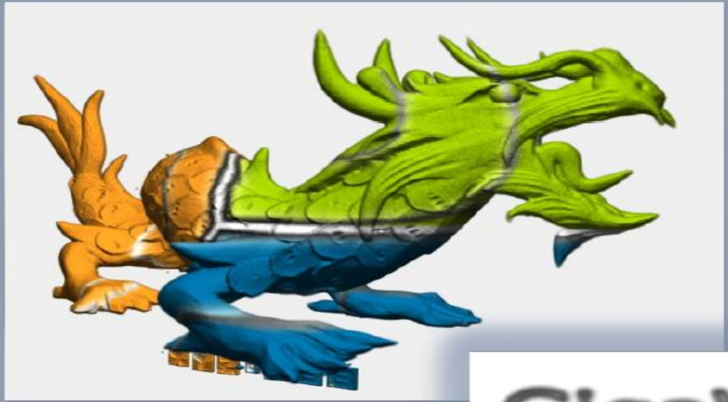
GigaVoxels, Real-time Voxel-based Library to Render Large and Detailed Objects

Pascal Guehl, Fabrice Neyret

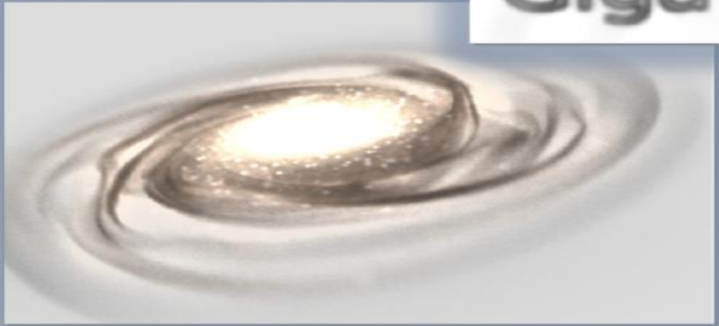
Maverick

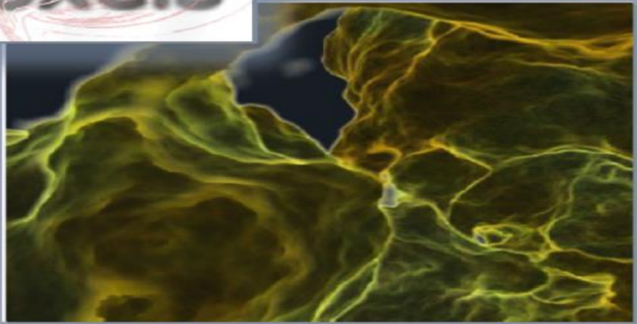
A voxel-based rendering pipeline for efficient exploration of large and detailed scenes

Pascal GUEHL
R&D Engineer



GigaVoxels





Videos Games

Special Effects

Scientific Visualization

Inria
INVENTORS FOR THE DIGITAL WORLD

cnrs
dépasser les frontières

LJK

Between Research & Industry

http://gigavoxels.inrialpes.fr/

GigaVoxels

What is all about ?

R&D project about real-time exploration of

- large and detailed objects/scenes
- eventually generated on the fly
- visually realistic

voxel based medical dataset generated from CT scan (2048x2048x2048, 32GB on disc)

Target audience

- Video games
- Special effects
- Special case : scientific visualization

Goal

Present our implementation of the « GigaVoxels » technology

- [1] - Reminder : what is GigaVoxels ? – Key Concepts / Features
- [2] - Show fonctionnalities through examples of the SDK
- [3] - A survey : explain how to program

PART 1 - GigaVoxels

Exploratory Research phase

- PhD Thesis : « GigaVoxels: A Voxel-Based Rendering Pipeline For Efficient Exploration Of Large And Detailed Scenes »
- Team : INRIA/CNRS/LJK (Cyril Crassin, Fabrice Neyret)
- Based on an OpenGL / GLSL + CUDA prototype

Engineering phase

- Started in 2011 : clean, maintain, add fonctionnalities, …
- SDK (tutorials), doc, tools, …

Partnership

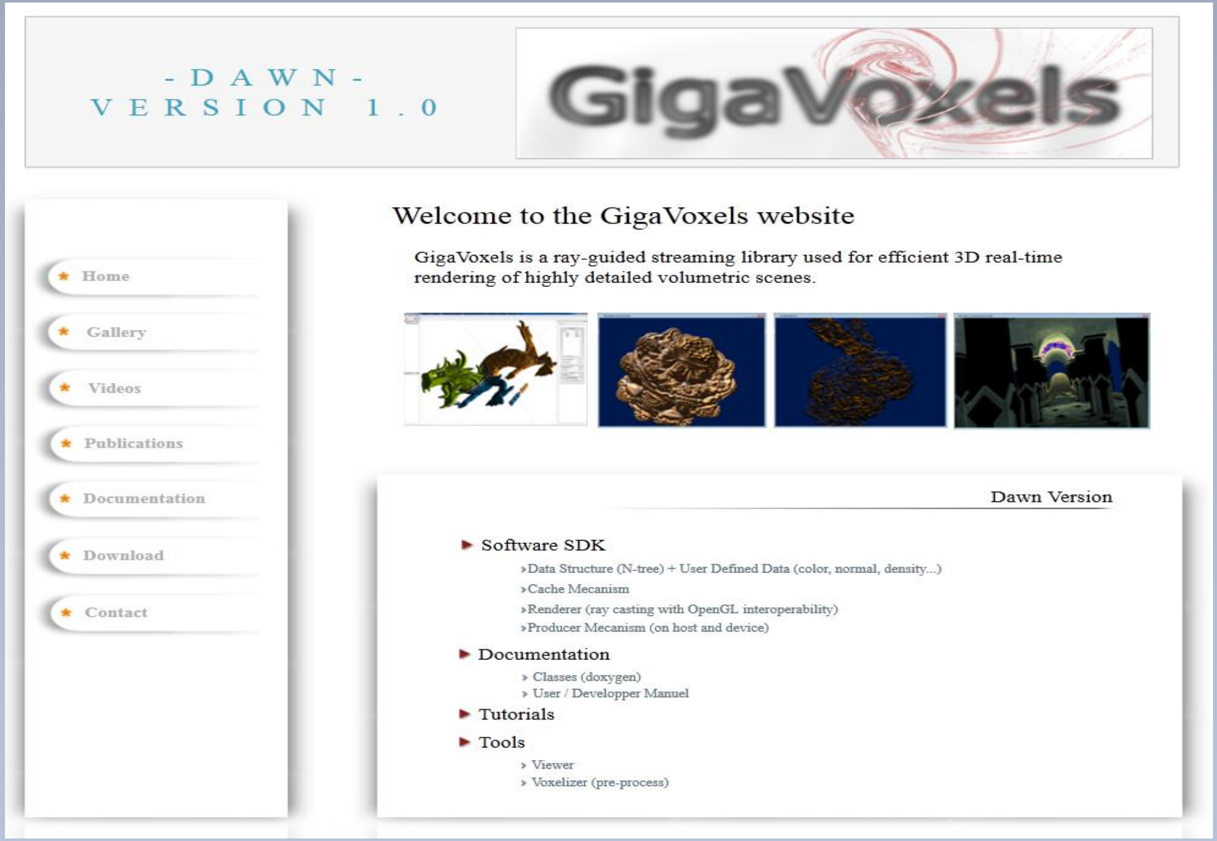
- RSA Cosmos : planetariums [funded by French ANR, 4 years research project]

GigaVoxels

Website

- image gallery
- videos
- publications
- documentation
- source code (not yet)
- contact

http://gigavoxels.inrialpes.fr/



Key Ideas

[x] Rendering only dependent on what is visible

- ray-tracing approach

[x] Load only needed data, at the needed resolution

- occlusion + LOD (level of details)
- ray-guided streaming

[x] Reuse loaded data as much as possible

- cache mechanism on GPU

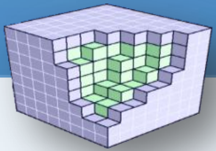
[x] Minimize computation, minimize memory transfers

Key Features

- **Tree Data Management** (space partitioning) to store and organize data (octree or generalized N3-tree, + SDK example kd-tree)
- **Cache System on GPU** : LRU mechanismn (least recently used) (to get temporal coherency)
- **Data Production Management** : on host, GPU, or hybrid mode
  Goal : produced data are kept in cache on GPU
- **Visit algorithm** : traverse your data (loaded in cache) as could be done for rendering
- **Renderer** (hierarchical volume ray-casting, cone tracing, emission of requests, brick marching)

Data Structure

Spare Voxel Mipmap Pyramid



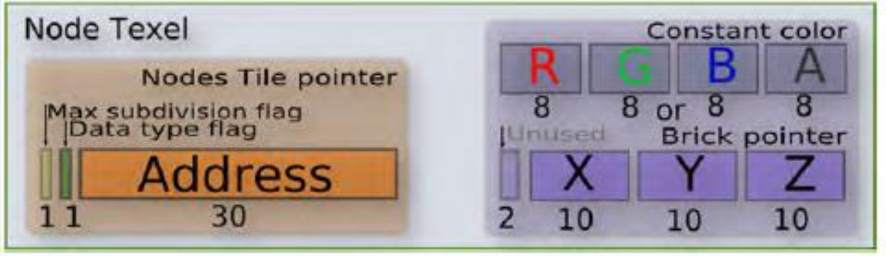
Generalized N3-tree (octree)

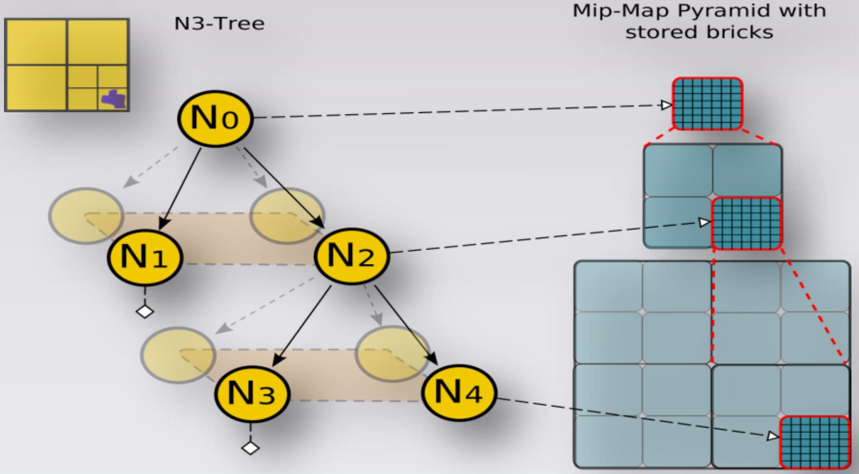
- Space partitioning
- Empty space compaction

Bricks of voxels

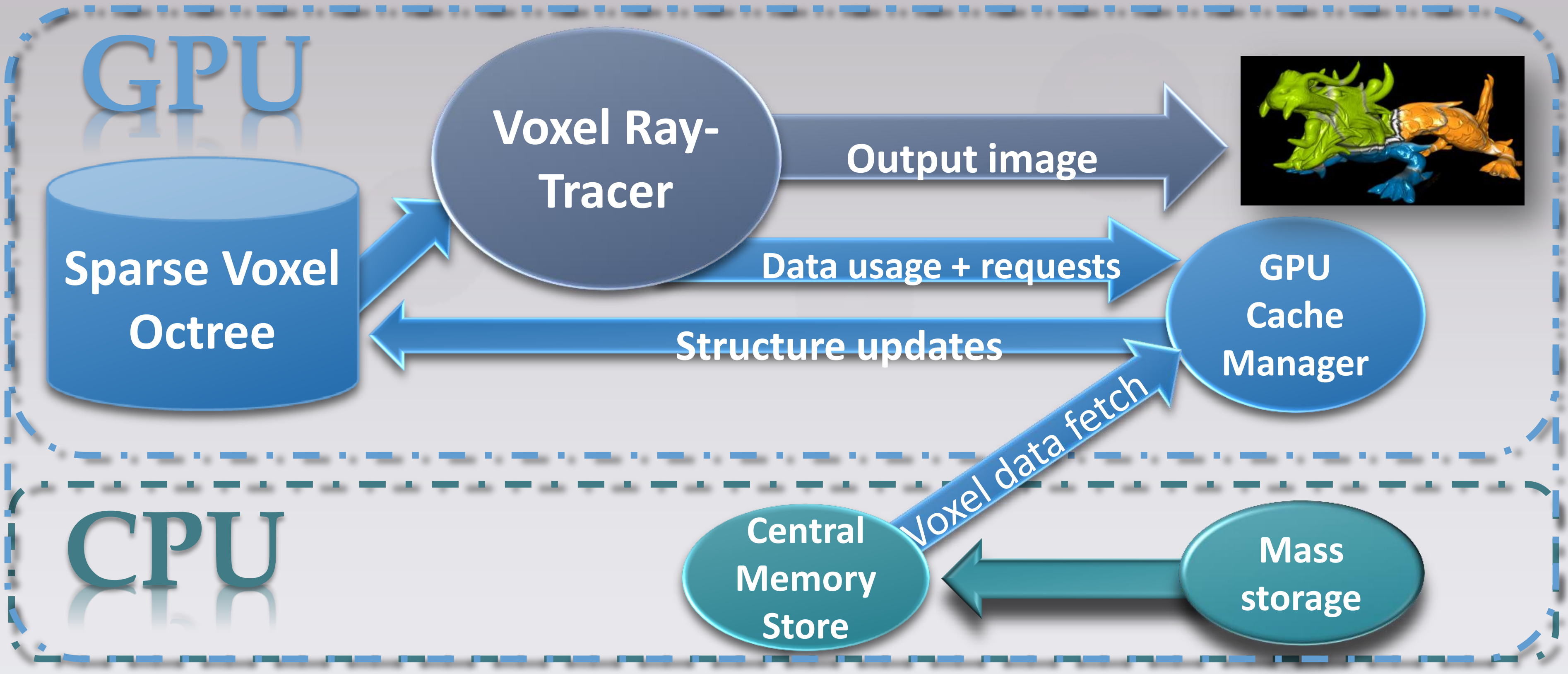
- Linked by octree nodes
- Store opacity, color, normal,…

"Node pointer based" data structure



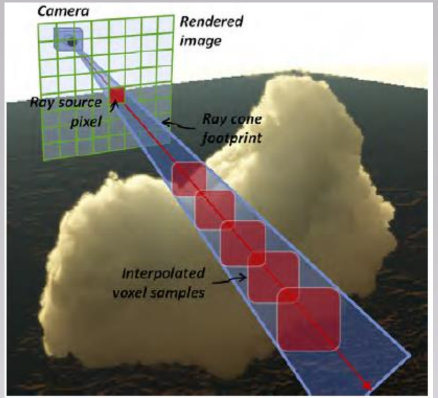


GigaVoxels Pipeline

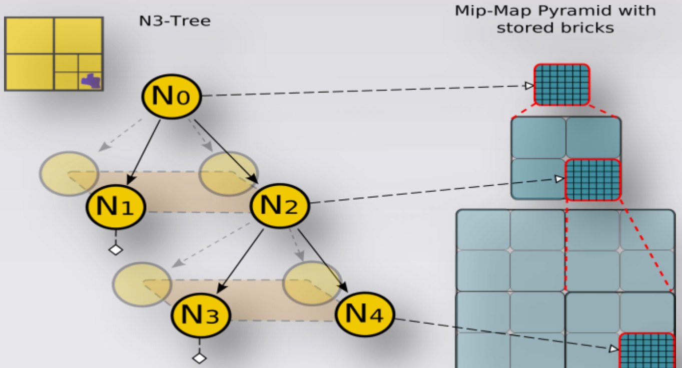


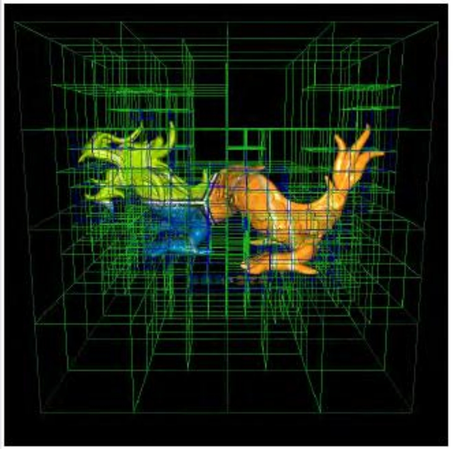
GigaVoxels Pipeline + data structure

- unified data structure (geometry + texture)
- load only needed data at needed resolution
- smooth transitions and continuously reveals details
- Handle semi-transparent objects
- Alias free filtered images (cone tracing)

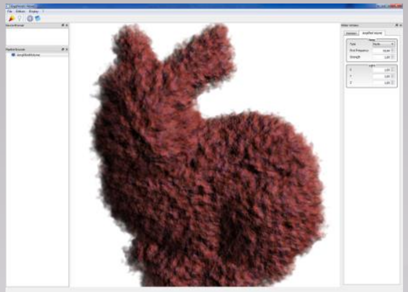


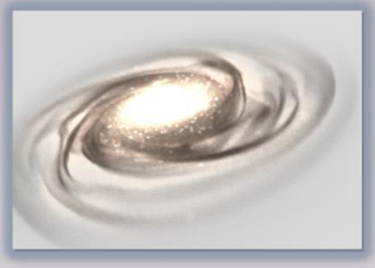
Cone tracing

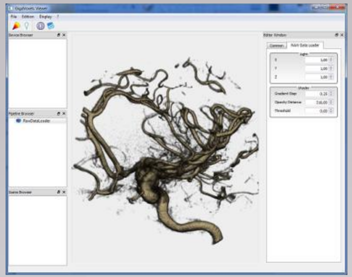


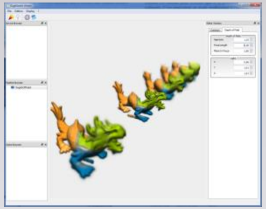


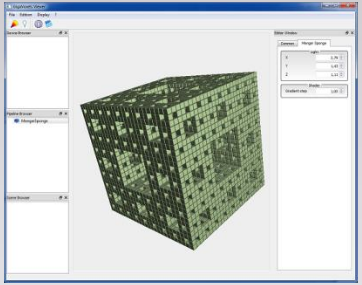
PART 2 - Fonctionnalities through SDK examples

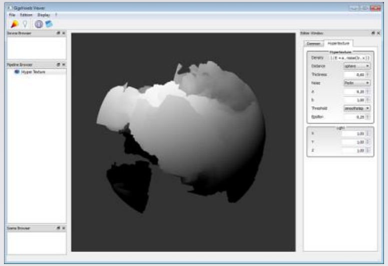


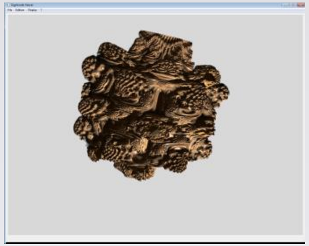












Data loading

Data streaming

Load data « on demand ». Two modes :

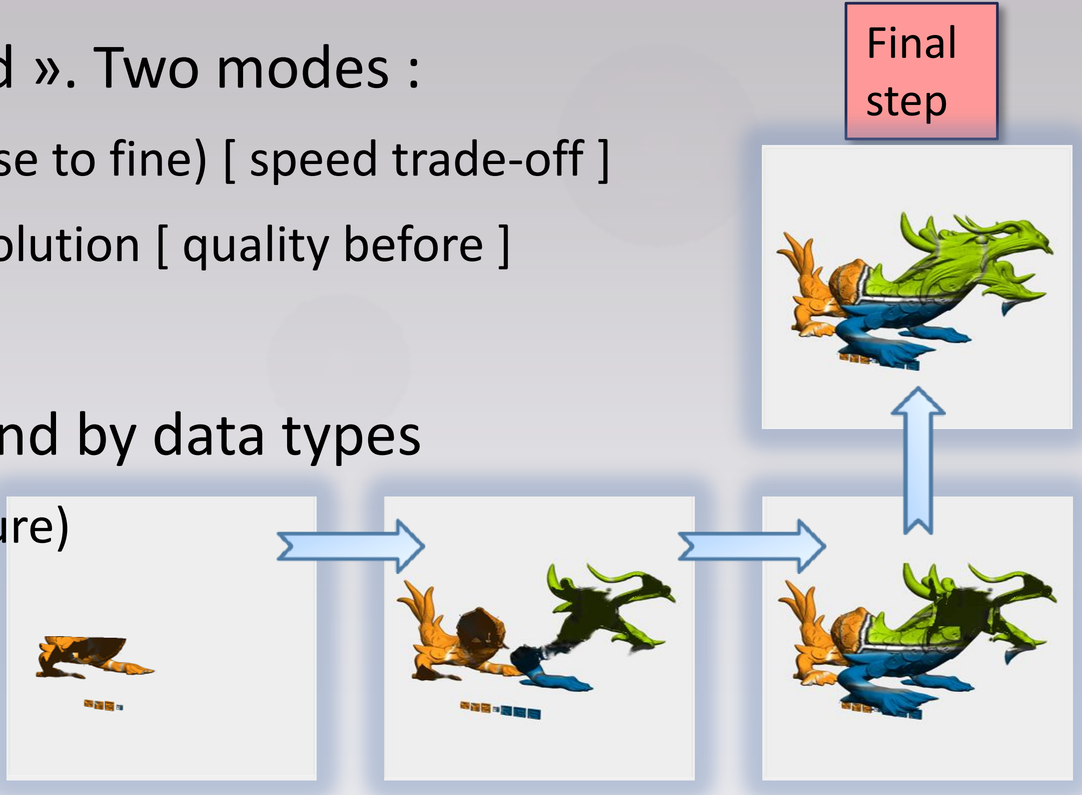
- level by level (from coarse to fine) [speed trade-off]
- directly max level of resolution [quality before]

File format

By level of resolution and by data types

- 1 - nodes (spatial structure)
- 2 - bricks of voxels

no header, no meta-file…

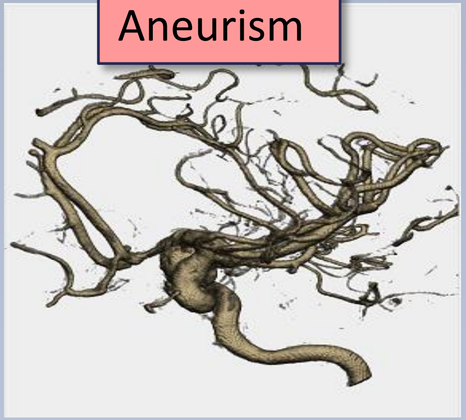


Import your own data

Custom file importer

RAW data [scientific visualization]

- apply transfer function
- threshold data
- clipping plane [region of interest]



Aneurism

Skull

Foot
+ threshold

Procedural data generation

Mandelbulb

Goal : generate environments

Fractal object : 3D extension of Mandelbrot set

$$\langle x,y,z\rangle^n = r^n \langle \cos(n\theta)\cos(n\phi), \sin(n\theta)\cos(n\phi), \sin(n\phi)\rangle$$

$$\text{où} \left\{ \begin{array}{lcl} r & = & \sqrt{x^2+y^2+z^2} \\ \theta & = & \arctan(y/x) \\ \phi & = & \arctan(z/\sqrt{x^2+y^2}) = \arcsin(z/r) \end{array} \right\}$$

pour la nième puissance du nombre hypercomplexe 3D. Les points sont calculés par itération de $z \mapsto z^n + c$ où z et c sont des nombres hypercomplexes dans un espace de dimension 3 et $z \mapsto z^n$ l'application définie ci-dessus. Ici $n = 8$.

Mandelbulb

Procedural data generation

Mandelbulb

Noise - Hypertextures

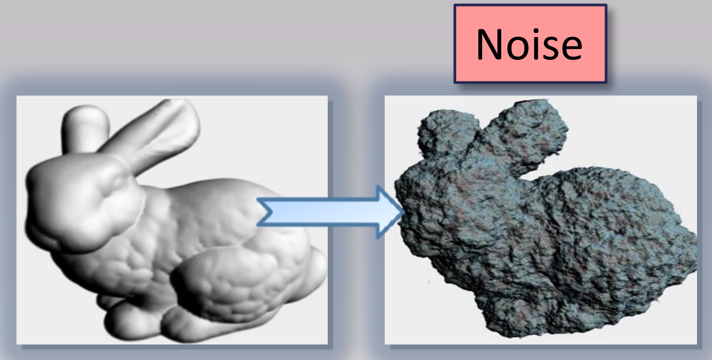
Goals

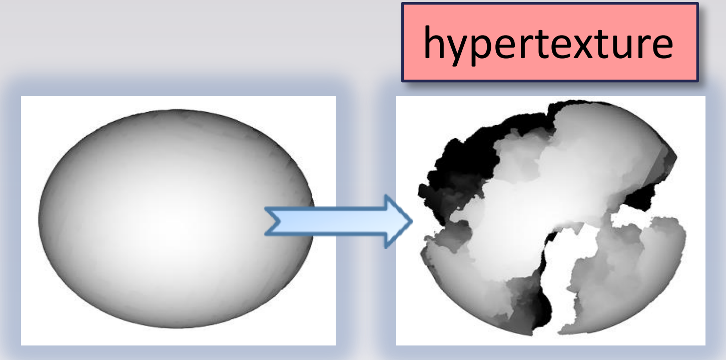
Add details on 3D models

- smooth transitions and continuously reveals details
- alias free filtered images
- handle parallax effect

Theory

- Ken Perlin
- book : « Texturing and Modeling, a procedural approach », chapter 12



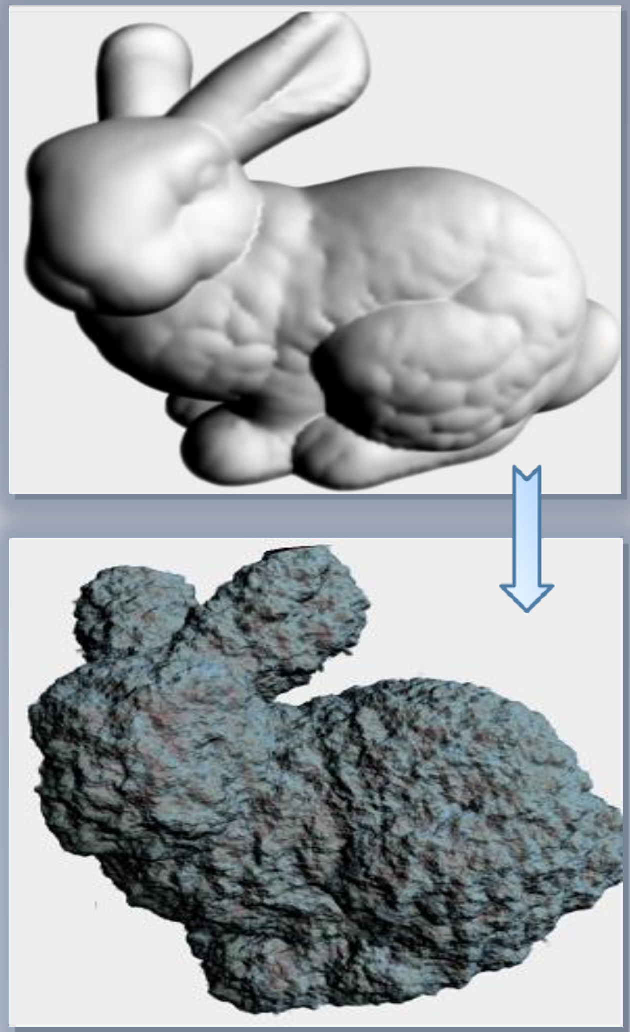


Noise

Input

3D model : Signed Distance Field

- Noise : applied on distance and normal
- Transfer Function : convert distance to RGBA color



Noise : optimisation(s)

Idea : (use cache)

Mimic the LOD mechanism that continuously add details :

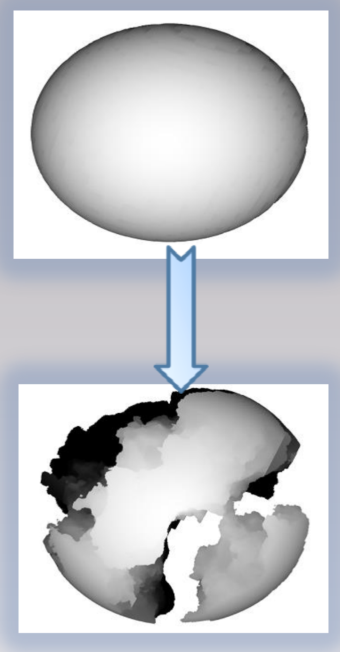
➔ Re-use noise computation at previous resolution level

- noise : sum of octaves (frequencies)
- compute only one octave by level of resolution
- store them in GPU cache
- reproduce the sum :
- F(level N) = currentNoise(level N) + previousNoise(level N-1)
- Finally : replace “noise computation” by “data fetch in cache”

Hypertextures

Hypertexture (shape + solid texturing)

- F(x)==0 : outside the object
- F(x)==1 : strictly inside the object
- 0<F(x)<1 : inside a fuzzy region

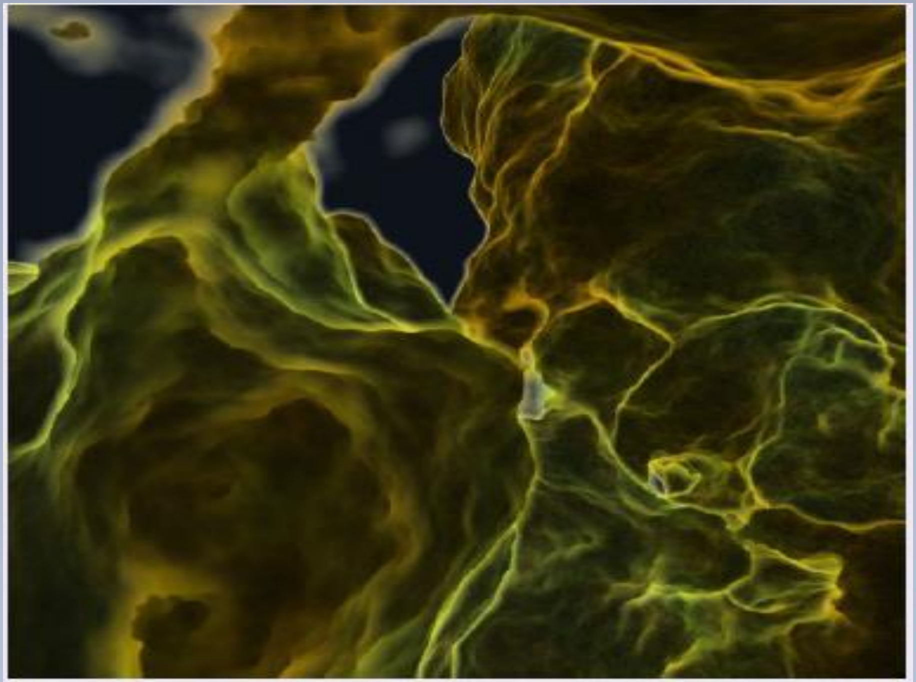


hypertexture

Idea : add details on armor soldier

- Distance function : sphere
- Thickness : fuzzy region (Perlin noise)
- Current work : optimizations
  - Stop adding noise components if density is outside

Hypertextures



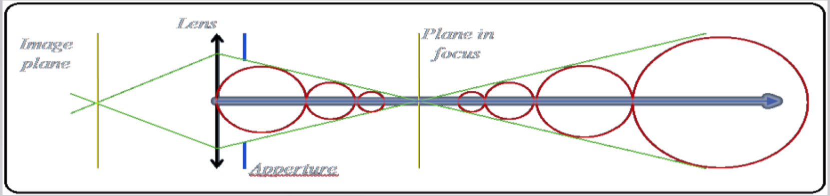
Depth of Field

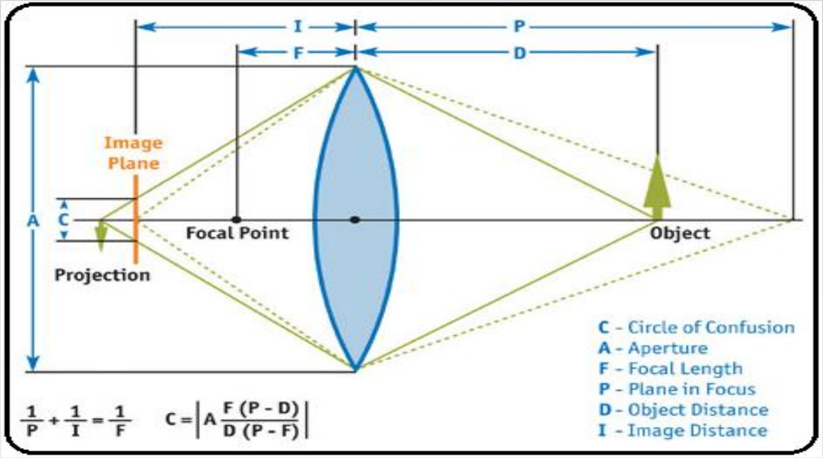
Goal

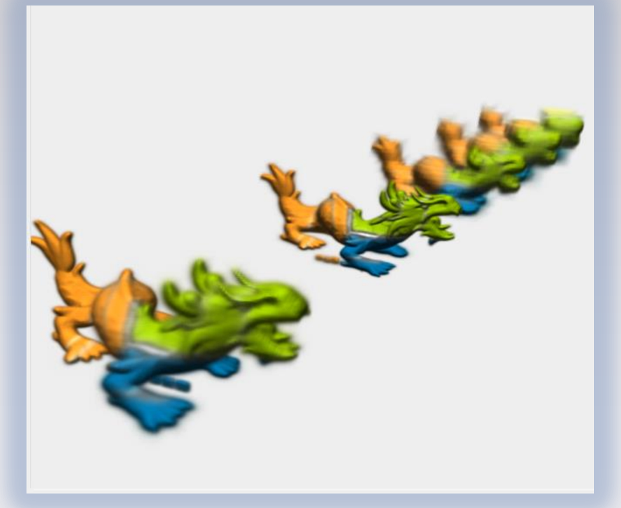
Depth of Field

Add more realism to images

- mimic camera lens (focus plane)
- double lens cone





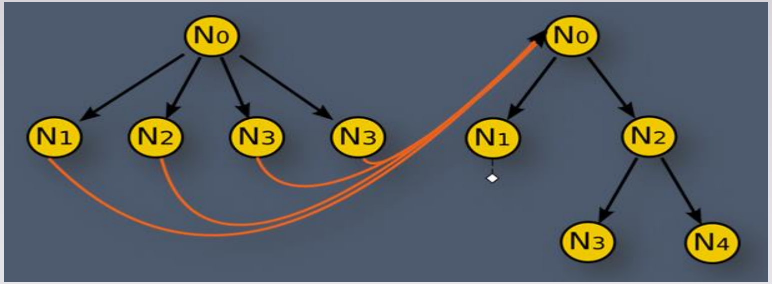


Voxel data synthesis

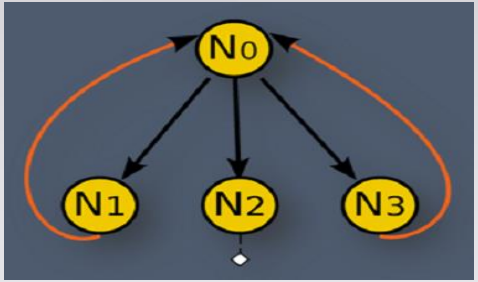
Goal : Simulate environments

Instanciation and recursion

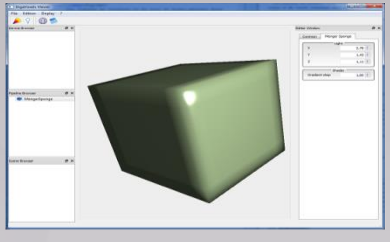
- node pointers based system

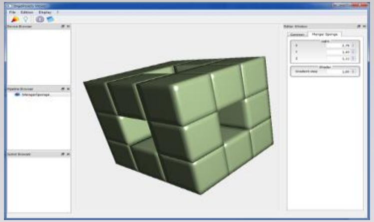


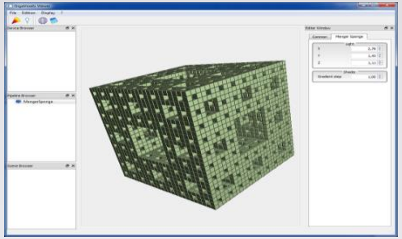
Instanciation



Recursivity

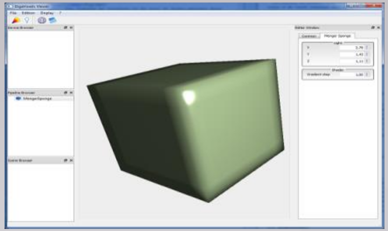


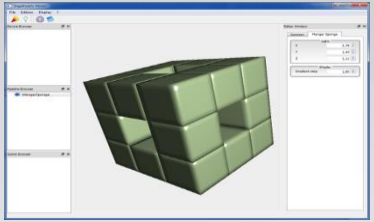


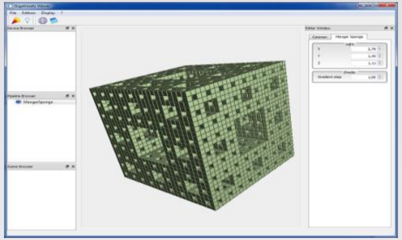


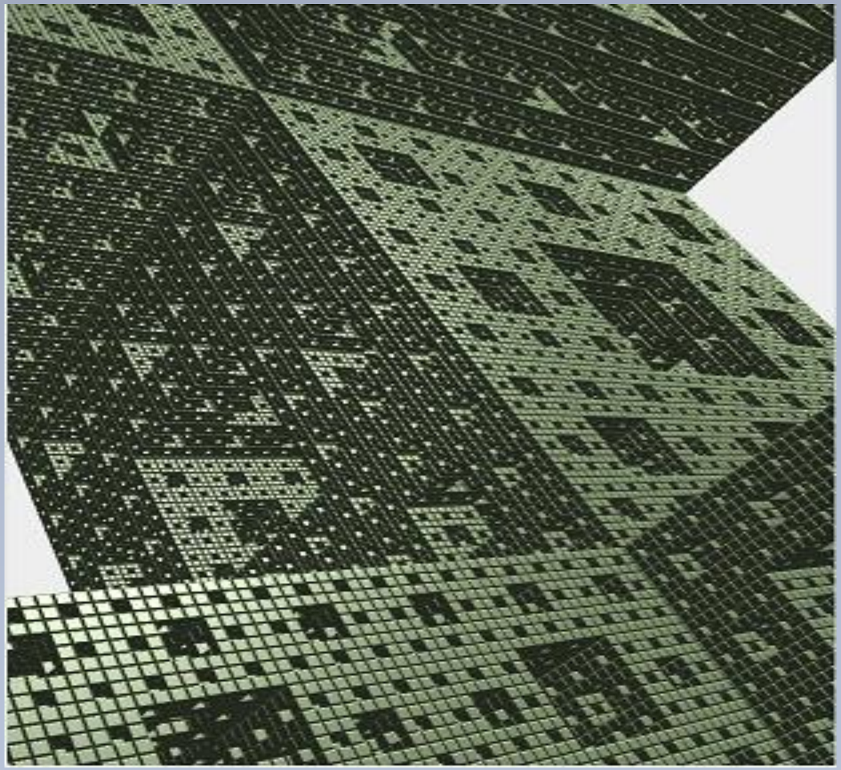
Voxel data synthesis

Menger/Serpinski Sponge





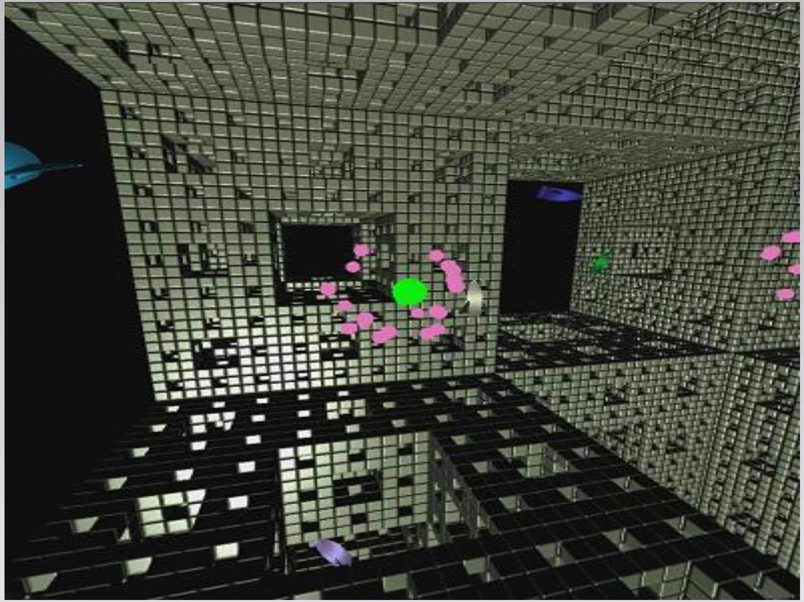




OpenGL interoperability

Mix triangles and voxels

- integration with traditional CG rasterized scenes (or compositing)
- renderer takes color and depth buffer as input and updates them with voxels



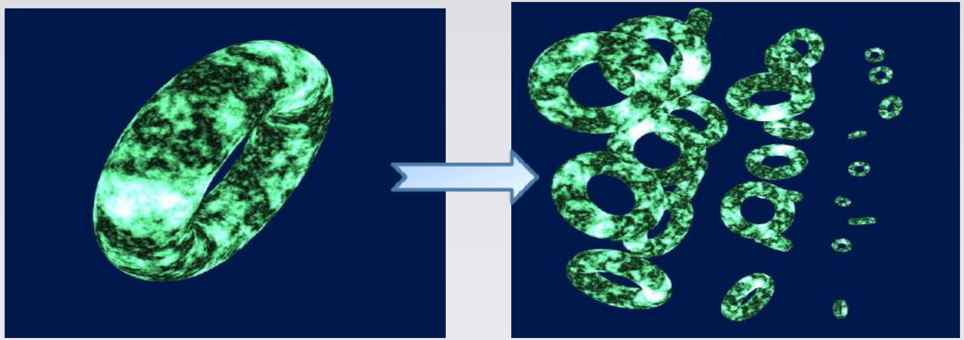
OpenGL interoperability

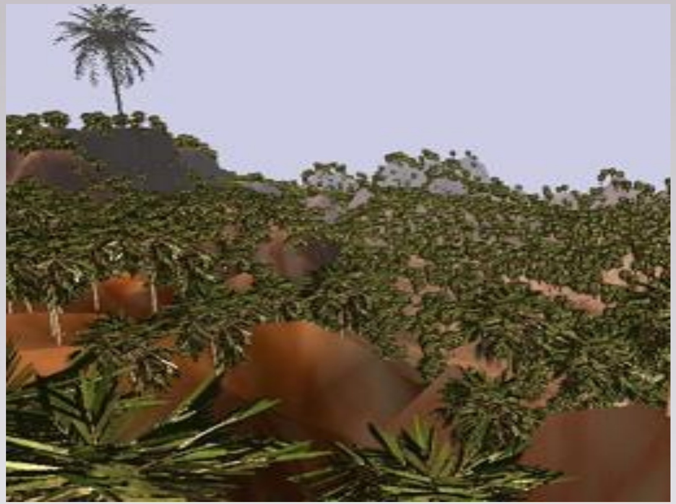
Voxel-based Instancing

<u>Goal</u> (not yet, in study/progress)

Have several GigaVoxels entities (forest)

- Need proxy geometry
- Render projected 2D BBox
- Use GLSL fragment shader
- (rays start + direction)





Instancing

Tools : Viewer

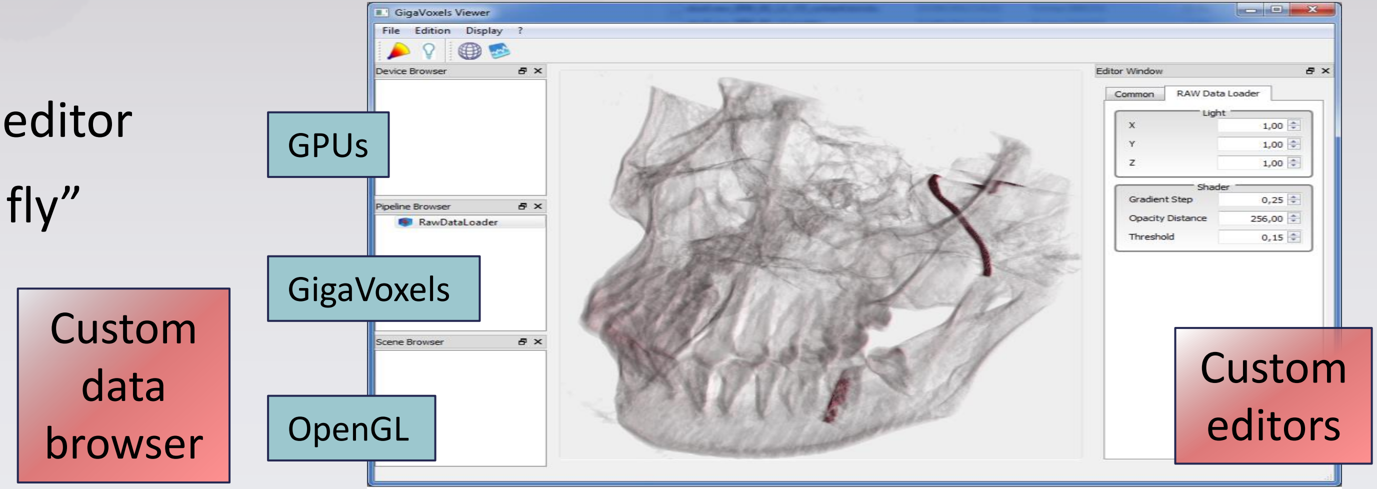
Goal

Environment to study, test, profile, debug…

- Kind of "generic" API : browsers, editors, etc…
- Tools : transfer function, performance monitor, etc…
- 3D models importer (+ GLSL shaders editor)
- Futur hope :

  CUDA functions editor

"recompile on the fly"



Outils : Viewer

Goal

Plugin « GigaVoxels Pipeline » : dynamic library (.dll, .so)

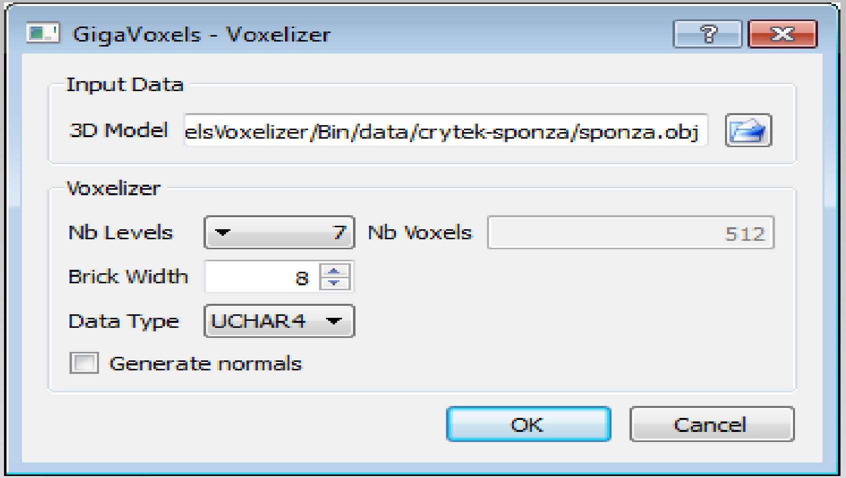
=> kind of « effect »

- Idea : plug this “node” in a scene graph à la OpenSceneGraph (see the “ppu” project) or Ogre3D
- Not yet finished : it has been “polluted” with Qt to have USER custom editors.

Outils : Voxelizer

- Pre-process step
- Futur work :
- - optimize code
- - smooth resulting data
- - idea : voxelize data

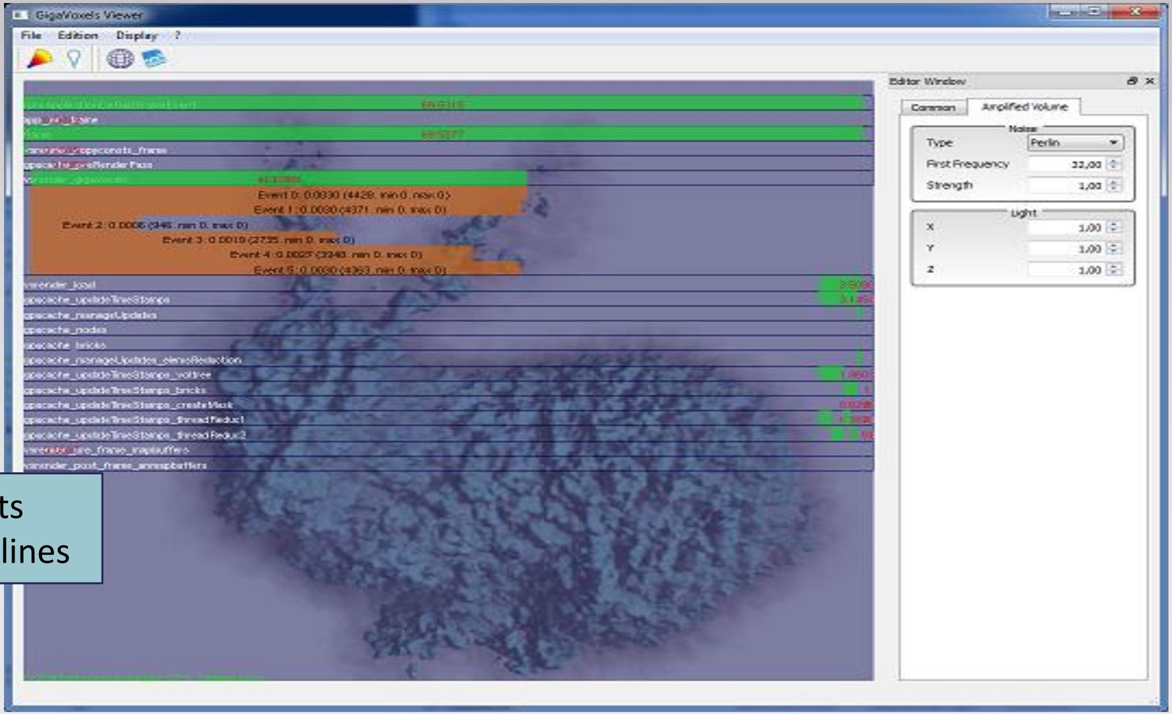
"on the fly" in the producers



Voxelizer Tool

Outils : Performance Monitor (still in debug…)

- Use events to record time between kernel functions
- Special case : record “device” functions (1 thread per pixel)



Events Timelines

Performance Monitor

Outils : Performance Monitor

- Record device function for Rendering kernel (1 thread per pixel), then compute average time on all pixels

```
#ifdef WIN32
	typedef unsigned __int64	uint64;
#else
	typedef unsigned long long	uint64;
#endif

__device__ uint64  getClock()
{
	uint64   result;
	// Using inline PTX assembly in CUDA.
	// Target ISA Notes : %clock64 requires sm_20 or higher.
	//
	// The constraint on output is "=l" :
	//   - '=' modifier specified that the register is written to
	//   - 'l' modifier refers to the register type ".u64 reg"
	asm  volatile ("mov.u64 %0,%clock64;" : "=l"(result) : : );
	return   result;
}
```

RTIGE

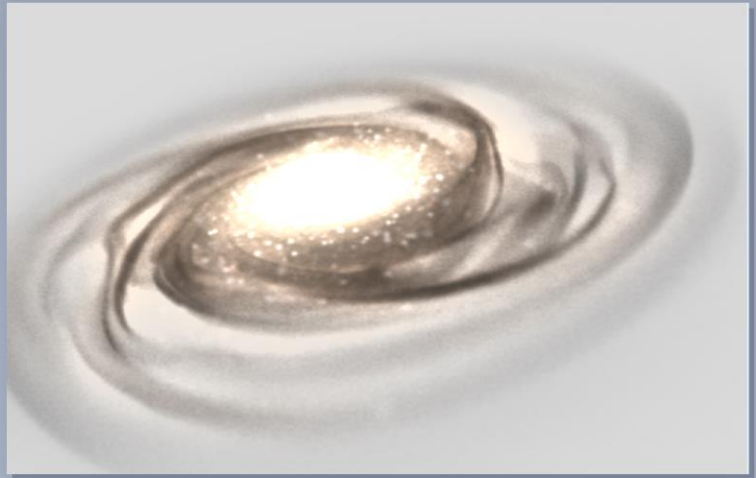
French ANR Research Project

RSA Cosmos : planetariums [2010-2014]

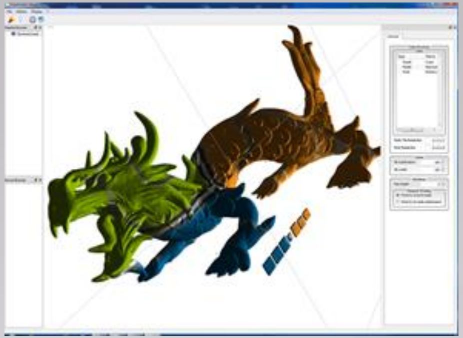
- “Real-Time and Interactive Galaxy for Edutainment”
- I. Visualize static galaxies
- II. Data amplification (procedural generation)
- III. Animate galaxies

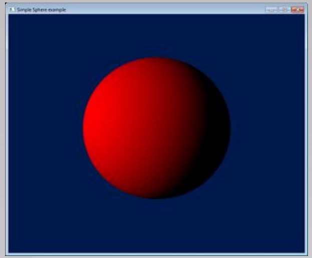
Optimisations

- use OpenGL billboards to stop rays (VBO)
- multi-GPUs ?
- time budget ?, priority on bricks ?

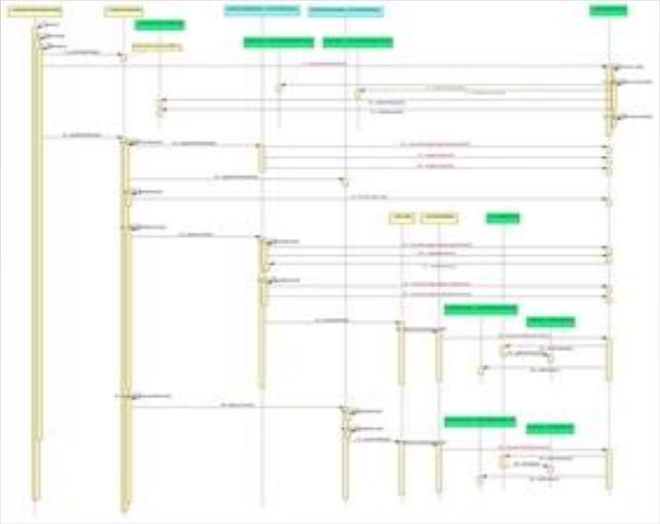


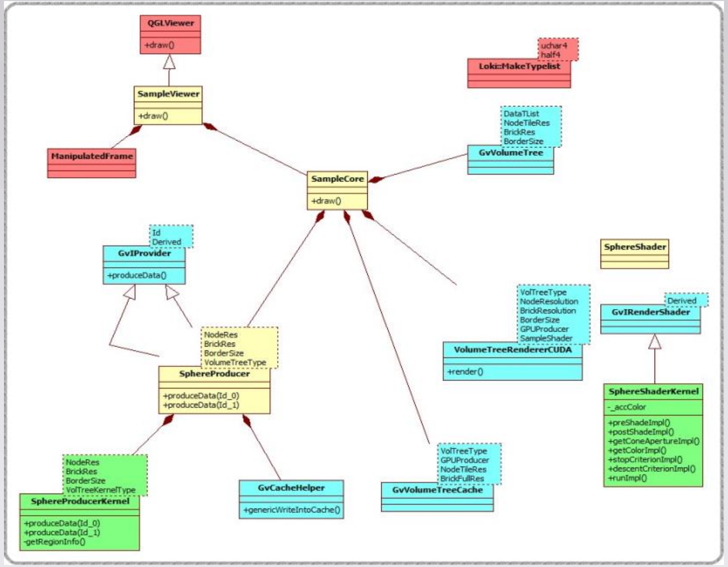
PART 3 - The library





- [1] - Core library
- [2] - User custom API





The library

Goal

- Capitalize on the knowledge of the team
- Continue research on the subject
- Hide the complexity of the underlying « core » library (cache mechanism, data structure management, etc…)
- Give USER access to customize the « data production » and the « shader »

The library

Technologies

- C++ (template)
- GPU Computing : CUDA + libraries (cudpp / thrust)
- CMake
- IHM : Qt
- Viewer : QGLViewer
- 3D : OpenGL (GLSL)
- Others : Loki, Assimp, CImg, ImageMagick
- OS : Windows (7), Linux (Ubuntu) + 32/64 bits
- Requirements : Cuda 4.x and Compute Capability SM at least 2.0

Library

[1] - Common API : « hidden » generic mechanisms

- **Tree Data Management** (space partitioning) to store and organize data

  (octree or generalized N3-tree, + SDK example kd-tree)

- **Cache System on GPU** : LRU mechanismn (least recently used)

  (to get temporal coherency)

- **Data Production Management** : on host, GPU, or hybrid mode

  Goal : produced data are kept in cache on GPU

- **Visit algorithm** : traverse your data (loaded in cache) as could be done for rendering

- **Renderer** (hierarchical volume ray-casting, cone tracing, emission of requests, brick marching)

Library

[2] – USER access

USER Customizable API

- **Producer** (load or produce our own data)

  ⇨ used during Data Production Management

- **Shader** (write your custom shader)

  ⇨ used during Visit algorithm and Rendering

Library

<u>Data Production Management :</u>

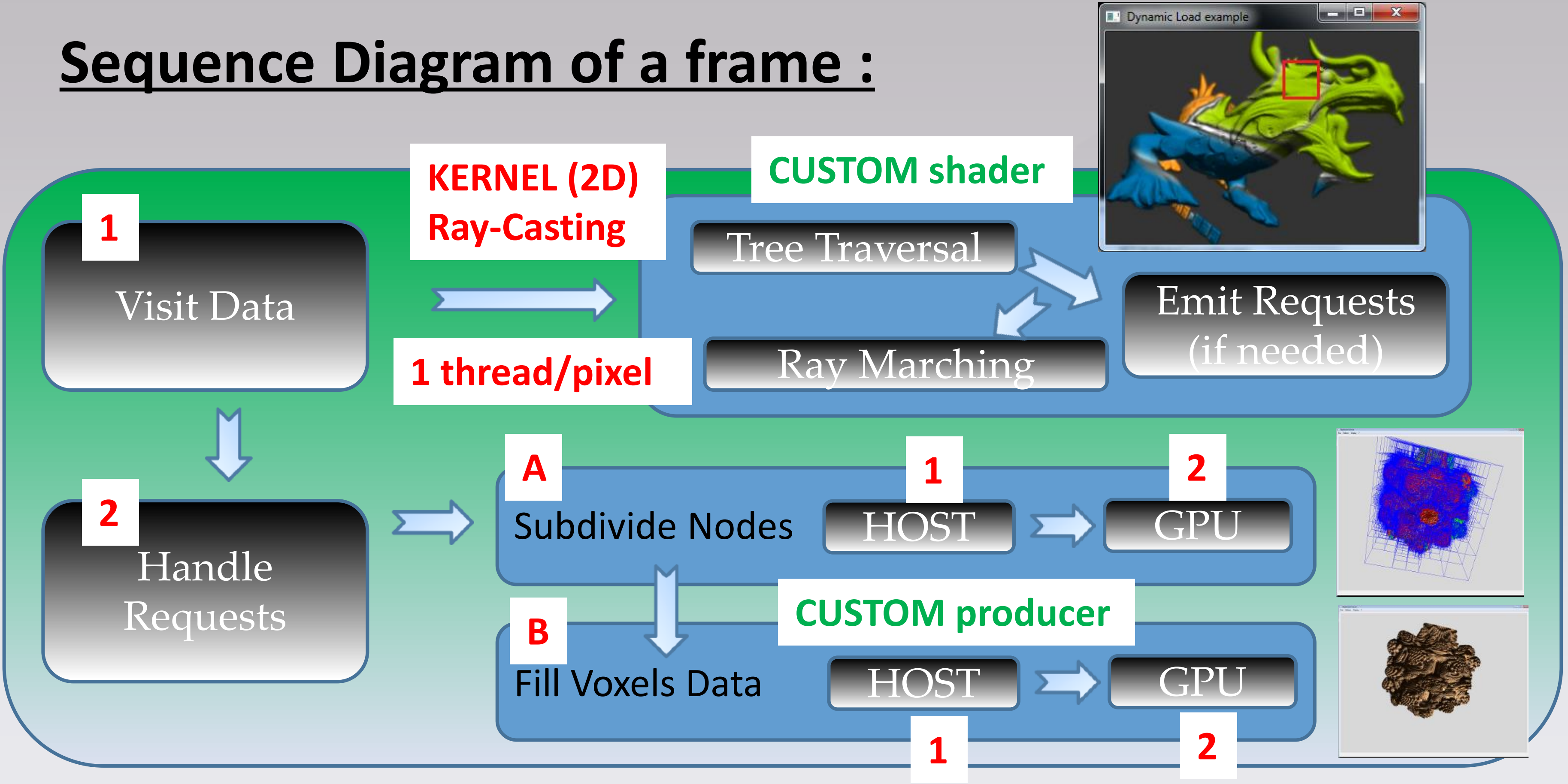
- Nodes subdivision (data refinement)
- Load or compute bricks of voxels (fill data)

USER has to write :

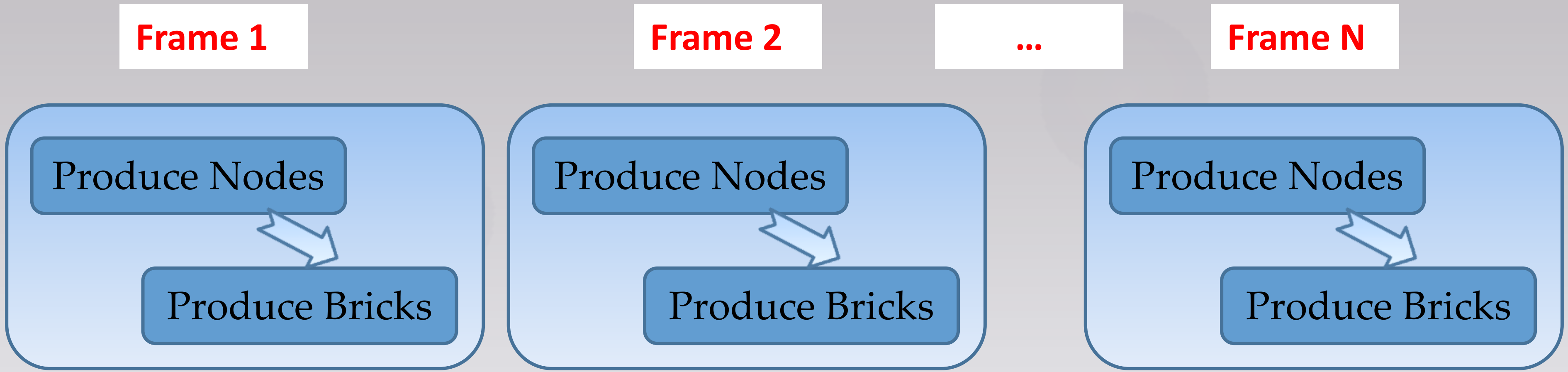
- a HOST producer
- and its associated GPU producer

Data Production Management

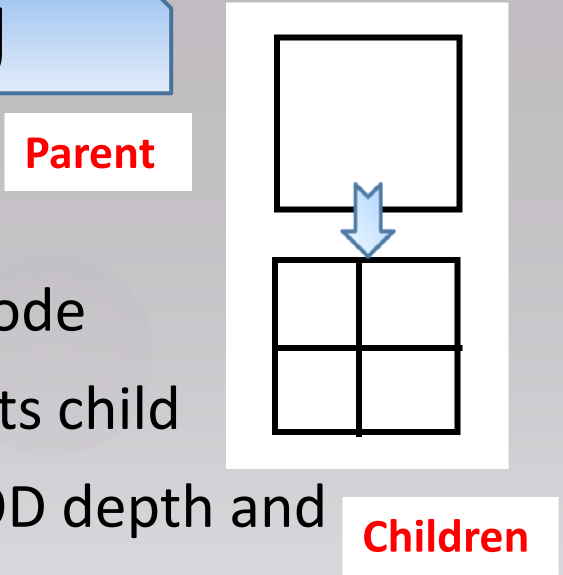
Sequence Diagram of a frame :



Sequence


Frame 1
Frame 2
...
Frame N
Produce Nodes
Produce Bricks
Produce Nodes
Produce Bricks
Produce Nodes
Produce Bricks

Ex : sphere on GPU



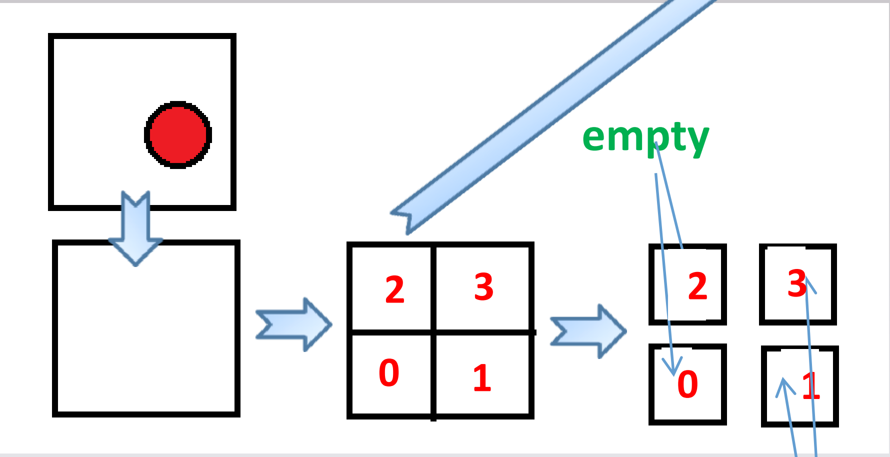
Nodes subdivision :

- KERNEL : 1 bloc/node and 1 thread/child_node
- Each node has to say what's inside each of its child
- INPUT : localization info of current node (LOD depth and spatial index pos)
- INPUT : address in "node cache" where to write new child nodes
- Test if it is in a sphere (analytically)
- Write nodes in cache

Ex : sphere on GPU

Nodes subdivision :

WORLD : sphere



Parent

Children
- what's inside ?

data

1st step

FLAG Children

- EMPTY
- DATA inside
- MAX RESOLUTION reached

Retrieve 3D world position with help of INPUT localization info (depth, index position)

2nd step

Write result in cache

- Next frame, rendrer will ask for the node data production (brick of voxels)

Ex : sphere on GPU

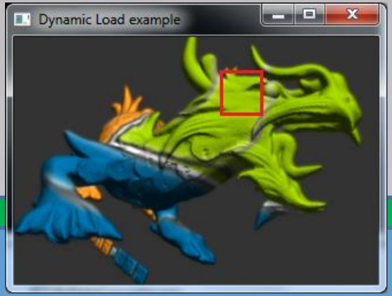
<u>Bricks of voxels production :</u>

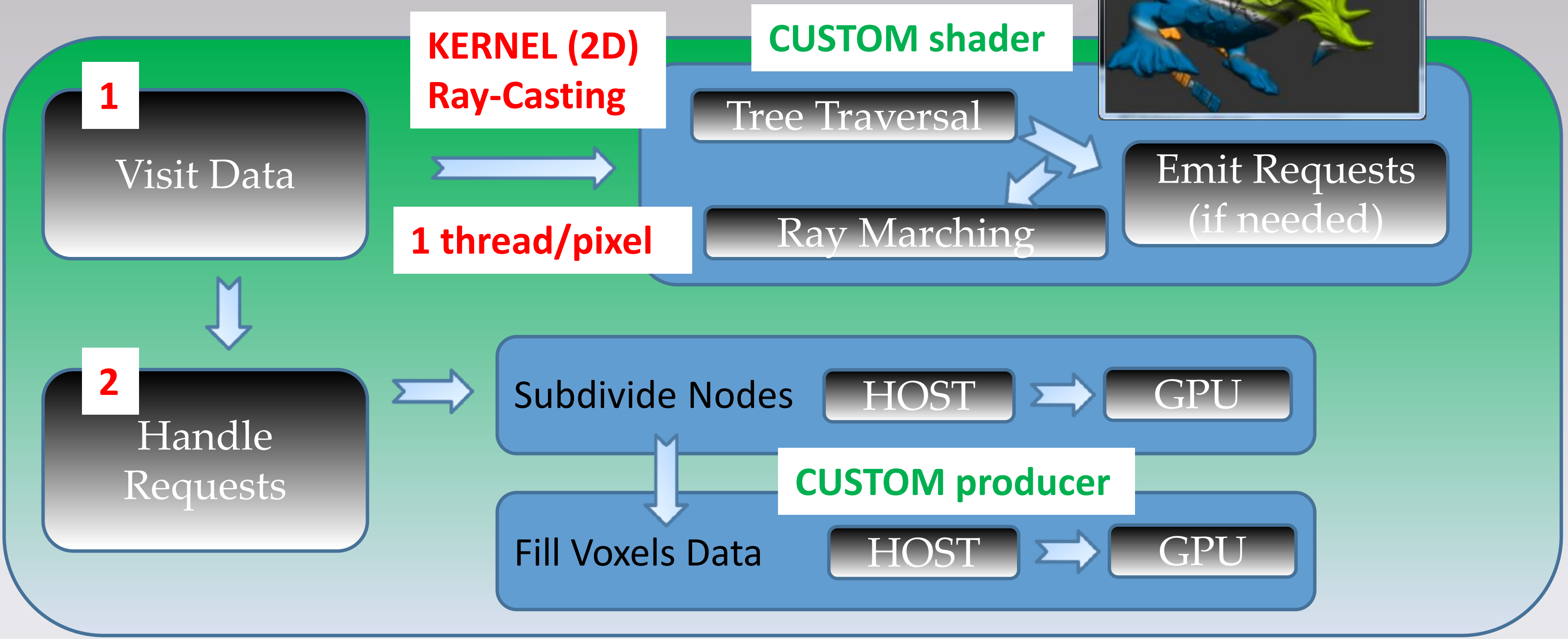
(same principe as for nodes)

- KERNEL : 1 bloc/brick and thread is as you want
- USER is in 1 brick and has to populate its voxels
- INPUT : localization info of current node (LOD depth and spatial index pos)
- INPUT : address in “data cache” where to write new voxels
- Write voxels in cache

Ex : sphere on GPU

<u>Reminder</u> : SHADER management





Ex : sphere on GPU

SHADER :

- INPUT : “data sampler” and current position
- Sample data, retrieve USER defined channel (color, normal, etc…) and accumulate color along the current ray

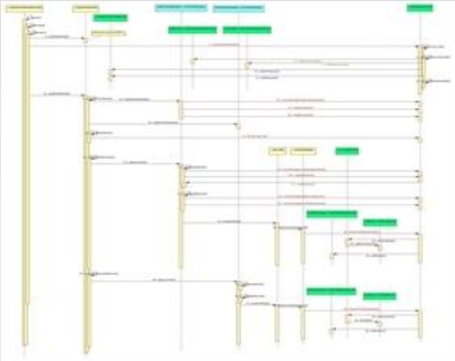
```
// Retrieve first channel element : color
__device__  void  ShaderKernel::run( const SamplerType&  brickSampler, … )
{
      float4 color  =   brickSampler.getValue< 0  >( coneAperture );        // channel 0 is color

      If  (  color.w > 0.0f  )  {  _accumulatedColor = _accumulatedColor + ( 1.0f - _accumulatedColor.w ) * color;  }
}
```

Sphere on GPU

SHADER :

- CUSTOM api provide "other entry points" :
- getConeAperture() [modify cone aperture]
- getStopCritrion() [ex : accumulatedColor.w >= 0,98f]
- getDescentCriterion() [used during "visit" traversal]
- …



GigaVoxels Sequence Diagram

Library

Tips and tricks :

- Template meta-programmation : curiously recursive template pattern (to avoid polyphormism on GPU)

This technique achieves a similar effect to the use of virtual functions, without the costs (and some flexibility) of dynamic polymorphism.

- Data cache : 3D texture to read, and bind with surfaces to write data
- Loki : use to access different textures types
- Cudpp(/thrust) : cache mechanism on GPU (stream compaction to get "used" and "non-used" elements at current frame)
- Write Z-buffer : slow => idea => use color and do conversion

OpenGL interoperability

<u>Mix triangles and voxels</u> :

- integration with traditional CG rasterized scenes (or compositing)
- renderer takes color and depth buffer as input and updates them with voxels
- Opaque objects rendered first (depth buffer) to skip occluded parts
- GigaVoxels registers « textures, renderBuffer, PBO, … » with optimized flags

(see GTC 2013 : S3070 – « Part 1 – Configuring, Programming and Debugging Applications for Multi-GPUs » from Wil Braithwaite [NVidia]

cudaGraphicsRegisterFlagsReadOnly, cudaGraphicsRegisterFlagsWriteDiscard, …

)

OpenGL interoperability

Mix triangles and voxels

Simple mode : [no input] + [only write color]

```
// [ 1 ] - Init texture (with window size)
glGenTextures( 1, &colorTex );
glBindTexture( GL_TEXTURE_RECTANGLE_EXT, colorTex );
glTexImage2D( GL_TEXTURE_RECTANGLE_EXT, 0, GL_RGBA8, width, height, 0, GL_RGBA, GL_UNSIGNED_BYTE, NULL );
// [ 2 ] - Register texture in WRITE ONLY slot in GigaVoxels
renderer->connect( Gv::eColorWriteSlot, colorTex, GL_TEXTURE_RECTANGLE_EXT );
```

```
// Launch GigaVoxels rendering engine
renderer->render( /*OpenGL matrices*/ );
// Draw a full screen textured quad
glBindTexture( GL_TEXTURE_RECTANGLE_EXT, colorTex );
glBegin( GL_QUADS );
...
```

```
enum GraphicsResourceSlot
{
    eColorReadSlot,
    eColorWriteSlot,
    eColorReadWriteSlot,
    eDepthReadSlot,
    eDepthWriteSlot,
    eDepthReadWriteSlot,
    eNbGraphicsResourceSlots
};
```

Slots

OpenGL interoperability

Current work

[1] - Proxy geometry

“rasterized (approximate) geometry” containing non-empty areas of volume, providing starting and exit point for each ray, speeding-up the skipping of empty spaces

- Help skip empty regions
- Can add volumetric details on a triangle mesh

[2] – kind of Geometry Instancing

- Would like to have demo with forest

OpenGL interoperability

Current work : based on a galaxy visualization research project

Number of stars reprensented by points (VBO) can be very huge :

[1] Sphere Ray-Tracing (change representation)

- When bricks are near empty, generate spheres coordinates in « producer »
- Replace brick-marching by Ray-Tracing at rendering phase (fetch positions)

[2] -VBO generation

- add details by generating stars (OpenGL vbo points) in a GigaVoxels « producer »
- dump result in VBO dynamically (only visible nodes)
- => kind of view frustum culling

… the futur…

Ideas

- Working on performance (Visual Profiler, NSight)

  + Handle time budget for a frame, priority on bricks
- Use CUDA 5 : linker (recompile USER functions on the fly ?)
- Store points inside voxel (VBO generation according to visibility)
- ✓ Geometry instancing (forest)
- ✓ Voxel animation (with shellmaps)

…

User / developer guide

Library / SDK content

- Core library documented
- SDK tutorials fully documented
- Developer guide : soon

  - kind of “behind the scene”) : technical implementations detailed

Thanks

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Questions

Thanks for your attention

http://gigavoxels.inrialpes.fr/