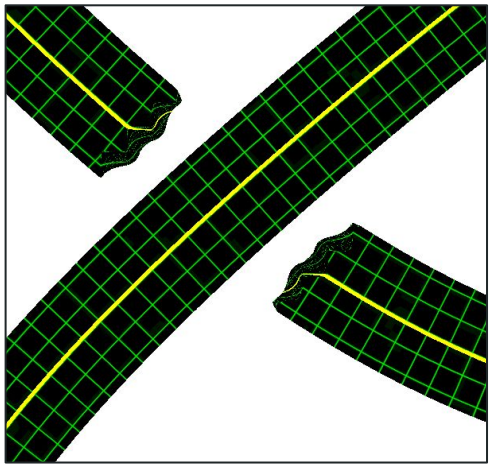
Defining valid cells



Choosing the right resolution and interpolation



Handling superposition of objects



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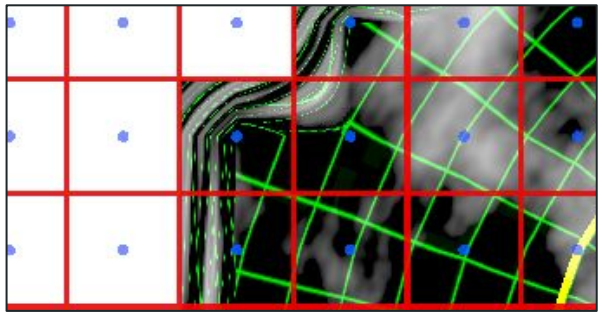

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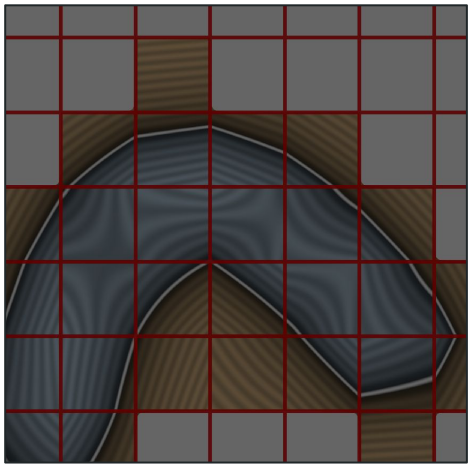

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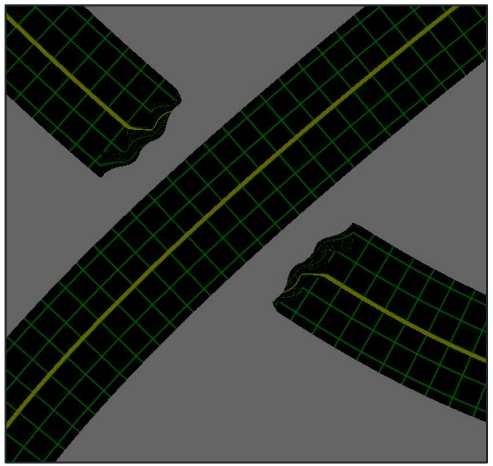
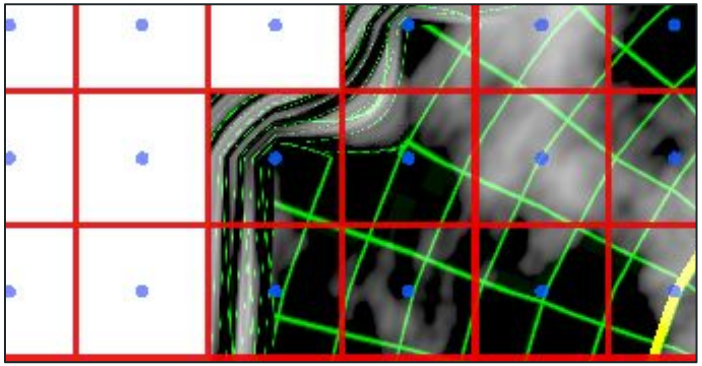
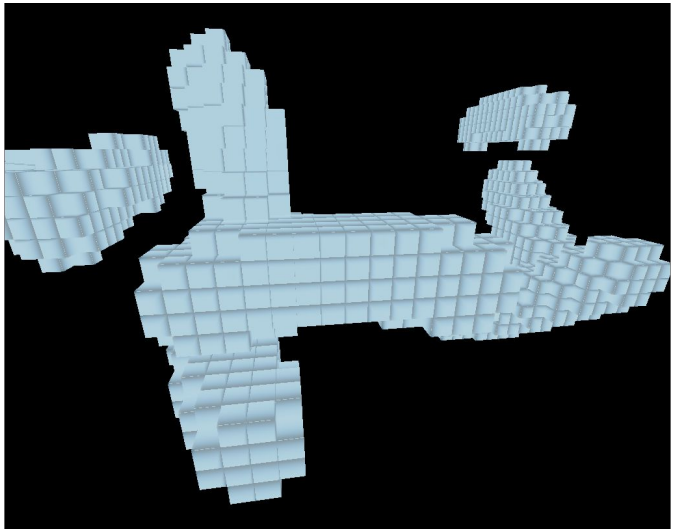


3.1. Defining valid cells

- During pre-computation:
  - **“valid” flag**
- At runtime:
  - if inside empty cell, skip
  - else, interpolation is valid
    - Interpolate SDF and mapping

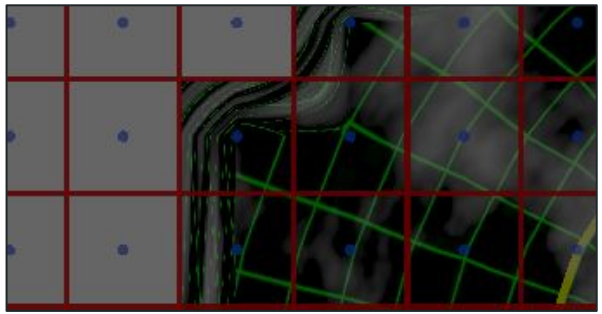
Simple way to **skip empty spaces**



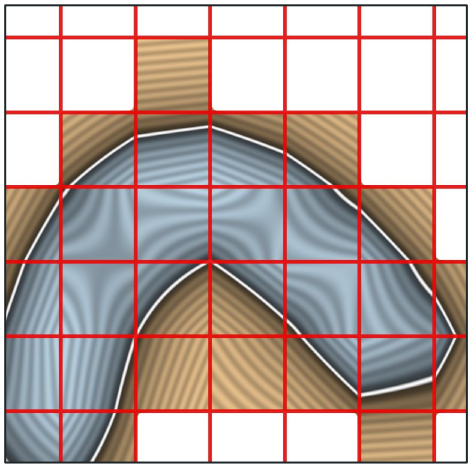


3D grid associated challenges

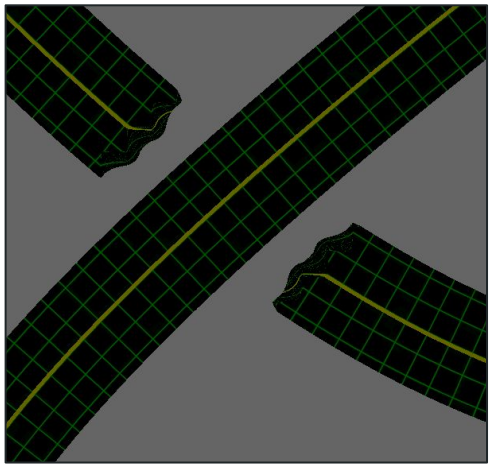
Defining valid cells



Choosing the right resolution and interpolation



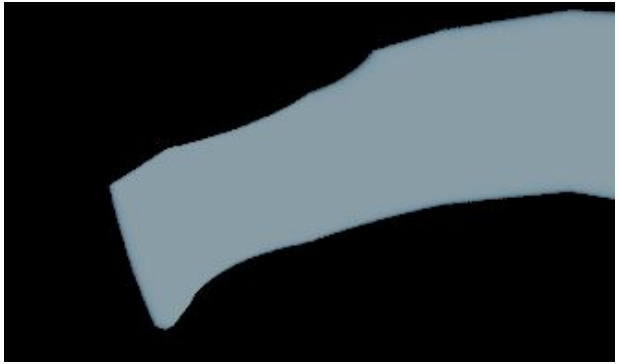
Handling superposition of objects



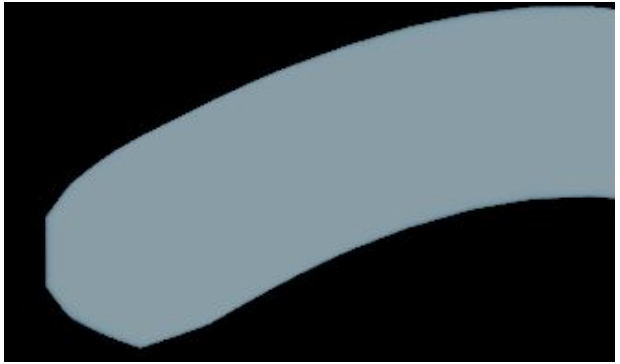
3.2. The optimal resolution: SDF

SDF reconstructions (3D):

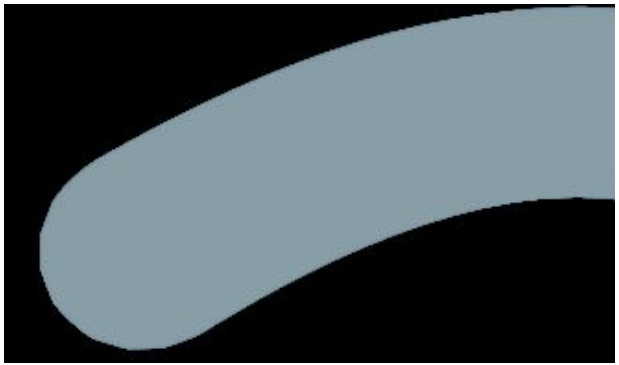
32^3 :



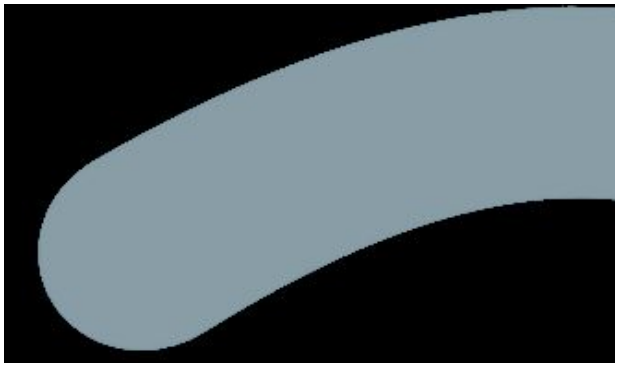
64^3 :



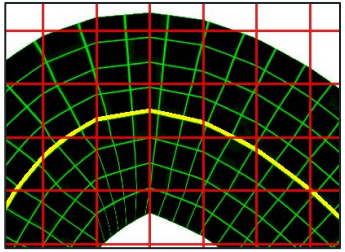
128^3 :



256^3 :

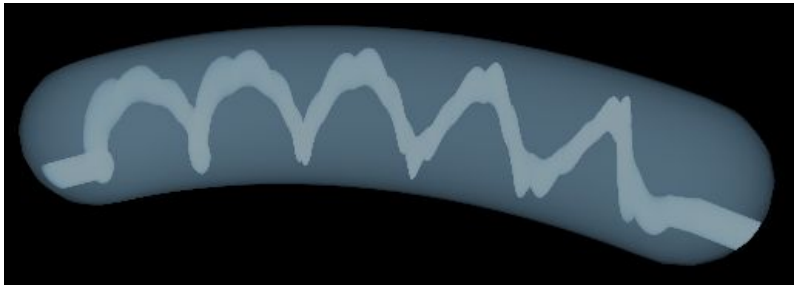


3.2. The optimal resolution: Mapping

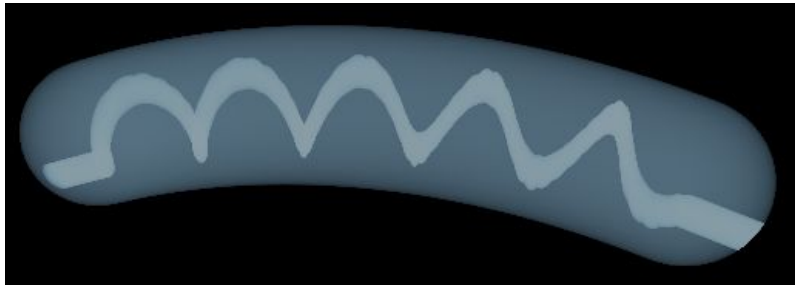


Mapping “torsion” reconstructions (3D):

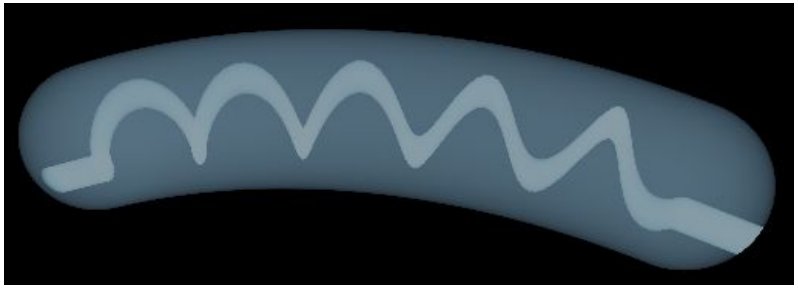
128^3 :



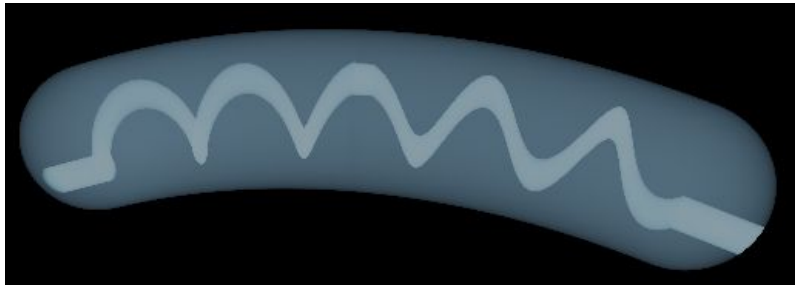
256^3 :



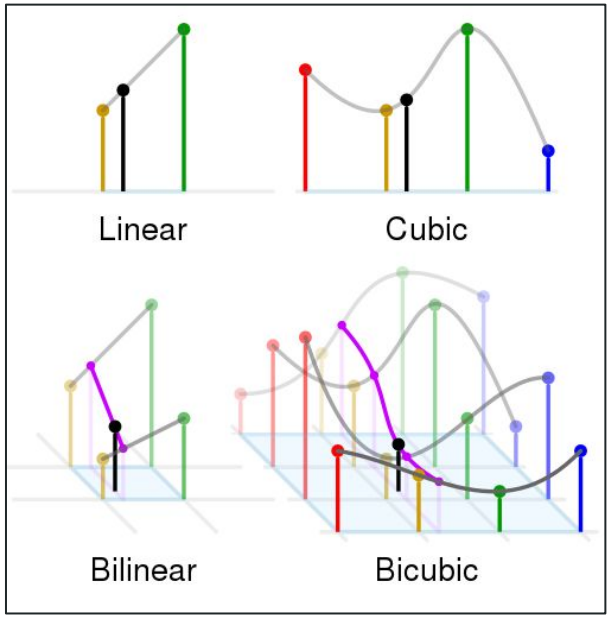
512^3 :



Exact :



3.2. Cubic interpolation



Linear: 2 samples

Bilinear: 2x2 (4) samples

Trilinear: 2x2x2 (8) samples

Cubic: 4 samples

Bicubic: 4x4 (16) samples

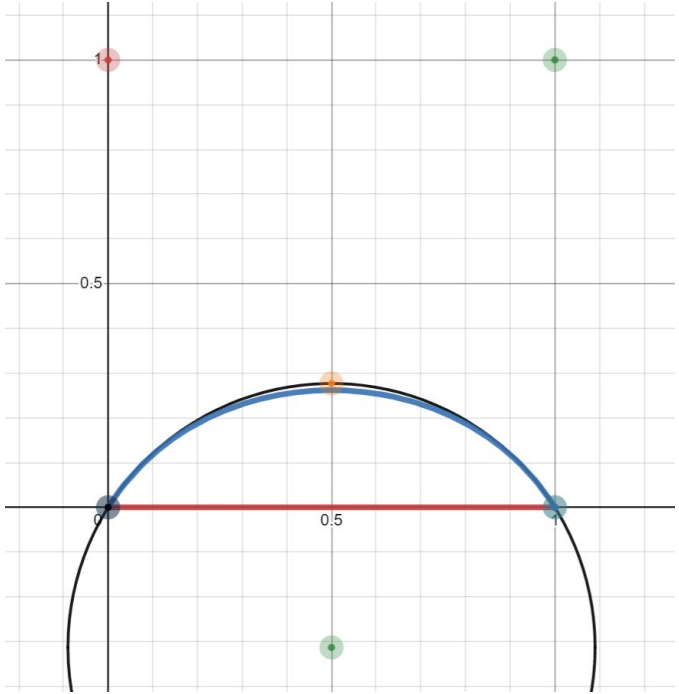
Tricubic: 4x4x4 (64) samples

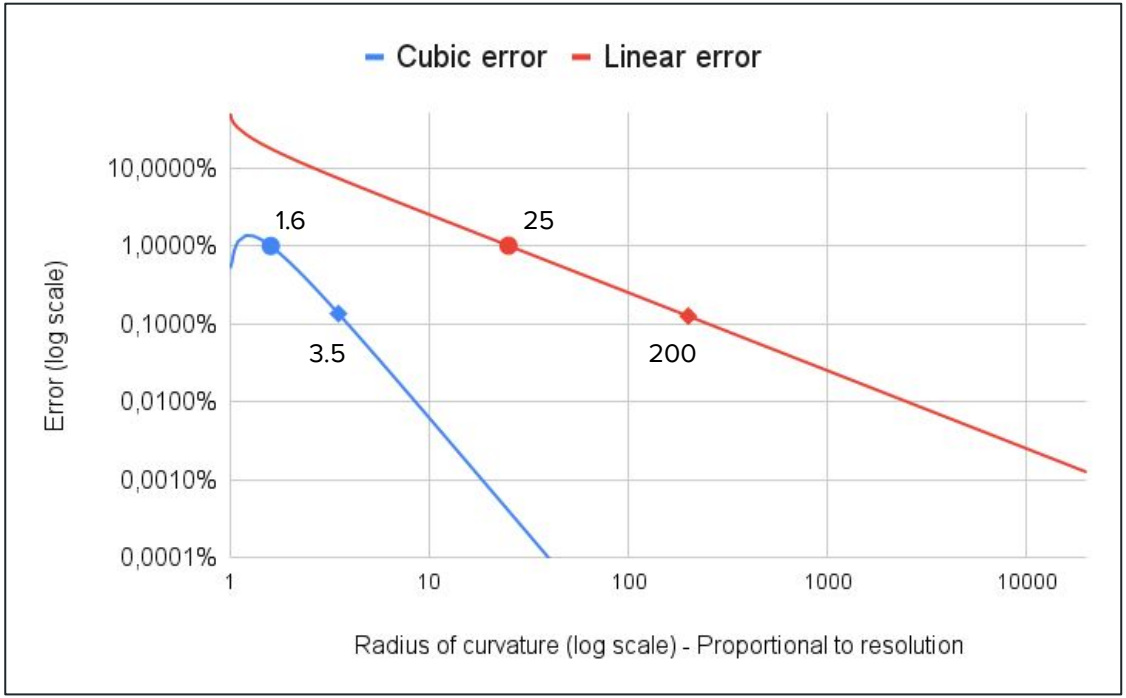
Cubic interpolation:

- is 8 times more expensive
- requires information further away

3.2. Cubic interpolation

Error depending on curvature test :



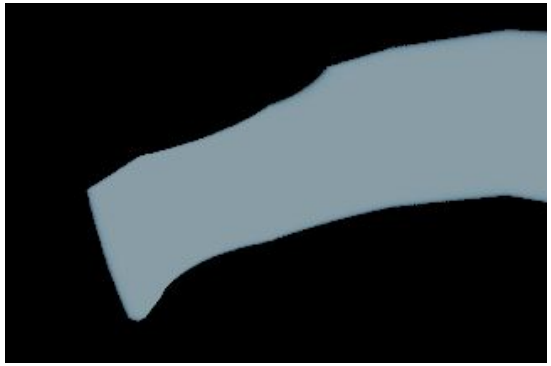


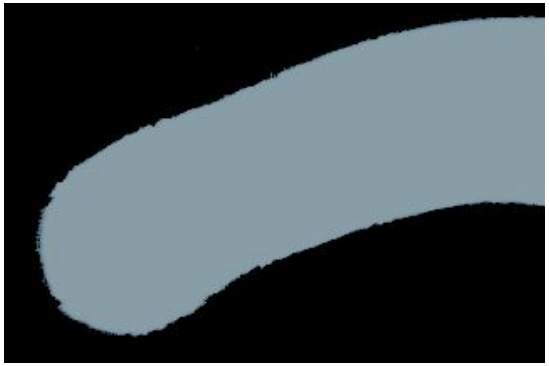
3.2. Cubic interpolation: SDF

Tri-linear :

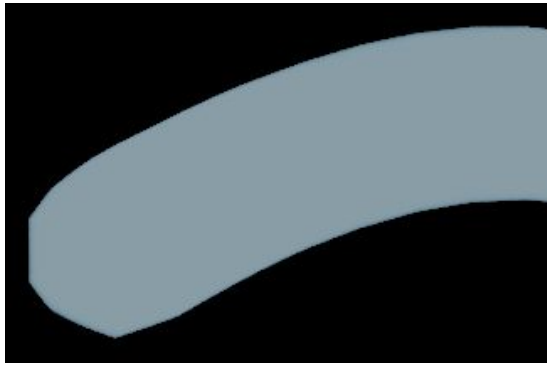
Tri-cubic :

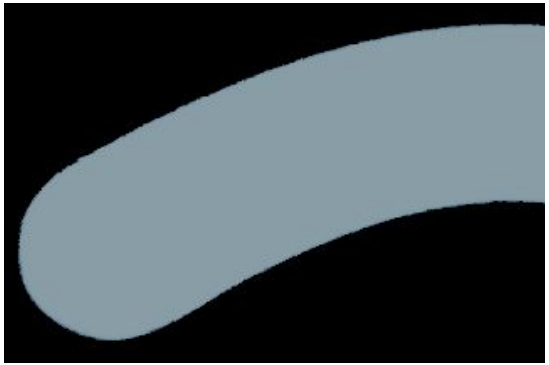
32^3 :



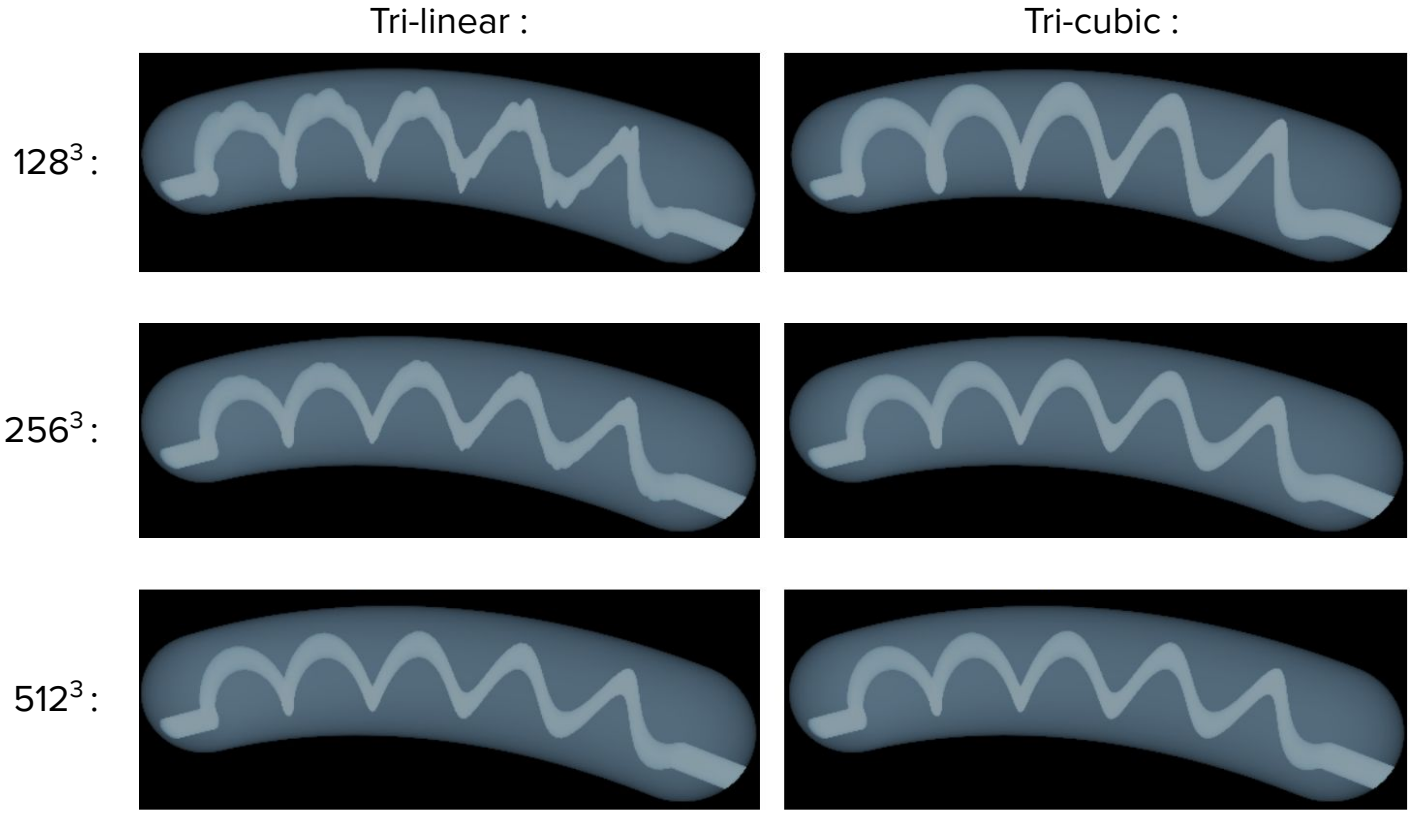


64^3 :



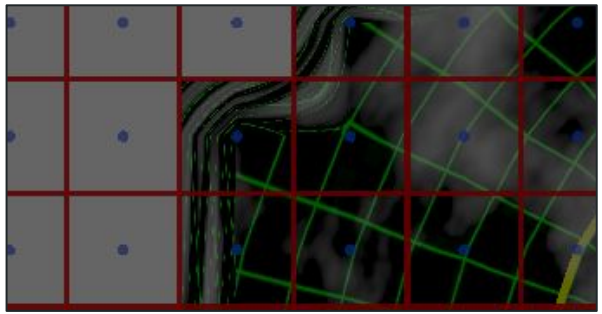


3.2. Cubic interpolation: Mapping

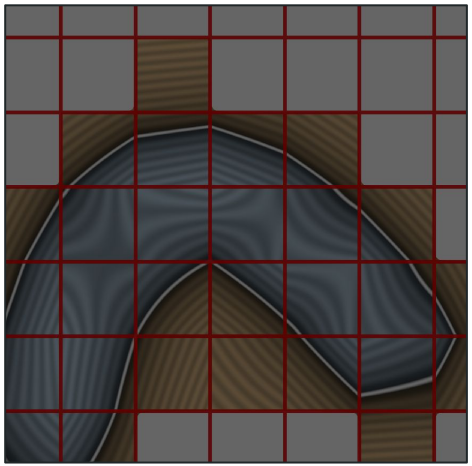


3D grid associated challenges

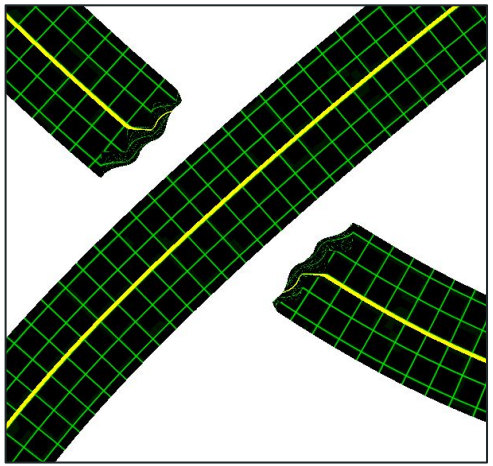
Defining valid cells



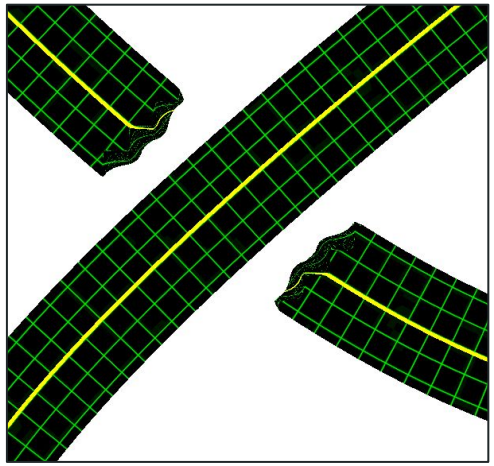
Choosing the right resolution and interpolation

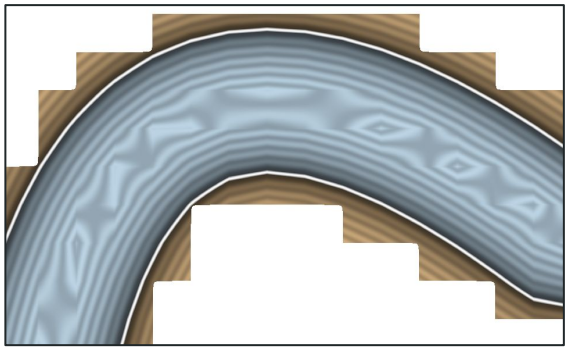


Handling superposition of objects



3.3. Overlapping objects





- Objects **footprint** are **bigger than they appear**
- They can sometime **overlap** (even if not visually)
- Grid nodes cannot store N values for N objects

Naive solution:

- One grid per object

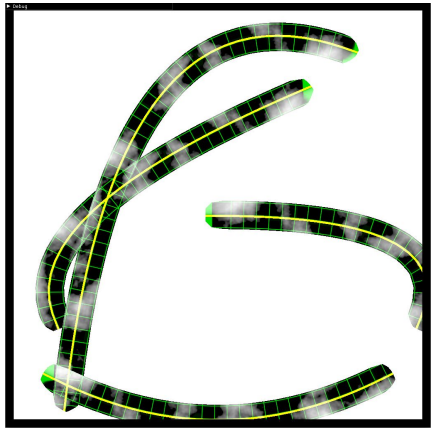
Observation : Overlap at **one place** << total number of overlaps.

Better solution:

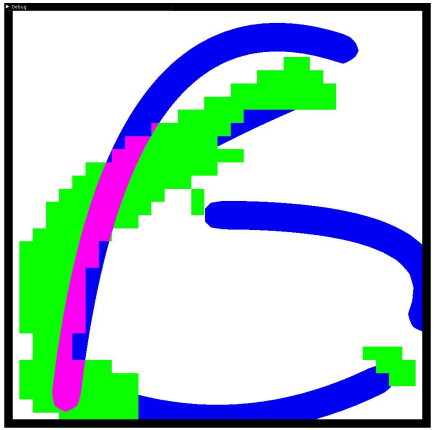
- One grid per allowed overlap at the same place

3.3. Overlapping objects

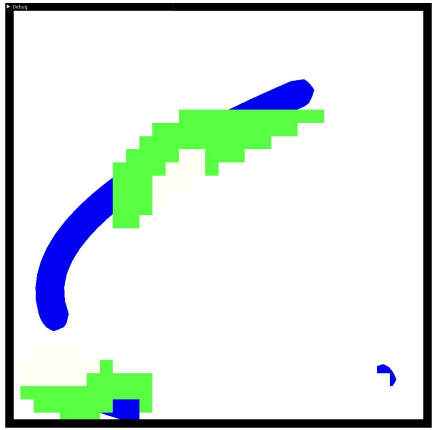
3 objects (2D - 32^3)



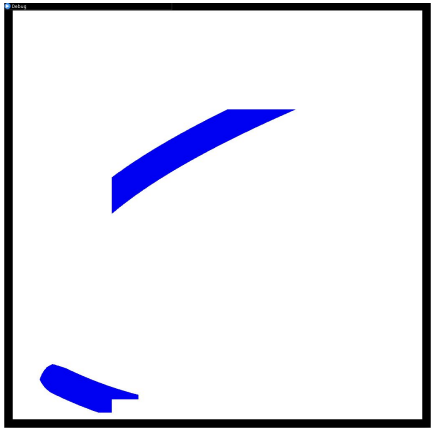
Layer 1 :



Layer 2 :



Layer 3 :



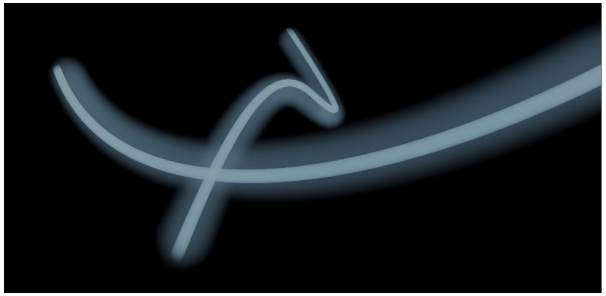
Can store most objects on the **same layer** !

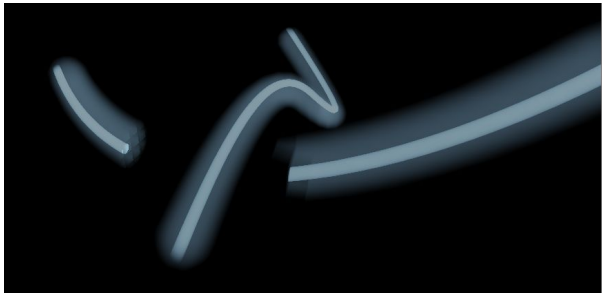
3.3. Overlapping objects

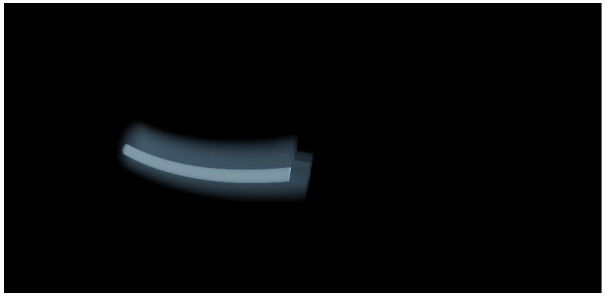
2 objects (3D - 64^3)

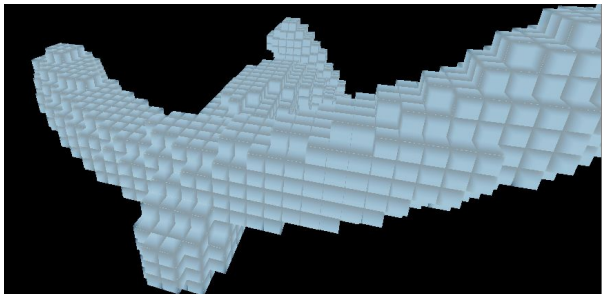
Layer 1 :

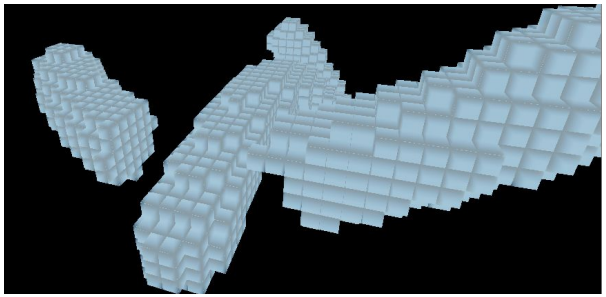
Layer 2 :

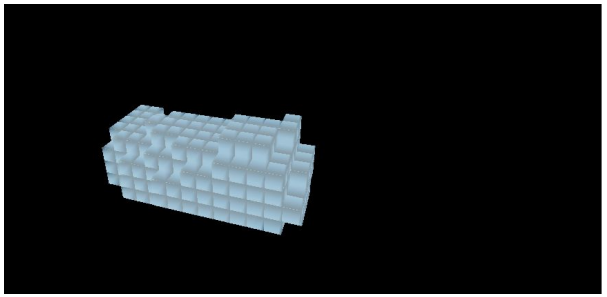








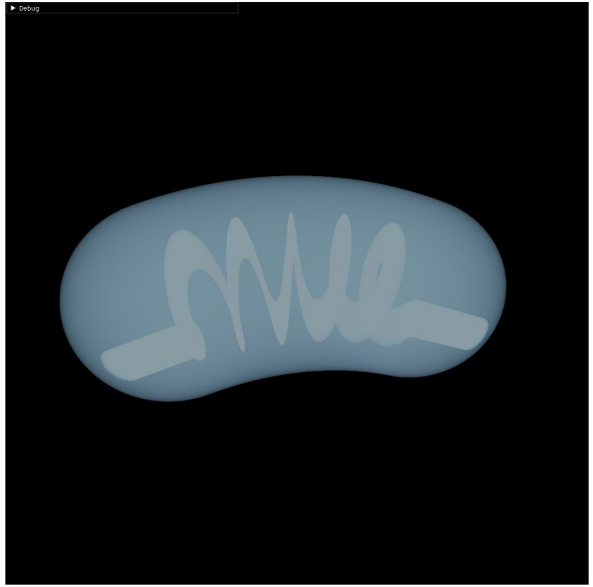




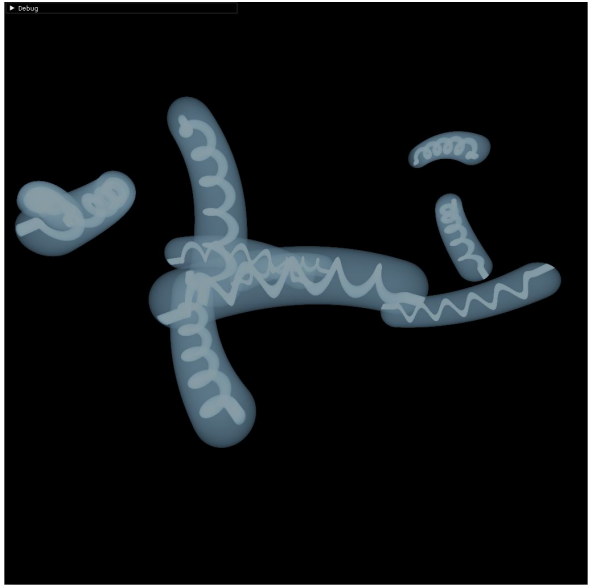
Performances & results

Performances: Test scenes

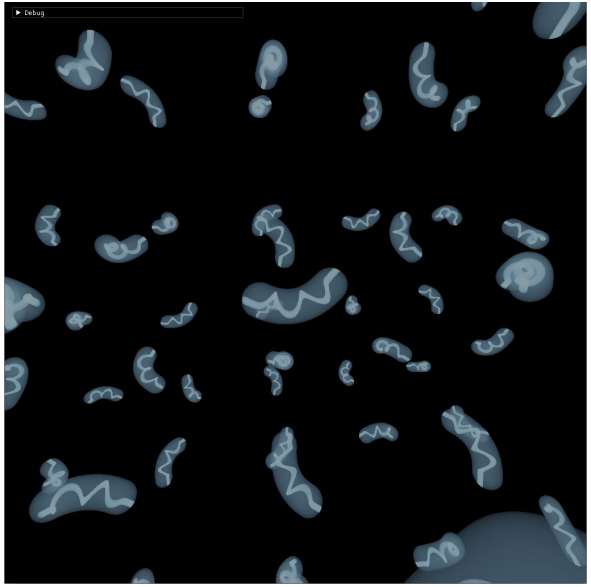
Scene N°1 (1 object) :



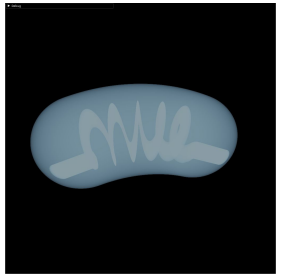
Scene N°2 (10 object) :

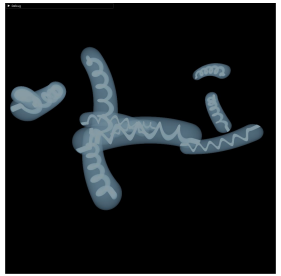


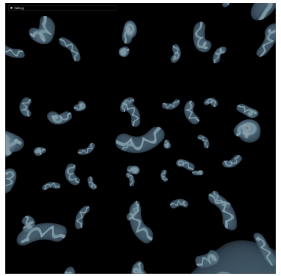
Scene N°3 (125 object) :



Performances







Performance Metrics - GTX 1080Ti (11Go Vram) - 1024x1024				
Scene	Grid resolution	Linear (ms)	Cubic (ms)	[MM22] (ms)
N°1 (1 object)	32	11.5	64.8	17.5
	64	10.4	49.7	
	128	11.4	41	
	256	18	41	
	512	24	46.6	
N°2 (10 objects)	32	9.7	31	105.1
	64	8.6	21.3	
	128	9.3	22.5	
	256	13.6	23	
	512	22	29	
N°3 (125 objects)	32	/	/	805
	64	/	/	
	128	9	20.6	
	256	13.5	21.6	
	512	/	/	

Performances: pre-computation

Scene	Grid resolution	Pre-computation (ms)	[MM22] (ms)
N°1 (1 object)	32	0.2	17.5
	64	0.9	
	128	5.2	
	256	22.2	
	512	731	
N°2 (10 objects)	32	1	105.1
	64	5.6	
	128	42	
	256	326.4	
	512	2678	
N°3 (125 objects)	32	8.3	805
	64	60.3	
	128	501	
	256	3996.5	
	512	/	

We used **implicit volumes** (spline tubes)

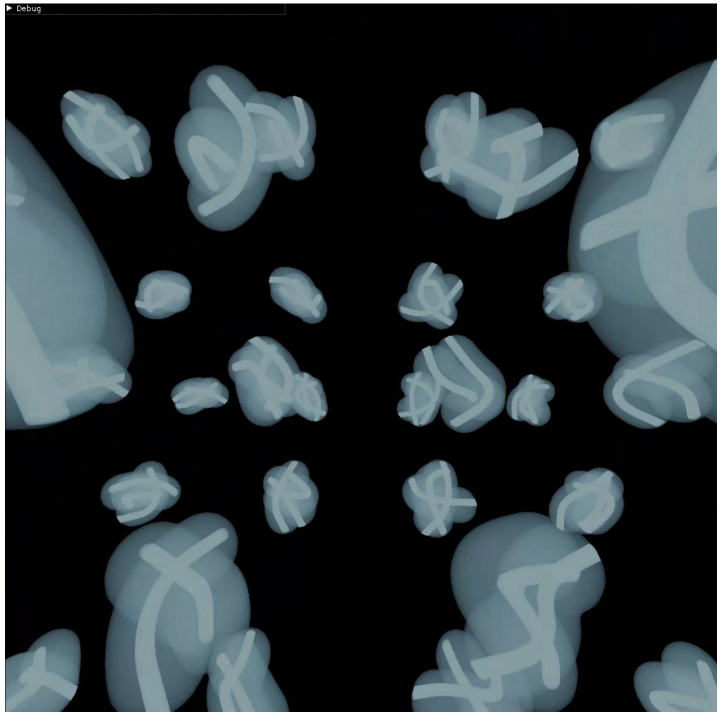
Performances ➜ At reasonable quality, could refresh grid often

Compatible with infinite scene ?

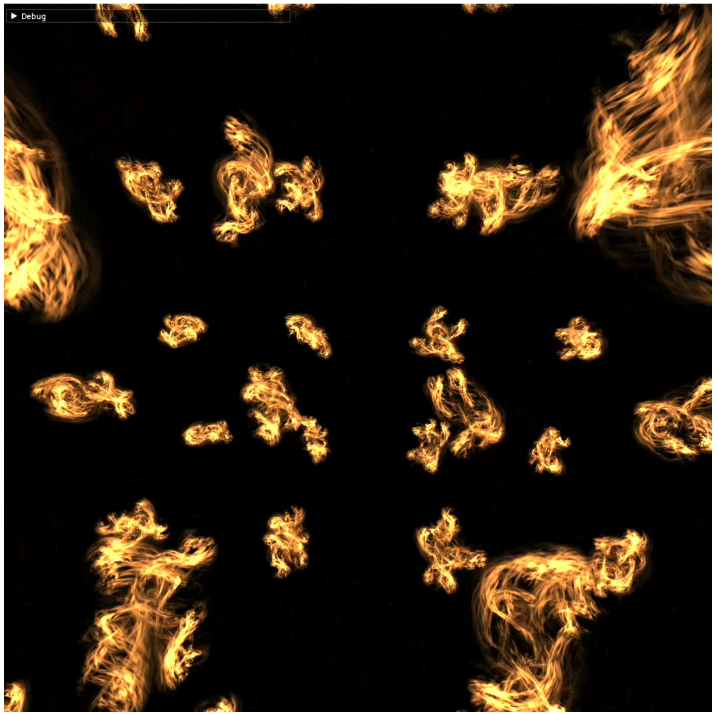
- On the fly generation

Results

150 spline tubes ($128^3 \approx 8$ MB):

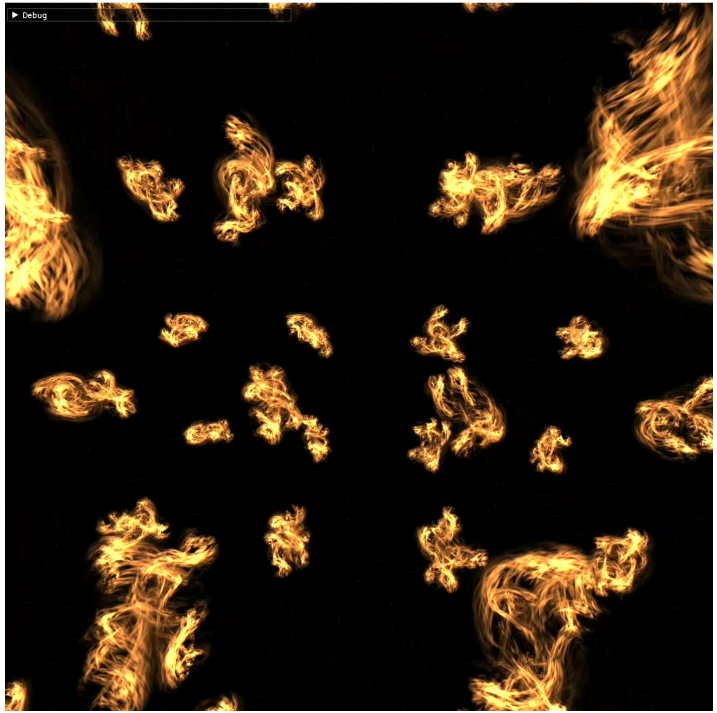


“Solar flare” material applied:

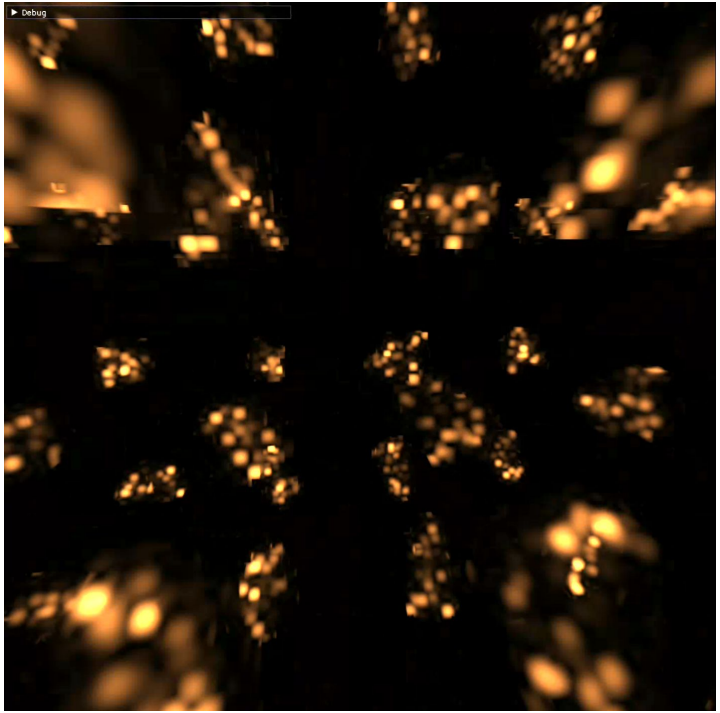


Results

“Solar flare” material: Ours (50 fps)/ [MM22] (1 fps)



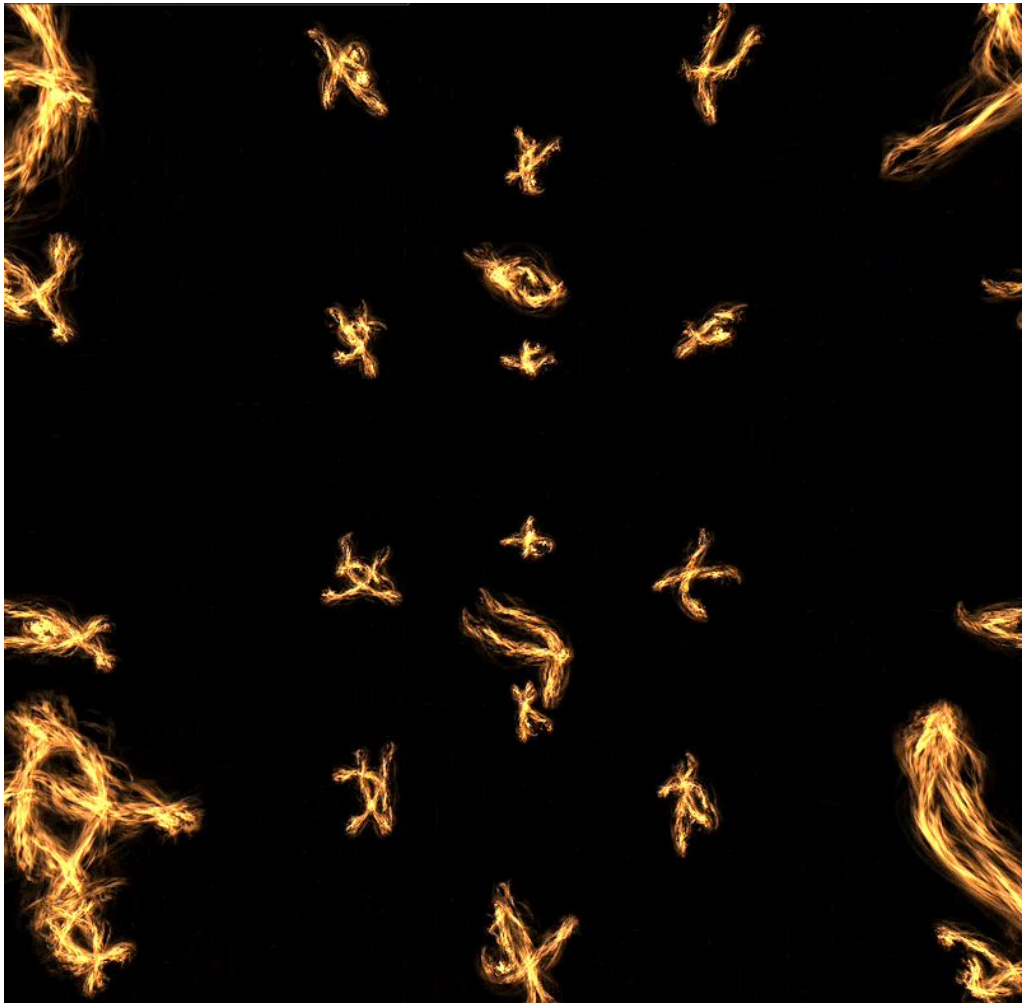
“Solar flare” material: Density directly (15 fps)



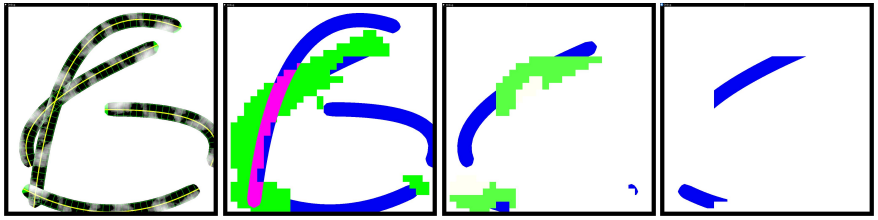
Results

Animated “solar flare” material:

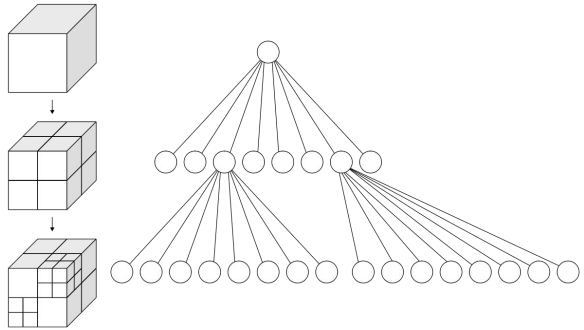
- 150 objects (up to 3 overlaps)
- 128^3 grid (≈ 8 MB)
- Linear interpolation
- 50 fps (1024x1024 image)



Future work



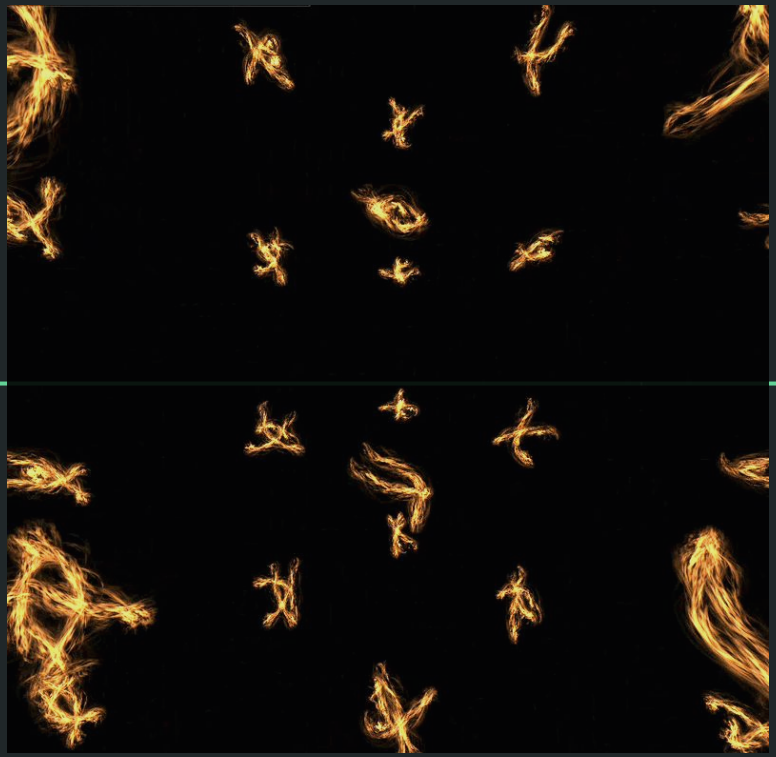
- Memory optimizations
  - sparse texture
  - octree
- Explore other construction methods:
  - “Painting” the grid values
  - Particle system



Thank you for your attention.

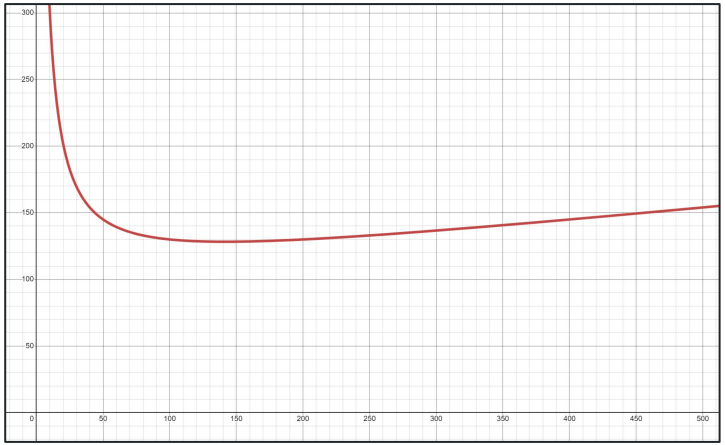
Animated “solar flare” material:

- 150 objects
- 128^3 grid (8 MB)
- 50 fps (1024x1024 image)



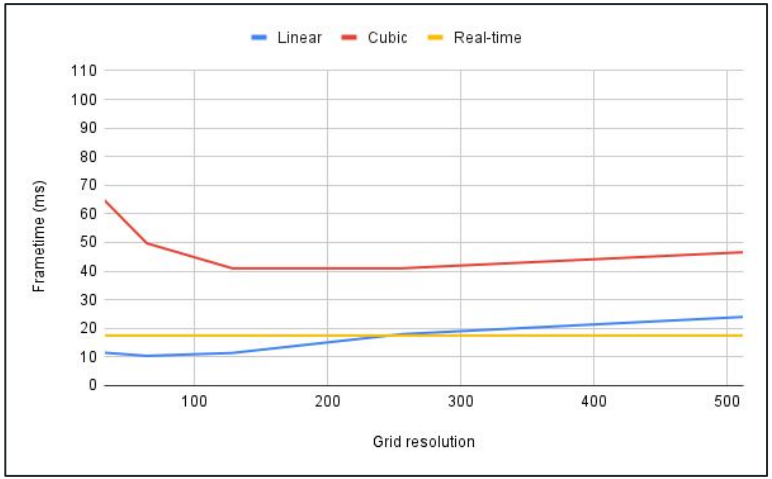
Vol ray casting cost

Theoretical performances :

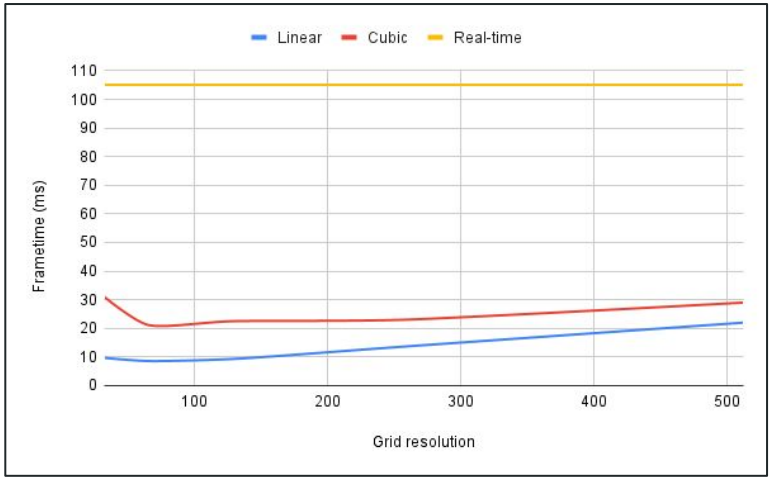


Measured performances :

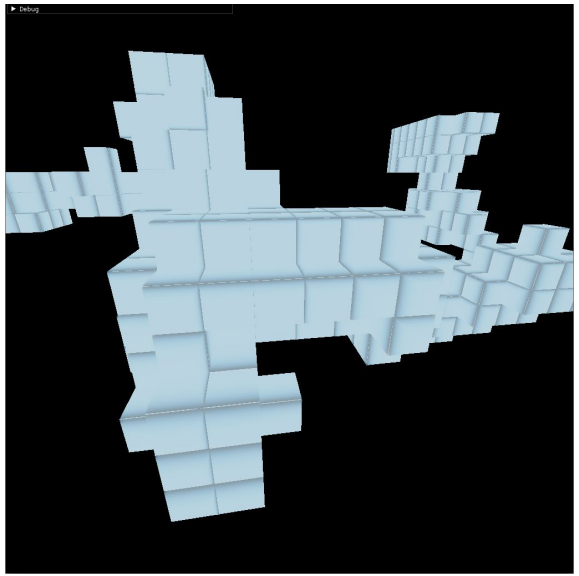
Scene 1 :

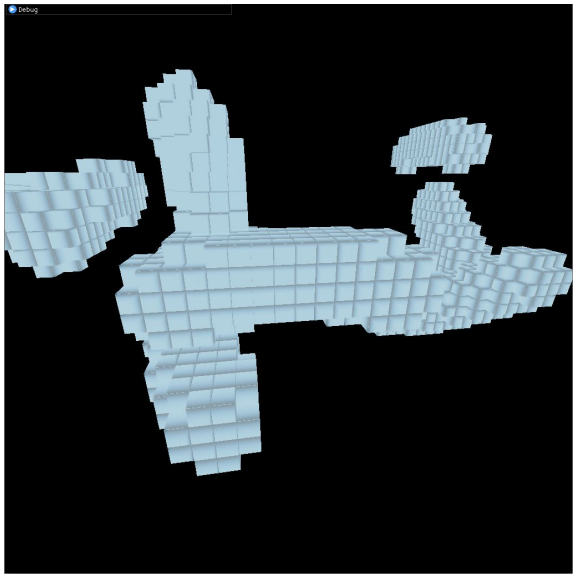


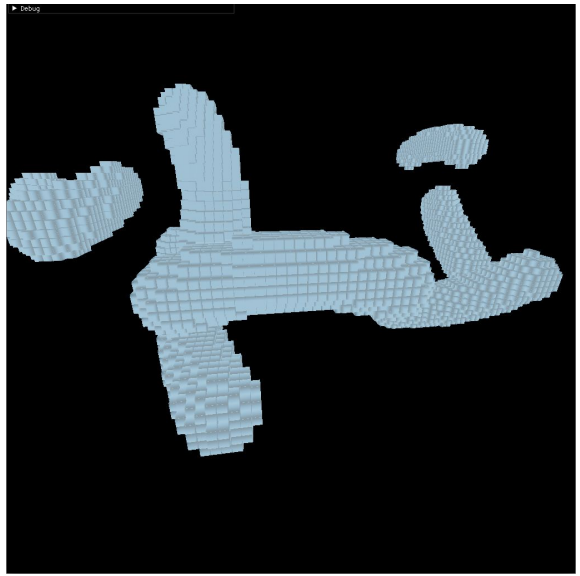
Scene 2 :



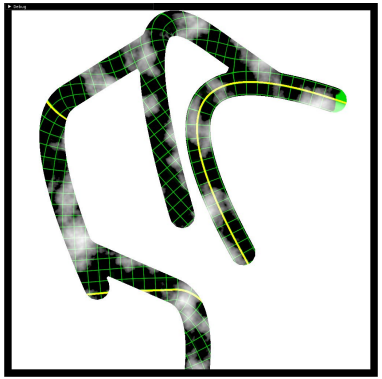
Bounding volume depending on resolution

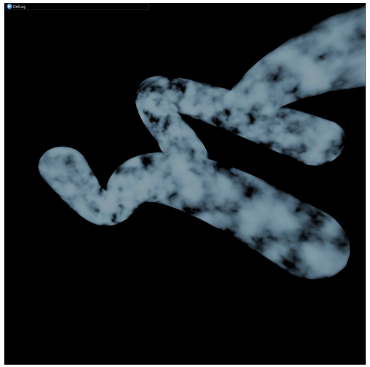


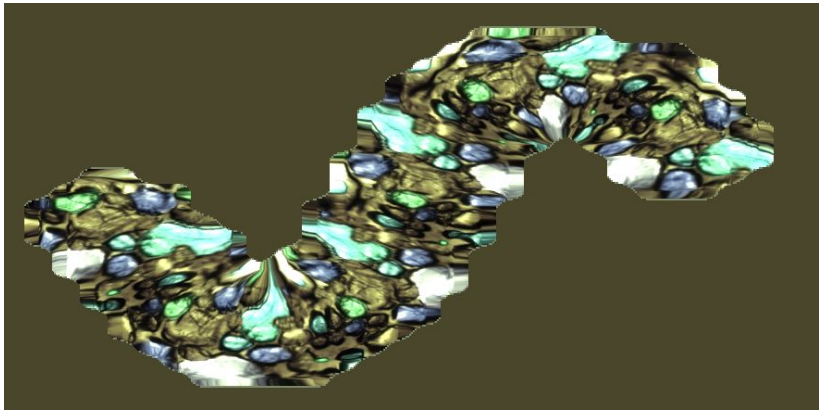




Representable objects







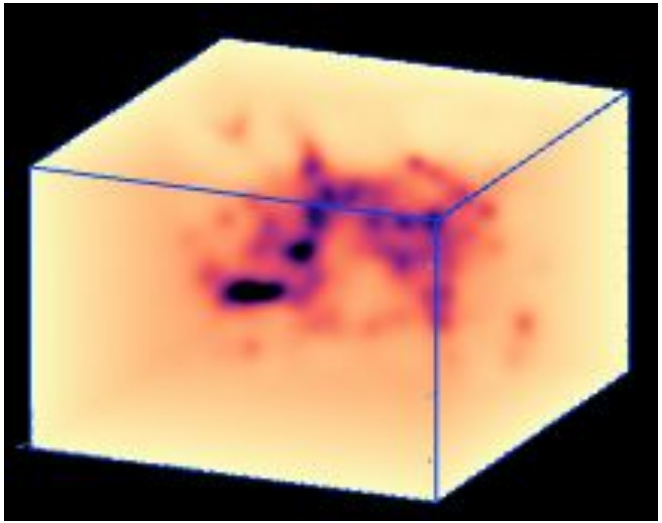
- Implicit volumes
  - spline tubes, spline trees
- “Painting”
- Mesh based
- Physic based simulation

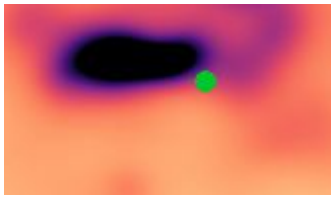
Extreme lack of reference data

Orion nebula (M42) (≂25ly):

Orion Molecular Cloud Complex (≂1000-1500ly):

[Dharmawardena, et al., 2022]





2D splatting