NVIDIA®
GVDB Voxels

Programming Guide

Version 1.0

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Introduction

1.1. GVDB Voxels Overview

NVIDIA® GVDB Voxels is a framework for large scale data storage, computation, simulation and rendering of sparse volumetric data on GPUs. Inspired by the award-winning open source OpenVDB data structure, GVDB Voxels uses a sparse hierarchy of grids to efficiently represent large data volumes. Taking advantage of CUDA for GPU computation enables developers to create massively parallel simulations and rendering engines that scale with future NVIDIA hardware.

GVDB Voxels envisions sparse structures and voxel data as a fundamental unit for data computation and thus has widespread applicability to motion pictures, 3D printing, scientific simulation and data visualization. GVDB Voxels is based on computation at its core with the only dependency being CUDA. With this premise, GVDB Voxels introduces two distinct programming APIs for compute and rendering. The Compute API allows for sparse computation, simulaton and analysis without any dependency on a graphics APIs. When efficient rendering or visualization is desired, the Raytracing API provides both a native CUDA raycasting engine and integration with NVIDIA OptiX for high quality raytracing. This focus on computation allows GVDB Voxels to be easily ported to headless graphics systems such as the Tesla architecture for massive supercomputing applications, or to devices such as the Jetson TX1/TX2 with Tegra for embedded applications. An emphasis on computation allows the application developer to decide when and how to visualize results.

GVDB Voxels was designed with the idea that sparse 3D computation can be broadly applied while the underlying data type is flexible. Therefore, while voxels are the most common data type, GVDB can be used in other applications where sparse acceleration is needed. For example, entity tracking as applied to crowd simulation may track people moving in a three dimensional space as points moving on a sparse grid, making use of topology acceleration without the need for voxels. Other applications, such as 3D printing may involve transforming between different geometry primitives such as polygons and voxels.

Overall, the design of NVIDIA® GVDB Voxels meets an increasing demand for efficient storage, simulation and rendering of very large data stored on grid structures.

1.1.1. Motivation

Increasing demands for large scale data representations can be found in many applications areas. In the motion pictures industry, the need for high quality fluid and smoke simulations motivates efficient computation with massive volumetric data. In additive manufacturing there is an growing need for part analysis and model processing, in addition to rendering, which motivates the need for flexible large-scale computation. In scientific visualization, modern instruments enable the collection of extremely large, out-of-core data sets that are difficult to manipulate, analyze and render with classical techniques.

The goal of NVIDIA® GVDB Voxels is to enable a range of applications in multiple disciplines where there is a need for large scale computation with the greatest flexibility at the point of computation.

1.1.2. Design for Computation

The desire to create a broad framework for computation influenced several design choices for NVIDIA® GVDB Voxels. Some of the most important among these factors are:

- Core computation on sparse 3D grids
- Minimal external dependencies
- Easy to build and deploy on many architectures
- Flexible and easy authoring of compute kernels, without sacrificing performance
- Customization at level of both the library and user level
- No strict dependency on graphics (while still providing it)

Core Computation

The core of NVIDIA® GVDB Voxels consists of a CUDA-based engine which maintains a sparse **topology** and multiple **atlases** of data.

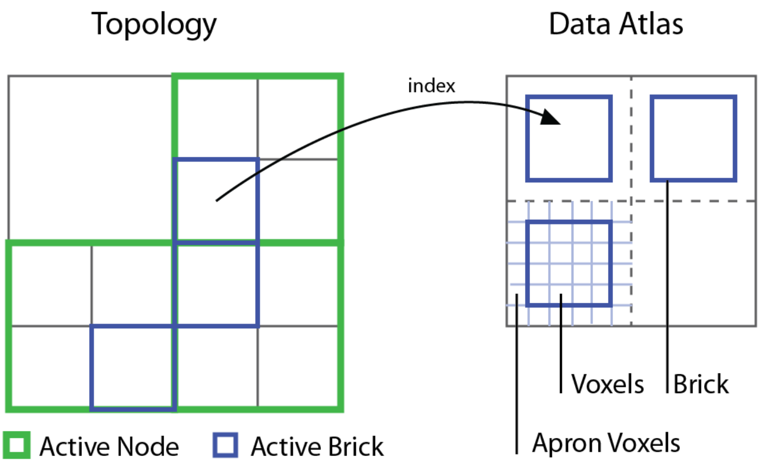


Figure 1.1. The VDB **topology** is an acceleration structure that indexes into voxel data stored in an **atlas**. A group of voxels in an atlas is a **brick**.

The **topology** represents a 3D spatial layout of potentially very large data sets, and the sparse quality implies this data is stored only near interesting features.

Although GVDB Voxels is ideally suited to strongly sparse data, it still provides several benefits in accelerating dense data (see Chapter 3.2).

An atlas represents voxel data as a set of **bricks**, where each brick is a small unit of data – often 16^3 or 32^3 voxels – whose size is choosen to balance performance and memory. A voxel atlas, similar to a texture atlas, is a collection of bricks packed into 3D texture memory for easy access.

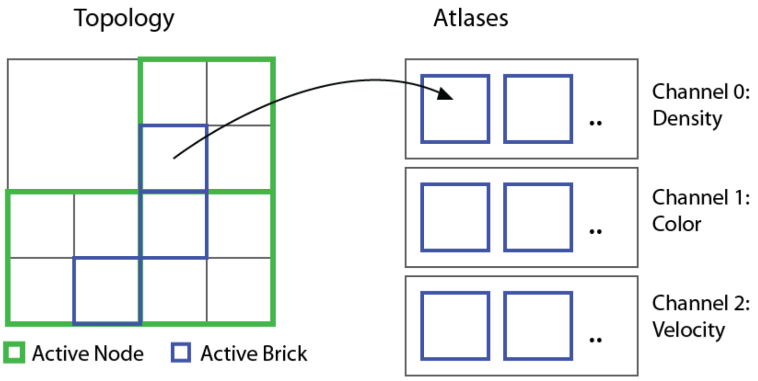
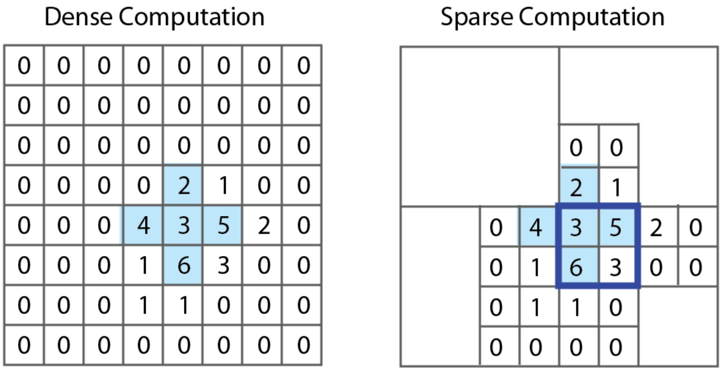


Figure 1.2. Multiple atlases are used to store **channels** of data, or per-voxel attributes. A brick has the same index in each channel.

Multiple **atlases** are used to implement voxel data **channels**. Each data channel has a specific type, such as a float, unsigned char, or float3 (vector). Together, these multiple channels provide an arbitrary set of per-voxel attributes over the entire volume. With this flexibility, it is possible to author complex fluid simulations, generative computations, and many other applications.

Computing with Virtual Neighbors

Performing massively parallel computations is the premise of GVDB Voxels. While the benefit of sparse volumes is greater efficiency and lower memory footprint, a common criticism is that this increases complexity for the developer.



0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	2	1	0	0
0	0	0	4	3	5	2	0
0	0	0	1	6	3	0	0
0	0	0	1	1	0	0	0
0	0	0	0	0	0	0	0

		0	0		
		2	1		
0	4	3	5	2	0
0	1	6	3	0	0
0	1	1	0		
0	0	0	0		

Figure 1.3. Dense computation gives easy access to neighbors (left), but performs too many calculations. Sparse computation is efficient but makes neighbor lookup across brick boundaries more difficult (right).

GVDB Voxels eliminates kernel code complex by allowing developers to write voxel-based computations *as if they were on a dense grid*. We refer to this as computing with **virtual neighbors,** a method which internally optimizes neighbor lookups so you don't have to and presents kernels with fast access to neighbors even at brick boundaries. This frees the developer to focus on the details of computation and write kernels with simple neighbor stencil operators without conditions. This is accomplished with apron voxels and a generic method for apron updates interspersed with user kernels.

Virtual neighbors is a key feature in the development of optimized simulations as one can write stencil kernels that make implicit use of shared memory, equalize the occupancy of interior and brick-boundary voxels, and create balanced, branch-free threads – all with simple finite difference style kernels. Addition details on the implementation of virtual neighbors computing can be found in Chapter 5, Compute API.

Customization

To provide the greatest flexibility, NVIDIA® GVDB Voxels is released as open source software. This gives developers significant freedom in modifying GVDB Voxels to suit the needs of any given application.

For complex applications, it may be necessary to taylor the GVDB structures to suit a particular problem. Influenced by the pioneering work of OpenVDB we anticipated that as a general computing framework GVDB could not support multiple disciplines without being open source since the number of algorithms and their variations grows rapidly. Therefore, GVDB can be modified at every level so that developers can meet their particular needs.

For simpler applications, one should not have to modify deep structures within GVDB in order to achieve customization of functionality. Therefore, we designed GVDB Voxels with several layers. First, GVDB Voxels is implemented as a **library**, and the simplest applications make API calls to perform build-in functions such as smoothing or rendering.

At the next level, users can implement **custom kernels** for either computation or rendering. These CUDA kernels are written and compiled in the application code but launched from special GVDB functions (named ComputeKernel and RenderKernel). This allows the user-code to reside outside the library, while the GVDB library still has the ability to perform acceleration and boundary-free computing. The gRenderKernel sample shows how to implement a custom kernel for rendering. Beyond the use of custom kernels, application developers can call lower level functions, such as changing topology to perform GVDB operations without modifying the library.

At deeper layers, the GVDB Library can be modified as needed. The simplest of these changes is to modify or write new algorithms over the data structures already provided by GVDB. For example, one might write a raytracing algorithm that uses two channels simulatenously - one for density, another for material ID. The most extreme changes to GVDB involve modifying the underlying representation of topology, or **nodes**, of the tree. Multiple channels can achieve most goals where voxel attributes are needed, but it could be necessary to modify nodes themselves when implementing complex features such as out-of-core rendering (e.g. to track brick residency). As open source software, all of these levels of GVDB are available to the developer.

Computational Geometry

Many applications require complex interoperation between different types of geometry. For example, rigid body and fluid simulations in Motion Pictures often utilize both point clouds and voxel grids to perform efficient, and accurate, simulations. 3D Printing often involves a conversion from a polygonal mesh to a voxel grid. One of the most challenging aspects of general GPU-computing is that each combination of geometry and data suggests a very specific parallel algorithm.

NVIDIA® GVDB Voxels helps to alleviate this difficult problem by observing that each geometry – points, polygons, or voxels – lends itself to a particular GPU representation that aids in issues such as coherency and locality. For example, a common pattern established for dynamic point clouds (such as SPH fluids) is to perform a *binning* and *sorting* operation that reduces the problem size for neighbor search. For voxels, the division of space into *bricks* helps to localize computation for the GPU while eliminating unnecessary calculations when the data is sparse. Naturally it is not possible address every combination of geometry and acceleration structure, therefore we present a generic approach that can be specialized as needed.

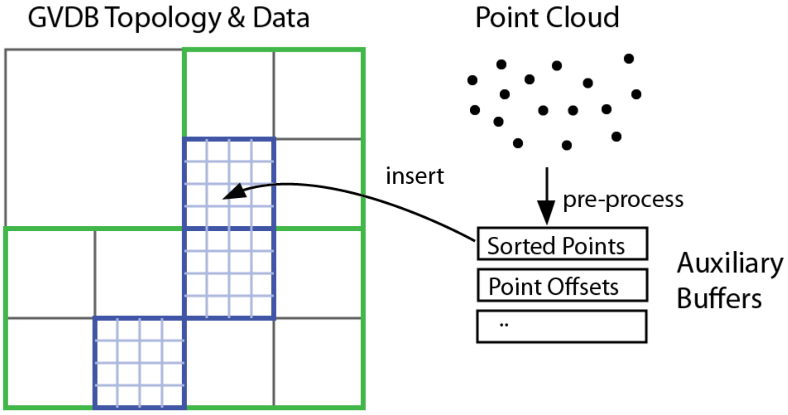


Figure 1.4. Computation is accelerated with **auxiliary buffers.** For example, directly inserting a point cloud into a volume is inefficient. Parallel computation suggests pre-sorting by brick for coherence. Multiple auxiliary buffers are used for pre-processing, and points are inserted from these.

GVDB Voxels introduces **auxiliary buffers** to help accelerate any computation performed with geometry other than voxels, or in relation to voxels. Auxiliary buffers provide memory management and CPU-GPU transfer for arbitrary types of data. They have a wide variety of uses, from point cloud insertion to polygonal conversion. GVDB natively implements several API functions for computational geometry. These include:

- Polygon-to-Voxel conversion
- Point Cloud insertion and lookup
- Point Cloud-to-Voxel scattering and gathering
- Tracing of Rays with arbitrary origin & direction

Each technique may utilize several auxiliary buffers to achieve high GPU performance. For example, Point Cloud insertion utilizes one aux buffer to insert points into a grid, then another to perform a prefix scan for data locality, and a third aux buffer as a deep copy for data coherence. This principle is applied throughout GVDB Voxels, where *scan* and *reduction* on auxiliary buffers are performed as needed to accelerate a wide variety of geometric types in a relatively uniform way.

Memory Management

Memory management in GVDB Voxels was designed to eliminate many of the common issues often associated with GPU-computing, while also providing flexibility to advanced developers seeking greater control over peformance.

Among the most difficult challenges for new projects is management of both CPU and GPU memory. With CUDA 6, NVIDIA introduced Unified Memory, or managed memory, to provide a single memory space so that applications no longer concern themselves with the CPU-GPU memory barrier. The latest Pascal Architecture, with CUDA 8, provides way to optimize the locality of data and provide hints to improve performance.

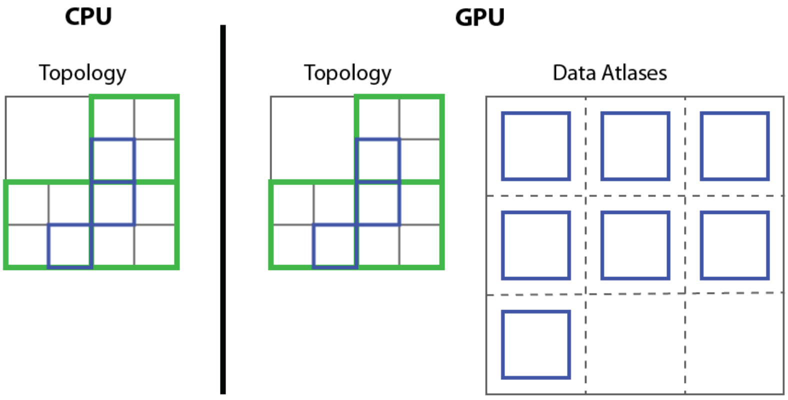


Figure 1.5. Typical memory usage in GVDB Voxels. The CPU and GPU both store the entire topology, with a typical size around 5-10 MB. Only the GPU stores the atlas data, which can occupy several gigabytes.

NVIDIA® GVDB Voxels uses an explicit memory allocation layer that results in identical data on both the CPU and GPU, and does *not* make use of Unified Memory. The topology of GVDB uses indices so that transfers are easy and transparent to the user. The atlas data is selectively transferred to the GPU, and often has no backing store on the CPU to conserve memory. Brick transfers, which can occur often in out-of-core applications, are more easily accomplished if the data representation can reside on both CPU or GPU without translation.

GVDB Voxels provides an explicit, seamless, memory allocator with API functions to allow the developer to decide exactly when to perform transfers without having to examine or modify the data.

Distributed Computing

NVIDIA® GVDB Voxels is well suited as a core engine for distributed computing, but does provide any explicitly features in this area. The focus of GVDB Voxels is to provide the best performance and scaling on single-GPUs so that distributed applications that wish to use GVDB will scale accordingly.

Several design decisions make GVDB Voxels a good choice as the core framework for distributed applications. First, GVDB depends only on CUDA, make it suitable for Tesla, GRID and supercomputing architectures without graphics output. Second, voxel operations scale naturally in GVDB with better per-node hardware. Finally, the structure of a VDB grid naturally partitions space which requires only minimal transfer of data between nodes in distrubted computing environments.

In the future NVIDIA® GVDB Voxels may provide addition features to facilitate brick-level transfers between GPUs, transfer of node boundaries between GPUs, or other features that enable distributed computing. In this current release, GVDB Voxels focuses on single-GPU scaling and performance.

Flexible Architecture

The current version of NVIDIA® GVDB Voxels implements a VDB topology over 3D texture-based atlases. Due to the connection between topology and data, it should be relatively easy (compared to other frameworks) for developers to drop in a different topology, or different data storage.

The current atlases are stored using 3D textures with CUDA bindless texture objects, allowing multiple channels to be accessed simultaneously from a single kernel. However, it may be useful to experiment with linear memory, or sparse hardware textures, as the atlas storage type. Currently, GVDB can already switch between OpenGL generated 3D textures and textures created as CUarrays (cuArrayCreate3D). As the code is available, developers are welcome to experiment with other storage methods.

The topology is the most central aspect of GVDB Voxels. However, the API was designed to facilitate operations that would be applicable to many different topologies. The VDB grid itself is already capable of imitating several different layouts such as octrees, N-ary trees and tilemaps. However, it may be desirable to drop in specific alternatives such as optimized hash tables (tilemaps) or explicit octrees. The GVDB Voxels API abstracts such operations a spatial coverage (ActivateSpace), topology completion (FinishTopology) and atlas updates. We recommend that developers pursuing alternative methods follow these API patterns as they lend themselves to sweep-based parallel computation.

1.1.3. Design for Rendering

The motivation of NVIDIA® GVDB Voxels for rendering is to provide basic high quality, accelerated raytracing of voxel data essentially for *free*, with the ability to extend to more complex rendering as desired. In scientific computing the primary effort is often the simulation, where one often wishes to visualize the result without fuss (for “free”) but with sufficiently high quality to resolve details. To that end, the GVDB Voxels provides native CUDA and OptiX rendering pathways with previsualization or high quality rendering.

In many applications the goal may be to improve on rendering quality. Thus, in addition to the native pathways, GVDB Voxels provides a custom rendering pathway which enables the developer to author kernels that seamlessly integrate with GVDB sparse acceleration.

CUDA & OptiX Rendering

GVDB Voxels provides two pathways for rendering volumes. The first is a CUDA-only raycasting renderer that gives previsualization quality with high performance. The second is an OptiX-integrated raytracer that allows for high quality multiple scattering at interactive rates. Both rendering engines are capable of switch modes to render with volumetric deep sampling (ray-sampling), rendering isosurfaces with on-the-fly trilinear or tricubic filtering, rendering level sets, and rendering voxel previews (tiny cubes).

GVDB Voxels is primarily written in CUDA, with the same raytracing kernels being used for OptiX since the latter is also based on CUDA. The only addition in GVDB Voxels to support OptiX is an alternative pathway for declaring and accessing variables which is handled via header files. The code pathways are otherwise identical. For the sake of simplicity, GVDB Voxels itself does not link to OptiX or contain any host code for OptiX. Instead we have included a sample, gInteractiveOptiX, which contains an integration OptixScene class that handles the communication between OptiX and GVDB.

Customization

Developers who wish to explore new methods in rendering have several options for customization. The most basic customization is to provide a Custom Render Kernel (see Chapter 6.4) that shades a return hit point, allowing GVDB to perform the raycast. At the next level, users can write kernels to modify the way points are sampled within a deep volume. A more complex customization would access multiple channels of data to mix additional per-voxel attributes such as color or material ID. Finally, the GVDB ray tracing technique is open source so that developers can modify the tree traversal itself, typically to return or pass new information between leves. These customizations are described in Chapters 5.4 and 6.4.

Interaction with OpenGL

For greatest flexibility, GVDB Voxels uses multiple CUDA buffers for output results. These are maintained by the API with **render buffers** that are requested before hand. We have provided an interop mechanism that allows applications to return render buffers an OpenGL textures. This gives a simple way to integrate CUDA or OptiX rendering into interactive applications. For example, several demos render GVDB volumes to a full screen texture and then overlay additional OpenGL GUI widgets in the sample.

For proper integration of volumes into OpenGL scenes, it is necessary to return a depth buffer so that OpenGL objects can be mixed with volumes based on depth. GVDB Voxels provides a mechanism to use depth as input during volume rendering, and to return depth buffers as output.

Chapter 2. Programming Overview

The GVDB API is designed as a C++ class interface with built-in functions for common operations. More advanced users can access the host and GPU device API separately with custom compute and rendering kernels.

2.1. Topology & Data

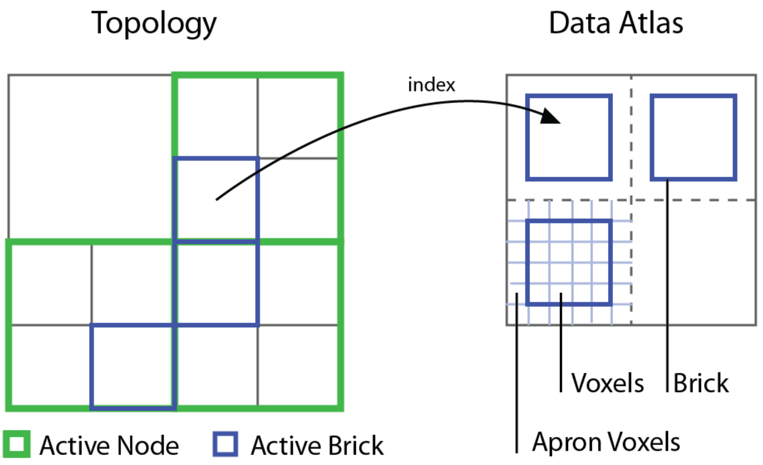


Figure 2.1. The GVDB paradigm separates the *topology* from the *data* to provide several benefits in flexibility. Data is maintained in multiple *channels*, stored in memory with 3D textures called *atlases*.

NVIDIA® GVDB Voxels makes a separation between the **topology** and **atlas** of sparse voxel data. The topology must still refer to data in the atlas via some mechanism and, unlike tree implementations using pointers, GVDB Voxels uses indices both for tree nodes and atlas indexing.

2.1.1. Topology

The **topology**, as used in GVDB Voxels, describes an acceleration structure over a spatial domain. For example, a BVH, an octree, and an *n*-ary tree are all acceleration structures with different properties, splitting conditions and branching factors. The topology implemented by GVDB is a hierarchy of grids based on [Hoetzlein 2016] and [Museth 2013], which has advantages over other structures for dynamic changes. A unique feature of a VDB topology is that it generalizes many other structures, including octress and *n*-ary trees. In this document the topology typically refers to the GVDB hierarchy of grids unless otherwise noted.

A topology is composed of multiple **nodes**, and the lowest level of the tree consists of nodes which refer to **bricks**, and which have no children. For any given level, all the nodes at that level will have the same resolution.

2.1.2. VDB Configuration

The key feature of a VDB topology is its **configuration**, which specifies in shorthand the resolution of the nodes at each layer of hierarchy of grids. The configuration is a vector which gives the log2-dimension of each level.

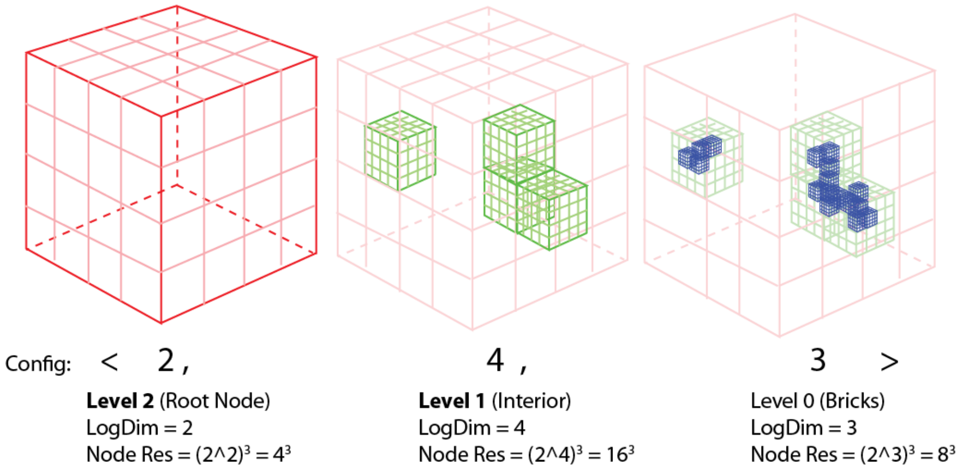


Figure 2.2. Configuration of a <2, 4, 3> tree. Each component is the log2dim of that level. For example, the interior (middle) level has logdim = 4, resulting in $(2^4)^3$ or 16^3 node resolution. All bricks at that level will be 16^3 voxel.

In GVDB Voxels, the configuration can be specified at run-time. The maximum number of levels defaults to 5, although most scenarios will use fewer levels. Unused levels contain 1 or 0 nodes. Nearly all use cases can be covered with five level trees, as the maximum addressable space is $(10\text{^}12)^3$ voxels using an <8,8,8,8,8> tree.

The only scenario in which more levels are needed is when using a very large domain with very small bricks. For example, an octree quickly requires more than 5 levels. To increase the maximum beyond five, the GVDB Library can be rebuilt with a higher limit.

The **maxmum resolution** of a VDB grid can be found by multiplying the node resolutions at each level. For the example in *Figure 2.2.*

$$\begin{aligned}\text{Maximum Res} &= [\ (2\text{^}\mathbf{2})*(2\text{^}\mathbf{4})*(2\text{^}\mathbf{3})\ ]^3 \\ &= [4\ *\ 16\ *\ 8]^3 \\ &= 512^3\end{aligned}$$

Thus, the <2,4,3> tree is equivalent to a 512^3 volume.

The VDB configuration can be specified with Configure():

```
gvdb.Configure ( 3, 3, 3, 3, 5 );
```

A recommended VDB grid configuration for most scenarios is the <3,3,3,3,5> grid. This is based on research by Hoetzlein [2016], which shows that smaller upper levels, and larger bricks, are more efficient for raytracing traversal. This configuration has a maximum resolution of $131{,}072^3$

2.1.3. Atlas Data

The **atlas data** refers to the actual storage of voxels or other entities. The atlas is composed of a number of **bricks** which are dynamically allocated at run-time. Each brick is a small, cubic sub-domain of voxels for a single attribute. A common size for bricks is 16^3, 32^3 or 64^3

The key feature of an atlas is its **type** and **size**. An atlas is allocated in GVDB as a 3D texture (or CUarray) of a specific data type. The overall **size** of the atlas determines the maximum number of bricks it can contain.

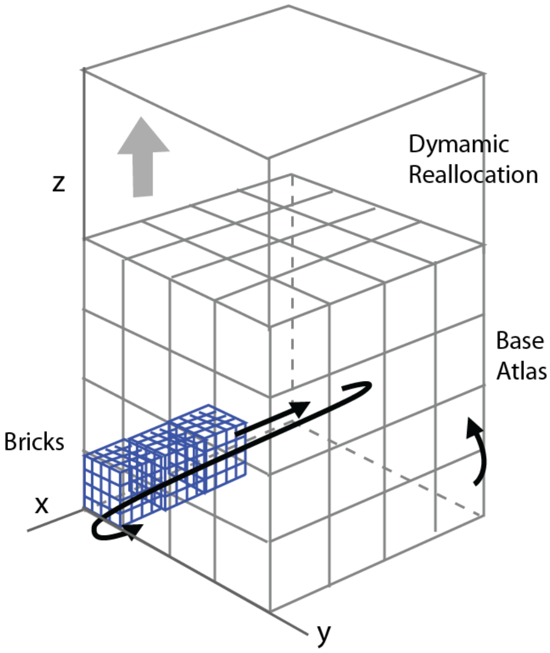


Figure 2.3. Atlas structure with bricks allocated along X, then Y, then Z. When more bricks are needed, the atlas will be dynamically resized along the Z-axis. The atlas also contains apron voxels (not shown) for neighbor lookups.

An atlases stores bricks in arbitrary order with no correlation to world space. GVDB assigns bricks along the X and Y axes, and then continues to stack them upward in Z. To allow for dynamic topology, the atlas may be reallocated with a higher Z-height in order to accommodate more bricks.

Maintaining data in *atlases*, distinct from the topology, enables a number of unique benefits. First, multiple atlases can be introduced to store different types of data at each spatial location, called *channels* in GVDB. Second, since the data is typically much larger than the topology, it is possible to move large amounts of data for manipulation, computation, or I/O, without touching the topology. Third, as the topology is somewhat independent of the data, it is possible to experiment with the performance of different topology configurations without altering the data. These benefits and others motivate the distinction between *topology* and *atlas data.*

2.1.4. Implementation

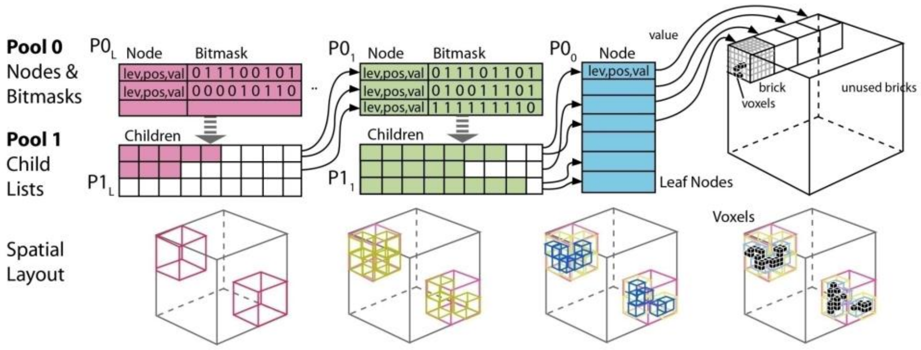


Figure 2.4. Internal representation of a GVDB grid uses multiple node pools; one per level (e.g. blue, green, red). Each level is divided into two groups. Group P0 contains node data & bitmasks, group P1 contains child lists. Each leaf node indexes into a brick in a data atlas. [Hoetzlein 2016].

Internally, the topology of GVDB is implemented using a set of memory pools as described in [Hoetzlein 2016]. This design significantly improves performance for dynamic brick allocation and simplifies data transfers between CPU and GPU.

2.2. Basic API Design

NVIDIA GVDB is designed as a simple, command-based API for common functional tasks. These tasks operate on the topology and data of a sparse volume. Every GVDB application makes use of the basic API to prepare, populate and manipulate data whether using built-in or custom kernels.

The main API categories are:

- **Initialization** – Functions that start or prepare GVDB
- **Data Preparation** – Functions, including file I/O and compute operations, that load, manipulate, or process volumetric data.
- **Scene Settings** – Functions that initialize common settings for volume rendering such as lights and cameras.
- **Render Buffers** – Functions that maintain one or more render buffers used for rendered output, depth buffers, or depth inputs.
- **Raytracing** – Functions that perform built-in or custom raytracing of volumetric data with different styles.
- **Points & Polygons –** Functions that convert to or from point clouds, polygons and voxels, with algorithms for transforming between them.
- **Dynamic API –** Functions that rebuild a topology or allow for dynamic topology changes over time.
- **Accessor API** – Functions for low-level manipulation of the GVDB topology and data values available on both the host and device.

These API categories are covered in increasing complexity in this Programming Guide. This chapter addresses the most basic API use of common built-in functions to perform simple tasks.

2.3. Initialization

Initialization of GVDB is achieved by linking your application to the GVDB Library and declaring a VolumeGVDB object. The primary interface for GVDB is the VolumeGVDB class, which can be initialized as follows:

```
#include "gvdb.h"
using namespace nvdb;

VolumeGVDB   gvdb;
```

The VolumeGVDB object resides in the **nvdb** namespace, so it is common to use this namespace to access the object.

Limitation: In this release, only a single VolumeGVDB object may be created per program as a singleton.

Once created, the VolumeGVDB object is used to initialize GVDB as follows:

```
int devid = -1;
gvdb.SetVerbose ( true );
gvdb.SetProfile ( false );
gvdb.SetCudaDevice ( devid );
gvdb.Initialize ();
```

SetVerbose turns on or off verbose output from GVDB, including measurement of the performance statistics discussed in section 3.3.

SetProfile turns on or off profiling, which enabled nvtx performance markers for GPU Profiling with NVIDIA NSight, and also CPU Profiling with high performance counters output to a console window.

SetCudaDevice specifies which CUDA Device should be used by GVDB. A value of -1 indicates that GVDB is free to initialize the first CUDA Device it finds. Other values can be specified after enumerating devices.

The **Initialize** function starts GVDB itself and prepares all necessary internal structures, but *does not* create a topology or atlas data.

StartRasterGL is used to initialize OpenGL with GVDB, and is only needed when using functionality that requires an OpenGL context. This should be called after the application creates an OpenGL context. Such functions, like PolyToVoxelsGL are suffixed by GL. An example of these function in use can be found in the g3DPrint sample.

2.4. Data Preparation

Data preparation refers to several different methods available to build a GVDB topology and populate atlases with data. Several key concepts are involved in preparing a GVDB with data for rendering or further processing. These steps usually occur in order, although some many be repeated when working with dynamic data.

- Configuration – Specifying the structure and shape of a *topology,* without creating any nodes.
- Adding Channels – Specifying the *data* format and number of data channels, without adding any data
- Activating Space – Requesting GVDB to add topology nodes to define the sparse regions of the spatial domain to be covered.
- Update Atlas – Requesting GVDB to expand or restructure the atlas channels to support the changes in topology.
- Adding Data – Steps to create, generate, or import actual data into channels.
- Output/Rendering – Making output data or creating rendered images of the stored data.

Every application with perform these steps in some way, although often several of these steps will be hidden inside simpler built-in functions. For example, LoadVBX performs all steps above except rendering. A few different use cases for data preparation are worth nothing.

Case 1. Load existing Topology and Data

The simplest method of data preparation is to read volumetric data from disk using a load function. These are described in detail in chapter 10, and include support for VBX, RAW and OpenVDB files formats.

The native format of GVDB is the VBX format, which can be loaded with LoadVBX.

```
gvdb.LoadVBX ( “data.vbx” );
```

Loading a data file from VBX or OpenVDB automatically reads the configuration, atlas definition, node layout and atlas data, thereby making a scene ready for rendering.

Case 2. User Configuration, Generated Nodes and Data

In many applications, the user will configure the topology and voxel size to achieve a specific performance or quality goal. Then, the application might call GVDB functions that will generate nodes and atlas data automatically. A good example, shown here, is the SolidVoxelize function for converting a polygonal mesh to voxels.

The first steps are to configure the tree, add data channels, and set the voxel size (or resolution):

```
gvdb.Configure ( 3, 3, 3, 3, 5 );

gvdb.AddChannel ( 0, T_UCHAR, 1 );

gvdb.SetVoxelSize ( 0.4, 0.4, 0.4 );
```

The **Configure** function defines the *shape* of the topology and initializes it to an empty tree with no nodes. See section 3.1 for details on topology configuration. For many applications, the <3,3,3,3,5> configuration is suitable.

The **AddChannel** function defines the data type for a given channel, and initializes these with empty atlases containing no data. This can be called multiple times to create additional channels. See section 3.2 for details on atlas definition.

The **SetVoxelSize** function defines the size of a voxel in world units. This allows for direct control over the voxel resolution, and defines the smallest size of a voxel. A corresponding function **SetVoxelRes** can be used instead, if it is more natural to specify the overall effective resolution of the world domain. See section 3.3 for details on resolution.

Once the tree is configured, and channels are specified, it is possible to call functions such as SolidVoxelize to generate nodes and data. Note that with automatically perform the steps of activating space, updating the atlas, and adding data, but leaves the earlier configuration steps to the user.

```
Model* m = gvdb.getScene()->getModel(0);
gvdb.SolidVoxelize ( 0, m, &xform );
```

This function takes the polygonal mesh (m) applies the transform (xform), and voxelizes the model into the atlas channel #0. Notice the function does not take the resolution as input, but relies on the earlier setup to determine the rasterized resolution of the model.

Case 3. User-Specified Configuration, Topology and Data

The most generic use case is when the configuration, activation of sparse regions of space, and data creation are all performed by the developer. A good example of this is the authoring of a novel fluid simulation technique where the developer requires explicit control over the sparse dynamics and multiple channels of data. Another example is authoring a custom data format for import into GVDB.

```
gvdb.Configure ( 3, 3, 3, 3, 5, Vector3DF(1,1,1), 1);
gvdb.AddChannel ( 0, T_FLOAT, 1 );
gvdb.SetVoxelSize ( 0.4, 0.4, 0.4 );

gvdb.ClearTopology ();
for (int n=0; n < num_pnts; n++ ) {
     gvdb.ActivateSpace ( pnt[n] );
}
gvdb.FinishTopology ();

gvdb.UpdateAtlas ();
gvdb.ClearAtlas ();
```

The functions for ClearTopology, ActivateSpace, and FinishTopology request that spatial domains are added to the topology of the tree. ActivateSpace will generate all the nodes in the GVDB tree required to ensure that the incoming world point is covered by brick data. See Chapter 8.2 on Topology Rebuild.

The functions UpdateAtlas, ClearAtlas ensure that the atlas channels provide data storage for the nodes, creating bricks as need, and clearing those bricks by zeroing them out. See Chapter 8.3 on Atlas Rebuild.

Summary

NVIDIA® GVDB Voxels allows the steps for data preparation to be performed at any stage in the application for the greatest flexibility. Simple applications can make use of built-in functions, such as load/save, which perform many of these steps internally. More complex applications are able to generate their own topological coverage, update data stored in atlases, dynamically change resolution, or even add and remove data channels at run-time.

Chapter 3.Scene Settings

Scene settings are required to perform native GVDB rendering. Once a VDB configuration is specific, and data is prepared, scene settings provide minimal information on lights, cameras and transfer functions for rendering.

When using built-in rendering fuctionality, settings for *lights* and *cameras* are needed to setup a scene. Unlike NVIDIA OptiX, whose goal is to provide a scene graph hierarchy with a complete set of objects, transformations, and multiple cameras and light sources, the scene structure of NVIDIA GVDB is a simple fixed list of cameras and lights. GVDB Voxels was not designed as a scene graph system, but rather as a basic primitive to fit into other scene systems (including OptiX itself). The scene lights and cameras in GVDB are only used by the built-in CUDA rendering functionality, which provides a limited range of shading choices.

For complete flexibility in rendering, see section 4.3 on Custom Rendering Kernels, which allows the user to write arbitrarily complex CUDA kernels or OptiX programs to achieve any desired look. The definition of complex cameras, lights and other scene objects is left to the application developer to pass into these custom render kernels.

3.1. Scene

Scenes are accessed using the nvdb::Scene object, which can be retrieved from the GVDB object.

```
using namespace nvdb;

Scene* scn = gvdb.getScene();
```

There is only one scene object per GVDB object.
The scene object provides access to:

- Cameras
- Lights
- Polygonal Models (for polygon-to-voxel conversion, etc)
- Transfer Functions
- Volume Raycast Settings

3.2. Camera

Cameras are allocated and managed by the caller. The current camera to be used for GVDB rendering is specified with **SetCamera().**

```
using namespace nvdb;

Scene* scn = gvdb.getScene();
Camera3D* cam = new Camera3D;
cam->setFov ( 30.0 );
cam->setOrbit( Vector3DF(50,30,0), Vector3DF(150,70,150),
                         400, 1.0 );
scn->SetCamera ( cam );
```

This specifies an orbiting-style camera with orbit angles of (50,30,0) (angle, tilt, pitch), a target loction at (150,70,150), with a orbit distance of 400.0
and dolly of 1.0. For a complete list of the Camera3D functions, see the file **gvdb_camera.h** in \source\gvdb_library.

The function scn->**SetCamera**(cam) indicates that this camera is to be used during GVDB rendering. Since the caller maintains cameras, it is possible to create several cameras and switch between them to perform multiple renderings, for example when implementing multiple views.

Interactive rendering is possible by updating the camera parameters and performing a GVDB rendering on each frame, as demonstrated in the gInteractiveGL sample.

3.3. Lights

Lights are also allocated and managed by the caller.

```
Scene* scn = gvdb.getScene();
Light* lgt = new Light;
lgt->setOrbit( Vector3DF(0,40,0),
        Vector3DF(250,250,250), 500, 1.0 );
scn->SetLight ( 0, lgt );
```

The function scn->**SetLight(index, Light*)** assigns a light to the given index number. This allows multiple light sources to be specified.

Lights are used for shadowing and simple shading when using
built-in CUDA-based rendering functions via gvdb.Render.

3.4. Polygonal Models

Models are used to provide polygonal geometry for poly-to-voxel and solid voxelization functions in GVDB.

```
Scene* scn = gvdb.getScene();
scn->AddModel ( “lucy.obj”, scale, tx, ty, tz );
scn->CommitGeometry ( 0 );
```

The **AddModel** function loads an .OBJ formatted polygonal model file from disk a saves it into the next available model slot. The ‘scale’ is pre-computation that scales the model vertices, and ‘tx/ty/tz’ are pre-computed translation applied directly to the incoming vertices during load. Multiple models can be loaded into the indexed list by calling AddModel repeatedly.

The **CommitGeometry** function transfers the polygonal model into an OpenGL vertex buffer object (VBO) for using the on the GPU. The argument indicates which model slot to commit, base 0. Since polygonal models are accelerated with OpenGL VBOs, the **StartRasterGL** function must be called during initialization to provide an OpenGL context.

Models in GVDB are *not* a suitable location for storing models used in mixed polygon rendering, or as a means to store data for generic scene graphs. Rather, models should be viewed as a temporary holding location for polygon-voxel operations.

3.5. Transfer Functions

A *transfer function* is a common way to describe how a volumetric model with various densities should be rendered on screen. Transfer functions are often using in medical and scientific imaging to highlight specific features in volumetric data. Whispy smoke may have a white color with a very low opacity over all density ranges, while a rolling fire might have red, yellow and black colors with high opacity. The purpose of the transfer function is to map, or transfer, the incoming data to a visibile color scheme.

Transfer functions are defined in GVDB Voxels via the Scene object.

LinearTransferFunc (*t-start*, *t-end*, *color-start*, *color-end*);

For generality, a **LinearTransferFunc** call is used to specify a piecewise-linear section of a transfer function. This can be invoked multiple times to define the complete transfer function in small sections with arbitrary detail over the domain range from 0.0 to 1.0.

```
scn->LinearTransferFunc ( 0.0, 1.0,
         Vector4DF(0,0,0,0), Vector4DF(1,1,1,0.5)
```

The simplest transfer function specifies a single linear change over the entire range from 0 to 1. Notice the start and end are 0 and 1.0 respectively. The left-most color is black, no opacity (transparent), and the right-most color is white with half opacity.

Figure 3.1. Linear transfer function from black to white over the range [0,1]

Values outside the range of 0.0 to 1.0 are ignored by the transfer function. However, the volume data may contain densities or values outside this range. The **SetVolumeRange** function is used to map the actual data value to a transfer function value in the range of 0 to 1, which then determines the color and opacity.

SetVolumeRange (*iso-value, min-value, max-value)*

```
scn->SetVolumeRange ( 0.1, -1.0, 2.0 );
```

This indicates the density channel contains values from -1.0 to 2.0, and will remap these to [0,1] before transfer. The value 0.1 gives an isovalue used as a threshold when doing surface rendering.

Several linear functions can be combined to create arbitrarily complex transfer functions.

```
scn->LinearTransferFunc ( 0.00f, 0.25f,
          Vector4DF(1,1,1,0), Vector4DF(1,0,0,0.1f) );

scn->LinearTransferFunc ( 0.25f, 0.50f,
          Vector4DF(1,0,0,.1f), Vector4DF(1,1,0,0.2f) );

scn->LinearTransferFunc ( 0.50f, 0.75f,
          Vector4DF(1,1,0,.1f), Vector4DF(0,1,0,0.3f) );

scn->LinearTransferFunc ( 0.75f, 1.00f,
          Vector4DF(0,1,0,.3f), Vector4DF(0,0,1,0.5f) );

gvdb.CommitTransferFunc ();
```

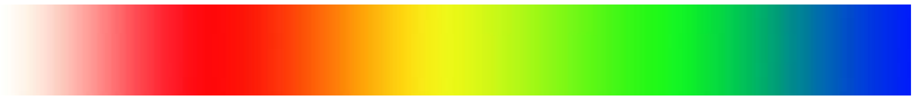


Figure 3.2. Transfer function created from linear piecewise sections using the code above. Notice the t-values can be shifted to compress portions function or make discontinuities, and the alpha channel can be modified with the color.

For an example of using transfer functions in practice see the gRenderToFile or gInteractiveGL samples.

Commit Transfer Function

After specifying a transfer function, it is necessary to commit the function to GPU so that it can be used for raytracing. This is accomplished with CommitTransferFunc().

```
gvdb.CommitTransferFunc();
```

To rewrite the transfer function, overwrite the values with new calls to LinearTransferFunc over the domain [0,1] and call CommitTransferFunc again.

For information on using transfer functions in OptiX, see Chapter 6.2 on OptiX Raytracing.

Chapter 4.
Data Structures

4.1. Spatial Layout

Voxels exist in a **world space**, which are represented in GVDB using a topology of nodes that have a location in **index space**. Together these define the position of voxels in a 3D world. As mentioned in Chapter 2, the actual storage of voxels is resides in an atlas composed of bricks. Two additional spaces helps to acceleration calculation: **atlas space** and **bricks space**. The motivation for these spaces, and transformations between them are describe here.

4.1.1. World & Index Space

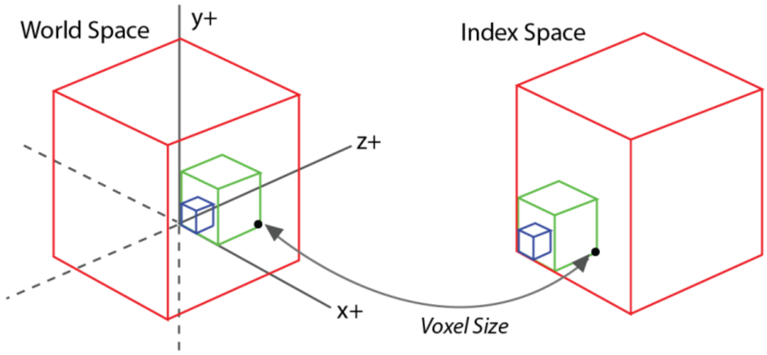


Figure 4.1. World and Index Space

A voxel has a real 3D position in **world space**. This position a real number where the distance from voxel to voxel is the **voxel size**.

The **index space** of a voxel is an integer index which is found by dividing world space by voxel size.

$$I_{vox} = W_{vox} / \text{ voxelsize}$$

The position of all nodes in GVDB Voxels are stored using index space, since this allows for precise sub-division of the world into a hierarchy of grids. Notice that both W_{vox} and I_{vox} can be negative in order to cover the negative domain.

Limitation: The transformation between world and index space is ideally an arbitrary 4x4 matrix. In this release, world and index space are related by the 3D scaling vector **voxel size.**

4.1.2. Atlas Space

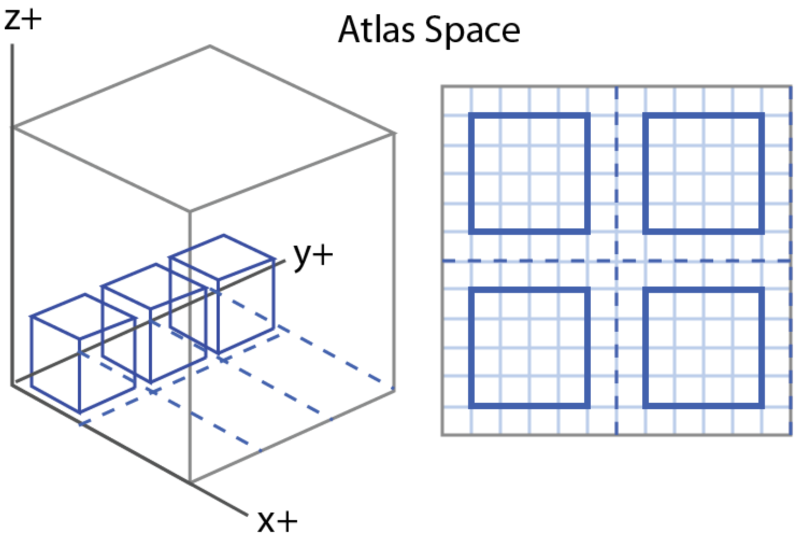


Figure 4.2. Atlas Space. The is the space defined by the texture atlas storing voxel bricks.

Atlas space referes to points or voxels referenced in the data atlas.

The primary purpose of **atlas space** is to perform efficient calculations on the entire sparse volume. Consider the goal of adding noise to each voxel by adding a random value. An inefficient, non-sparse way would be to scan over the entire **world space**, then find each voxel as stored in the atlas space, and add a random number to it. A better, but still inefficient way, would be to launch a kernel for each brick in the atlas, and add a random value to each voxel in the brick.

The most efficient way is to modify *only sparse voxels,* ignoring the rest of the world. This is exactly what is stored in the data atlas. To perform efficient sparse calculations over an entire volume, GVDB Voxels launches a kernel over **atlas space** voxels.

Operations performed using gvdb.Compute all work in this way. There is a single kernel launch over all voxels in the atlas. Voxel operators such as smoothing or noise begin by identifying the atlas space voxel for the current thread. This is common enough that a device macro, GVDB_VOX, is provided to give the **atlas space** voxel. (See cuda_gvdb_operators.cuh)

```
GVDB_VOX:

uint3 vox = blockIdx * blockDim + threadIdx +make_uint3(1,1,1);
if ( vox.x >= res.x|| vox.y >= res.y || vox.z >= res.z )
        return;
```

For many operations, like adding noise, the world position of the voxel is not needed. One only needs to read and write the voxel values:

```
__global___ gvdbOpNoise ( int3 res, uchar chan )
{
    GVDB_VOX

   float v = tex3D<float> ( volIn[chan], vox.x, vox.y, vox.z );
   v += noise();

   surf3Dwrite ( v, volOut[chan], vox.x*sizeof(float), vox.y,
vox.z);
}
```

This simple kernel adds noise to the entire sparse volume. The GVDB_VOX macro sets the 'vox' variable for the **atlas space** voxel in this thread.

Atlas-to-World Space

Often while performing a full volume calculation it is necessary to have the world position of a voxel. Again it is more efficient to launch kernels over the atlas space and then compute their world space than to go the other way. An example is computing the per-voxel distance for each voxel to a world-space object like a sphere.

The device function getAtlasToWorld transforms from atlas to world space.

```
__global___ gvdbOpDistToSphere ( int3 res, uchar chan )
{
    GVDB_VOX

    float3 wpos;
    if ( !getAtlasToWorld ( vox, wpos )) return;
    float v = wpos - sphere.pos;     // distance to sphere
    surf3Dwrite ( v, volOut[chan], vox.x*sizeof(float), vox.y,
vox.z);
}
```

getAtlasToWorld returns true if the world point exists, and false if the atlas voxel does not currently map to a brick in the world. The value of 'wpos' is set upon return to the **world space** position of the atlas voxel.

Additional device functions help to perform tasks in atlas space:

- getAtlasToWorld return the world position from an atlas position
- getAtlasToWorldID returns the brick ID at an atlas position
- getAtlasNode returns a brick map from an atlas position
- getNodeAtPoint return the VDB Node at a world position

See Chapter 5, Compute API, for more details.

4.1.3. Brick Space

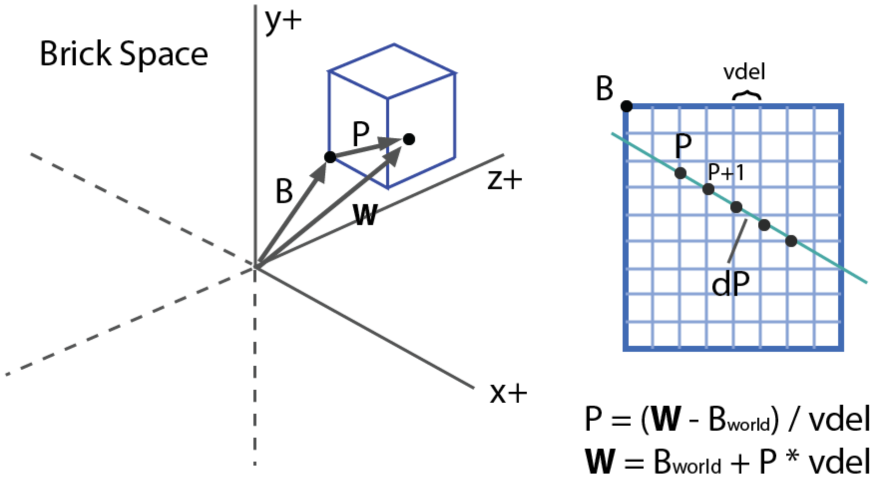


Figure 4.2. Brick Space is a local coordinate system relative to a specific brick.

Brick space referes to a local coordinate inside a specific brick. Recall that a brick is a small, cubic subset of voxels stored in the atlas.

Brick space is used primarily during raytracing. Whereas atlas space is useful when one wishes to perform calculations over all the voxels in a sparse volume, during raytracing one may only know the entry and exit locations for a brick, leaving the rest of the raytracing up to the rendering engine.

Raytracing is more efficient on bricks because one can quickly access and test the data atlas with a brick coordinate. GVDB Voxels uses **brick functions** to perform these calculations, which are internal or customized functions that return the results for a given ray inside a brick. See Chapter 6, Raytracing API, for further details on efficient raytracing with bricks.

World-to-Brick Space

The raytracer will enter a **brick function** with a starting 't' value (parametric coordinate along the ray) along a specific ray, requesting a hit or sample value, as in Figure 4.2. The 't' value gives the starting world coordinate of the entry point.

To march through brick space one first converts the 't' value of a world coordinate, and then transforms from world-to-brick space with the following:

$$P = (\mathbf{W} - B_{world}) / vdel$$

The point in the brick is denoted as *P*. (Figure 4.2). The range of P is $0 \le P < B_{res}$. Thus the brick coordinate P has no meaning outside the resolution of the brick, which may include apron voxels.

The world coordinate of the point is **W**, the world coordinate of the bottom corner of the brick is B_{world}, and vdel is the **voxel size** at node level 0.

Recall that the purpose is to *very quickly* scan through a brick during raytracing. The inner loop should therefore do very few calculations.

Here is a simplfieid example from the rayDeepBrick function which does sample-based volumetric raytracing:

```
__device__ void rayDeepBrick ( char shade, int nodeid, float3 
t, float3 rpos, float3 rdir, float3& pstep, float3& hit, 
float3& norm, float4& clr )
{
   VDBNode* node = getNode ( 0, nodeid, &vmin );
   float3 W = rpos + t.x * rdir;         // world space
   float3 p = (W-vmin) / gvdb.vdel[0];  // brick space
   float3 o = make_float3( node->mValue );
   float val = 0;

   for (iter=0; iter < MAX_ITER && inBounds(p); iter++)
   {
       val += tex3D(volTexIn, p.x+o.x, p.y+o.y, p.z+o.z);
       p += SCN_PSTEP * rdir;
   }
}
```

The value ('val') is the desired accumulated sampling along the ray.

First, the starting position in world space (W) is computed from the ray position (rpos), the ray direction (rdir) and the 't' value. Next, the starting **brick space** coordinate (P) is found using the world-to-brick transformation. Finally, the inner loop scan in PSTEPS (dP) along the ray direction, sampling the data atlas at each sample using the brick coordinates. The offset 'o' is the location of the brick in the atlas, and (P+o) gives the coordinate of the current sample in atlas space for direct texture lookup using tex3D.

This technique is common in GVDB Voxels and results in very efficient raytracing as the inner loop is greatly simplified. GVDB takes care of the sparse processing of rays as they traverse the hierarchy and travel in and out of bricks, allowing the developer to write concise, efficient **brick functions**.

Brick-to-World Space

At times it is necessary to convet from brick space back to world space. This may occur when a ray hits a point and one wishes to return the world hit location. The inverse transformation is:

$$\mathbf{W} = B_{world} + P * vdel$$

An example of this can be found in the raySurfaceTrilinearBrick function, which is a brick function that returns the first hit isosurface in a brick of voxels.

```
__device__ void raySurfaceTrilinearBrick ( … )
{
   ..
   for (iter=0; iter < MAX_ITER && inbounds(P); iter++ ) {
     // check if voxel is above is isoval, if so..
     if tex3D(volTexIn, p.x+o.x, p.y+o.y, p.z+o.z ) > thresh)
     {
          hit = p * gvdb.vdel[0] + vmin; // compute world hit
          return;                        // (vmin = Bworld)
     }
     p += SCN_PSTEP*dir;   // next sample
   }
}
```

4.1.4. Extents and Effective Resolution

Working with actual volume data in GVDB Voxels will cover a finite, sparse 3D volume of the world. A common bound on this data is the **bounding box**, which defines the minimum and maximum extents of the active data in **world space**. GVDB Voxels uses **extents** to refers to the same bounding box in index space for a given volume.

When using dense 3D textures for voxel data, the texture has a a maximum resolution. However, sparse volumes do not have a maximum since they can expand to cover more space as needed. Instead, a useful description of a sparse data set is its **effective resolution**, which is the number of active voxels along each axis. This can be computed as the size of the extents:

Effective Resolution $= E_{max} - E_{min}$

Since the extents E are related to the bounding box by voxel size, we notice that the effective resolution is also equal to:

Effective Resolution $= (\mathbf{B_{max} - B_{min}})$ **/ voxelsize**

This gives a very useful relationship between the **resolution** (detail) of a data set, its **bounding box** in the 3D world, and the **voxel size**.

This calculation comes up frequently in 3D Printing, for example. Let's assume the voxel size is set to the layer thickness of 0.1 mm (10 microns) of a 3D Printer, e.g. voxelsize = <0.1, 0.1, 0.1mm>. Now, the user has requested that the model be printed with a height of 100mm (about 4 inches). This means we can compute the effective resolution, or detail, of the data set required for printing using this equation:

Effective Resolution (Z) = (100mm – 0mm) / 0.1mm = 1000 voxels

Thus, the given parameters result in a volume 1000 voxels high, which can be related to memory footprint and output quality.

4.2. Topology Structures

4.2.1. Nodes

The GVDB Voxels topology is stored as a set of **nodes** residing in memory pools. The same node struct is used at every level of the hierarchy to simplify the design with uniform computation.

For the most part, developers do to not need to understand nodes in order to make use of GVDB. The compute API givers direct access to voxels for computation, and the raytracing API provides user-customizable brick functions to traverse rays through brick and atlas space. An understanding of nodes is helpful when dealing with dynamic topology, for raytracing customization, or when extending GVDB with new functionality.

The GVDB Node structure is:

```
struct ALIGN(16) GVDB_API Node {
public:
       uchar         mLev;          // Tree Level    1 byte
       uchar         mFlags;        // Flags         1 byte
       uchar         mPriority;     // Priority      1 byte
       uchar         pad;           // Padding       1 byte
       Vector3DI     mPos;          // Pos in Index-space   12 byte
       Vector3DI     mValue;        // Value in Atlas       12 byte
       Vector3DF     mVRange;       // Value min, max, ave  12 byte
       ulong         mParent;       // Parent ID     8 byte
       ulong         mChildList;    // Child List    8 byte
       uint64        mMask;         // Start of BITMASK bytes
}
```

The node header, not including the mask bytes, is 56 bytes.
With 16-byte alignment the actual node header size is 64 bytes.
Note that a Node struct is never allocated outright, but always preallocated with additional bytes for the bitmask at the end of the node.
See VolumeGVDB::Configure for examples of how PoolCreate is used to allocate actual nodes.

Node variables have the following meaning:

RESERVED = For future use.

mLev Level of the node in the tree. Level 0 is the brick.

mFlags [RESERVED] Flags for residency, etc.
mPriority [RESERVED] Priority for ray-guided rendering or out-of-core residency swap calculations
pad [RESERVED] Padding byte for future functionality

mPos Position of bottom corner of the node in index space.

mValue The 'value' of the node as an an atlas space position.

mVRange [RESERVED] The minimum, maximum and average range of values for a node. To be recalculated as needed for a given channel ID

mParent Index of the parent node (into pool group 0)

mChildList Index of the child list (into pool group 1)

mMask Starting byte of the node bitmask. Not actually stored.

Location, Size & Extent

The **range**, or index-space size, of a node is determined by the node level:
Nrange = gvdb.getRange (node.mLev);

The **cover**, or world-space size, of a node is determined with the voxel size:
Ncover = gvdb.getCover (node.mLev);

The mPos expresses the **index-space** bottom corner of a node. The opposite top corner index-space is given by:
Nimax = node.mPos + Nrange

The world space **bounding box** of a node can be found by transforming the node from index-to-world.

Nwmin = node.mPos * voxelsize = getWorldMin (node);

Nwmax = (node.mPos + Nrange)*voxelsize = getWorldMax (node);

Bricks and Values

The **value** of a node relates the topology to a data brick in the atlas. Presently, every node in the GVDB hierarchy has a value variable, but only those at level 0 are utilized. This is to allow for future growth in the area of level-of-detail where data bricks might exist at different levels of the hierarchy.

A value of -1 indicates a node has not yet been assigned a brick in the atlas, but is a leaf node residing in world space. That is the topology covers a 3D space with a node but does not yet contain data.

When non-negative, the value is an **atlas-space** position of the brick containing data in the atlas. This position skips the outer apron and refers to the bottom corner of the first actual data voxel.

Parent Node

The **parent** variable (mParent) is a reference to the parent of the current node. References are encoded as a pool group, level and index, packed into a 64-bit value.

```
ref  = Elem ( group, level, index )
     = uint64(group) | (unit64(lev) << 8) | (uint64(index) << 16)
```

The parent of a node always resides in group=0.
The null, or undefined reference value is:

```
#define ID_UNDEFL   0xFFFFFFFF
```

This null value is found for the parent of the root node, and in other contexts.

Children List & Bitmask

The **children** variable is a reference to a list-of-children found in pool group 1.

The list-of-children is decoded using the **bitmask** located in the memory space at the end of the current node. Within the subdivided space of the node, the bitmask indicates which child nodes are active. Those with active bits will have a child present in the list-of-children.

The size of the node bitmask is the number of *potential* nodes is contains, which is given by the log2-dimension of the VDB configuration. For example, with a <2, 4, 3> configuration, all nodes at level 1 have a log2dim=4, which means that all nodes at this level are subdivided with $(2^4)^3$ **= 16**^{3} voxels = **4096** voxels. This is the number of bits which can be active or inactive. The **bitmask** will therefore contain **4096** bits = **512** bytes.

GVDB Voxels has a number of functions to access and traverse children.
See Chapter 8, Host & Device Access, for details.

4.2.2. Memory Pools

The GVDB Voxels topology is stored in two memory pool groups as described in [Hoetzlein 2016]. Each group is a set of separately allocated memory pools residing on both the CPU and GPU, with one allocation for each level of the tree. The following is for reference on the current implementation:

Pool Group 0 – Nodes & Masks

Pool 0 stores the nodes and bitmasks for each level of the topology.
A single pool is allocated per level of the hierarchy, and multiple nodes reside within each level. Since, by VDB definition all the nodes at a given level have the same dimensions, the bitmask size at a specific level will be constant (per level). Therefore, it is possible to allocate a pool group with a fixed width and height as follows:

P0 (group, level) = width * height

= (NodeHeader(level) + BitmaskSize(level)) *
maximum_nodes_at_level

The maximum number of nodes at each level (pool height) is initialized to a small value, typically 4. When more nodes are needed the pools will dynamically expand by powers-of-two to contain additional nodes.

Pool Group 1 – Children Lists

Pool 1 stores the lists-of-children for each node in Pool 0.
Since this list may change size itself, a separate pool group is used.
A list-of-children pool is allocated for each level of the hierarchy. Each child entry is a 64-bit reference back into Pool 0 at the next lower level.
The maximum number of references in the list-of-children is equal to the number of bits (voxels) in the bitmask for that level.

Limitation:
Consistent with OpenVDB, the original intent of Pool Group 1 was to minimize the extra space needed for children by compacting them and using bit counting. However, compaction introduces runtime overhead and the added space of storing complete child lists is not significantly different than compacted lists. Additionally, non-compacted lists would eliminate the need for the bitmask entirely and improve performance by removing bit counting. Currently, Pool Group 1 is compacted (children stored next to one another in order) but with maximum width.

Future versions of GVDB may eliminate Pool Group 1 entirely and merge the children lists with the bitmask. We welcome analysis and feedback on this topic.

4.3. Atlas Structures

Voxel data is contains in multiple **atlases**, where an atlas is stored in device memory as a 3D Texture allocated as either a a CUarray, or less typically as an OpenGL 3D Texture. Allocation of atlases with OpenGL is required when using OptiX, and CUDA-GL interop is performed to acquire a CUarray in that case.

4.3.1. Channels

A **channel** is the concept of a per-voxel attribute, and is central to computation using GVDB Voxels. The need for many voxel attributes arises in many situations. In fluid simulation, it may be necessary to store density, color, velocity and pressure at each voxel cell. These are attributes defined as channels.

Each **channel** is implemented as another **atlas**. There is a one-to-one mapping from a channel to an atlas. However, the atlas is a more generic concept which can be applied to other problem as well. For example, three atlases may be used for a density, color and velocity channel. Five *additional* atlas might be used to express the level-of-detail data for just density. Atlas is thus a more generic concept for a "store of voxels", whatever its usage, while channel is the concept of "per-voxel attributes". Currently the only use of atlases in GVDB is channels, but this is expected to change in future versions.

Channels can be allocated or destroyed at runtime:

gvdb.AddChannel (channel ID, data type, apron)

```
gvdb.DestroyChannels();
gvdb.AddChannel  ( 0, T_FLOAT, 1 );    // density
gvdb.AddChannel  ( 1, T_UCHAR4, 1 );   // color
```

DestroyChannels() removes all previous channels and associated data.

AddChannel() takes the new channel ID, requested data type, and the number of apron voxels (one sided).

Channels can be cleared to a value using FillChannel():

```
gvdb.FillChannel  ( 0, Vector4DF(0,0,0,0));
```

For flexibility, the second argument to FillChannel is a Vec4F. In single-value channels of type T_FLOAT or T_UCHAR, only the first element is used.

Color Channels

The native rendering in GVDB Voxels uses one channel by default, a density channel at location #0. Colored volume rendering, where each voxel has a unique color, is also supported by indicating the color channel with SetColorChannel.

```
gvdb.SetColorChannel  ( 1 );   // channel ID
```

When SetColorChannel is used, that channel must be added as a T_UCHAR4 type to be interpreted as RGBA values.

Limitation: The native rendering pathways currently require that density is present in channel #0. In the future, this limitation will be removed so that any channel can be specified as primary. (See SetupAtlasAccess)

4.3.2. Voxel Size

The global voxel size is specified with SetVoxelSize().
The default is (1,1,1).

```
gvdb.SetVoxelSize ( 0.1, 0.1, 0.1)
```

4.3.3. Atlas Size

An atlas is resized to contain resident bricks.

As described in Chapter 2.1, the dimensions of an atlas determine the maximum number of bricks it can contain. As the number of bricks increases (more data), the atlas will dynamically resize along the Z-axis to accommodate more bricks.

The maximum texture size of a given GPU device determines the limits of the atlas size. This can be found by querying cuDevuceGetAttribute with the following CUdevice attributes:

```
CU_DEVICE_ATTRIBUTE_MAXIMUM_TEXTURE3D_WIDTH
CU_DEVICE_ATTRIBUTE_MAXIMUM_TEXTURE3D_HEIGHT
CU_DEVICE_ATTRIBUTE_MAXIMUM_TEXTURE3D_DEPTH
```

Keep in mind the width, height and depth refer to the number of *voxels* along each axis, not the number of bricks.

For an atlas with width/height/depth in voxels, the maximum number of supported bricks can be calculated as:

Maximum bricks = width*height*depth / (brickres+apron*2)^3

When UpdateAtlas() is called, GVDB Voxels will reallocate the atlas, increasing height until the required number of bricks can be met. If the maximum texture height is reached, the call may fail. Additionally, it can fail when GPU memory is exceeded. To maintain some control over the failure due to dimensions, GVD provides a function, SetChannelDefaults to indicate the desired **base dimensions** of the atlas in bricks.

```
gvdb.SetChannelDefaults ( 16, 16, 16 );
```

Sets the default allocation to 16x16x16 bricks. This is suitable for larger data sets where the number of bricks would meet or exceed 16$^{3.}$ Since the brick dimensions are known, it is possible to calculate good defaults using the GPU device limits queried above.

Chapter 5.
Compute API

The Compute API for GVDB Voxels implements a workflow to enable sparse calculations to be performed as if they were on a dense grid. Developers can make use of the built-in compute operations, or more commonly, author custom kernels.

5.1. Built-In Compute

Performing simple calculations such as smoothing or additive noise can be done using built-in compute functions. A single API function, gvdb.Compute(), launches built-in functions with enums to select the function.

```
Compute ( func_id, channel, iteratons, Vec3DF params, update );
```

The arguments are:
- func_id The enum ID of the function to be called.
- channel The voxel channel ID to preform the computation on.
- iterations Number of times to repeat the calculation
- params Vector3DF with three parameters specific to the function
- update A boolean indicating whether to update the apron after each iteration

The currently available built-in functions are:

FUNC_SMOOTH Smoothing with a 7-point stencil kernel
FUNC_NOISE Add noise to a float channel
FUNC_GROW Increase a level-set function by adding to all non-zero voxels.
FUNC_CLR_EXPAND Expand a color channel (UCHAR4) outward while preserving existing colors.
FUNC_EXPANDC Expand a single-byte (UCHAR) channel outward with another value

The list of built-in functions is intentionally short as we expect that most developers will choose to author their own compute kernels. The built-in functions are intended to grow, through open source sharing, as a set of compute kernels for common operations. They also offer examples of how to write simple kernels for these sparse compute tasks.

The meaning of the 3-vector parameters vary with each function. Due to virtual neighbors, most kernels are no longer than 10 lines. The easiest way is to examine these is by looking at the **gvdbOp**{..} functions found in \source\cuda_gvdb_operators.cuh

5.2. Design Goals

Several goals motivate the solution for sparse computation in GVD Voxels. These are:

- Efficient access to neighbor voxels
- Efficient kernel launches (one for the entire volume)
- Equalize workload of interior and border voxels of a brick
- High thread occupancy

It is instructive to examine these goals to understand how computation is performed by GVDB Voxels. This will later help to describe the workflow.

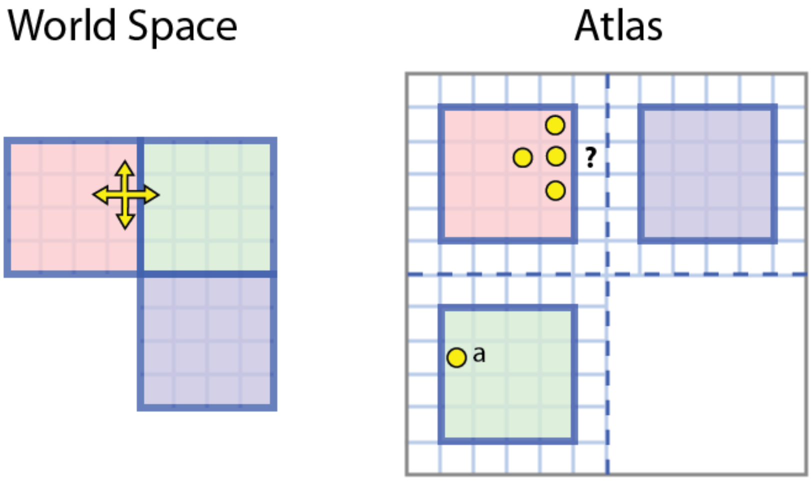


Figure 5.1. A key challenge in sparse computation is to compute stencil operations (neighbor lookup) at all active voxels. In world space (left) these are physically adjacent voxels. When stored in a data atlas (right), neighbor voxels may not be nearby in memory. In this example the right-side neighbor lies in another brick (point 'a') and must be accessed differently.

The benefit of sparse computation is that no calculations are perform on unoccupied space. However, neighbor lookups are more difficult (see Figure 5.1) as the neighbors of boundary voxels reside elsewhere in the data atlas, within other bricks.

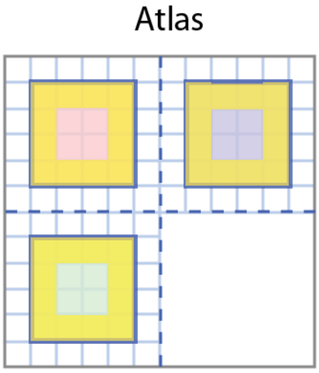


Figure 5.2. Trivial (inefficient) solution to neighbor lookups on sparse grids. Boundary voxels, highlighted, could directly locate the adjacent voxels in other bricks through indirection. Yet this leaves interior voxels mostly idle.

A trivial solution is to perform extra operations at the boundary voxels to search the atlas for their values. However this introduces GPU inefficiency.
The search for neighbors at boundary voxels, highlighted in *Figure* 5.2, can require multiple indirections and conditional checks to find the correct voxel. This search is not necessary for interior voxels which are able to access neighbors directly, and introduces an imbalance in GPU thread occupancy as interior voxels will complete their work before boundary voxels. Since there are many more interior voxels, most threads will remain idle while the boundary voxels search for neighbors. Thus the GPU will be idle most of the time.

GVDB Voxels uses a common, improved solution called **apron voxels,** where neighbors are directly accessible via additional atlas storage.

5.3. Apron Voxels

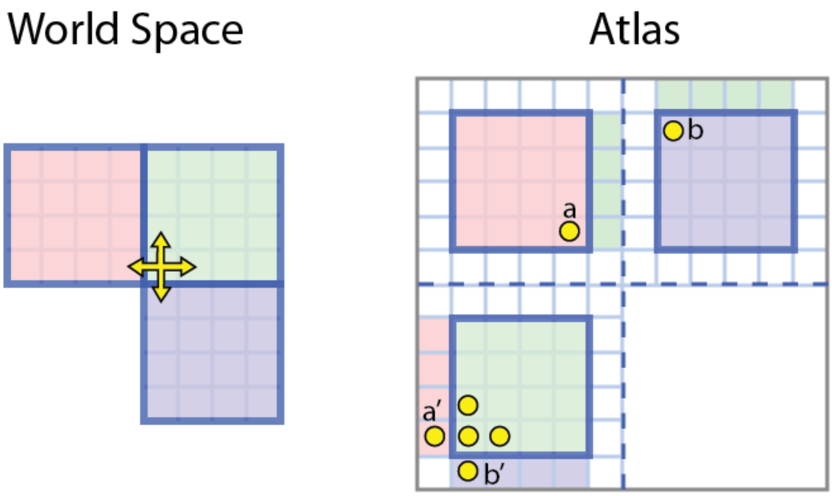


Figure 5.3. The ideal solution is each voxel has direct access to its neighbors. To enable this, **apron voxels** are stored with each brick. The apron voxels are correct world space neighbors at the brick boundaries.

Ideal GPU computations perform the same amount of work on every voxel, which is the work desired by the user. To accomplish this each voxel must have direct access to its neighbors. This is solved with **apron voxels**, shown in *Figure* 5.3. From the perspective of the target voxel (left), the neighbors are two green, one red and one blue voxel. The green ones are already accessible. The correct values for red and blue are at points **a** and **b** in the atlas (right). These are copied into the locations **a'** and **b'** so they are *directly adjacent* to the target voxel. Apron voxels allow all voxels to directly access neighbors.

Kernel launches for compute are be performed over **atlas space** instead of world space. This assigns a GPU thread to each voxel in the atlas. User kernels can then perform calculations with direct neighbor lookups.

5.3.1. Apron Width

The width of the apron determines the size of stencil operations that can be peformed efficiently. More apron voxels support bigger stencils but at the cost of memory overhead. For example, a 1-width apron (on each side) can support all 3x3 stencil kernels, and a 2-width apron supports 5x5 stencil kernels. To implement a 5x5 kernel with only a 1-width apron requires the slower direct-lookup technique at boundaries, which is also available in GVDB Voxels.

Apron voxels require extra space in the data atlas. The ratio of brick voxels to apron voxels determines this overhead. Here is a quick summary of apron overheads for different brick sizes.

Brick Size	Apron Width	Apron Voxels	Memory Overhead
8^3	1	392	76%
16^3	1	1,544	37%
32^3	1	6,152	18%
64^3	1	24,584	9%
8^3	2	832	162%
16^3	2	3,136	76%
32^3	2	12,352	37%
64^3	2	49,216	18%

Figure 5.4. Effect of brick size and apron width on memory overhead. Larger bricks require more apron voxels, but significantly reduce overhead because the number of interior voxels grows as n^3 while the number of apron voxels grows as n^2. Less memory is used overall with larger bricks.

Keep in mind that apron voxels are duplicates of other voxels in the atlas, and present solely for the purpose of efficient computation. Thus we want to minimize the number of apron voxels required. We can change this overhead with careful selection of brick size and apron width. Figure 5.4 shows the memory overhead for common settings.

The apron width is specified when adding a channel.

```
gvdb.AddChannel ( channel, data_type, apron_width );
```

5.3.2. Apron Updates

Apron voxels must typically be updated after every compute operation, before performing a new calculation. When voxel values change due to a computation their neighbors also change. Since the apron voxels are duplicates of neighbors at boundary voxel they must be updated to reflect any changes.

Two compute API functions quickly update apron voxels:

UpdateApron(channel)	Updates apron voxels in a specific channel
UpdateApron()	Updates apron voxels in all channels

5.4. Custom Kernels

The most common way to perform computations for motion pictures, 3D volume processing, or scientific simulation in GVDB Voxels is with **custom kernels** in the Compute API. Custom kernels allow one to author and compile a kernel in user code which is then launched by the GVDB library.

The typical workflow with custom kernels is as follows:

- **Kernel Authoring** Kernels are written and compiled with CUDA on the application side.
- **Kernel Loading** Kernels are loaded in the application with common CUDA functions such as cuModuleLoad, cuModuleGetFunction and cuModuleGetGlobal

- **GVDB Configuration** GVDB is initialized and configured with the desired topology and voxel size.
- **Channels** (Aprons) Add channels for voxel attributes. Specify the apron width to be applied to that channel.

- **Compute kernels** The custom kernels defined in steps above are launched with gvdb.ComputeKernel (..) by passing a CUfunction pointer to GVDB.

- **Update Aprons** Apron voxels are updated by calling gvdb.UpdateApron.

Additional compute operations are performed with repeated calls to ComputeKernel followed by UpdateApron as needed. Many compute kernels can be defined in a single application-side .cu file and loaded together with cuModuelGetFunciton. As long as these kernels conform to GVDB requirements, they can be passed as custom kernels to the gvdb.ComputeKernel function which will launch the kernel over every voxel in the sparse volume.

5.4.1. Voxel Kernels

GVDB **voxel compute** kernels are CUDA kernels with just a few minor differences and constraints. Voxel kernels must take only two arguments, an int3 for the atlas resolution, and a uchar for the channel they operate on. Any other function variables can be accessed with global device variables in the user CUDA code that are read by the kernel. There are no other restrictions in the style of CUDA code. Structures, classes, share memory and calling other device functions are all permitted in **voxel compute** kernels.

One must remember that voxel kernels are launched over all voxels in **atlas space**. Some computations, such as adding noise or 3x3 stencils, do not require knowledge of world space. Therefore calculations can be performed entire with atlas space voxels and neighbors.

The following example reads a voxel, adds noise to it, and writes the voxel:

```
__global___ gvdbOpNoise ( int3 res, uchar chan )
{
    GVDB_VOX

   float v = tex3D<float> ( volIn[chan], vox.x, vox.y, vox.z );
   v += noise();

   surf3Dwrite ( v, volOut[chan], vox.x*sizeof(float), vox.y,
vox.z);
}
```

In other calculations it may be necessary to have the world position of a voxel. An example is computing the per-voxel distance for each voxel to a world-space object like a sphere.

The device function **getAtlasToWorld** transforms from atlas to world space. Here is an example that gets the world position of the current voxel, determines the distance to a user-defined sphere (global structure), and writes that value:

```
__device__ Sphere  sphere;

__global___ gvdbOpDistToSphere ( int3 res, uchar chan )
{
    GVDB_VOX

    float3 wpos;
    if ( !getAtlasToWorld ( vox, wpos )) return;
    float v = wpos - sphere.pos;     // distance to sphere
    surf3Dwrite ( v, volOut[chan], vox.x*sizeof(float), vox.y,
vox.z);
}
```

As described in Chapter 4.1.2 (Atlas Space), the macro GVDB_VOX is shorthand for setting the 'vox' variable for the voxel assigned to the current thread.

5.4.2. Neighbor Access

Kernel macros are provided to facilitate writing efficient voxel kernels. These are included with the cuda_gvdb_operators.cuh header file.

The following kernel macros are available:

GVDB_VOX	Sets the 'vox' variable for the atlas voxel of the current thread
GVDB_COPY_SMEM_F	Sets up a 'vox', and also 'svox' shared memory variable for lookup of the voxel neighbors.
GVDB_COPY_SMEM_UC/4	Sets up a 'vox' and 'svox' similar to _SMEM_F, but for UCHAR and UCHAR4 channel types.

These macros arrange fast access to neighbors by creating a shared memory array 'svox' that contains the neighbors for the current thread block.

Thread blocks in GVDB Voxels are fixed at 8x8x8 and for efficiency they do not correspond to brick sizes. The distinction between thread blocks and

GVDB blocks is described further in the Implementation section below.

The shared memory array 'svox' gives access to neighbors:

```
__global__ void gvdbOpSmooth ( int3 res, uchar chan, float p1,
             float p2, float p3 )
{
       GVDB_COPY_SMEM_F

       float v = p1 * svox[ndx.x][ndx.y][ndx.z];
       v += svox[ndx.x-1][ndx.y][ndx.z];
       v += svox[ndx.x+1][ndx.y][ndx.z];
       v += svox[ndx.x][ndx.y-1][ndx.z];
       v += svox[ndx.x][ndx.y+1][ndx.z];
       v += svox[ndx.x][ndx.y][ndx.z-1];
       v += svox[ndx.x][ndx.y][ndx.z+1];
       v = v / (p1 + 6.0) + p2;

       surf3Dwrite ( v, volOut[chan], vox.x*sizeof(float),
                              vox.y, vox.z );
}
```

This is the entire kernel for a 7-point smoothing function. The first line, GVDB_COPY_SMEM_F sets up the variable 'svox', 'ndx' and 'vox':

svox	A shared memory table for the neighbors of the current voxel
ndx	A variable for offset access to the 'svox' neighbor values
vox	A variable for the voxel coordinates in atlas space
wpos	Computed by calling getAtlasToWorld, gives the world space position of 'vox'

The variable 'vox' is used when performing read/write into the target atlas texture with tex3D or surf3Dwrite.
The variable 'ndx' is used when accessing the +/- axis neighbor voxels values of the current voxel.
The variable 'wpos' is used when the world position of the voxel is needed.

5.4.3. Channel Read/Write

The primary channel (#0) can be read/written using the global access variables **volTexIn** and **volTexOut**. These are texture and surface *references* (texref, surfref) for accessing 3D textures in CUDA.

```
float v = tex3D( volTexIn, vox.x, vox.y, vox.z );
```

```
surf3Dwrite( v, volTexOut, vox.x*sizeof(float), vox.y, vox.z);
```

The variables volTexIn and volTexOut are **texture references** and surface references (see the CUDA Texture Reference API, 3.2.11.1.2). The texture atlas is bound to these references automatically by GVDB Voxels. However, an important limitation of texture references is that their type must be defined at compile time. Since the 3D texture atlas is owned by GVDB, this greatly restricts their usefulness. Thus only the primary channel, when it is used as a float channel, can be accessed in this way. The texture/surface reference access to GVDB textures was maintained for compatibility. A more generic solution is texture objects.

All channels can be read/written with global access arrays **volIn** and **volOut**. These variables are **texture objects** (see the CUDA Texture Object API, 3.2.11.1.1). Texture objects correspond to bindless textures as they do not need to be bound to a specific type. This implies they can be used for access to voxels channels with different types defined at run-time.

```
float v = tex3D<float> ( volIn[chan], vox.x, vox.y, vox.z );
```

```
surf3Dwrite( v, volOut[chan], vox.x*sizeof(float),vox.y,vox.z);
```

Notice how the tex3D function for Texture Objects differs from the above. It accepts a template type <float>, and the texture is specified with the channel ID given by 'chan'. Thus a voxel kernels can read voxel attributes from any channel, which can be of arbitrary type.

The surf3Dwrite function is also flexible since its type is baked into the width as a stride multiplier, sizeof(float). Write operations can take either texture references or texture objects, so there is no type templating like tex3D.

5.4.4. Kernel Loading

Custom voxel kernels are compiled with CUDA and loaded by the application at any time using cuModuleLoad, cuModuleGetFunction and cuModuleGetGlobal. The following complete example shows how to generate a density functions with a customer kernel.

HOST CODE

```
CUmodule     cuGenerateModule;          // app module
CUfunction   cuGenerateDensity;         // app function
CUdeviceptr  cuDensity;                 // app global var

cuModuleLoad ( &cuGenerateModule, "generate.ptx" );
cuModuleGetFunction ( &cuGenerateDensity, cuGenerateModule,
                           "myDensityFunc" );
cuModuleGetGlobal ( &cuDensity, &sz, cuGenerateModule,
                           "gDensity");

gvdb.Initialize ();
gvdb.AddChannel ( 0, T_FLOAT, 1 );      // voxel density
gvdb.AddChannel ( 1, T_UCHAR, 1 );      // voxel status

float density = 0.25;
cuMemcpyHtoD ( cuDensity, &density, sizeof(float) );
gvdb.ComputeKernel ( cuGenerateModule, cuGenerateDensity,
                           1, true );
```

The host code for loading a voxel kernel declares a module for the application, and CUfunction variables for each kernel function. Additional global variables used in the kernel are declare by the host as CUdeviceptr.

The .cu kernel source is compiled to a .ptx by CUDA (nvcc), which is then loaded by cuModuleLoad. The custom **voxel kernel** is called "myDensityFunc", and is loaded into a variable with cuModuleGetFunction. This follows typical patterns from the CUDA Device API for loading modules and functions.

After creating channels used by the voxel kernel, we send any global variables to the kernel using `cuMemcpyHtoD` for each variable or structure.

Finally, gvdb.**ComputeKernel** is called with the application module and the custom voxel kernel. Two additional arguments specify the primary channel to operate on, and whether an apron update should be performed.

ComputeKernel (CUmodule, CUfunction, int channel, bool update_apron);

The custom voxel kernel is launched over all the voxels in atlas space.

Notice that the code for loading modules, kernels and variables follows basic CUDA patterns without restriction. GVDB Voxels accepts the module and function, and a primary channel. Any other specialized variables used by the kernel are left to the application and set with cuMemcpyHtoD.

DEVICE CODE

```
//-------------------------------- GVDB Includes
#define CUDA_PATHWAY
#include "cuda_gvdb_scene.cuh"          // GVDB Scene
#include "cuda_gvdb_nodes.cuh"          // GVDB Node structure
#include "cuda_gvdb_geom.cuh"           // GVDB Geom helpers
#include "cuda_gvdb_operators.cuh"      // GVDB Operator macros
//--------------------------------

__device__ float    gDensity;

__global__ void myDensityFunc ( int3 res, uchar chan )
{
       GVDB_COPY_SMEM_UC          // macro to setup neighbors

       uchar v = tex3D<uchar>( volIn[chan], vox.x,vox.y,vox.z);
       if ( v==0 ) return;        // return if

       surf3Dwrite ( gDensity, volOut[0],
                    vox.x*sizeof(float), vox.y, vox.z);
}
```

Let's examine the device code for the above example. The GVDB Includes give access to the GVDB data structures, helpers, and macros for neighbor lookups.

gDensity is an application (user-side) variable specific to this example, and is set prior to calling gvdb.ComputeKernel. The voxel kernel must take an int3 for atlas resolution, and a uchar for the primary channel, with no return value.

The macro GVDB_COPY_SMEM_UC sets up the local variables 'vox', 'ndx', and 'svox' for access to the current voxel, and the neighbor tables. The channel 'chan' must correspond to the input channel type for the neighbor macro.

The next line, tex3D<uchar>, reads a voxel from the input channel (1), at the current thread's voxel location (vox), as an unsigned char. This voxel attribute is being used as the status of the voxel, so that a voxel status = 0 indicates an inactive voxels -- resulting in a return. Other values may have different meaning, but this kernel only cares that the voxel is active (non-zero status).

The last line takes the user-specified global density and, if the voxel is active, sets it using the volOut texture for the output channel 0, which in this case is a `float` channel for voxel density.

Two channels are present, one for voxel density (float), another for voxel status (uchar). Since we are using texture objects, volIn and volOut, we can read/write to either of these from the kernel. However, only one is passed in as the primary input (chan) to prepare neighbor macros.

5.4.5. Compute Kernel

Custom voxel kernels are launched with gvdb.ComputeKernel:

ComputeKernel (CUmodule, CUfunction, int channel, bool update_apron);

- CUmodule	Indicates the application module for the kernel
- CUfunction	Indicates the CUDA function which follows the guidelines for a GVDB Voxel's custom kernel
- Channel	The primary channel for input. This channel will be used to prepare neighbor voxels arrays.
- Update Apron	A boolean indicating whether an UpdateApron should be performed after the kernel finishes.

The 'channel' passed to ComputeKernel is for simple kernels that typically read/write to only one channel. For voxel kernels that wish to access or modify multiple channels, the application and user device code should track additional input/output channels with global device variables. In this case, the channel variable is used to indicate the input channel for shared neighbor voxels.

The **ComputeKernel** function always launches with one thread per sparse voxel in the atlas. It is thus suitable for calculations that might touch (read or write) all sparse voxels.

If you wish to launch a thread over some custom object (thread-per-polygon, or thead-per-point), or if you wish to process a small subset of the volume, you may want to **directly launch** the kernel as describe in the next section on Modules.

5.5. Modules

The GVDB Library and user Application reside in different **module** spaces according to CUDA. This is how custom functions are pass to a precompiled and linked GVDB library. Therefore, the GVDB module for built-in compute functions is different than the module for application kernels. Yet both desire access to the same GVDB volume data.

The Compute API of GVDB Voxels has functions for switching the GVDB and application modules.

```
gvdb.SetModule ();
```

The SetModule function, without arguments, returns GVDB to the default GVDB Library module. With this module set GVDB can perform built-in compute tasks, apron updates and CUDA raytracing. Any kernel function that is part of the GVDB Library itself requires the default module. As this is the default setting, normally this is transparent to the user of GVDB Voxels when no other application kernels/modules are defined.

```
gvdb.SetModule ( CUmodule );
```

When an argument is provided, SetModule sets the GVDB module to the Application module given. Now each time a custom voxel kernel is launched with ComputeKernel, GVDB Voxels will first set the module to the application, and then *assign the GVDB topology data to it*. In this way, both the user Application and GVDB Library have access to the GVDB topology and data on the GPU across the library boundary.

Note that **gvdb.SetModule** is specific to GVDB Voxels. You can still launch arbitrary CUDA kernels on the application without calling SetModule each time. Typically, you would call SetModule when you want to guarantee that GVDB is delivering GVDB topology & data to a specific kernel.

Directly Launched Kernels

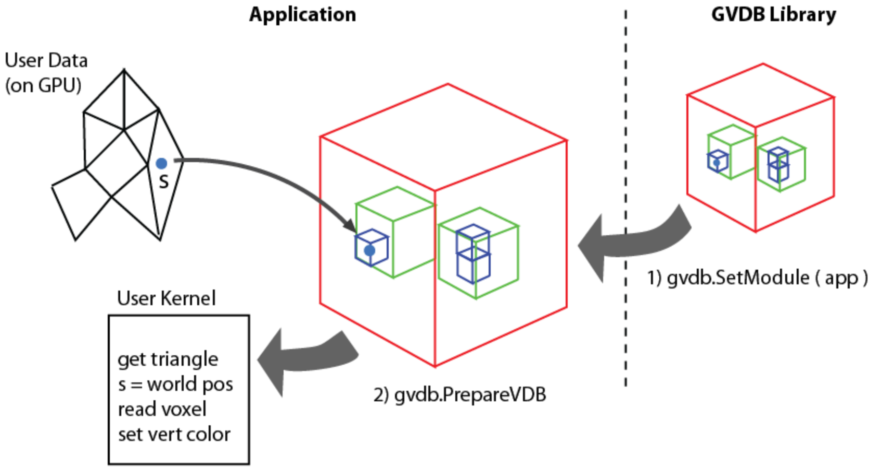


Figure 5.5. A complex task between a user data structure, a polygonal mesh on GPU, and a sparse volume in GVDB Voxels. Step 1 gives the application access to the GVDB topology & data which is typically owned by the GVDB Library. Step 2 prepares the *current* GVDB data, which may have changed by other calls to GVDB, for the user kernel. Finally the kernel is launched with cuLaunch, since only the application knows how to assign threads per triangle.

The only time to call SetModule explicitly is when launching user kernels that are **directly launched** by your application, as in Figure 5.5. For example, perhaps you wish to perform a novel calculation over a different data structure such as a polygonal surface -- but using data from GVDB Voxels. In this case, you would not call ComputeKernel, because it is only for computations where the input/output is the voxel volume. Threads of ComputeKernel correspond to all sparse voxels.

Your custom kernel has threads which correspond to polygons, not voxels. In this case, you call gvdb.SetModule(..) with your application module, and call gvdb.PrepareVDB(). Then you can launch the kernel yourself with **cuLaunch**. Your kernel will still have accces to the GVDB Voxel data structures even though it operates on voxels. The kernel could, for example, get the world position of the polygon's vertices, and then perform a GVDB atlas lookup to get the voxel color. In this way, you would 'paint' the volume onto a polygonal model. This process for **direct launch** is not needed with ComputeKernels, since that function internally sets the module for you, prepares GVDB data, and launches your custom kernel over all sparse voxels.

Chapter 6.
Raytracing API

Rendering with NVIDIA® GVDB Voxels is accomplished with either the pure CUDA Raytracing pathway or with OptiX integrated Raytracing. In both cases, custom raytracing kernels can be authored to create a specific look. Native pathways support raytracing of isosurfaces with trilinear or tricubic filtering, volumetric sampling with transfer functions, level set raytracing, and voxel rendering mode.

6.1. Render Buffers

Rendering outputs and inputs are placed into **render buffers**. These are two dimensional linear buffers (not textures) that typically contain RGBA values. Multiple render buffers may be used for additional depth buffers or for intermediate shading outputs, e.g. diffuse, etc.

Render buffers are created during initialization with AddRenderBuf():

AddRenderBuf (render_chan, width, height, bytes_per_pixel);

The following example creates a primary render buffer for color output:

```
gvdb.AddRenderBuf ( 0, 1920, 1080, 4 ); // 32-bit color (RGBA)
```

During viewport resize, it may be necessary to resize a render buffer.

```
gvdb.ResizeRenderBuf ( 0, width, height, 4 );
```

To return the results of a render buffer from GPU to CPU as linear memory, use the following:

ReadRenderBuf (render_chan, uchar* bytes);

One must pre-allocate the destination data before calling ReadRenderBuf:

```
uchar* dat = (uchar*) malloc ( width*height*4 );
gvdb.ReadRenderBuf ( 0, dat );
  // use dat here
free ( dat );
```

The **render channel** is not the same thing as a GVDB Atlas channel. Atlas channels contain per-voxel attributes stored in 3D textures. Render channels are list of 2D buffers in linear GPU memory.

Another use for render buffers is to store additional image results from other views. For example, the g3DPrint sample uses one render buffer for the primary 3D rendering, and a second one to generate the 2D cross-section slices that are sent to a 3D printer.

ReadRenderBuf can be used to retrieve the output data. The sample utilities (\sample_utils) contains an image helper class which can write out PNG images:

```
nvImg img;
img.Create ( res_x, res_y, IMG_RGBA);
uchar* dat = img.getData();       // get pixel pointer

gvdb.ReadRenderBuf ( 1, dat );    // get render buffer #1

char sname[1024];
sprintf ( sname, "slice_%d.png", y );
img.FlipY ();
img.SavePng ( sname );            // save as png
```

Render buffers may also be used as inputs. For example, a depth buffer may be written by OpenGL and then used by GVDB Voxels to perform depth-based volumetric compositing.

6.1.1. OpenGL Readback

For interactive applications, it is desirable to place the GVDB Voxel rendering output into a 2D OpenGL texture for on-screen display. All GVDB render buffers are allocated with CUDA linear memory. However, utility functions are provided to transfer this into OpenGL textures.

Typically, the application generates an OpenGL texture of the same size as the render buffer. Then one uses ReadRenderTexGL to transfer the GVDB Voxel results into it.

```
gvdb.AddRenderBuf ( 0, width, height, 4 );

GLuint output_glid;
glGenTextures ( 1, &output_glid );
glBindTexture ( GL_TEXTURE_2D, output_glid );
glTexImage2D ( GL_TEXTURE_2D, 0, GL_RGBA8, width, height, 0, GL_RGBA,
GL_UNSIGNED_BYTE, 0 );

gvdb.ReadRenderTexGL ( 0, output_glid );    // return render chan 0
```

After ReadRenderTexGL the application can use the OpenGL texture for on-screen display or other purposes. Each time a new gvdb.Render() is performed, the render buffers will change. So, although one generates the 2D texture once, it is necessary to call ReadRenderTexGL after each render to update the OpenGL texture.

One can also write OpenGL textures to GVDB render buffers for use as inputs.

```
gvdb.WriteRenderTexGL ( 0, input_glid ); // send render chan 0
```

Render buffer inputs must be read using custom render kernels since the native volume rendering pathways do not make use of this.

6.1.2. Depth Buffers

Special render buffers are used as **depth buffers** for reading and writing depth maps. These buffers reside in the same slot locations as render buffers (technically, they are also render buffers, but with special allocation).

A set of functions is provided, similar to render buffers, for creating, reading and writing depth buffers.

AddDepthBuf (int render_chan, int w, int h);   // Add a depth buffer
ResizeDepthBuf (int render_chan, int w, int h);   // Resize a depth buffer
WriteDepthTexGL (int render_chan, int glid);   // Write depth from GL

Depth buffers are special, handled differently from other render buffers, because they create OpenGL Depth textures automatically, in addition to linear CUDA memory. Since CUDA-GL interop requires that depth textures are always created in OpenGL and mapped to CUDA linear memory (interop cannot be performed in the other direction), this would require multiple interop calls and an extra transfer. For performance reasons, GVDB depth buffer generate OpenGL Depth textures first and perform the interop once. Both the OpenGL texture and the CUDA memory are owned by GVDB.

WriteDepthTexGL uses framebuffer objects (FBOs) to efficiently transfer depth buffer data from the input GL texture to the GVDB depth buffer with a GPU-to-GPU copy.

6.1.3. Writing to Buffers

The primary render buffer is passed by argument to native rendering kernels.

Output color is written directly to the rendering buffer.

```
__global__ void gvdbRaytrace ( uchar4* outBuf )
{
      // get pixel for this thread
      int x = blockIdx.x * blockDim.x + threadIdx.x;
      int y = blockIdx.y * blockDim.y + threadIdx.y;
      if ( x >= scn.width || y >= scn.height ) return;
      float4 clr = make_float4(1,1,1,1);

      // .. perform raytracing ..

      outBuf[ y*scn.width + x ] =
     make_uchar4(clr.x*255, clr.y*255, clr.z*255, clr.w*255);
}
```

Since the type of outBuf is a pointer to uchar4 the pixel stride is already included. The width of the render buffer is given in CUDA render kernels by **scn.width, scn.height**.

6.2. CUDA Raytracing

The GVDB Raytracing API is primarily a CUDA pathway for native and custom rendering of sparse volumes. GVDB Voxels distinguishes between **surface rendering**, which occurs at a hit point, and **volume rendering**, in which voxels are sampled and shaded at many points along the ray.

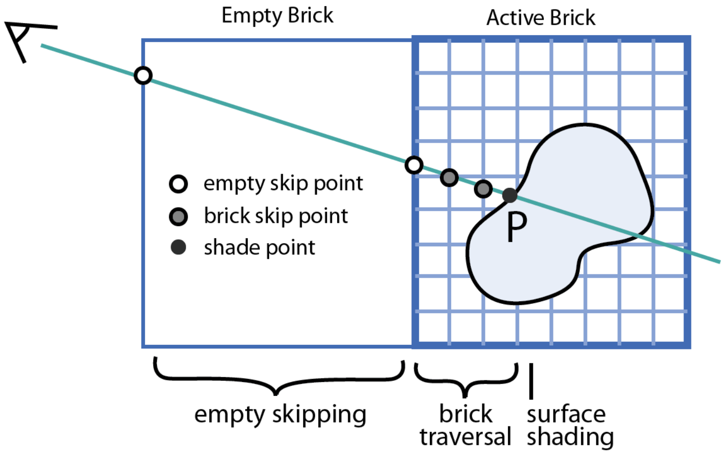


Figure 6.1. **Surface rendering** a sparse volume consists of a) empty skipping, b) brick traversal, and c) surface shading at the hit point.

The basics of **surface rendering** for sparse voxels are showin Figure 6.1. In this type of rendering the voxel data is treated as an isosurface or level set surface. The camera ray travels through the volume, skipping empty space in the VDB tree, and arriving at a brick. At the brick, sample testing rejects individual voxels until a hit surface is detected. At the hit point (P), the normal is computed and the surface point is shaded.

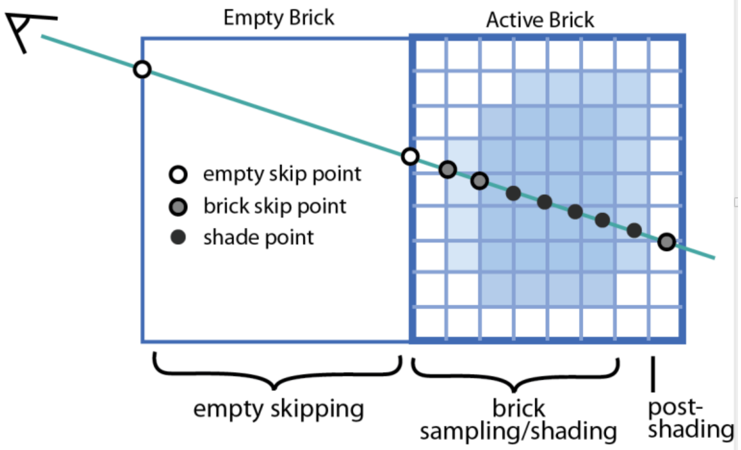


Figure 6.2. **Volume rendering** a sparse volume consists of a) empty skipping, b) brick sampling/shading, and c) post-shading. Unlike surface rendering, volume rendering may sample and shade many points in the volume.

The basics of **volume rendering** are shownin Figure 621. This style of rendering treats the volume as a density field with differing opacity at each voxel. Example of such volumes are smoke, fire and gases. Camera rays travel through the volume skipping empty space. At the brick, the ray continues and each voxel sample contributes some accumulated shading to final output color. Finally, the background is blended in to give the pixel color.

GVDB Voxels was designed to support both **surface and volume rendering** in a consistent way. We notice that empty skipping is identical in both, whereas brick traversal and shader are different. Therefore, GVDB consists of the following components:

- **Empty skipping**	Efficient traversal of the GVDB hierarchy
- **Brick functions**	Brick-level functions for rendering different types of volumetric data. (isosurface, deep, level sets)
- **Native shading**	Built-in examples of specific shading kernels and styles
- Helper functions	Perform useful operations for custom brick functions.

Empty skipping is highly optimized for GVDB hierarchy traversal on the GPU, and is provided as a generic starting-point for a ray. Brick functions are specific to the style and type of voxel data, such as level sets or semi-opaque volumes. Native shading functions provide built-in examples of shading styles which may be customized with custom render kernels.

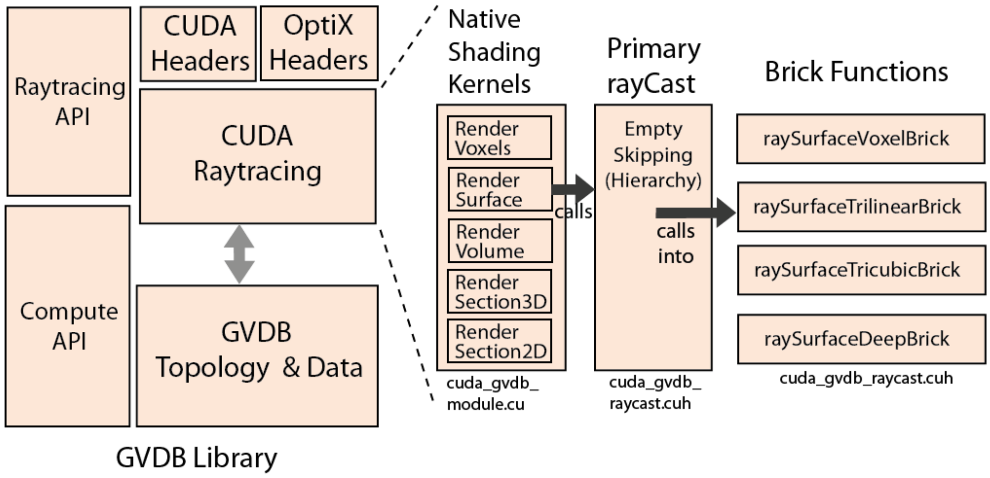


Figure 6.3. Overview of CUDA raytracing in GVDB Voxels. The Raytracing and Compute APIs are the outward facing functions called by applications. The internal design of the CUDA raytracing pathway is shown here.

An overview of the CUDA Raytracing pathway is shown in **Figure** 6.3. Rendering begins in **shading kernels**, which initiates a ray and then calls the rayCast function, pass it a CUfunction pointer to a brick function. The **rayCast** function performs empty space skipping in a generic way, and then calls into the provided brick function for traversal and sampling. Results are returned to the shading kernel for final shading.

To render volume data with GVDB, one first prepares a light, camera and transfer function as described in Chapter 3. Additionally, at least one render buffer is needed for output, as described in Chapter 6.1 (Render Buffers).

Once volume data is loaded or created, native rendering is done with the Render function:

```
Render ( render_chan, style, filtering, frame,
         sample, max_sample, shadow_amt, depth_chan );
```

- **render_chan** The render buffer ID for output

- **style** Style of rendering desired. Can be one of:
  SHADE_VOXEL
  SHADE_SECTION2D
  SHADE_SECTION3D
  SHADE_EMPTYSKIP
  SHADE_TRILINEAR
  SHADE_TRICUBIC
  SHADE_LEVELSET
  SHADE_VOLUME
  SHADE_OFF

- **filtering** Filtering mode/amount. [unused in native render]
- **frame** Current render frame. [unused in native render]
- **sample** Current accumulated sample. [unused in native render]
- **max_sample** Maximum number of samples. [unused in native render]
- **shadow_amt** Shadow darkness, 0 to 1
- **depth_chan** Option render buffer ID for a depth channel.

The render_chan ID must be an RGBA (4 byte) output when using the native render function. The Render function produces a specific look based on a single light source, with Phong shading for surfaces, and a piecewise Transfer function for deep volumes. For different looks, see Custom Render Kernels (Chapter 6.4). Notice the arguments for filtering, frame, sample and max_sample have no effect on native rendering, but can be read when used in custom kernels. When shadow_amt is 0, no shadow rays are cast, otherwise there is an additional ray cost for the shadow.

Upon completion, it is common to retrieve the output either as a CPU buffer or into an OpenGL texture for display.

```
gvdb.Render ( 0, SHADE_VOXEL, 0, 0, 1, 1, 1.0 );
gvdb.ReadRenderTexGL ( 0, output_glid );
```

6.2.1. Native Shading Kernels

All rays are initiated in a **shading kernel**, which generates the ray, casts it into a volume, and performs shading. **Native shading kernels** are built in to GVDB Voxels to provide sample styles based on a single light source. **Custom shading kernels** are build by the user to achieve a specific look.

A native shading kernels is selected with the 'style' argument to the Render function. The following styles are available:

SHADE_VOXEL Function: **gvdbRaySurfaceVoxel**

Voxel style with each voxel rendered as a cube.
Single light source with Phong shading and shadows.

SHADE_SECTION2D Function: **gvdbSection2D**

Renders a cross-section of the volume directly into the 2D render buffer. The transfer function is applied, and the cross-section plane is defined with gvdb.SetCrossSection.

SHADE_SECTION3D Function: **gvdbSection3D**

Renders the scene in 3D similar to SHADE_TRILINEAR, but with a 2D cross-section cutting the model. Single light source, trilinear surface shading is used on the model, and the transfer function is applied to the cross-section.

SHADE_EMPTYSKIP Function: **gvdbRayEmptySkip**

Renders the scene up to the GVDB bricks, but does not traverse into the brick. Bricks are colored by world position. This mode is useful for profiling empty skipping.

SHADE_TRILINEAR Function: **gvdbRaySurfaceTrilinear**

Renders the volume data as an isosurface with trilinear smoothing and normals, Phong shading, and one light source. The isovalue is set using scene SetVolumeRange (iso, vmin, vmax).

SHADE_TRICUBIC Function: **gvdbRaySurfaceTricubic**

Renders the volume data as an isosurface with tri**cubic** smoothing. Note that the voxel data must be prepared using AddChannel with an apron=2 for this to work, since tricubic sampling requires a 5x5 neighborhood.

SHADE_LEVELSET Function: **gvdbRayLevelSet**

Renders the volume as a level set surface. Outside values are +1, and inside values are -1. Displays with Phong shading, one light source.

SHADE_DEEP Function: **gvdbRayDeep**

Renders the data as a semi-transparent volume with deep, accumulated sampling. The transfer function is applied to each sample point. Use scene**.SetSteps**(..) to set the voxel-to-voxel sample spacing for render quality, use scene**.SetCutoff**() to define the minimum contributing voxel value and the alpha cutoff value, and use scene.**SetExtinct**(..) to set the extinction and albedo for accumulation. Use scene.**SetBackgroundClr**(..) to set the background color value for semi-transparent rays.

The functions listed above which implement these styles are found in **cuda_gvdb_module.cu.** When authoring custom kernels these often serve as a useful reference.

6.3. OptiX Raytracing

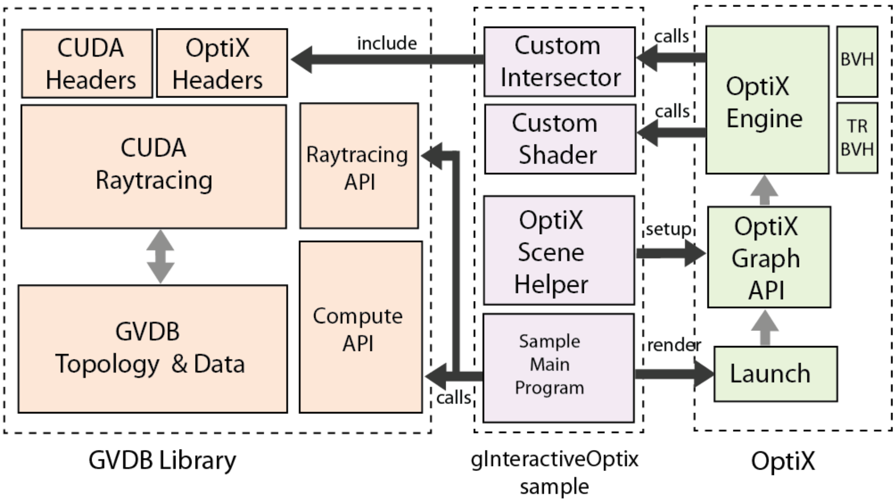


Figure 6.4. Overview of the relationships between the GVDB Library, the OptiX Library, and the gInteractiveOptiX sample.

NVIDIA® GVDB Voxels has an OptiX raytracing pathway for rendering volumes with high quality, multi-scattering via communication with NVIDIA® OptiX. An overview of the components of GVDB-OptiX raytracing are shown in *Figure* 6.4. Notice that GVDB does not contain OptiX code, and nor does OptiX contain GVDB code. This was done to simplify and maintain independence of both SDKs. Instead, the gInteractiveOptiX sample which comes with GVDB Voxels includes a generic **OptiX Scene Helper** which connects GVDB to OptiX. This generic class can be used in any applications that wish to render GVDB sparse volumes with OptiX.

Since both NVIDIA® OptiX and NVIDIA® GVDB Voxels are built on CUDA, the core GVDB raytracing functions for empty skipping and brick traversal are the same in both pathways. The only functions that must be handled differently are the shading kernels, which must be implemented as OptiX shadering programs.

From the perspective of OptiX, the GVDB volume is handled with a new **custom intersector program** that is able to traverse and hit voxels. This can be found in optix_vol_interactive.cu file in the gInteractiveOptiX sample. The intersector program calls the primary rayCast function of GVDB.

Since OptiX performs shading, the native shading kernels of GVDB Voxels are not used. Instead, OptiX launches rays, performs intersections with the GVDB custom intersector, and does shading with a custom OptiX shading program.

OptiX requires that 3D textures are provided by OpenGL and declared using rtTextureSampler<float, 3> (this is found in cuda_gvdb_nodes.cuh). Therefore, the GVDB Voxels atlas data must be created using OpenGL by calling the UseOpenGLAtlas() function during initialization.

```
gvdb.UseOpenGLAtlas ( true );
```

6.3.1. OptiX Scene Helper

The OptiX Scene class, found in the gInteractiveOptix sample, contains generic functions for adding GVDB Voxels to an OptiX scene graph. The following shows the sequence of steps performed by RebuildOptixGraph in this sample, which makes use of the OptixScene class.

```
OptixScene      optx;           // declare the OptiX Scene helper

optx.InitializeOptix (w, h);    // Initialize OptiX with width, height.

optx.ClearGraph();              // Clear the OptiX scene graph

optx.AddMaterial ( .. );        // Adds a material based on a custom
                                // OptiX shading program.

optx.AddVolume (..);            // Adds a GVDB volume to the OptiX graph

optx.AddPolygons (..);          // Adds a polygonal model to OptiX graph

optx.SetTransferFunc (..);      // Sets the GVDB transfer functions for
                                // use by OptiX

optx.ValidateGraph (..);        // Validates the OptiX graph

optx.AssignGVDB (..);           // Assigns the GVDB data to OptiX
```

See **main_interactive_optix.cpp** in gInteractiveOptiX sample for details.
See **optix_scene.cpp** in gInteractiveOptiX for the implementation.

The function **AddVolume** creates a simple sub-graph in which GVDB Voxels is a geometric bounding box in the OptiX acceleration BVH. The GVDB volume sub-graph consists of the following:

- Transform — A transformation applied to the entire volume
- GeometryGroup — A group with only one child, the GeometryInstance, and an SBVH acceleration structure.
- GeometryInstance — The geometry instance holds the OptiX materal ID for the GVDB volume. Other OptiX objects, such as polygonal models, will have different IDs
- Geometry — The geometry node contains a simple bounding box for the GVDB volume. The OptiX intersector program is set based on whether the volume is an isosurface, a level set, or semi-transparent data.

OptiX will cast rays throughout the scene. When the Geometry node for the GVDB volume is found, it will test the bounding box of the volume. If a hit is found, then the GVDB custom intersector program will takeover traversal of the sparse voxels. Rays may also start inside the bounding box, which is also handled by the GVDB intersector.

The final step of **optx.AddVolume** is to create an OptiX Texture Sample so that the GVDB atlas data is available to OptiX programs as a 3D texture. The OptiX context function **createTextureSamplerFromGLImage** is called with the OpenGL ID of the 3D texture for the atlas. The GVDB Raytracing functions will then use this atlas data as the "volTexIn" OptiX variable.

Limitation:
The OptixScene class currently creates only one Texture Sampler. Therefore, multiple channels are not supported by GVDB Voxel raytracing with OptiX. The only voxel attribute read is the primary channel (#0) for density. Color is achieved via surface materials and transfer functions.

6.3.2. GVDB Intersectors

A GVDB Intersector is a custom OptiX **intersection program** for tracing into sparse volumes. These functions, vol_intersect, vol_deep and vol_levelset, can be found in optix_vol_intersect.cu in the gInteractiveOptix sample.

Surface Intersector

Intersection programs are expected to return and report potential intersections. For isosurfaces, this is naturally accomplished using the GVDB **rayCast** function with a surface brick function.

The surface intersector program is:

```
RT_PROGRAM void vol_intersect( int primIdx )
{
        float3 hit = make_float3(NOHIT,NOHIT,NOHIT);
        float3 norm = make_float3(0,0,0);
        float4 clr = make_float4(0,0,0,0);
        float t;

        // GVDB raycasting
        float4 hclr;
        rayCast ( SCN_SHADE, gvdb.top_lev, 0, ray.origin,
              ray.direction, hit, norm, hclr, raySurfaceBrick );
        if ( hit.z == NOHIT) return;
        t = length ( hit - ray.origin );

        // Report intersection to optix
        if ( rtPotentialIntersection( t ) ) {

                shading_normal = norm;
                geometric_normal = norm;
                front_hit_point = hit + shading_normal*gvdb.voxelsize;
                back_hit_point= hit - shading_normal*gvdb.voxelsize*5;
                deep_color = make_float4(1,1,1,1);
                if ( prd_radiance.rtype == SHADOW_RAY ) deep_color.w =
                           (hit.x==NOHIT) ? 1 : 0;

                rtReportIntersection( mat_id );
        }
}
```

Notice this intersection program calls GVDB **rayCast** to perform empty skipping and brick intersection on voxel data. The result is a **hit point** and **surface normal** for the volume isosurface, which are reported as an intersection to OptiX.

Deep Intersector

For volume rendering of semi-transparent voxels there is no hit surface to return to OptiX. However, OptiX raytracing performance (with polygonal models) is based on the notion of skip-hit-shade, in which rays quickly traverse empty space with BVH acceleration, and then perform shading at surface hit points which may spawn additional rays.

Adopting this paradigm to volumetric sampling would imply a per-voxel shading program with the capability to spawn new rays at each voxel. However, this breaks the performance advantage of skip-hit-shade since *every voxel sample* in the volume could potentially cast N new rays. Therefore the approach taken by the deep intersection program in GVDB Voxels is to return the first voxel above a threshold as the "hit" point, but to also return a deeply sampled color which is the accumulated sample along the volume ray.

For secondary scattering in semi-transparent volumes with OptiX, developers are encouraged to pursue a wavefront based approach with GVDB Voxels rather than per-sample spawning of rays. This technique may be explored in future releases of GVDB Voxels.

6.3.3. Mixed Polygon-Voxel Raytracing

Mixed raytracing in this context refers to rendering scenes which contain both polygonal and voxel models toegether.

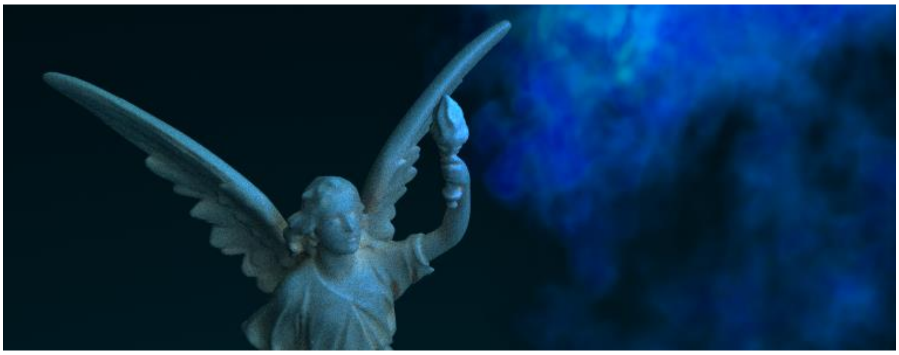


Figure 6.5. Mixed polygon-voxel rendering in the gInteractiveOptix sample. Notice the blue reflections and shadows in the polygonal model caused by reflections of the illuminated semi-transparent volume.

An OptiX shading program is agnostic with respect to the *type* of object that is hit, so long as intersector programs are able to return hit points and normals (or deep colors). Therefore it is possible to build OptiX graphs that contain both traditional polygonal models and GVDB sparse volumes. OptiX will automatically test the mesh-intersector to hit triangles, and test the GVDB-intersectors to hit volumetric data.

Rendering with mixed polygon-voxel raytracing results in interesting effects. Volumes can cast shadows on polygons, and polygons can show diffuse reflections of volumes. These mixed object interactions are visible in the gInteractiveOptix sample, *Figure* 6.5. In addition to AddVolume, the OptixScene class has an AddPolygons function to add polygonal meshes to the scene.

6.4. Custom Shading Kernels

Shading kernels define the look and appearance of surface rendering by specifying how to perform shading at the hit point of isosurfaces or level sets defined by sparse voxels.

Brick functions define the look and appearance of volume rendering by specifying how to perform shading at each sample voxel within a semi-transparent volume.

Users can provide **custom shading or brick kernels** to create a specific look or style. Similar to the compute API, custom shading kernels are compiled on the application side and passed to GVDB Voxels as CUfunctions for rendering. Custom shading kernels will typically call the generic **rayCast** function to allow GVDB to handle hierarchy traversal for empty skipping, greatly simplifying shading kernels.

Custom shading kernels are launched using **gvdb.RenderKernel().**

RenderKernel (render_chan, CUfunction, shading,
filtering, frame, samples, max_samples, shadow
);

The CUfunction is an application-side CUDA function loaded using cuModuleGetFunction. The same rules for modules apply to the Rendering API and they do for the Compute API. See chapter 5.5 (Modules) for details.

The remaining arguments can be specified at each rendering launch and read by the custom kernel using the 'scn' device variable.

- **shading**	scn.shading
- **filtering**	scn.filtering
- **frame**	scn.frame
- **samples**	scn.samples
- **shadow**	scn.shadow_amt

These variables can have whatever meaning is desired by the kernel.

Additional user data for the custom shading kernel is managed using standard CUDA global device variables and set with cuMemcpyHtoD.

Running a custom kernel requires loading the module, getting the kernel function, setting the module, and calling RenderKernel.

```
CUmodule      cuCustom;             // App module
CUfunction    cuMyRaycast;          // App kernel

cuModuleLoad ( &cuCustom, "render_custom.ptx" );
cuModuleGetFunction ( &cuMyRaycast, cuCustom, "my_raycast" );

gvdb.getScene()->SetSteps ( 0.2, 16, 0.2 );    // Set render vars
gvdb.getScene()->SetVolumeRange ( 0.1, 0.0, 1.0 );

gvdb.SetModule ( cuCustom );        // Set GVDB to custom module
gvdb.RenderKernel ( 0, cuMyRaycast, SHADE_TRILINEAR,
                      0, 0, 1, 1, 1 );   // Call MyRaycast
```

The argument SHADE_TRILINEAR set the global scn.shading, and may be optionally used by custom shading kernels.

Notice that **SetModule** must be called explicitly by the application before RenderKernel. This is for performance reasons since switching the CUDA module incurs an overhead cost and it may be desireable to call RenderKernel multiple times for each frame. Thus one would call SetModule once and RenderKernel many times so long as other GVDB functions are not called in between. If other GVDB compute/raytrace functions are called, then the application should call SetModule() (no arguments) before them to reset the module to GVDB.

An example of custom shader kernel loading and device code can be found in the gRenderKernel sample.

Raytracing Device Code

```
//----------------------------- GVDB Headers
#define CUDA_PATHWAY
#include "cuda_gvdb_scene.cuh"   // GVDB Scene
#include "cuda_gvdb_nodes.cuh"   // GVDB Node structure
#include "cuda_gvdb_geom.cuh"    // GVDB Geom helpers
#include "cuda_gvdb_dda.cuh"     // GVDB DDA
#include "cuda_gvdb_raycast.cuh" // GVDB Raycasting
//-----------------------------

__global__ void MyShadingKernel ( uchar4* outBuf )
{
  // Get pixel x,y
  int x = blockIdx.x * blockDim.x + threadIdx.x;
  int y = blockIdx.y * blockDim.y + threadIdx.y;
  if ( x >= scn.width || y >= scn.height ) return;

  float3 hit = make_float3(NOHIT,NOHIT,NOHIT);
  float4 clr = make_float4(1,1,1,1);
  float3 norm;

  // Generate view ray
  float3 rdir = normalize ( getViewRay (
(float(x)+0.5)/scn.width, (float(y)+0.5)/scn.height ) );

  // Ask GVDB to perform empty skipping
  rayCast ( SCN_SHADE, gvdb.top_lev, 0, scn.campos, rdir, hit,
norm, clr, raySurfaceTrilinearBrick );

  if ( hit.z != NOHIT) {
       float3 lightdir = normalize ( scn.light_pos - hit );
       float3 eyedir= normalize ( scn.campos - hit );
       float3 R = normalize ( reflect3 ( eyedir, norm ) );
       float diffuse= max(0.0f, dot( norm, lightdir ));
       float refl = min(1.0f, max(0.0f, R.y ));
       clr = diffuse*0.6 + refl * make_float4(0,0.3,0.7, 1.0);
  } else {
       clr = make_float4 ( 0.0, 0.0, 0.1, 1.0 );
  }
  outBuf [ y*scn.width + x ] =
     make_uchar4( clr.x*255, clr.y*255, clr.z*255, 255 );
}
```

Custom GVDB shading kernels follow a few guidelines. An example is shown in the code above. First, like compute kernels, all GVDB kernels must contain the GVDB header block. Custom shading functions must have only one argument (uchar4) for the output buffer and no return value.

Each thread is expected to handle a single pixel in the output. Therefore the beginning of the shading kernel should compute the pixel x,y as shown. Next the kernel typically generates a view ray from the pixel. This is not strictly required as kernels can do whatever they like with the pixel, but is common.

The **rayCast** function can be called to perform empty skipping in GVDB with a specific brick function. Here, raySurfaceTrilinearBrick is used to get a surface hit and normal for an isosurface. One can also author and send customize brick functions into rayCast, and would usually write them just above the shading kernel (in the same .cu file). This gives a great deal of flexibility in handling brick-level sampling while still allowing GVDB Voxels to perform efficient sparse traversal.

Custom shading can be as complex as desired. This example generates a reflection vector and uses it to give a metallic like appearance to the volume isosurface. Another shading effect might be to implement multiple light sources.

The last step in custom shading should be to write the color value to the provided output buffer using **outBuf**, a linear array of type UCHAR4.

6.5. Explicit Raytracing

Typical GVDB rendering with CUDA or OptiX launches a kernel over a render buffer with a thread for each pixel. **Explicit raytracing** allows an application to launch a kernel over the rays themselves. This distinction lets the user cast rays from arbitrary locations (not pixels), and in arbitrary directions, into a sparse volume.

One use of **explicit raytracing** might be to implement monte-carlo path tracing with GVDB Voxels. Path tracing is a physically realistic rendering technique were rays are randomly cast from either a light source or a camera and with additional rays building multiple light paths through a scene. Path tracing could be implemented with explicit raytracing as a set of wavefronts where each bundle of rays adds another segment to all light paths.

Another use of explicit raytracing is provided in the gSprayDeposit sample, which simulates the spray deposition of a particulate material onto a CAD part. Here, rays are generated randomly from a source to emulate molecules being ejected from a wand which then strike and stick to a 3D model. The angle and occlusion of the particle rays determine how the spray surface builds up. Applications can perform many kinds of tasks on sparse voxels with explicit raytracing, and are not limited to rendering only.

6.5.1. Defining Rays

To perform **explicit raytracing** the rays must be individually defined.

The GVDB API functions for AllocData, getDataPtr and CommitData are used to create, retrieve, and send ray data to the GPU. For details on data functions, see Chapter 9 (Host & Device Access).

A public structure, ScnRay, is given by GVDB Voxels to specify a ray.
This data structure is:

```
struct ALIGN(16) ScnRay {
  float3     hit;          // hit point
  float3     normal;       // hit normal
  float3     orig;         // ray origin
  float3     dir;          // ray direction
  uint       clr;          // ray color
  uint       pnode;        // internal
  uint       pndx;         // internal
};
```

The first step is to allocate memory for the rays:

```
DataPtr m_rays;
m_numrays = 1000;
gvdb.AllocData ( m_rays, m_numrays, sizeof(ScnRay) );
```

GVDB is used for allocation as the data can reside on CPU, GPU or both.
A basic application will retrieve a CPU pointer to set ray origins and directions:

```
// get CPU pointer to first ray
ScnRay* ray = (ScnRay*) gvdb.getDataPtr( 0, m_rays );

for (int n=0; n < m_numrays; n++ ) {
       // ray origin at 0
       ray->orig = Vector3DF(0,0,0);
       // random direction
       ray->dir.Random ( -1,1, -1,1, -1,1 );
       ray->dir.Normalize ();
       ray++;                     // next ray
}
```

Ray data created on the CPU must be committed to the GPU:

```
gvdb.CommitData ( m_rays );
```

Ideally, for performance, rays might be initialized using CUDA kernels that write ray data directly to GPU memory.

6.5.2. Tracing Rays

Once the application has defined ray origins and directions, and made this available in GPU memory, then the gvdb.Raytrace function is called:

Raytrace (DataPtr rays, float bias);

All rays given by the 'rays' dataptr will be traced in parallel.
The bias will shift resulting hit points back along the ray direction by a small constant amount.

After rays have been traced, each ray 'hit' and 'normal' will be set. These results can be used directly on the GPU in other CUDA kernels, or they can be retrieved back to the CPU for other uses:

```
gvdb.RetrieveData ( m_rays );
```

Chapter 7. Point Clouds & Meshes

A useful operation is to **voxelize** a point cloud or a polygonal model to a sparse volume. Voxelization (voxel rasterization) is the process of identifying all the voxels touched by a set of points or polygons. GVDB Voxels supports both point cloud and polygon voxelization with efficient GPU acceleration.

7.1. Point Cloud Voxelization

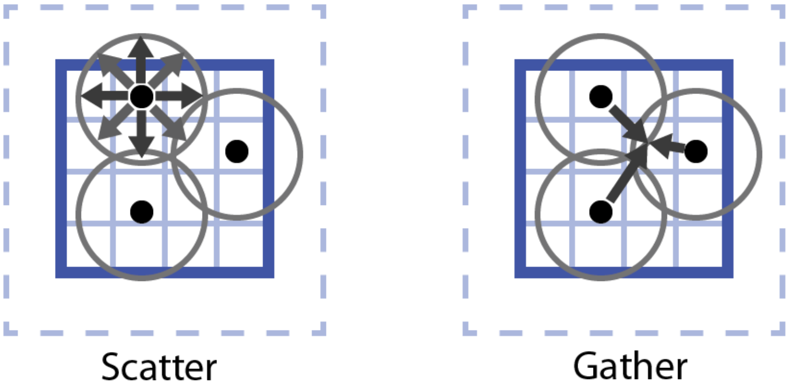


Figure 7.1. Point cloud voxelization may be performed as either a scatter, from points to voxels, or as a gather from voxels to points.

Point cloud voxelization identifies or shades all the voxels touched by a set of points within a given radius. The size of the problem depends on both the voxel grid resolution and on the number of points. Two techniques for point voxelization are shown in Figure 7.1. Point **scattering** begins with each points and identifies all the neighboring voxels touched by it. Point **gathering** begins with each voxel and finds all the neighboring points touched by it. Each method has certain advantages and disadvantages while both are supported by GVDB Voxels.

7.1.1. Defining Point Data

Points are defined using the Data access API by calling AllocData, getDataPtr and CommitData.. See Chapter 9 for details. When loading point clouds from disk, points typically reside in CPU memory first. They are transferred to GPU with the CommitData function.

```
// Allocate GPU and GPU memory
int numpnts;
DataPtr pntpos, pntclr;
gvdb.AllocData ( pntpos, numpnts, sizeof(Vector3DF), true);
gvdb.AllocData ( pntclr, numpnts, sizeof(uint), true );

// Get CPU pointers
Vector3DF* pos =    (Vector3DF*) gvdb.getDataPtr( 0, pntpos );
uint* clr =         (uint*)      gvdb.getDataPtr( 0, pntclr );
// .. load points into CPU here ..

// Commit point data to GPU
gvdb.CommitData ( pntpos, m_numpnts, (char*) m_pntpos.cpu,
                    0, sizeof(Vector3DF) );
gvdb.CommitData ( pntclr, m_numpnts, (char*) m_pntclr.cpu,
                    0, sizeof(uint) );
```

AllocData has the following arguments:

AllocData (DataPtr, int count, int stride, bool bAlsoCPU);

The last argument to AllocData indicates that we want point buffers to reside on both the CPU and GPU. For point voxelization the point data must be loaded into separate buffers for position and color, where the stride of the point locations is Vector3DF and the stride of the point color is uint (RGBA).

Since the data must reside on the GPU for point voxelization we call CommitData to perform the transfer.

The last step in defining point clouds for GVDB Voxels is to inform GVDB which data buffers will be used for subsequence voxelization steps.

SetPoints (DataPtr pos, DataPtr clr);

SetPoints takes two DataPtr buffers as input: point positions and colors. The number of points is defined during AllocData or reallocation. The DataPtrs contain all the information necessary for voxelization.

Direct-from-GPU Data

In many cases, such as during a simulation, the point cloud data may already reside on the GPU. In this case we want to avoid the bidirectional GPU-CPU transfer since CPU buffers are not needed.

GVDB Voxels supports user-defined data buffers where the DataPtr becomes a handle rather than an owner of the point data. The functions **SetDataCPU** and **SetDataGPU** are used to initialize a DataPtr with an explicit source.

SetDataCPU (DataPtr, int count, char* cpuptr, int offset, int
stride);
SetDataGPU (DataPtr, int count, CUdeviceptr gpu, offset,
stride);

Notice that SetDataCPU takes a CPU pointer, and SetDataGPU takes a GPU pointer for the source data. The returned DataPtr is a handle, and points to the original data which is still owned by the application.

```
DataPtr pntpos, pntclr;

gvdb.SetDataGPU ( pntpos, numpnts, my_gpu_points,
                        0, sizeof(Vector3DF) );
gvdb.SetDataGPU ( pntclr, numpnts, my_gpu_colors,
                        0, sizeof(uint) );
```

In this example two separate, existing GPU pointers are given from the application as input for the point positions and colors. The stride of each is the size of a single element in the array.

The offset argument is useful when the application point data resides in structures rather than separate arrays:

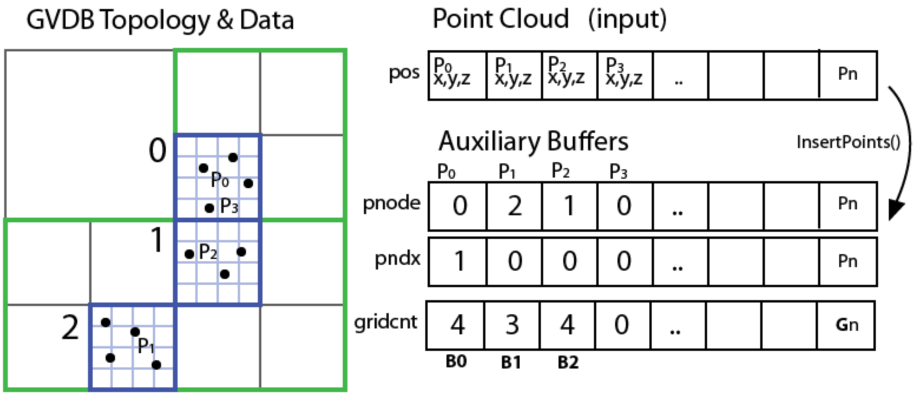
```
struct TPnt {
  Vector3DF  pos;
  Vector3DF  velocity;
  uint       clr;
} MyPnt;

DataPtr pntpos, pntclr;

gvdb.SetDataGPU ( pntpos, numpnts, my_gpu_points,
                        0, sizeof(MyPnt) );
gvdb.SetDataGPU ( pntclr, numpnts, my_gpu_colors,
                        24, sizeof(MyPnt) );
```

Here the offset is used to indicate where in the structure the position and color values reside. The stride of each is the size of the entire structure.

7.1.2. Point Insertion



	P_0	P_1	P_2	P_3				
pos	P_0 x,y,z	P_1 x,y,z	P_2 x,y,z	P_3 x,y,z	..			Pn
pnode	0	2	1	0	..			Pn
pndx	1	0	0	0	..			Pn
gridcnt	4	3	4	0	..			Gn
	B0	B1	B2					

Figure 7.2. Pre-processing point clouds for efficient voxelization with **point insertion.** Auxiliary buffers are used to improve performance.

Efficient parallel voxelization is possible when the points are pre-sorted into GVDB bricks. This pre-processing step is performed by **InsertPoints**(). The details of InsertPoints can be seen in *Figure* 7.2. Each point is assigned to a brick (pnode), and its index within the brick is recorded (pndx). With this information, it is possible to count the total points-per-brick (gricnt) and optionally the grid offsets (as a prefix scan). The technique is fully described in the GTC 2014 talk "Fast Fixed-Radius Nearest Neighbors" [Hoetzlein 2014].

An application performs point insertion by simply called InsertPoints.

InsertPoints (int count, Vector3DF translate, bool prefix);

It is necessary to call this function before an point voxelization and is often the first step in other operations using point clouds.

- **count** Indiates the number of points to insert
- **translate** A world translation factor applied to all points. This is useful, when needed, to ensure that the points all reside in the positive domain.
- **prefix** A boolean indicating whether a brick prefix scan should be performed. This is required for some point cloud operations.

7.1.3. Point Scatter and Gather

Scatter Voxelization

The scattering method for point voxelization is accomplished with the function:

ScatterPointDensity (int count, float radius, float amp, Vector3DF translate,
bool expand, bool averageColor);

ScatterPointDensity uses the scattering method for voxelization. With this method points are not able to identify target voxels across brick boundaries, but can write to apron voxels, therefore the maximum radius supported by ScatterPointDensity is 3.0. Larger values are also possible but may introduce boundary clipping.

```
gvdb.InsertPoints ( numpnts, translate, false );
gvdb.ScatterPointDensity ( numpnts, 3.0, 1.0, translate );
```

The 'false' argument in InsertPoints indicates that no prefix scan is needed before calling ScatterPointDensity. The 'amp' sets the peak value written to a voxel which is centered on a point, with linear falloff. ScatterPointDensity typically writes to the primary channel, but will also write to a color channel when the SetColorChannel function (to indicate which channel will hold per-voxel color output attributes), and when gvdb.SetPoints indicates both position and color data (which holds the input per-point color attributes).

Limitation:
ScatterPointDensity is a suitable technique when the support radius is small. For radii above 2 voxels, the parallel scatter method implies that many points will attempt to write to the same voxel. Since this operation is not atomic on 3D textures some writes may be skipped. ScatterPointDensity should not be used when the accumulated values must be an exact sum. This method is best suited for fast, point cloud pre-visualization. Often a smoothing step is performed afterward for hole filling.

Gather Voxelization

The **gathering** method of point voxelization is accomplished with:

GatherPointDensity (int count, float raidus, int channel);

GatherPointDensity is used to perform point voxelization with larger radii, and to compute exact sums at voxel locations. For example, this method is ideal for FLIP-type fluid simulations where point density must be projected onto a sparse voxel grid. Unlike ScatterPointDensity, this technique does require a prefix scan during insertion.

```
gvdb.InsertPoints ( numpnts, translate, true );
gvdb.GatherPointDensity ( numpnts, 5.0, 0 );
```

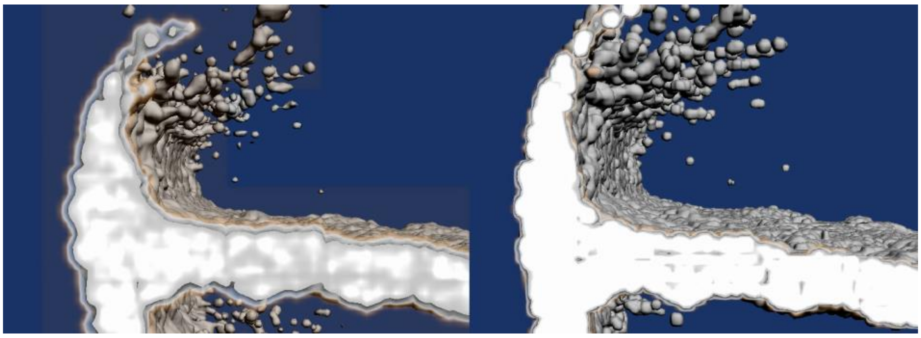


Figure 7.3. Examples of the **scatter** (left) and **gather** (right) techniques for point cloud voxelization from the gFluidSurface sample.

An example of scatter and gather point voxelization can be found in the gFluidSurface sample, which performs an SPH (Smoothed Particle Hydrodynamics) particle simulation and then voxelizes the points to create a rendered surface.

Limitation:
GatherPointDensity is still experimental in GVDB SDK release 1.0, with improvements expected into future releases.

7.2. Mesh Voxelization

GVDB Voxels introduces a novel technique for efficient, hieararchical solid **mesh voxelization** to determine the voxels touched by a triangle mesh. The output for each voxel may be one of three values: inside, outside, or surface.

Surface voxelization sets all the voxels which intersect a polygonal mesh, thus creating a voxel surface with an empty interior. **Solid voxelization** fills the interior voxels of a watertight polygonal mesh. The SolidVoxelize() function of GVDB Voxels generates both results at the same time.

The technique used for mesh voxelization was designed with several goals and features:

- Interior & Surface — Voxelizes both the surface and interior voxels simultaneously
- Exact Result — Solid voxelization in GVDB is exact. Unlike graphics raster methods which may produce a voxelization with holes, or might be overly conservative, this technique generates the exact set of voxels which are touched by any part of a triangle.
- Out-of-Core — Sweep-based methods of mesh voxelization depend on the results of neighboring bricks. The technique in GVDB Voxels is out-of-core friendly, where the results of any sub-volume in space can be computed independently.
- Hierarchical — For performance the voxelization is hierarchical. Empty space will not be voxelized at the brick level.
- GPU Efficient — Mesh voxelization should be efficient for large models and high resolution volumes. This is achieved with GPU polygon binning and sort.

Polygonal voxelization is performed with the function:

```
  SolidVoxelize( chan, Model*, Matrix4F xform, surface_value
,inside_value );
```

The arguments are:

- channel — This must be a UCHAR channel which will receive the results of voxelization.
- Model* — A pointer to the polygonal model, typically loaded using **scene.AddModel**().
- xform — A transformation applied to the model. This allows for arbitrary scaling and orientation of the model with respect to the voxel grid.
- surface_val — Value to be set in the channel when the voxel is a surface voxel (any part touches a polygon).
- inside_val — Value to be set in the channel when the voxel is an interior voxel (fully inside the watertight mesh).

7.2.1. Voxelization Channel

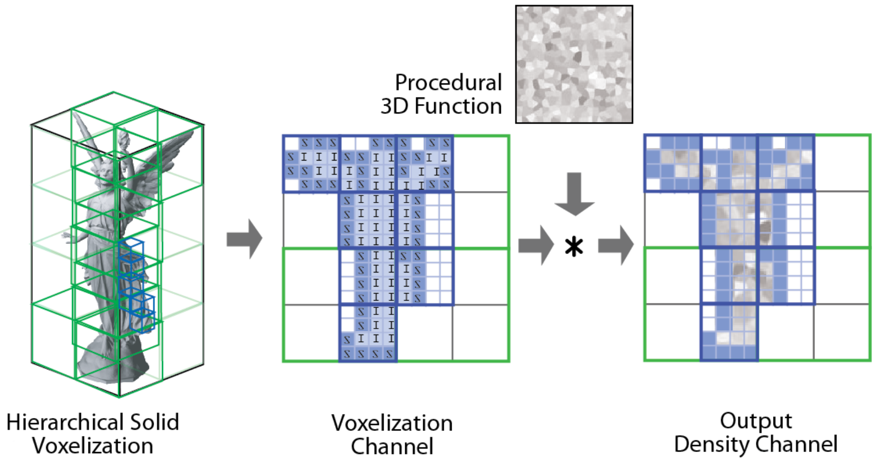


Figure 7.4. Solid voxelization writes to a **voxelization channel** to give the most flexibility to applications. Surface voxels are tagged ('S') separately from interior voxels ('I'). In this example, multiplying the voxelization channel by a 3D procedural function results in an 3D sparse voxel model with a procedurally defined interior density defined.

The output of solid voxelization is written to a **voxelization channel** which must be added as a UCHAR channel. Rather than writing density directly, this design gives applications the greatest flexibility in utilizing the result. The voxelization channel may be manipulated directly, or it can be multiplied by other 3D volumes to produce density which is only defined on the interior of a mesh. An example is the generation of complex in-filling for 3D printing where the model has a solid surface with a custom interior (see *Figure* 7.4). Typically, applications will write custom compute kernels that take advantage of the voxelization channel to produce additional results.

```
gvdb.Configure ( 3, 3, 3, 3, 5 );
gvdb.AddChannel ( 0, T_FLOAT, 1 );      // density
gvdb.AddChannel ( 1, T_UCHAR, 1 );      // mesh voxelization

// Solid Voxelize
Matrix4F xform;
Model* m = gvdb.getScene()->getModel(0);
gvdb.SolidVoxelize ( 1, m, &xform, 1, 128 );

// Expand surface border by 1 voxel
gvdb.Compute ( FUNC_EXPANDC, 1, 1,
                    Vector3DF(1, 255, 0), true );
```

This code example has two channels, density and the mesh voxelization result. The SolidVoxelize function indicates that surface voxels should be 1, and interior voxels have the value 128. The native operation FUNC_EXPANDC is called using the Compute API to perform a voxel expansion (grow outward) by one voxel. This function takes two parameters, which are the existing value ('1'), and the expanded voxel value ('255'). Since the value 1 represents surface voxels, the result is an extra layer of voxels surrounding the surface of the model that will have the new value '255'.

Another use of the voxelization channel is to cache results using Load/SaveVBX to store channels independently.

7.2.2. Implementation

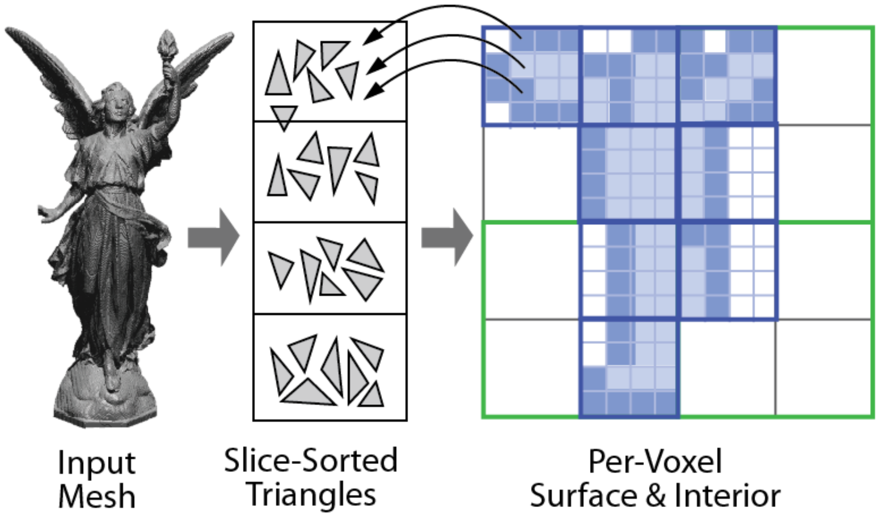


Figure 7.5. Algorithm used by SolidVoxelize. Triangles are sorted and inserted into stacked XY bins along the Z-axis. A thread-per-voxel kernel is launched over all sparse voxels which then examine the bins to test a subset of triangles.

The implementation details of solid voxelization are given here for reference. The steps in the algorithm are:

1) Triangle sorting - Triangles in the input mesh are sorted and inserted into horizontal bins that are stacked along the Z-axis. Any triangle that crosses a bin is inserted into both of them. Auxiliary buffers are used to maintain the sorted triangles.

2) Hierarchical activation - Voxelization is performed hierarchically with upper nodes of the VDB tree processed first. This produces a solid/interior result that indicates which children nodes should be activated. Nodes are processed at each level (breadth first) until all relevant voxel bricks have been identified.

3) Per-Voxel computation - A primary voxelization kernel is launched over all sparse voxels in the data atlas. This avoids processing voxels in empty space. Each voxel first checks if it is a surface voxel with the Schwarz-Seidel test or the Akenine-Moller test. These are exact tests to determine if a polygon touches a voxel. If the test fails, the voxel performs an Inside-Outside test to determine if it is an interior voxel. The resulting value is placed into the output channel.

To accelerate voxel testing only the polygons in the sorted bin corresponding to a given brick are checked. The parity test requires that all polygons along a ray extending from the voxel are included in its odd-even count, which is met since bins contain triangles that cross multiple bins but avoid those which are completely outside.

Since all tests are performed on the original polygonal data the result is an exact voxelization which is locally complete. This permits the same voxelization algorithm to be applied to different levels of the VDB hierarchy, or to additional bricks anywhere in space which may be stored on disk incrementally.

Chapter 8. Dynamic Topology

There are many scenarios in which a 3D volume varies over time. Simulations performed on sparse grids will activate new space as the fluid or smoke advances. Medical and scientific data might consist of a 3D volumetric time series, in which case the active space could vary from frame-to-frame. **Dynamic topology** refers to any application where the activate space changes over time, which requires that the GVDB topology updates.

Currently, dynamic topology in GVDB SDK release 1.0 is implemented on CPU only. Since the GVDB uses indexing, and the topology typically has a low footprint (<10 MB), transferring to new topology to the GPU is quick and efficient.

8.1. Overview

The **dynamic topology** API is separated into phases to improve application design and performance. The sequence of stages as typically appear in an application are as follows:

1. Topology rebuilding	Updating a topology without affecting the data atlases
1a. Clear	Clear the entire topology (optional)
1b. AcitvateSpace	Activate new space to be covered
1c. FinishTopology	Finalize topology changes prior to updating the atlas.
2. Atlas rebuilding	Updating the data atlases without affecting topology
2a. UpdateAtlas	Allocate additiona bricks if needed
2b. ClearAtlas	Clear all voxel data (optional)

The concept of **activating space** is a request to GVDB Voxels to generate the covering nodes of a point in space from the root down to the brick. After activating space additional leaf nodes are guaranteed to cover the requested points. However, prior to atlas rebuilding these nodes specify bricks which do not yet exist in the data atlas. This intermediate leaf node state allows changes to the GVDB topology to be completed prior to any changes in voxel allocation.

Once the atlas update is performed, any new leaf nodes will be allocated a new place in the data atlas. Thus the topology stage guarantees that new world space is covered (but without voxel data), and the atlas stage guarantees that new voxel data is allocated for covering nodes.

8.2. Topology Building

8.2.1. Activate Space

To change the VDB topology, the ActivateSpace function is called with a 3D world position to be covered (by a brick).

```
ActivateSpace ( Vector3DF pos );
```

In SDK release 1.0 this is a CPU-only function, and should be called repeatedly to activate space over multiple points. Future releases may introduce a GPU version that activates a list of points simultaneously.

An example of activating space can be found in the gFluidSurface sample, where a set of points moves over time based on an SPH simulation. As the points move, the VDB topology must dynamically reconfigure to cover them. On each frame, the VDB grid is cleared and reconfigured with ActivateSpace.

ActivateSpace will generate new interior and leaf nodes, and may create a new root or increased the tree depth if needed to cover the point(s). Space can be covered out to the maximum addressable extents of the volume (see Chapter 2.1.2).

Although the input to ActivateSpace is a point, this does not imply that only point clouds can activate space. When performing a grid-based fluid simulation new space might be activated as fluid voxels advect to touch brick boundaries. An application could detect when a boundry is touched by examining changes in apron voxels and recording neighboring inactive bricks. These bricks indicate 3D positions which can be activated by calling ActivateSpace with any point inside the brick space.

8.2.2. Finish Topology

Finish topology should be called after all new space has been activated.

```
FinishToplogy ();
```

This function performs a few important tasks for topology maintainence. These are:

- Recompute bounding box — The bounding box of the GVDB Volume is recomputed from the new topology.
- Commit topology to GPU — The new topology is transferred to the GPU for access by other tasks.
- Update request — Internally, a flag is set indicating that new VDB data is available during compute and rendering.

Notice that FinishTopology does not modify the data atlas, which remains in its previous state. At this point some leaf nodes (level 0) may indicate new bricks that are not yet allocated. These nodes will have a mValue attribute of -1, which is a request to allocate new voxel data.

8.3. Atlas Rebuild

8.3.1. Update Atlas

Once the topology has been updated, **atlas rebuild** will allocate new voxels in the data atlas. Two versions of UpdateAtlas are provided, one which updates a specific channel, and another which updates all channels.

```
UpdateAtlas();
UpdateAtlas( channel );
```

Typically all channels must be updated since GVDB does not track bricks separately by channel.

UpdateAtlas performs several steps to ensure that new voxels are allocated to all leaf nodes in the space:

- Resize atlas   All data atlases are dynamically resized to accommodate new leaf nodes. This resize step preserves previous data by expanding the atlas along the Z-axis. See chapter 2.1.3 for details.

- Assign bricks   New nodes are assigned to bricks in the atlas. Whereas a node is an abstract entity covering space, a brick contains the voxel data.

- Atlas map update   The atlas map is used internally in GVDB to provide reverse mapping from atlas-space to world-space. This data structure is updated on GPU.

- Commit to GPU   The new topology, with assigned brick values, are sent to GPU. In addition, the atlas accessors volIn/volOut are update to give kernels access to the data atlases in case their location in memory has changed.

Following UpdateAtlas all leaf nodes covering a space must have a valid mValue referring to a brick location in the atlas, since GVDB Voxels release 1.0 does not yet support non-resident (out-of-core) bricks.

8.3.2. Clear Channels

During each frame it may be necessary to clear previous voxel data. This should be done after UpdateAtlas has reallocated bricks. To clear a specific channel use the function FillChannel;

```
FillChannel ( uchar channel, Vector4DF value );
```

The value is a Vector4F to cover all possible channel types. Single component channels (T_FLOAT, T_UCHAR) will read value**.x**. Multi-component channels (T_FLOAT4, T_UCHAR4) will use all components of value.

To clear voxel data in all channels, one calls ClearAtlas ();

```
ClearAtlas ();
```

8.3.3. Rebuilding Channels

GVDB Voxels allows applications to destroy and rebuild voxel attribute channels at run-time. The function **DestroyChannels** removes all channels from memory and their associated atlases. Afterward, the application should rebuild the channels with AddChannel.

DestroyChannels should be called infrequently, since it incurs the overhead of tearing down and rebuilding all atlases. The only time to rebuild channels is when per-voxel attributes must be added or removed.

In a dynamic simulation the voxel attributes are typically fixed ahead of time - e.g. position, velocity, density. Thus changes in topology can be achieved with topology and atlas updates without adding, removing or destroying channels. This will be more efficient since GVDB will dynamically reallocate atlases to preserve prior data.

8.4. Limitations

Dynamic topology has several limitations in GVDB SDK release 1.0 which may be addressed in future releases. These are:

1. CPU only — ActivateSpace is currently CPU-only. However, transfer of the new topology to GPU is efficient.
2. Full residence — All leaf nodes must be resident in data atlases following UpdateAtlas. This limitation may be removed in the future to allow for non-resident bricks and out-of-core techniques.
3. DeactivateSpace — Deletion of bricks, or removal of space, is not yet supported. Currently applications may need to clear and reactivate all points. (See gFluidSurface example)
4. DeleteChannel — Deletion of channels at run-time is not yet supported. Applications can call DestroyChannels to remove all channels and rebuild the with AddChannel.

Chapter 9. Data Management

Data management is a generic API for handling CPU and GPU data provided to GVDB Voxels. Data may be used for point clouds (Chapter 7.1), triangle meshes (Chapter 7.2), rays (Chapter 6.5) or other entities that are inputs or outputs to GVDB. These functions implement smart points for memory management.

9.1. Allocation

Generic data is allocated on the GPU, and optionally on CPU, with AllocData.

```
AllocData ( DataPtr ptr, int count, int stride, bool onCPU );
```

The arguments are:

- **DataPtr**	The DataPtr handle that will be setup by this call.
- **count**	The number of elements to pre-allocate
- **stride**	The stride of each element. Typically sizeof(some struct)
- **onCPU**	A boolean indicating if CPU memory should also be allocated.

AllocData always allocates GPU linear memory.

When making repeated calls to AllocData with the same DataPtr object, any memory previously associated with either the CPU or the GPU are freed before new memory is allocated. The resulting DataPtr records the stride, count and CPU and GPU pointers for the requested memory.

9.2. Data Transfers

Data is transferred to/from the GPU with **RetrieveData** and **CommitData**.

```
RetrieveData ( DataPtr ptr );
```

RetrieveData transfers data from the GPU to the CPU for the given DataPtr. Note this implies that the DataPtr must have been allocated with onCPU true. The total amount of memory transferred is count*stride.

```
CommitData ( DataPtr ptr );
```

CommitData transfers data from the CPU to the GPU for the given DataPtr. Note this implies that the DataPtr must have been allocated with onCPU true, and the CPU data is owned by this DataPtr.

CommitData (DataPtr ptr, cnt, cpu_ptr, offs, stride)

An alterate version of CommitData transfers arbitrary CPU data to GPU.
The target GPU memory is given by the DataPtr.
The source CPU memory is given by the CPU pointer argument. The caller must specify the count, starting offset, and stride of the source memory.
This function does not require the DataPtr has been allocated with onCPU true.

9.3. Data Handles

The typical usage of data management is to create DataPtr objects by calling AllocData with the number and stride of new elements to allocate. In this case, the DataPtr *owns* the data which is allocated.

DataPtr structs can also be used as **data handles**. In this usage, a DataPtr represents a handle, or reference, to memory which is allocated and owned by the application itself. The purpose of data handles is to provide GVDB Voxels with lists of points, rays or triangles that are managed by the application.

DataPtr handles are created using **SetDataCPU** and **SetDataGPU.**

SetDataCPU (DataPtr, int count, char* cpuptr, int offset, int stride);
SetDataGPU (DataPtr, int count, CUdeviceptr gpu, offset, stride);

The given DataPtr should not be previously used for anything else.
Notice that SetDataCPU takes a CPU pointer, and SetDataGPU takes a GPU pointer for the source data. The returned DataPtr references (points to) the original data which is still owned by the application.

For flexibility, data handles support application data which is given either as a structure-of-arrays or as an array-of-structures.

Structure-of-Arrays

```
Vector3DF* pos;                   // list of positions
Vector3DF* vel;                   // list of velocities
uint*      clr;                   // list of colors

LoadData ( pos, vel, clr );       // application allocated

DataPtr p1, p2, p3;               // new handles

gvdb.SetDataCPU ( p1, num, pos, 0, sizeof(Vector3DF) );
gvdb.SetDataCPU ( p2, num, vel, 0, sizeof(Vector3DF) );
gvdb.SetDataCPU ( p3, num, clr, 0, sizeof(uint) );
```

When using DataPtr handles for a structure-of-arrays, the offsets are typically all zero, and the strides match the stride of each individual input array.
Notice that no data is allocated or freed. Also, since the DataPtr was not created with AllocData, there is no GPU pointer. The primary use of data handles is to present the data to GVDB Voxels function.

Array-of-Structures

An array-of-structures is a list of elements with attributes located together and grouped by a structure.

```
struct Pnt {
   Vector3DF* pos;                 // position
   Vector3DF* vel;                 // velocity
   uint*      clr;                 // color
}
Pnt* pnts;                         // list of points

LoadData ( pnts );                 // application allocated

DataPtr p1, p2, p3;                // new handles

gvdb.SetDataCPU ( p1, num, pnts,  0, sizeof(Pnt) );
gvdb.SetDataCPU ( p2, num, pnts, 12, sizeof(Pnt) );
gvdb.SetDataCPU ( p3, num, pnts, 24, sizeof(Pnt) );
```

When making DataPtr handles from an array-of-structures, the offsets refer to the starting byte of each variable, and the strides are all set to the width of the containing structure.

GPU Handles

Applications that allocate their own GPU memory with CUDA functions cuMemAlloc and cuMemFree can make **data handles** using SetDataGPU.

```
CUdeviceptr posGPU;                // position data
CUdeviceptr velGPU;                // velocity data
int num = 2000;

// application allocates GPU data
cuMemAlloc ( &pos, sizeof(Vector3DF)*num );
cuMemAlloc ( &vel, sizeof(Vector3DF)*num );

// application creates data
LoadData ( pos, vel );

DataPtr p1, p2, p3;                // new handles
gvdb.SetDataGPU ( p1, num, posGPU,  0, sizeof(Vector3DF) );
gvdb.SetDataGPU ( p2, num, velGPU,  0, sizeof(Vector3DF) );
```

Remember that a data handle does not own the memory it refers to. Therefore applications should not call AllocData, RetrieveData or CommitData on **data handles**.

For an example usage of **data handles**, see Chapter 7.1.1 (Point Cloud Voxelization).

9.4. DataPtr Struct

The DataPtr struct is a smart handle to memory which resides on both the GPU and CPU. Additionally, it contains members to keep track of the count and maximum of a number of elements with a given stride. This makes it suitable for managing simple data such as a fixed array of points or triangles.

A DataPtr is:

```
struct DataPtr {
  char type;         // Data type (T_UCHAR, T_FLOAT, etc)
  char apron;        // Apron size (Used by atlases)
  uint64 num;        // Number of elements
  uint64 max;        // Maximum element count
  uint64 size;       // Total amount of memory in bytes
  uint64 stride;     // Stride of the data
  Vec3DI subdim;     // Sub-dimensions of the data.
                                  (Used by atlases)
  Allocator* alloc; // Pointer to the Pool allocator which
                       owns this memory heap.
  char* cpu;         // CPU Pointer to data
  int glid;          // GPU OpenGL ID to data as 3D texture
  CUgraphicsResource grsc;  // GPU Graphics Resource (CUDA)
  CUarray garray;    // GPU CUarray (CUDA) to data on GPU
  CUdeviceptr gpu;   // GPU Linear memory (CUDA) pointer
}
```

The DataPtr is also used internally by GVDB Voxels to maintain both data atlases and node memory pools, with member variables to handle CUDA interop, OpenGL 3D textures, and to record atlas dimensions and type. Many of these variables are not used when creating simple linear memory with AllocData.

A DataPtr is a public struct, so applications that call AllocData can directly access the CPU memory via **data.cpu**, or read/write the number of elements with **data.num.** Care must be taken when directly modifying a DataPtr object.

Chapter 10. Host & Device Access API

The Access API is a set of functions, on host and device, that allow an application to query and traverse the GVDB Topology and Data. This API is useful for authoring custom compute and custom render kernels.

10.1. Host Access

The Host access functions are:

*** See gvdb_volume_gvdb.h for function arguments**

getNearestAbsVox	Gets the nearest voxel in index-space
getLD	Gets the node log2dim for the given level
getRes	Gets the node resolution for the given level
getVoxCnt	Gets the total voxel count for a node at given level
getMaskSize	Gets the bitmask size, in bytes, for a node at level
getBitPos	Gets the bit position for a point in local index-space for node at level
getPosFromBit	Gets the local index-space position from a bit
getCover	Gets the world-space covering size of a node at the given level
getRange	Gets the index-space covering size of a node at the given level
getRes3DI	Gets the resolution of a node as a Vec3I
getVolMin/Max	Gets the min/max bounding box of the entire sparse volume
getTransferPtr	Gets the transfer function as a DataPtr
getTransferFuncGPU	Gets the transfer function as a CUDA CUdeviceptr
getScene	Gets the GVDB scene object
getNumNodes	Gets number of nodes at a given level
getNode	Gets a Node struct from a group, level and index
getNode (nodeid)	Gets the Node struct from a node reference
getNodeAtlLevel	Gets the Node struct at a specific level and index

isLeaf	Returns true if the node is at level=0
getChildNode	Gets the child node reference at the specific bit position of the given parent node
getChildOffset	Gets the bit position of the given child node within the given parent node
getPosInNode	Returns true if the index-space position is inside the given node (and its bit), or false if outside
getVDBSize	Gets the size of the VDBInfo struct
getVDBInfo	Gets a pointer to the current VDBInfo struct
getWorldMin	Gets the world space bounding box min of the given node
getWorldMax	Gets the world space bounding box max of the given node
getVoxelSize	Gets the current global voxel size

10.2. Device Access

The Device access functions are:

*** See cuda_gvdb_nodes.cuh for function arguments**

numBitsOn	Counts the number of bits on in a 64-bit word
countOn	Counts the number of bits on in the given VDB node up to bit 'n'
isBitOn	Returns true if child bit 'n' is set (active) in the given VDB node
getAtlasNode (brickpos)	Gets a VDBAtlasNode* for the given brick-space position
getAtlasNodeFromIndex	Gets a VDBAtlasNode* for the given brick ID
getAtlasToWorld	Gets the world-space position from the atlas-space voxel. False if the atlas-space voxel is an unused brick (invalid).
getAtlasToWorldID	Gets the same results as getAtlasToWorld, but also gives the level-0 node ID for the point.
getChild	Gets the child index for the VDB node for the given bit count 'b'
getAtlasPos	Gets the atlas-space bottom corner ('value') for the given brick ID.
getBitPos	Gets the bit position for a point in local index-space for node at level
getNode (lev, n, vmin)	Gets a Node at the given level and index. Also returns the world-space position of the node.
getNodeAtPoint	Gets a brick Node covering the given world-position. (recursive)
getTricubic	Gets a tricubic interpolated value for the given local index-space in a node

getTrilinear	Gets a trilinear interpolated atlas value for the given local index-space in a node
getVolSampleC	Gets a uchar value for a T_UCHAR channel at the given world position.
getVolSampleF	Gets a float value for a T_FLOAT channel at the given world position.
getGradient	Gets the trilinear gradient at the given atlas-space point
getGradientLevelSet	Gets a level set gradient at the given local index-space point.
getGradientTricubic	Gets a tricubic gradient at the given local index-space point.
rayTricubic	Casts a fine-stepping ray for a tricubic surface inside the given node starting from the local point.
rayTrilinear	Casts a fine-stepping ray for a trilinear surface inside the given node starting from the local point
rayLevelSet	Casts a fine-stepping ray for a level set surface inside the given node starting from the local point
getColor	Gets a uchar4 value for a T_UCHAR4 color channel at the given atlas-space point
getColorF	Gets a float4 value (by casting) for a T_UCHAR4 color channel at the given atlas-space point
getLinearDepth	Gets the linear depth from an OpenGL depth buffer value

Appendix A.