



HAL
open science

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

Pascal Guehl, Fabrice Neyret

► **To cite this version:**

Pascal Guehl, Fabrice Neyret. GigaVoxels, Real-time Voxel-based Library to Render Large and Detailed Objects. NVIDIA GTC - GPU Technology Conference - 2013, Mar 2013, San Jose, United States. hal-00808121

HAL Id: hal-00808121

<https://inria.hal.science/hal-00808121v1>

Submitted on 4 Apr 2013

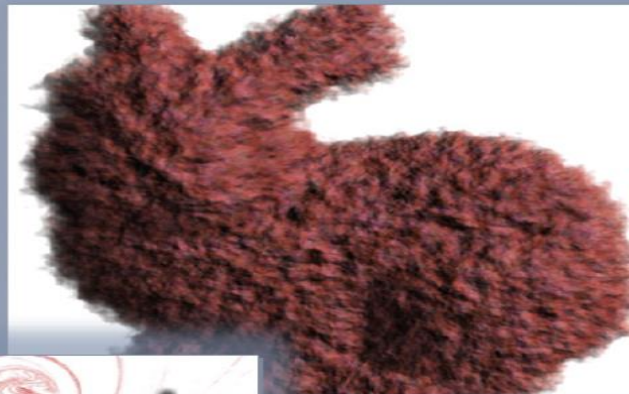
HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



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

Pascal GUEHL
R&D Engineer

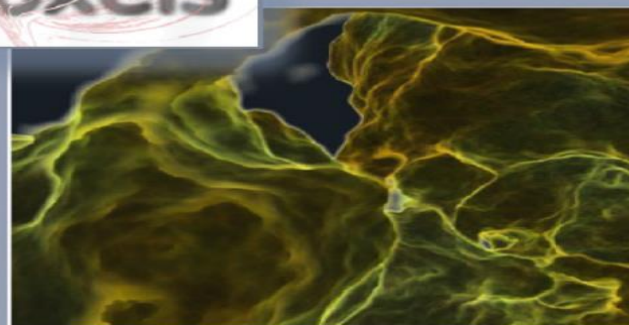
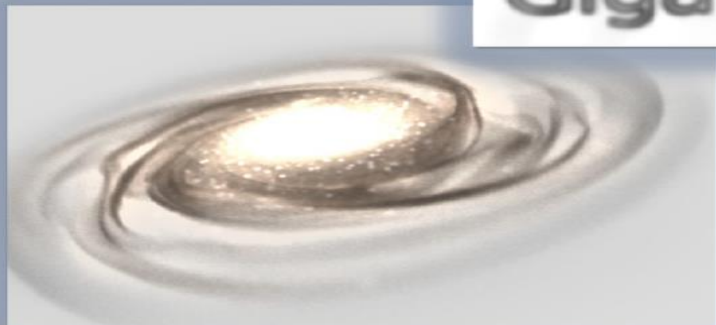


Videos Games

Special Effects

*Scientific
Visualization*

GigaVoxels



Between Research & Industry

<http://gigavoxels.inrialpes.fr/>

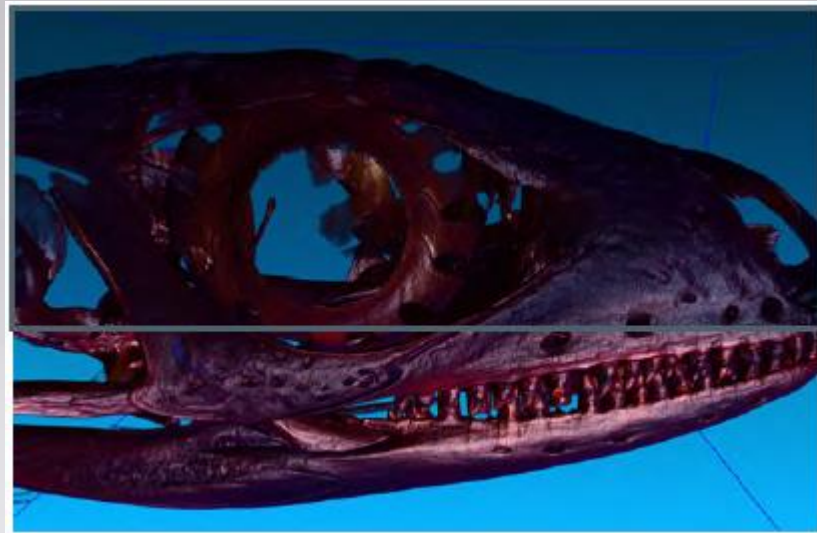
What is all about ?

R&D project about real-time exploration of

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

Target audience

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



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



Goal

Present our implementation of the « GigaVoxels » technology

- [1] - Reminder : what is GigaVoxels ? – Key Concepts / Features
- [2] - Show fonctionnalités 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 fonctionnalités, ...
- ▶ 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**

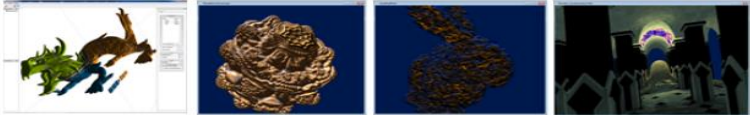
<http://gigavoxels.inrialpes.fr/>

- D A W N -
V E R S I O N 1 . 0



Welcome to the GigaVoxels website

GigaVoxels is a ray-guided streaming library used for efficient 3D real-time rendering of highly detailed volumetric scenes.



Dawn Version

- ▶ **Software SDK**
 - > Data Structure (N-tree) + User Defined Data (color, normal, density...)
 - > Cache Mecanism
 - > Renderer (ray casting with OpenGL interoperability)
 - > Producer Mecanism (on host and device)
- ▶ **Documentation**
 - > Classes (doxygen)
 - > User / Developer Manuel
- ▶ **Tutorials**
- ▶ **Tools**
 - > Viewer
 - > Voxelizier (pre-process)

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

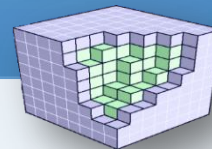
[x] Minimize computation, minimize memory transfers

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 mechanism (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



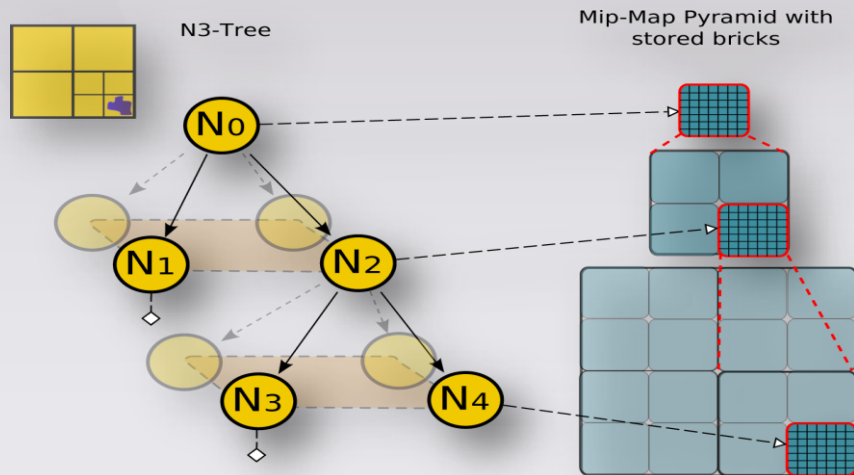
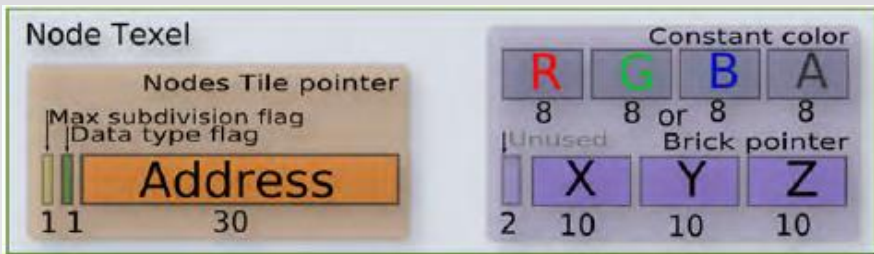
Generalized N₃-tree (octree)

- Space partitioning
- Empty space compaction

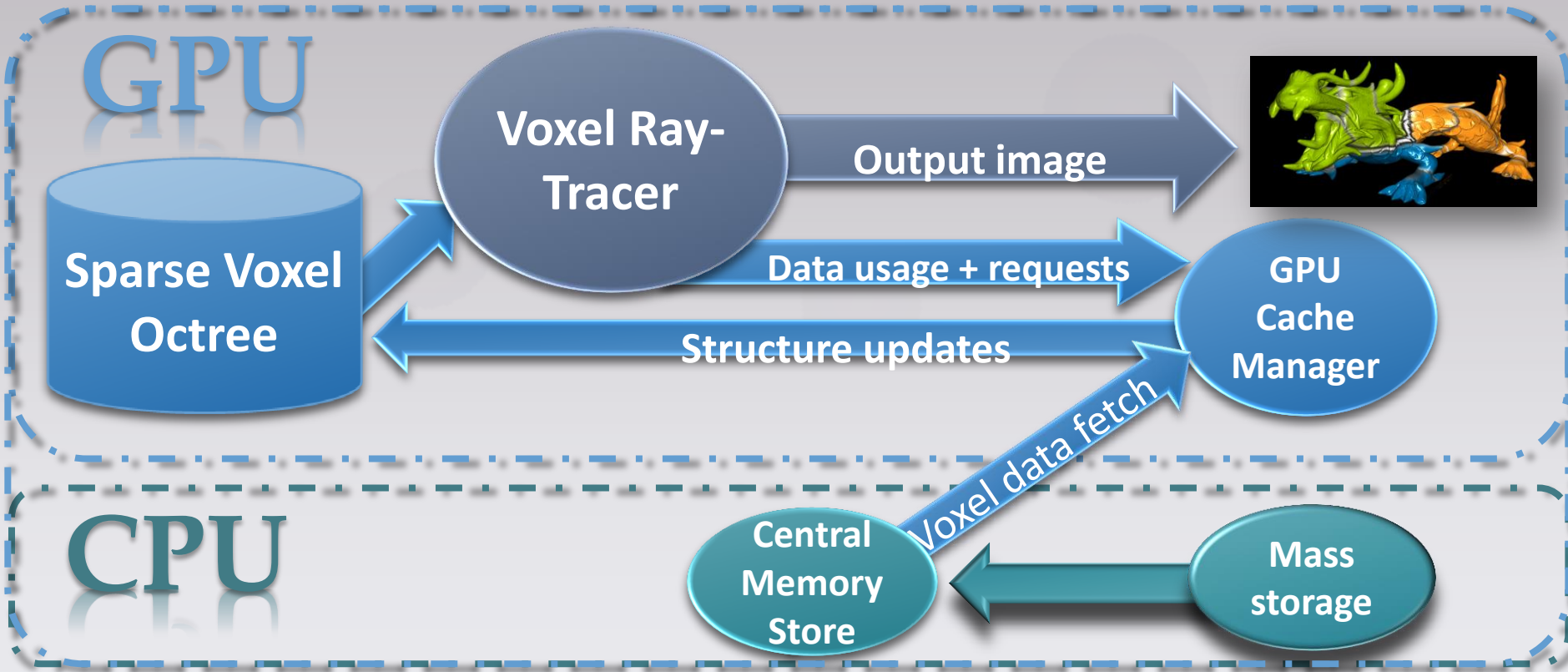
Bricks of voxels

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

“Node pointer based” data structure

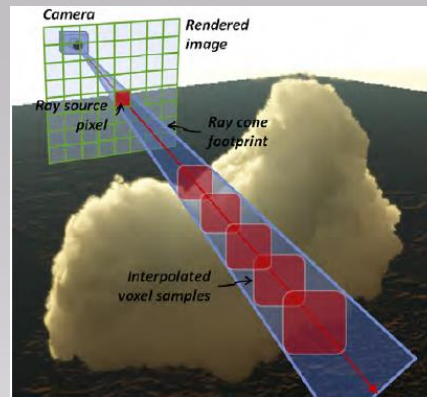


GigaVoxels Pipeline

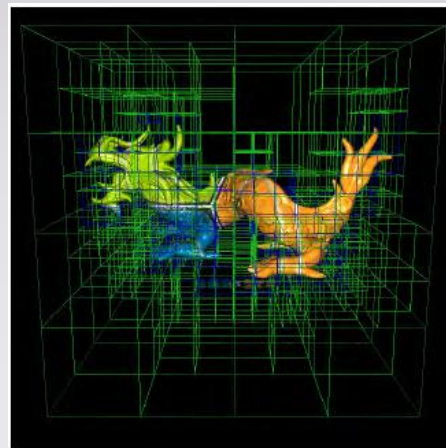
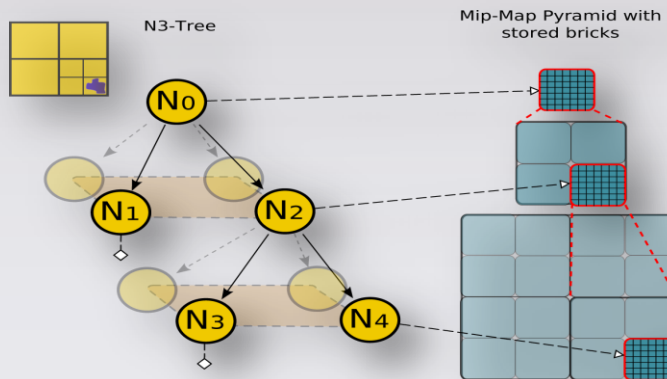


GigaVoxels Pipeline + data structure

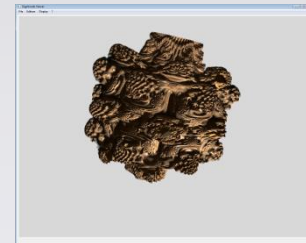
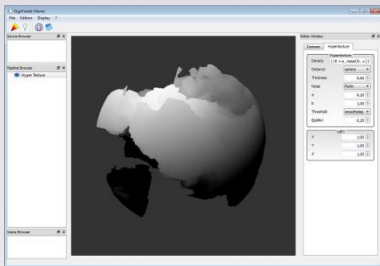
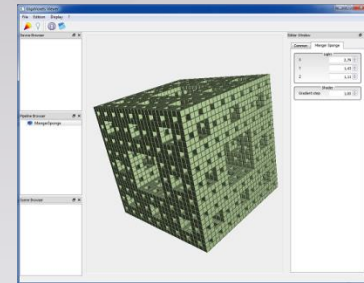
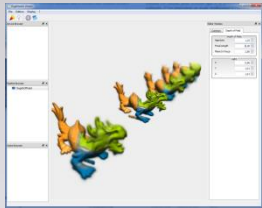
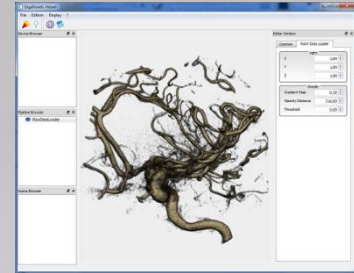
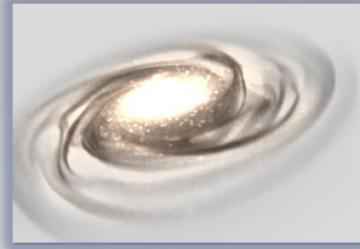
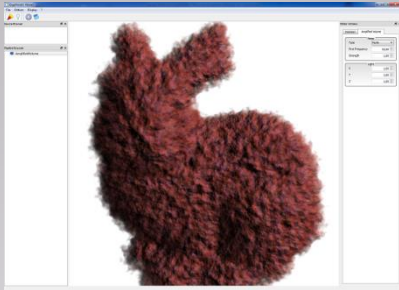
- unified data structure (geometry + texture)
- load only needed data at needed resolution
- smooth transitions and continuously reveals details
- Handle semi-transparent objects
- Alias free filtered images (cone tracing)



Cone tracing



PART 2 - Fonctionnalités 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...



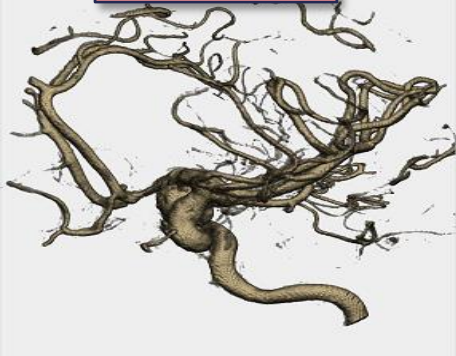
Import your own data

Custom file importer

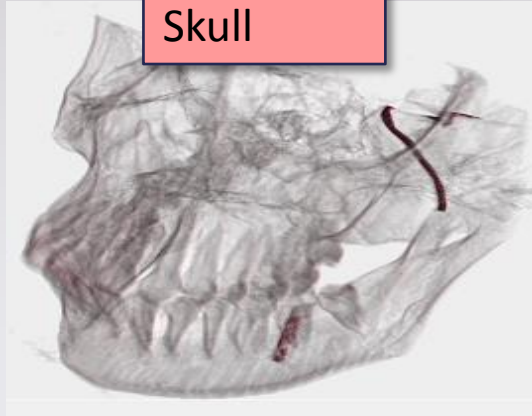
RAW data [scientific visualization]

- ▶ 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

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

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

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

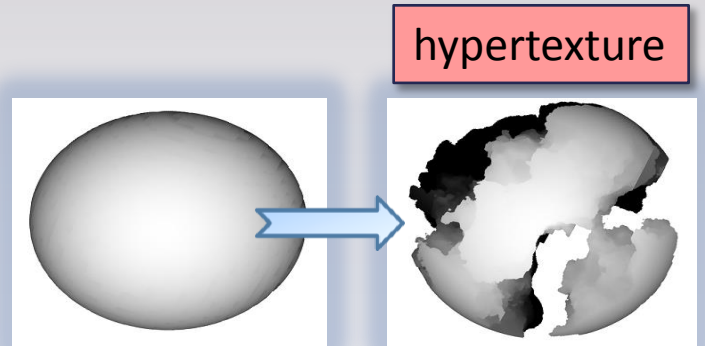
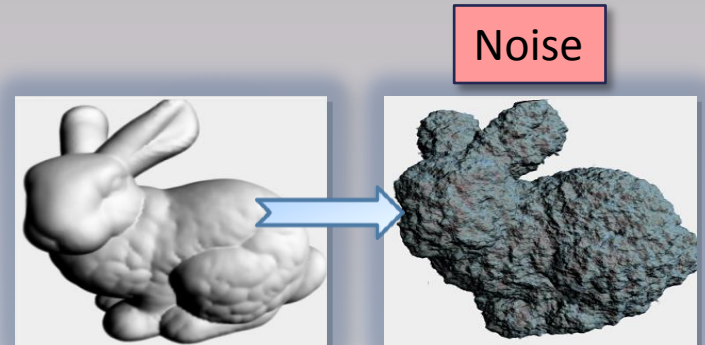
Goals

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

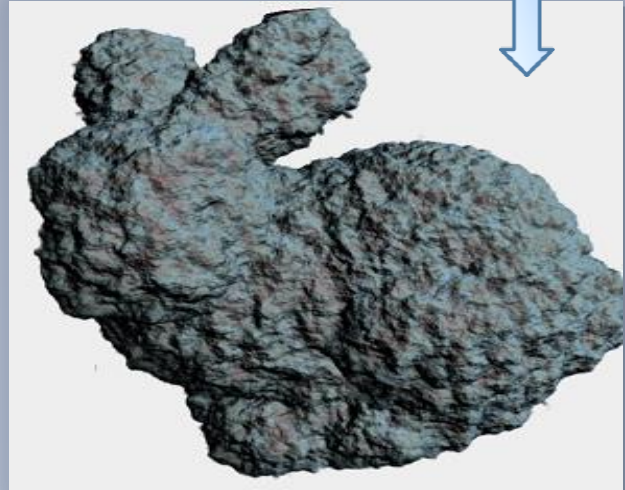
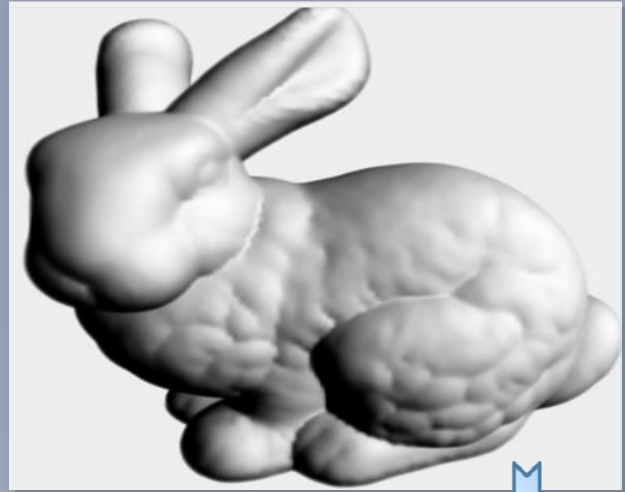


Noise

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 :
- $F(\text{level } N) = \text{currentNoise}(\text{level } N) + \text{previousNoise}(\text{level } N-1)$
- Finally : replace “noise computation” by “data fetch in cache”

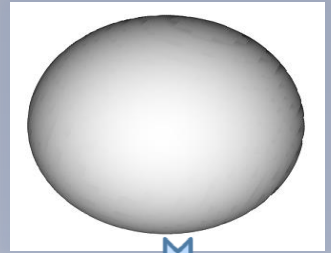
Hypertextures

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

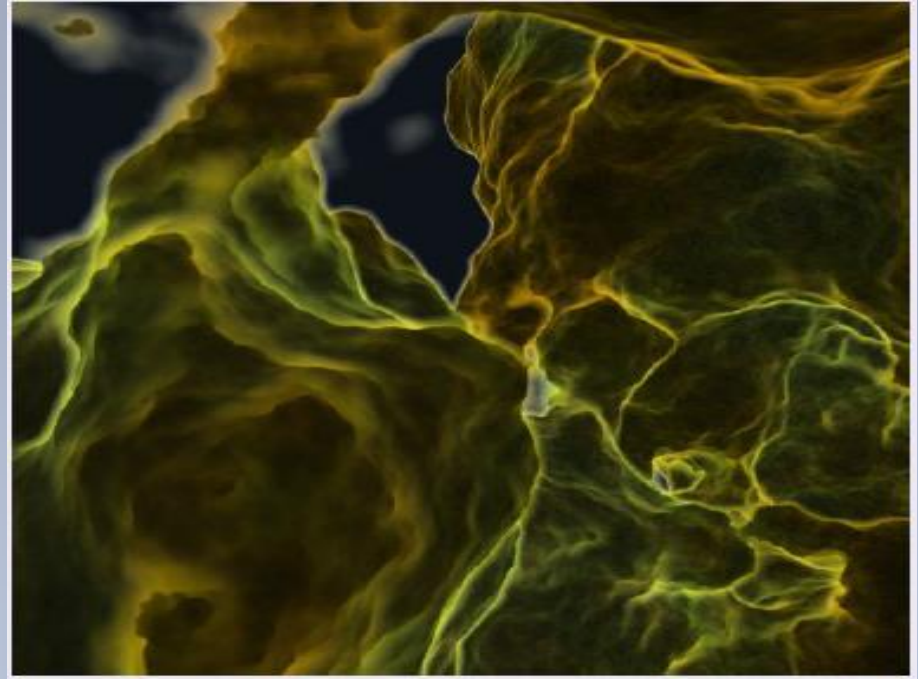
Idea : add details on armor soldier

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



hypertexture

Hypertextures



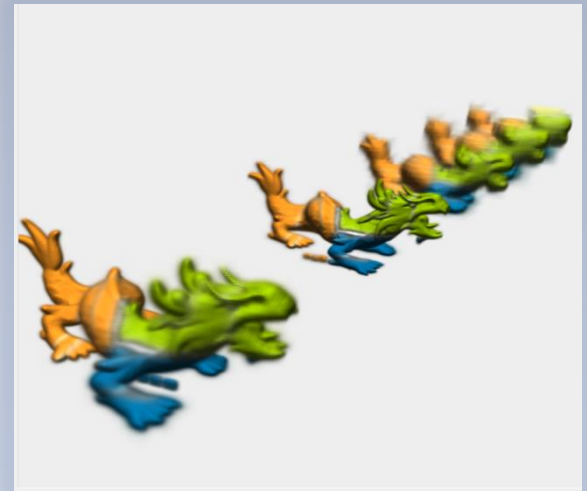
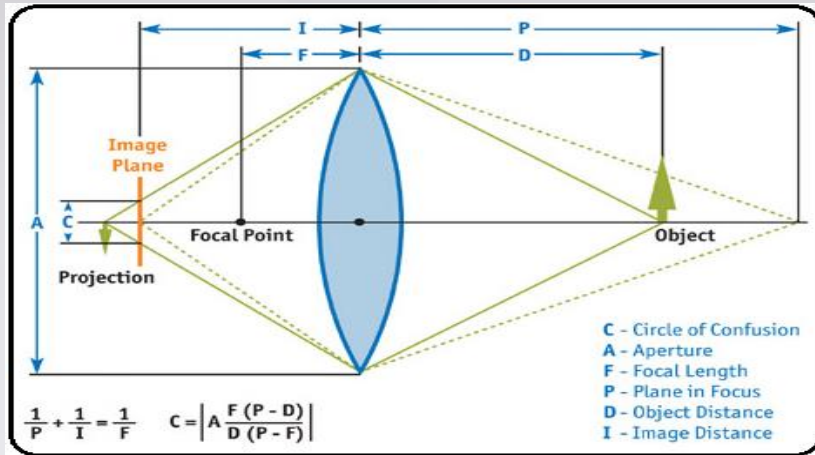
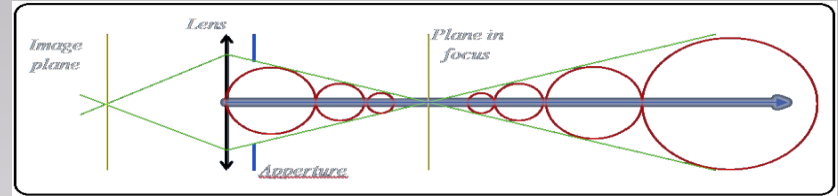
Depth of Field

Goal

Add more realism to images

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

Depth of Field

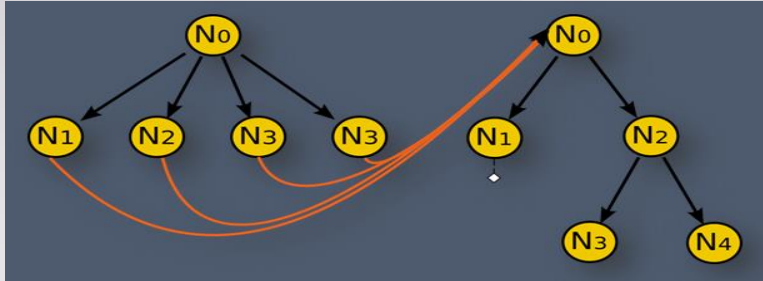


Voxel data synthesis

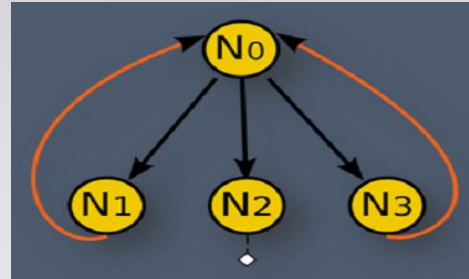
Goal : Simulate environments

Instanciacion and recursion

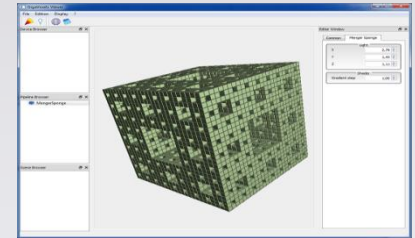
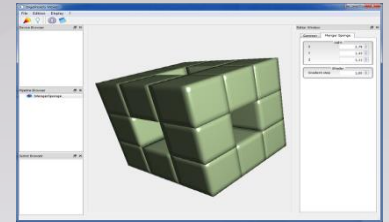
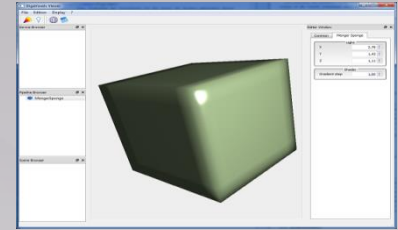
node pointers based system



Instanciacion

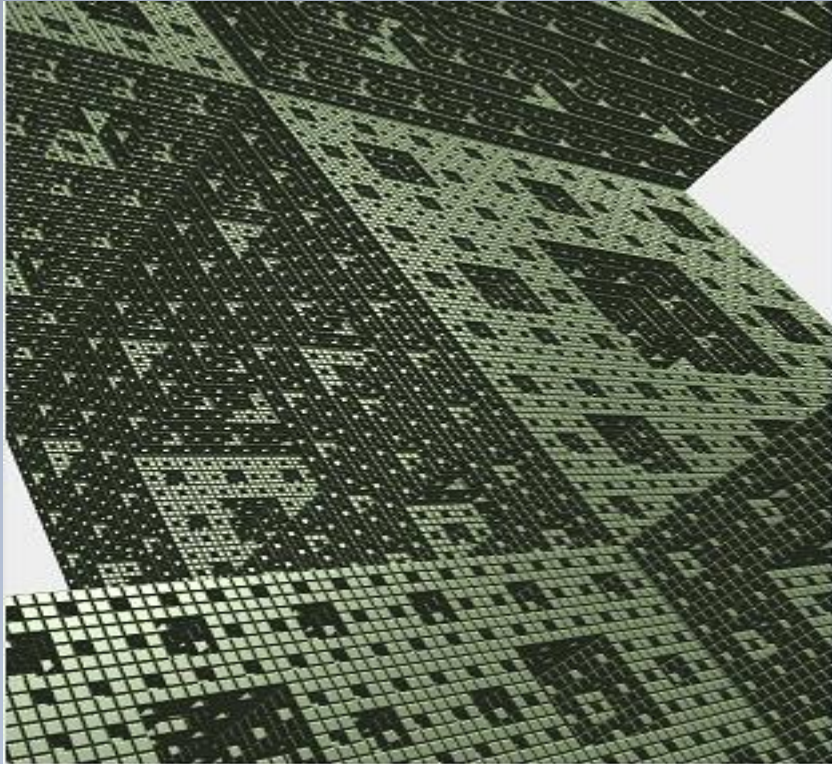
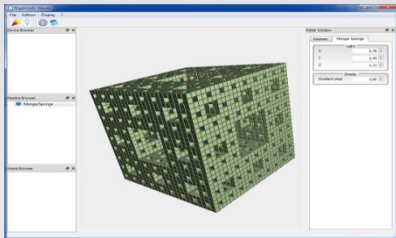
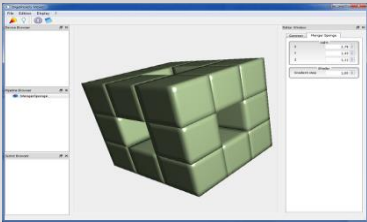
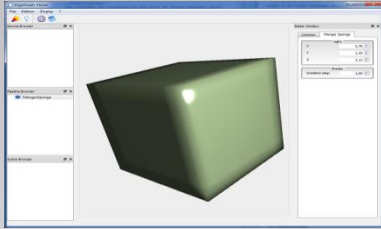


Recursivity



Voxel data synthesis

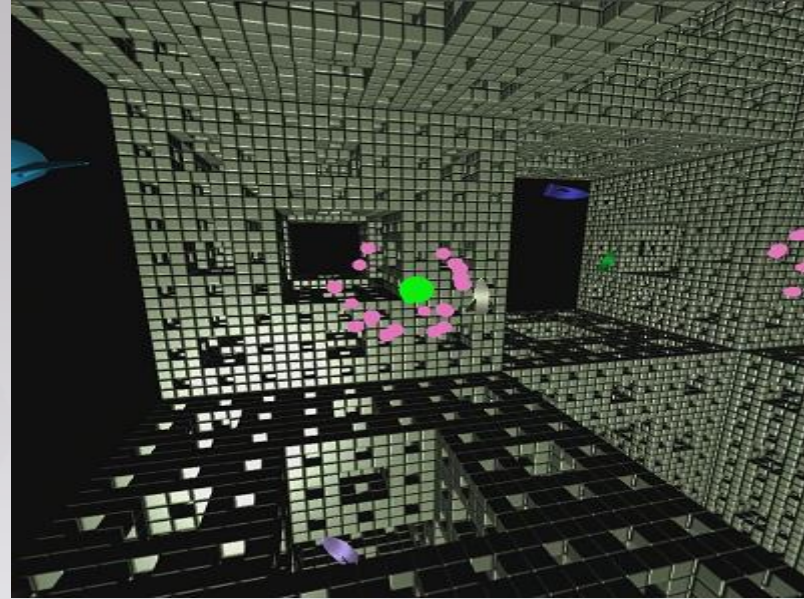
Menger/Serpinski Sponge



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



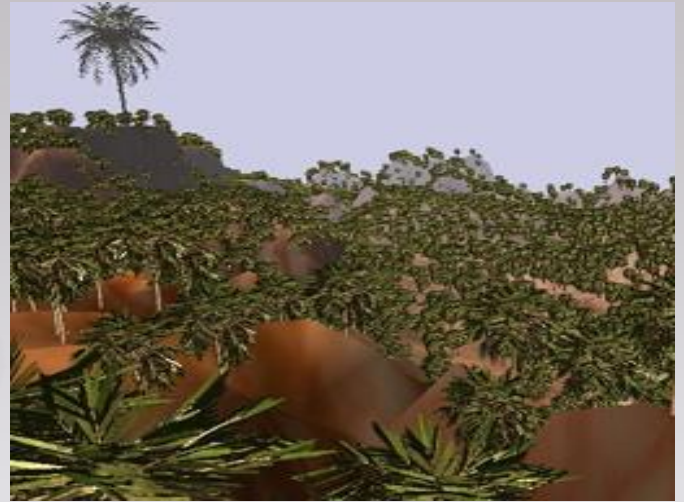
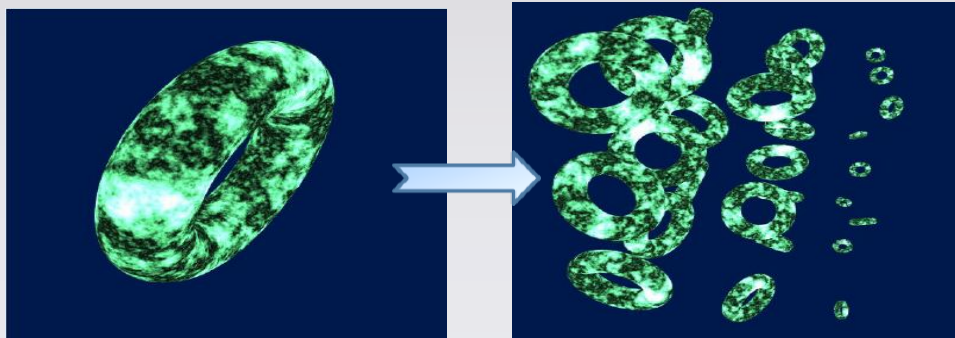
OpenGL
interoperability

Voxel-based Instancing

Goal (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

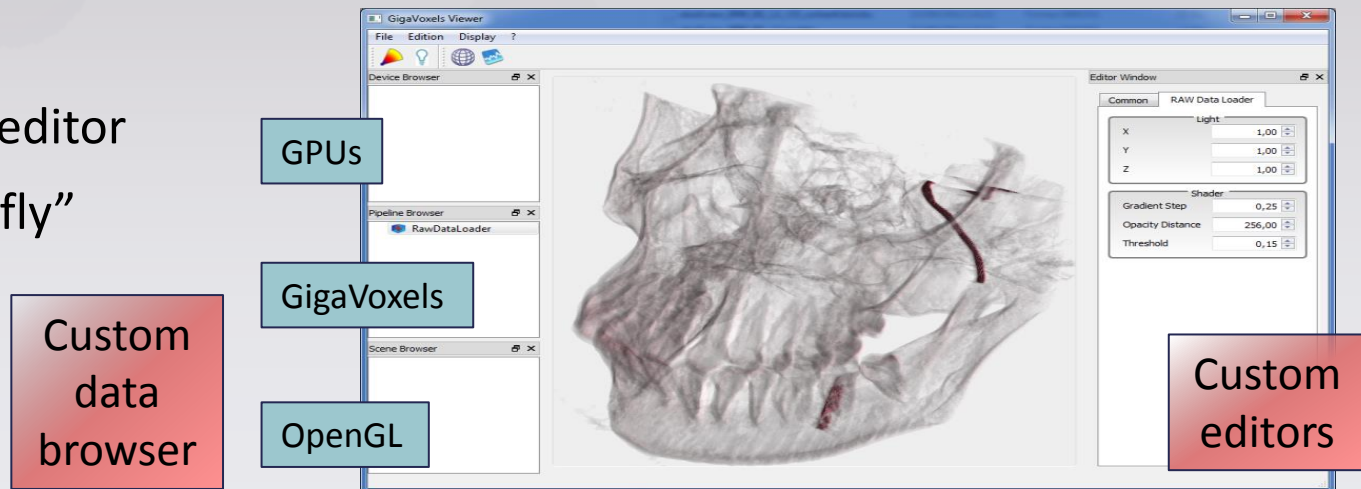
Goal

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

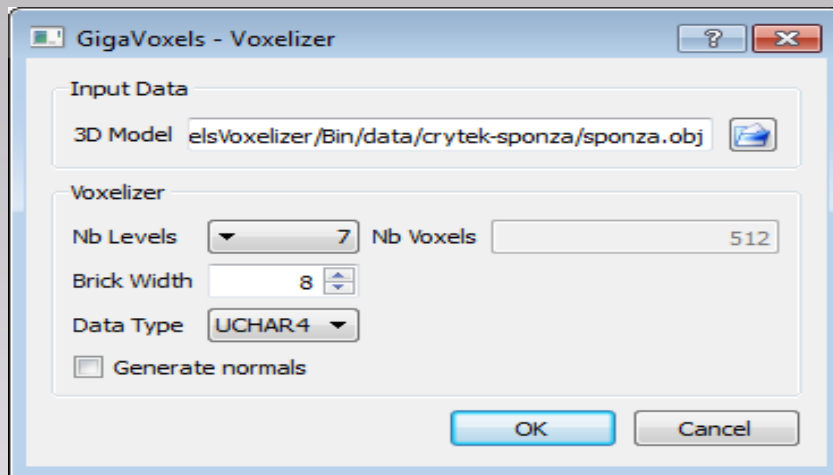
Plugin « GigaVoxels Pipeline » : dynamic library (.dll, .so)

=> 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

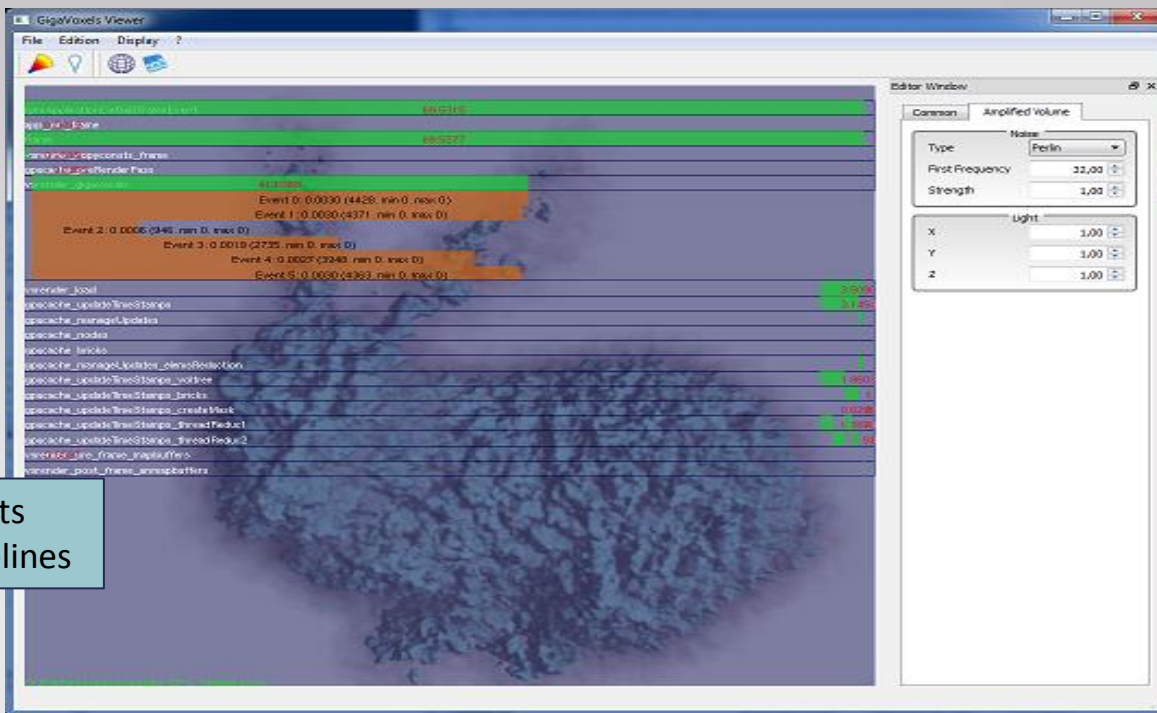
- Pre-process step
 - Futur work :
 - - optimize code
 - - smooth resulting data
 - - idea : voxelize data
- “on the fly” in the producers



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)



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

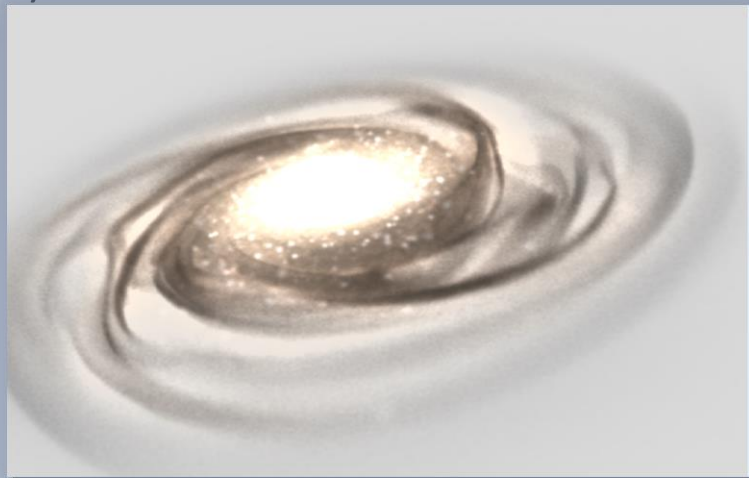
French ANR Research Project

RSA Cosmos : planetariums [2010-2014]

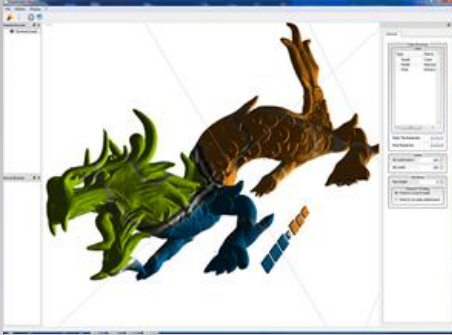
- “Real-Time and Interactive Galaxy for Edutainment”
- I. Visualize static galaxies
- II. Data amplification (procedural generation)
- III. Animate galaxies

Optimisations

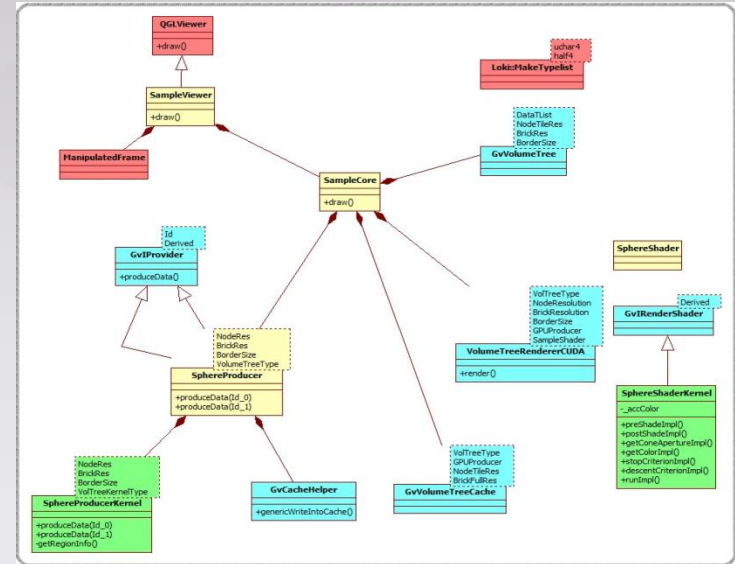
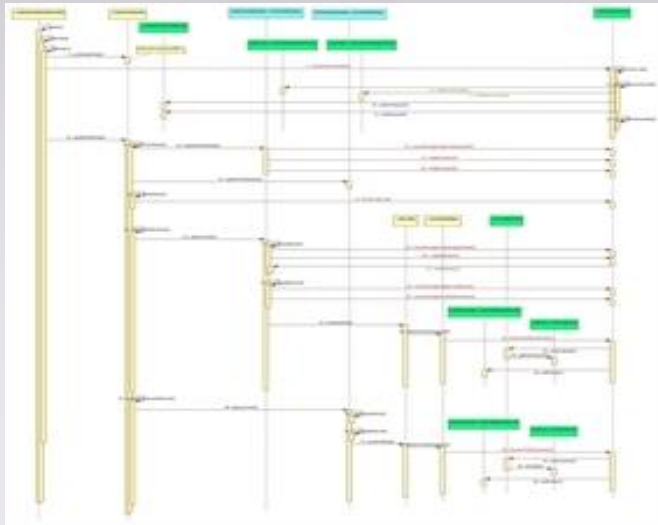
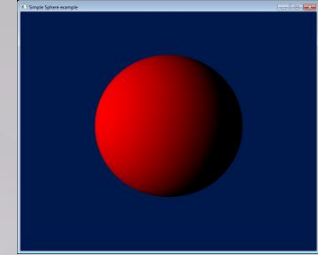
- use OpenGL billboards to stop rays (VBO)
- multi-GPUs ?
- time budget ?, priority on bricks ?



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 mechanism (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

Data Production Management :

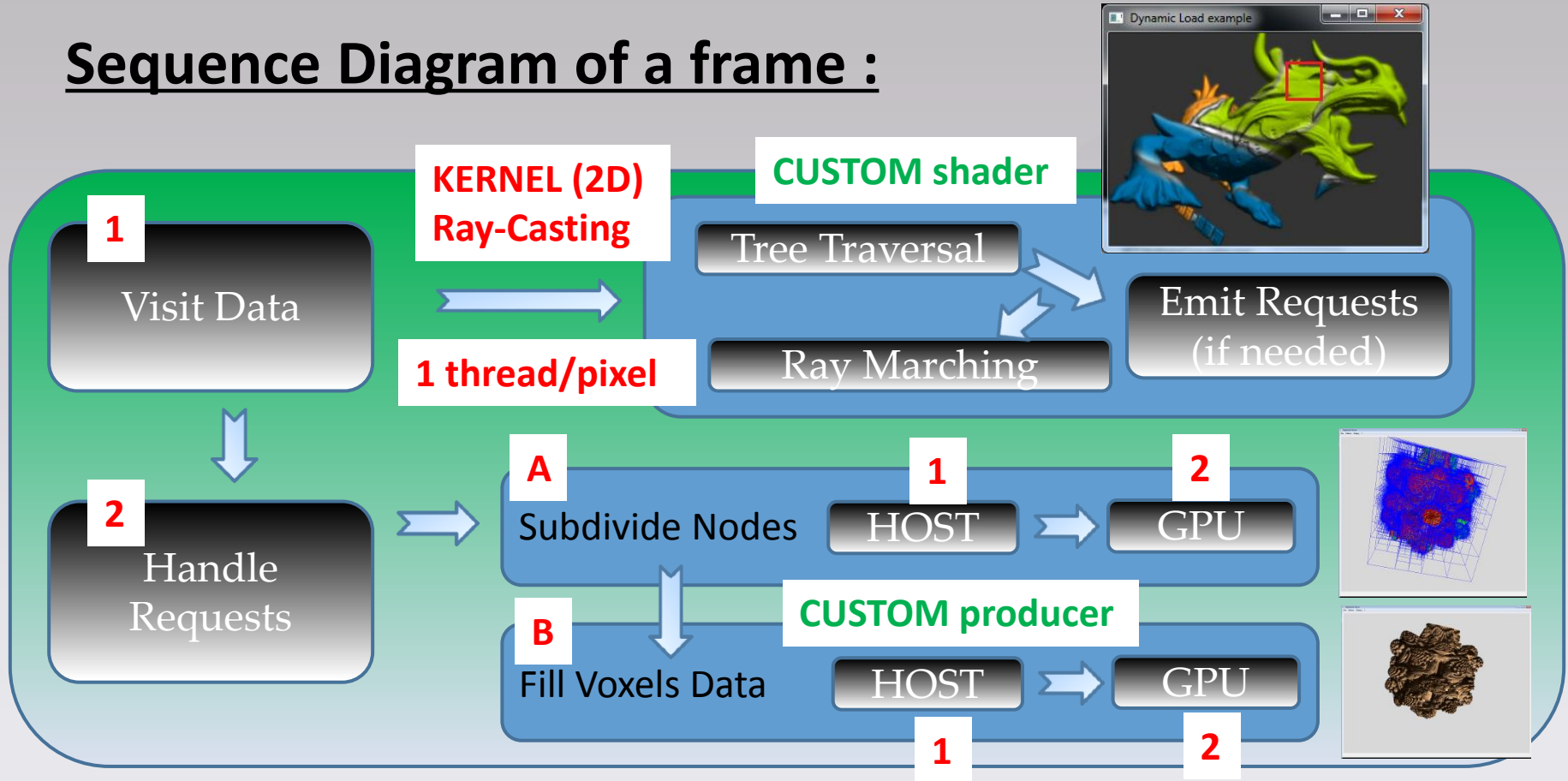
- Nodes subdivision (data refinement)
- Load or compute bricks of voxels (fill data)

USER has to write :

- a HOST producer
- and its associated GPU producer

Data Production Management

Sequence Diagram of a frame :



Sequence

Frame 1

Produce Nodes



Produce Bricks

Frame 2

Produce Nodes



Produce Bricks

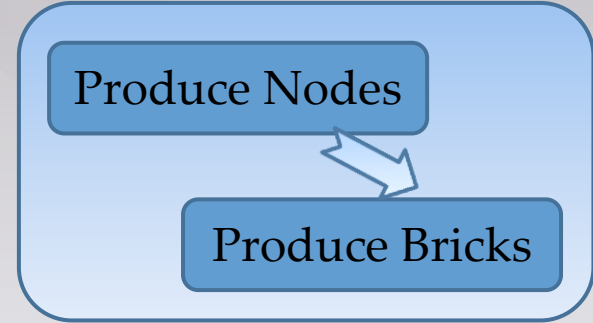
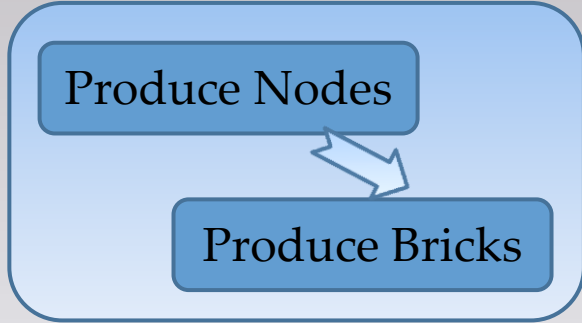
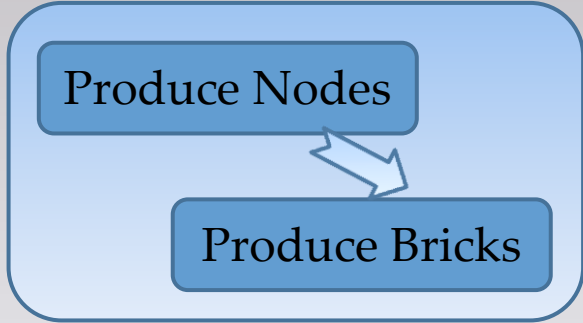
...

Frame N

Produce Nodes



Produce Bricks

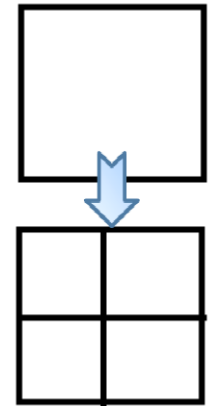


Ex : sphere on GPU

Parent

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



Children

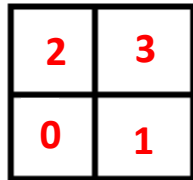
Ex : sphere on GPU

Nodes subdivision :

WORLD : sphere



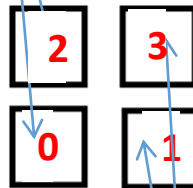
Parent



**Children
- what's inside ?**



empty



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, render will ask for the node data production (brick of voxels)

Ex : sphere on GPU

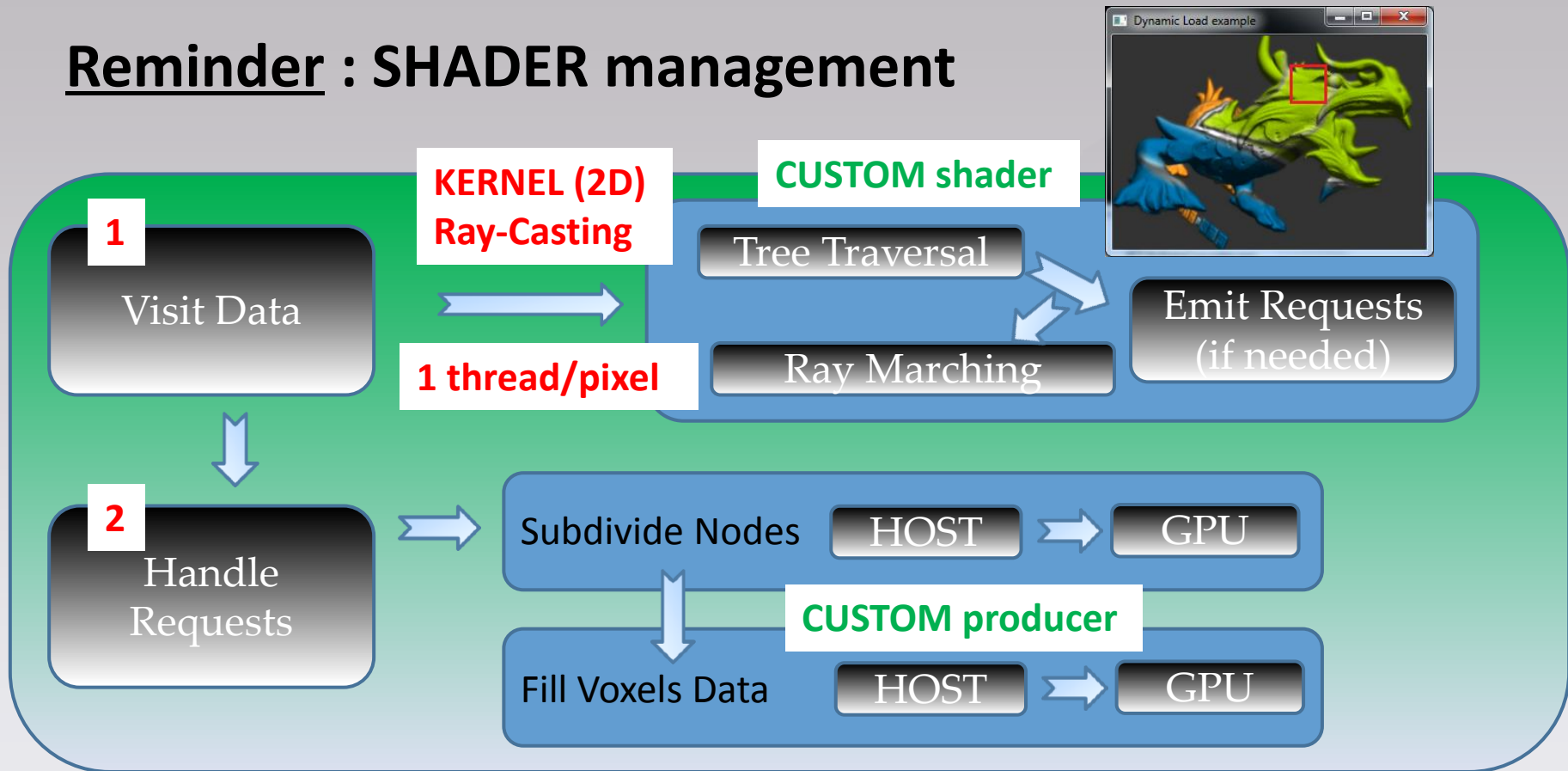
Bricks of voxels production :

(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

Reminder : 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

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
- 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 represented 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

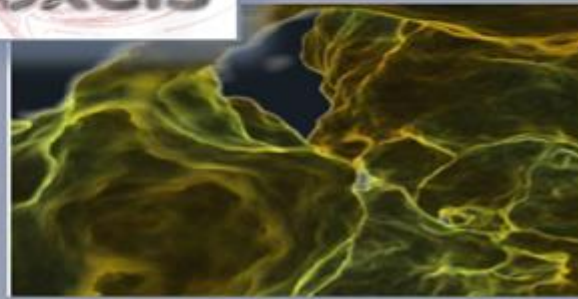
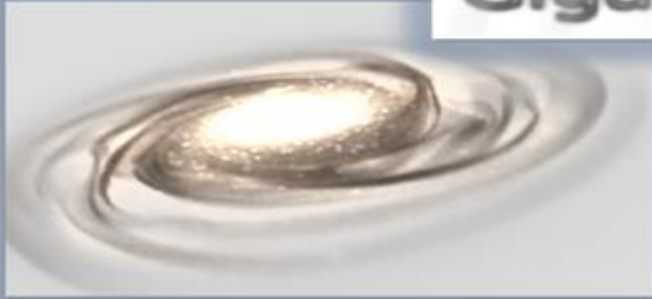
- Fabrice Neyret (CNRS, INRIA, LJK), M. Armand, E. Heitz, E. Eisemann, ...
- Cyril Crassin (NVidia)
- Nvidia : for cards donation (Chandra Cheij)
- ✓ RSA Cosmos : for testing the library
- ✓ French Research ANR :

GigaVoxels is supported and funded in the project
ANR "RTIGE" (Real-Time Interactive & Galaxy for Edutainment)
of reference ANR-10-CORD-0006

Questions



GigaVoxels



Thanks
for
your
attention

<http://gigavoxels.inrialpes.fr/>