

INTEL® OSPRAY

AN OPEN, SCALABLE, PARALLEL, RAY TRACING BASED RENDERING ENGINE FOR HIGH-FIDELITY VISUALIZATION

Version 2.2.0
July 9, 2020

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Chapter 1

OSPRay Overview

Intel OSPRay is an open source, scalable, and portable ray tracing engine for high-performance, high-fidelity visualization on Intel Architecture CPUs. OSPRay is part of the [Intel oneAPI Rendering Toolkit](#) and is released under the permissive [Apache 2.0 license](#).

The purpose of OSPRay is to provide an open, powerful, and easy-to-use rendering library that allows one to easily build applications that use ray tracing based rendering for interactive applications (including both surface- and volume-based visualizations). OSPRay is completely CPU-based, and runs on anything from laptops, to workstations, to compute nodes in HPC systems.

OSPRay internally builds on top of [Intel Embree](#) and [ISPC \(Intel SPMD Program Compiler\)](#), and fully exploits modern instruction sets like Intel SSE4, AVX, AVX2, and AVX-512 to achieve high rendering performance, thus a CPU with support for at least SSE4.1 is required to run OSPRay.

1.1 OSPRay Support and Contact

OSPRay is under active development, and though we do our best to guarantee stable release versions a certain number of bugs, as-yet-missing features, inconsistencies, or any other issues are still possible. Should you find any such issues please report them immediately via [OSPRay's GitHub Issue Tracker](#) (or, if you should happen to have a fix for it, you can also send us a pull request); for missing features please contact us via email at ospray@googlegroups.com.

To receive release announcements simply “Watch” the OSPRay repository on GitHub.

Changes in v2.2.0:

- Support for texture transformation in SciVis OBJ material
- Add transformations for volume textures; volume texture lookups are now with local object coordinates (not world coordinates anymore)
- Changed behavior: if solely a texture is given, then the default value of the corresponding parameter is *not* multiplied
- Support for better antialiasing using a set of different pixel filters (e.g. box, Gaussian, ...). The size of the pixel filter is defined by the used filter type. Previously OSPRay implicitly used a box filter with a size of 1, for better results the default filter is now `OSP_PIXELFILTER_GAUSS`
- Support stereo3d mode for panoramic camera
- Add new camera `stereoMode` `OSP_STEREO_TOP_BOTTOM` (with left eye at top half of the image)
- Added support for random light sampling to the `pathtracer`, the number of sampled light sources per path vertex is defined by the `lightSamples`

- parameter
- Support ring light by extending spot with `innerRadius`
 - Fixed nonphysical behavior of the spot and sphere light sources
 - for area lights (when `radius > 0`) surfaces close to the light will be darker
 - the spot now has an angular falloff, such that a disk light is a proper lambertian area light, which leads to darker regions perpendicular to its direction (thus barely visible with a typically small `openingAngle`)
 - Support for Open VKL v0.10.0 and its new sampler object API, thus this is now the required minimum version
 - Added support for particle and VDB volumes
 - Move from `ospcommon` to `rkcommon` v1.4.2
 - New minimum ISPC version is 1.10.0
 - Status and error callbacks now support a user pointer
 - Enabled C++ wrappers (`ospray_cpp`) to work with non-rkcommon math types
 - Note that while the C API remains the same, the C++ wrappers will require some application updates to account for these changes
 - Fix bug where `ospGetCurrentDevice` would crash if used before `ospInit`
 - Allow NULL handles to be passed to `ospDeviceRetain` and `ospDeviceRelease`
 - ISPC generated headers containing the exported functions for OSPRay's ISPC types and functions are now distributed with the SDK
 - Add CarPaint `flakeColor` parameter, defaults to current Aluminium
 - Fixed Debug build (which were producing different images)
 - The path tracer now also regards the renderer materialist when creating geometry lights

Changes in v2.1.1:

- CarPaint material obeys `coat` weight parameter
- Correct depth buffer values with SciVis renderer
- Adoptions to Embree v3.10.0
- The Linux binary release finds `ospcommon` again

Changes in v2.1.0:

- New clipping geometries feature that allows clipping any scene (geometry and volumes); all OSPRay geometry types can be used as clipping geometry
 - Inverted clipping is supported via new `invertNormals` parameter of `GeometricMode1`
 - Currently there is a fixed upper limit (64) of how many clipping geometries can be nested
 - When clipping with curves geometry (any basis except linear) some rendering artifacts may appear
- New plane geometry defined via plane equation and optional bounding box
- Sun-sky light based on physical model of Hošek-Wilkie
- Support for photometric lights (e.g., IES or EULUMDAT)
- Add new `ospGetTaskDuration` API call to query execution time of asynchronous tasks
- Support for 16bit (unsigned short) textures

- Add static `cpp::Device::current` method as a C++ wrapper equivalent to `ospGetCurrentDevice`
- Generalized `cpp::Device` parameter setting to match other handle types
- Passing NULL to `ospRelease` is not reported as error anymore
- Fix computation of strides for `OSPData`
- Fix transparency in `scivis` renderer
- Add missing C++ wrapper for `ospGetVariance`
- Proper demonstration of `ospGetVariance` in `ospTutorialAsync`
- Fix handling of `--osp:device-params` to process and set all passed arguments first before committing the device, to ensure it is committed in a valid state
- Object factory functions are now registered during module initialization via the appropriate `registerType` function
- Fix issue with OSPRay ignoring tasking system thread count settings
- Fix issue where OSPRay always loaded the ISPC module, even if not required
- OSPRay now requires minimum Open VKL v0.9.0

For the complete history of changes have a look at the [CHANGELOG](#).

Chapter 2

Building and Finding OSPRay

The latest OSPRay sources are always available at the [OSPRay GitHub repository](#). The default `master` branch should always point to the latest bugfix release.

2.1 Prerequisites

OSPRay currently supports Linux, Mac OS X, and Windows. In addition, before you can build OSPRay you need the following prerequisites:

- You can clone the latest OSPRay sources via:

```
git clone https://github.com/ospray/ospray.git
```

- To build OSPRay you need [CMake](#), any form of C++11 compiler (we recommend using GCC, but also support Clang, MSVC, and [Intel® C++ Compiler \(icc\)](#)), and standard Linux development tools. To build the interactive tutorials, you should also have some version of OpenGL and GLFW.
- Additionally you require a copy of the [Intel® SPMD Program Compiler \(ISPC\)](#), version 1.10.0 or later. Please obtain a release of ISPC from the [ISPC downloads page](#). The build system looks for ISPC in the PATH and in the directory right “next to” the checked-out OSPRay sources.¹ Alternatively set the CMake variable `ISPC_EXECUTABLE` to the location of the ISPC compiler. Note: OSPRay is incompatible with ISPC v1.11.0.
- OSPRay builds on top of the Intel oneAPI Rendering Toolkit common library `rkcommon`. The library provides abstractions for tasking, aligned memory allocation, vector math types, among others. For users who also need to build `rkcommon`, we recommend the default the Intel [Threading Building Blocks](#) (TBB) as tasking system for performance and flexibility reasons. Alternatively you can set CMake variable `RKCOMMON_TASKING_SYSTEM` to OpenMP or Internal.
- OSPRay also heavily uses Intel [Embree](#), installing version 3.8.0 or newer is required. If Embree is not found by CMake its location can be hinted with the variable `embree_DIR`.
- OSPRay also heavily uses Intel [Open VKL](#), installing version 0.10.0 or newer is required. If Open VKL is not found by CMake its location can be hinted with the variable `openvk1_DIR`.
- OSPRay also provides an optional module that adds support for Intel [Open Image Denoise](#), which is enabled by `OSPRAY_MODULE_DENOISER`. When loaded, this module enables the denoiser image operation. You may need

¹ For example, if OSPRay is in `~/Projects/ospray`, ISPC will also be searched in `~/Projects/ispc-v1.12.0-linux`

to hint the location of the library with the CMake variable `OpenImageDenoise_DIR`.

Depending on your Linux distribution you can install these dependencies using `yum` or `apt-get`. Some of these packages might already be installed or might have slightly different names.

Type the following to install the dependencies using `yum`:

```
sudo yum install cmake.x86_64
sudo yum install tbb.x86_64 tbb-devel.x86_64
```

Type the following to install the dependencies using `apt-get`:

```
sudo apt-get install cmake-curses-gui
sudo apt-get install libtbb-dev
```

Under Mac OS X these dependencies can be installed using [MacPorts](#):

```
sudo port install cmake tbb
```

Under Windows please directly use the appropriate installers for [CMake](#), [TBB](#), [ISPC](#) (for your Visual Studio version) and [Embree](#).

2.2 CMake Superbuild

For convenience, OSPRay provides a CMake Superbuild script which will pull down OSPRay's dependencies and build OSPRay itself. By default, the result is an install directory, with each dependency in its own directory.

Run with:

```
mkdir build
cd build
cmake [<OSPRAY_SOURCE_LOC>/scripts/superbuild]
cmake --build .
```

On Windows make sure to select the non-default 64bit generator, e.g.

```
cmake -G "Visual Studio 15 2017 Win64" [<OSPRAY_SOURCE_LOC>/scripts/superbuild]
```

The resulting `install` directory (or the one set with `CMAKE_INSTALL_PREFIX`) will have everything in it, with one subdirectory per dependency.

CMake options to note (all have sensible defaults):

`CMAKE_INSTALL_PREFIX` will be the root directory where everything gets installed.

`BUILD_JOBS` sets the number given to `make -j` for parallel builds.

`INSTALL_IN_SEPARATE_DIRECTORIES` toggles installation of all libraries in separate or the same directory.

`BUILD_EMBREE_FROM_SOURCE` set to OFF will download a pre-built version of Embree.

`BUILD_OIDN_FROM_SOURCE` set to OFF will download a pre-built version of Open Image Denoise.

`BUILD_OIDN_VERSION` determines which version of Open Image Denoise to pull down.

For the full set of options, run:

```
ccmake [<OSPRAY_SOURCE_LOC>/scripts/superbuild]
```

or

```
cmake-gui [<OSPRAY_SOURCE_LOC>/scripts/superbuild]
```

2.3 Standard CMake build

2.3.1 Compiling OSPRay on Linux and Mac OS X

Assuming the above requisites are all fulfilled, building OSPRay through CMake is easy:

- Create a build directory, and go into it

```
mkdir ospray/build  
cd ospray/build
```

(We do recommend having separate build directories for different configurations such as release, debug, etc.).

- The compiler CMake will use will default to whatever the CC and CXX environment variables point to. Should you want to specify a different compiler, run cmake manually while specifying the desired compiler. The default compiler on most linux machines is gcc, but it can be pointed to clang instead by executing the following:

```
cmake -DCMAKE_CXX_COMPILER=clang++ -DCMAKE_C_COMPILER=clang ..
```

CMake will now use Clang instead of GCC. If you are ok with using the default compiler on your system, then simply skip this step. Note that the compiler variables cannot be changed after the first cmake or ccmake run.

- Open the CMake configuration dialog

```
ccmake ..
```

- Make sure to properly set build mode and enable the components you need, etc.; then type 'c'onfigure and 'g'enerate. When back on the command prompt, build it using

```
make
```

- You should now have libospray.[so,dylib] as well as a set of [example applications](#).

2.3.2 Compiling OSPRay on Windows

On Windows using the CMake GUI (cmake-gui.exe) is the most convenient way to configure OSPRay and to create the Visual Studio solution files:

- Browse to the OSPRay sources and specify a build directory (if it does not exist yet CMake will create it).
- Click “Configure” and select as generator the Visual Studio version you have (OSPRay needs Visual Studio 14 2015 or newer), for Win64 (32 bit builds are not supported by OSPRay), e.g., “Visual Studio 15 2017 Win64”.
- If the configuration fails because some dependencies could not be found then follow the instructions given in the error message, e.g., set the variable embree_DIR to the folder where Embree was installed and openvkl_DIR to where Open VKL was installed.
- Optionally change the default build options, and then click “Generate” to create the solution and project files in the build directory.

- Open the generated `OSPRay.sln` in Visual Studio, select the build configuration and compile the project.

Alternatively, OSPRay can also be built without any GUI, entirely on the console. In the Visual Studio command prompt type:

```
cd path\to\ospray
mkdir build
cd build
cmake -G "Visual Studio 15 2017 Win64" [-D VARIABLE=value] ..
cmake --build . --config Release
```

Use `-D` to set variables for CMake, e.g., the path to Embree with “`-D embree_DIR=\path\to\embree`”.

You can also build only some projects with the `--target` switch. Additional parameters after “`--`” will be passed to `msbuild`. For example, to build in parallel only the OSPRay library without the example applications use

```
cmake --build . --config Release --target ospray -- /m
```

2.4 Finding an OSPRay Install with CMake

Client applications using OSPRay can find it with CMake’s `find_package()` command. For example,

```
find_package(ospray 2.0.0 REQUIRED)
```

finds OSPRay via OSPRay’s configuration file `osprayConfig.cmake`². Once found, the following is all that is required to use OSPRay:

```
target_link_libraries(${client_target} ospray::ospray)
```

This will automatically propagate all required include paths, linked libraries, and compiler definitions to the client CMake target (either an executable or library).

Advanced users may want to link to additional targets which are exported in OSPRay’s CMake config, which includes all installed modules. All targets built with OSPRay are exported in the `ospray::` namespace, therefore all targets locally used in the OSPRay source tree can be accessed from an install. For example, `ospray_module_ispc` can be consumed directly via the `ospray::ospray_module_ispc` target. All targets have their libraries, includes, and definitions attached to them for public consumption (please [report bugs](#) if this is broken!).

² This file is usually in `${install_location}/[lib|lib64]/cmake/ospray-${version}/`. If CMake does not find it automatically, then specify its location in variable `ospray_DIR` (either an environment variable or CMake variable).

Chapter 3

OSPRay API

To access the OSPRay API you first need to include the OSPRay header

```
#include "ospray/ospray.h"
```

where the API is compatible with C99 and C++.

3.1 Initialization and Shutdown

To use the API, OSPRay must be initialized with a “device”. A device is the object which implements the API. Creating and initializing a device can be done in either of two ways: command line arguments using `ospInit` or manually instantiating a device and setting parameters on it.

3.1.1 Command Line Arguments

The first is to do so by giving OSPRay the command line from `main()` by calling

```
OSPError ospInit(int *argc, const char **argv);
```

OSPRay parses (and removes) its known command line parameters from your application’s `main` function. For an example see the [tutorial](#). For possible error codes see section [Error Handling and Status Messages](#). It is important to note that the arguments passed to `ospInit()` are processed in order they are listed. The following parameters (which are prefixed by convention with “`--osp:`”) are understood:

3.1.2 Manual Device Instantiation

The second method of initialization is to explicitly create the device and possibly set parameters. This method looks almost identical to how other [objects](#) are created and used by OSPRay (described in later sections). The first step is to create the device with

```
OSPDevice ospNewDevice(const char *type);
```

where the `type` string maps to a specific device implementation. OSPRay always provides the “cpu” device, which maps to a fast, local CPU implementation. Other devices can also be added through additional modules, such as distributed MPI device implementations.

Once a device is created, you can call

```
void ospDeviceSetParam(OSPObject, const char *id, OSPDataType type, const void *mem);
```

Table 3.1 – Command line parameters accepted by OSPRay’s `ospInit`.

Parameter	Description
<code>--osp:debug</code>	enables various extra checks and debug output, and disables multi-threading
<code>--osp:num-threads=<n></code>	use <code>n</code> threads instead of per default using all detected hardware threads
<code>--osp:log-level=<str></code>	set logging level; valid values (in order of severity) are <code>none</code> , <code>error</code> , <code>warning</code> , <code>info</code> , and <code>debug</code>
<code>--osp:warn-as-error</code>	send warning and error messages through the error callback, otherwise send warning messages through the message callback; must have sufficient <code>logLevel</code> to enable warnings
<code>--osp:verbose</code>	shortcut for <code>--osp:log-level=info</code> and enable debug output on <code>cout</code> , error output on <code>cerr</code>
<code>--osp:vv</code>	shortcut for <code>--osp:log-level=debug</code> and enable debug output on <code>cout</code> , error output on <code>cerr</code>
<code>--osp:load-modules=<name>[, . . .]</code>	load one or more modules during initialization; equivalent to calling <code>osLoadModule(name)</code>
<code>--osp:log-output=<dst></code>	convenience for setting where status messages go; valid values for <code>dst</code> are <code>cerr</code> and <code>cout</code>
<code>--osp:error-output=<dst></code>	convenience for setting where error messages go; valid values for <code>dst</code> are <code>cerr</code> and <code>cout</code>
<code>--osp:device=<name></code>	use <code>name</code> as the type of device for OSPRay to create; e.g., <code>--osp:device=cpu</code> gives you the default <code>cpu</code> device; Note if the device to be used is defined in a module, remember to pass <code>--osp:load-modules=<name></code> first
<code>--osp:set-affinity=<n></code>	if 1, bind software threads to hardware threads; 0 disables binding; default is 1 on KNL and 0 otherwise
<code>--osp:device-params=<param>:<value>[, . . .]</code>	set one or more other device parameters; equivalent to calling <code>ospDeviceSet*(param, value)</code>

Table 3.2 – Parameters shared by all devices.

Type	Name	Description
int	<code>numThreads</code>	number of threads which OSPRay should use
int	<code>logLevel</code>	logging level; valid values (in order of severity) are <code>OSP_LOG_NONE</code> , <code>OSP_LOG_ERROR</code> , <code>OSP_LOG_WARNING</code> , <code>OSP_LOG_INFO</code> , and <code>OSP_LOG_DEBUG</code>
string	<code>logOutput</code>	convenience for setting where status messages go; valid values are <code>cerr</code> and <code>cout</code>
string	<code>errorOutput</code>	convenience for setting where error messages go; valid values are <code>cerr</code> and <code>cout</code>
bool	<code>debug</code>	set debug mode; equivalent to <code>logLevel=debug</code> and <code>numThreads=1</code>
bool	<code>warnAsError</code>	send warning and error messages through the error callback, otherwise send warning messages through the message callback; must have sufficient <code>logLevel</code> to enable warnings
bool	<code>setAffinity</code>	bind software threads to hardware threads if set to 1; 0 disables binding omitting the parameter will let OSPRay choose

to set parameters on the device. The semantics of setting parameters is exactly the same as `ospSetParam`, which is documented below in the [parameters](#) section. The following parameters can be set on all devices:

Once parameters are set on the created device, the device must be committed

with

```
void ospDeviceCommit(OSPDevice);
```

To use the newly committed device, you must call

```
void ospSetCurrentDevice(OSPDevice);
```

This then sets the given device as the object which will respond to all other OSPRay API calls.

Device handle lifetimes are managed with two calls, the first which increments the internal reference count to the given OSPDevice

```
void ospDeviceRetain(OSPDevice)
```

and the second which decrements the reference count

```
void ospDeviceRelease(OSPDevice)
```

Users can change parameters on the device after initialization (from either method above), by calling

```
OSPDevice ospGetCurrentDevice();
```

This function returns the handle to the device currently used to respond to OSPRay API calls, where users can set/change parameters and recommit the device. If changes are made to the device that is already set as the current device, it does not need to be set as current again. Note this API call will increment the ref count of the returned device handle, so applications must use `ospDeviceRelease` when finished using the handle to avoid leaking the underlying device object. If there is no current device set, this will return an invalid NULL handle.

When a device is created, its reference count is initially 1. When a device is set as the current device, it internally has its reference count incremented. Note that `ospDeviceRetain` and `ospDeviceRelease` should only be used with reference counts that the application tracks: removing reference held by the current set device should be handled by `ospShutdown`. Thus, `ospDeviceRelease` should only decrement the reference counts that come from `ospNewDevice`, `ospGetCurrentDevice`, and the number of explicit calls to `ospDeviceRetain`.

OSPRay allows applications to query runtime properties of a device in order to do enhanced validation of what device was loaded at runtime. The following function can be used to get these device-specific properties (attributes about the device, not parameter values)

```
int64_t ospDeviceGetProperty(OSPDevice, OSPDeviceProperty);
```

It returns an integer value of the queried property and the following properties can be provided as parameter:

```
OSP_DEVICE_VERSION
OSP_DEVICE_VERSION_MAJOR
OSP_DEVICE_VERSION_MINOR
OSP_DEVICE_VERSION_PATCH
OSP_DEVICE_SO_VERSION
```

3.1.3 Environment Variables

OSPRay's generic device parameters can be overridden via environment variables for easy changes to OSPRay's behavior without needing to change the application (variables are prefixed by convention with "OSPRAY_"):

Note that these environment variables take precedence over values specified through `ospInit` or manually set device parameters.

Table 3.3 – Environment variables interpreted by OSPRay.

Variable	Description
OSPRAY_NUM_THREADS	equivalent to --osp:num-threads
OSPRAY_LOG_LEVEL	equivalent to --osp:log-level
OSPRAY_LOG_OUTPUT	equivalent to --osp:log-output
OSPRAY_ERROR_OUTPUT	equivalent to --osp:error-output
OSPRAY_DEBUG	equivalent to --osp:debug
OSPRAY_WARN_AS_ERROR	equivalent to --osp:warn-as-error
OSPRAY_SET_AFFINITY	equivalent to --osp:set-affinity
OSPRAY_LOAD_MODULES	equivalent to --osp:load-modules, can be a comma separated list of modules which will be loaded in order
OSPRAY_DEVICE	equivalent to --osp:device:

3.1.4 Error Handling and Status Messages

The following errors are currently used by OSPRay:

Name	Description
OSP_NO_ERROR	no error occurred
OSP_UNKNOWN_ERROR	an unknown error occurred
OSP_INVALID_ARGUMENT	an invalid argument was specified
OSP_INVALID_OPERATION	the operation is not allowed for the specified object
OSP_OUT_OF_MEMORY	there is not enough memory to execute the command
OSP_UNSUPPORTED_CPU	the CPU is not supported (minimum ISA is SSE4.1)
OSP_VERSION_MISMATCH	a module could not be loaded due to mismatching version

Table 3.4 – Possible error codes, i.e., valid named constants of type `OSPError`.

These error codes are either directly return by some API functions, or are recorded to be later queried by the application via

```
OSPError ospDeviceGetLastErrorCode(OSPDevice);
```

A more descriptive error message can be queried by calling

```
const char* ospDeviceGetLastErrorMsg(OSPDevice);
```

Alternatively, the application can also register a callback function of type

```
typedef void (*OSPErrorCallback)(void *userData, OSPError, const char* errorDetails);
```

via

```
void ospDeviceSetErrorCallback(OSPDevice, OSPErrorCallback, void *userData);
```

to get notified when errors occur.

Applications may be interested in messages which OSPRay emits, whether for debugging or logging events. Applications can call

```
void ospDeviceSetStatusCallback(OSPDevice, OSPStatusCallback, void *userData);
```

in order to register a callback function of type

```
typedef void (*OSPStatusCallback)(void *userData, const char* messageText);
```

which OSPRay will use to emit status messages. By default, OSPRay uses a callback which does nothing, so any output desired by an application will require that a callback is provided. Note that callbacks for C++ `std::cout` and `std::cerr` can be alternatively set through `ospInit()` or the `OSPRAY_LOG_OUTPUT` environment variable.

Applications can clear either callback by passing `nullptr` instead of an actual function pointer.

3.1.5 Loading OSPRay Extensions at Runtime

OSPRay's functionality can be extended via plugins (which we call "modules"), which are implemented in shared libraries. To load module `name` from `libospray_module_<name>.so` (on Linux and Mac OS X) or `ospray_module_<name>.dll` (on Windows) use

```
OSPError ospLoadModule(const char *name);
```

Modules are searched in OS-dependent paths. `ospLoadModule` returns `OSP_NO_ERROR` if the plugin could be successfully loaded.

3.1.6 Shutting Down OSPRay

When the application is finished using OSPRay (typically on application exit), the OSPRay API should be finalized with

```
void ospShutdown();
```

This API call ensures that the current device is cleaned up appropriately. Due to static object allocation having non-deterministic ordering, it is recommended that applications call `ospShutdown()` before the calling application process terminates.

3.2 Objects

All entities of OSPRay (the `renderer`, `volumes`, `geometries`, `lights`, `cameras`, ...) are a logical specialization of `OSPObject` and share common mechanism to deal with parameters and lifetime.

An important aspect of object parameters is that parameters do not get passed to objects immediately. Instead, parameters are not visible at all to objects until they get explicitly committed to a given object via a call to

```
void ospCommit(OSPObject);
```

at which time all previously additions or changes to parameters are visible at the same time. If a user wants to change the state of an existing object (e.g., to change the origin of an already existing camera) it is perfectly valid to do so, as long as the changed parameters are recommitted.

The commit semantic allow for batching up multiple small changes, and specifies exactly when changes to objects will occur. This can impact performance and consistency for devices crossing a PCI bus or across a network.

Note that OSPRay uses reference counting to manage the lifetime of all objects, so one cannot explicitly "delete" any object. Instead, to indicate that the application does not need and does not access the given object anymore, call

```
void ospRelease(OSPObject);
```

This decreases its reference count and if the count reaches 0 the object will automatically get deleted. Passing NULL is not an error.

Sometimes applications may want to have more than one reference to an object, where it is desirable for the application to increment the reference count of an object. This is done with

```
void ospRetain(OSPObject);
```

It is important to note that this is only necessary if the application wants to call `ospRelease` on an object more than once: objects which contain other objects as parameters internally increment/decrement ref counts and should not be explicitly done by the application.

3.2.1 Parameters

Parameters allow to configure the behavior of and to pass data to objects. However, objects do *not* have an explicit interface for reasons of high flexibility and a more stable compile-time API. Instead, parameters are passed separately to objects in an arbitrary order, and unknown parameters will simply be ignored (though a warning message will be posted). The following function allows adding various types of parameters with name `id` to a given object:

```
void ospSetParam(OSPObject, const char *id, OSPDataType type, const void *mem);
```

The valid parameter names for all `OSPObject`s and what types are valid are discussed in future sections.

Note that `mem` must always be a pointer *to* the object, otherwise accidental type casting can occur. This is especially true for pointer types (`OSP_VOID_PTR` and `OSPObject` handles), as they will implicitly cast to `void *`, but be incorrectly interpreted. To help with some of these issues, there also exist variants of `ospSetParam` for specific types, such as `ospSetInt` and `ospSetVec3f` in the OSPRay utility library (found in `ospray_util.h`).

Users can also remove parameters that have been explicitly set from `ospSetParam`. Any parameters which have been removed will go back to their default value during the next commit unless a new parameter was set after the parameter was removed. To remove a parameter, use

```
void ospRemoveParam(OSPObject, const char *id);
```

3.2.2 Data

OSPRay consumes data arrays from the application using a specific object type, `OSPData`. There are several components to describing a data array: element type, 1/2/3 dimensional striding, and whether the array is shared with the application or copied into opaque, OSPRay-owned memory.

Shared data arrays require that the application's array memory outlives the lifetime of the created `OSPData`, as OSPRay is referring to application memory. Where this is not preferable, applications use opaque arrays to allow the `OSPData` to own the lifetime of the array memory. However, opaque arrays dictate the cost of copying data into it, which should be kept in mind.

Thus, the most efficient way to specify a data array from the application is to create a shared data array, which is done with

```
OSPData ospNewSharedData(const void *sharedData,
                        OSPDataType,
                        uint64_t numItems1,
```

```
int64_t byteStride1 = 0,
uint64_t numItems2 = 1,
int64_t byteStride2 = 0,
uint64_t numItems3 = 1,
int64_t byteStride3 = 0);
```

The call returns an OSPData handle to the created array. The calling program guarantees that the sharedData pointer will remain valid for the duration that this data array is being used. The number of elements numItems must be positive (there cannot be an empty data object). The data is arranged in three dimensions, with specializations to two or one dimension (if some numItems are 1). The distance between consecutive elements (per dimension) is given in bytes with byteStride and can also be negative. If byteStride is zero it will be determined automatically (e.g., as sizeof(type)). Strides do not need to be ordered, i.e., byteStride2 can be smaller than byteStride1, which is equivalent to a transpose. However, if the stride should be calculated, then an ordering in dimensions is assumed to disambiguate, i.e., byteStride1 < byteStride2 < byteStride3.

The enum type OSPDataType describes the different element types that can be represented in OSPRay; valid constants are listed in the table below.

If the elements of the array are handles to objects, then their reference counter is incremented.

An opaque OSPData with memory allocated by OSPRay is created with

```
OSPData ospNewData(OSPDataType,
    uint32_t numItems1,
    uint32_t numItems2 = 1,
    uint32_t numItems3 = 1);
```

To allow for (partial) copies or updates of data arrays use

```
void ospCopyData(const OSPData source,
    OSPData destination,
    uint32_t destinationIndex1 = 0,
    uint32_t destinationIndex2 = 0,
    uint32_t destinationIndex3 = 0);
```

which will copy the whole¹ content of the source array into destination at the given location destinationIndex. The OSPDataTypes of the data objects must match. The region to be copied must be valid inside the destination, i.e., in all dimensions, destinationIndex + sourceSize <= destinationSize. The affected region [destinationIndex, destinationIndex + sourceSize) is marked as dirty, which may be used by OSPRay to only process or update that sub-region (e.g., updating an acceleration structure). If the destination array is shared with OSPData by the application (created with ospNewSharedData), then

- the source array must be shared as well (thus ospCopyData cannot be used to read opaque data)
- if source and destination memory overlaps (aliasing), then behavior is undefined
- except if source and destination regions are identical (including matching strides), which can be used by application to mark that region as dirty (instead of the whole OSPData)

To add a data array as parameter named id to another object call also use

```
void ospSetObject(OSPObject, const char *id, OSPData);
```

¹ The number of items to be copied is defined by the size of the source array

Type/Name	Description
OSP_DEVICE	API device object reference
OSP_DATA	data reference
OSP_OBJECT	generic object reference
OSP_CAMERA	camera object reference
OSP_FRAMEBUFFER	framebuffer object reference
OSP_LIGHT	light object reference
OSP_MATERIAL	material object reference
OSP_TEXTURE	texture object reference
OSP_RENDERER	renderer object reference
OSP_WORLD	world object reference
OSP_GEOMETRY	geometry object reference
OSP_VOLUME	volume object reference
OSP_TRANSFER_FUNCTION	transfer function object reference
OSP_IMAGE_OPERATION	image operation object reference
OSP_STRING	C-style zero-terminated character string
OSP_CHAR	8 bit signed character scalar
OSP_UCHAR	8 bit unsigned character scalar
OSP_VEC[234]UC	... and [234]-element vector
OSP USHORT	16 bit unsigned integer scalar
OSP_VEC[234]US	... and [234]-element vector
OSP_INT	32 bit signed integer scalar
OSP_VEC[234]I	... and [234]-element vector
OSP_UINT	32 bit unsigned integer scalar
OSP_VEC[234]UI	... and [234]-element vector
OSP_LONG	64 bit signed integer scalar
OSP_VEC[234]L	... and [234]-element vector
OSP ULONG	64 bit unsigned integer scalar
OSP_VEC[234]UL	... and [234]-element vector
OSP_FLOAT	32 bit single precision floating-point scalar
OSP_VEC[234]F	... and [234]-element vector
OSP_DOUBLE	64 bit double precision floating-point scalar
OSP_BOX[1234]I	32 bit integer box (lower + upper bounds)
OSP_BOX[1234]F	32 bit single precision floating-point box (lower + upper bounds)
OSP_LINEAR[23]F	32 bit single precision floating-point linear transform ([23] vectors)
OSP_AFFINE[23]F	32 bit single precision floating-point affine transform (linear transform plus translation)
OSP_VOID_PTR	raw memory address (only found in module extensions)

Table 3.5 – Valid named constants for OSPDataType.

3.3 Volumes

Volumes are volumetric data sets with discretely sampled values in 3D space, typically a 3D scalar field. To create a new volume object of given type use

```
OSPVolume ospNewVolume(const char *type);
```

Note that OSPRay's implementation forwards type directly to Open VKL, allowing new Open VKL volume types to be usable within OSPRay without the need to change (or even recompile) OSPRay.

3.3.1 Structured Regular Volume

Structured volumes only need to store the values of the samples, because their addresses in memory can be easily computed from a 3D position. A common type of structured volumes are regular grids.

Structured regular volumes are created by passing the type string “structuredRegular” to `ospNewVolume`. Structured volumes are represented through an `OSPData` 3D array `data` (which may or may not be shared with the application), where currently the voxel data needs to be laid out compact in memory in xyz-order²

The parameters understood by structured volumes are summarized in the table below.

Type	Name	Default	Description
vec3f	gridOrigin	(0, 0, 0)	origin of the grid in object-space
vec3f	gridSpacing	(1, 1, 1)	size of the grid cells in object-space
OSPData	data		the actual voxel 3D <code>data</code>

The size of the volume is inferred from the size of the 3D array `data`, as is the type of the voxel values (currently supported are: `OSP_UCHAR`, `OSP_SHORT`, `OSP USHORT`, `OSP_FLOAT`, and `OSP_DOUBLE`).

3.3.2 Structured Spherical Volume

Structured spherical volumes are also supported, which are created by passing a type string of “structuredSpherical” to `ospNewVolume`. The grid dimensions and parameters are defined in terms of radial distance r , inclination angle θ , and azimuthal angle ϕ , conforming with the ISO convention for spherical coordinate systems. The coordinate system and parameters understood by structured spherical volumes are summarized below.

Type	Name	Default	Description
vec3f	gridOrigin	(0, 0, 0)	origin of the grid in units of (r, θ, ϕ) ; angles in degrees
vec3f	gridSpacing	(1, 1, 1)	size of the grid cells in units of (r, θ, ϕ) ; angles in degrees
OSPData	data		the actual voxel 3D <code>data</code>

The dimensions (r, θ, ϕ) of the volume are inferred from the size of the 3D array `data`, as is the type of the voxel values (currently supported are: `OSP_UCHAR`, `OSP_SHORT`, `OSP USHORT`, `OSP_FLOAT`, and `OSP_DOUBLE`).

² For consecutive memory addresses the x-index of the corresponding voxel changes the quickest.

Table 3.6 – Configuration parameters for structured regular volumes.

Table 3.7 – Configuration parameters for structured spherical volumes.

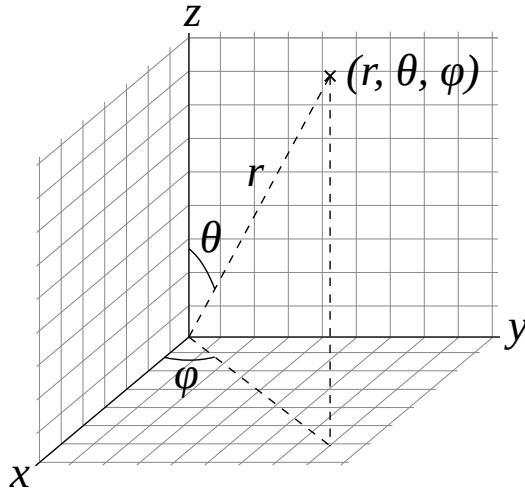


Figure 3.1 – Coordinate system of structured spherical volumes.

These grid parameters support flexible specification of spheres, hemispheres, spherical shells, spherical wedges, and so forth. The grid extents (computed as `[gridOrigin, gridOrigin + (dimensions - 1) * gridSpacing]`) however must be constrained such that:

- $r \geq 0$
- $0 \leq \theta \leq 180$
- $0 \leq \phi \leq 360$

3.3.3 Adaptive Mesh Refinement (AMR) Volume

OSPRay currently supports block-structured (Berger-Colella) AMR volumes. Volumes are specified as a list of blocks, which exist at levels of refinement in potentially overlapping regions. Blocks exist in a tree structure, with coarser refinement level blocks containing finer blocks. The cell width is equal for all blocks at the same refinement level, though blocks at a coarser level have a larger cell width than finer levels.

There can be any number of refinement levels and any number of blocks at any level of refinement. An AMR volume type is created by passing the type string “`amr`” to `ospNewVolume`.

Blocks are defined by three parameters: their bounds, the refinement level in which they reside, and the scalar data contained within each block.

Note that cell widths are defined *per refinement level*, not per block.

Lastly, note that the `gridOrigin` and `gridSpacing` parameters act just like the structured volume equivalent, but they only modify the root (coarsest level) of refinement.

In particular, OSPRay’s / Open VKL’s AMR implementation was designed to cover Berger-Colella [1] and Chombo [2] AMR data. The `method` parameter above determines the interpolation method used when sampling the volume.

`OSP_AMR_CURRENT` finds the finest refinement level at that cell and interpolates through this “current” level

`OSP_AMR_FINEST` will interpolate at the closest existing cell in the volume-wide finest refinement level regardless of the sample cell’s level

`OSP_AMR_OCTANT` interpolates through all available refinement levels at that cell. This method avoids discontinuities at refinement level boundaries at the cost of performance

Details and more information can be found in the publication for the implementation [3].

Table 3.8 – Configuration parameters for AMR volumes.

Type	Name	Default	Description
OSPAMRMethod	method	OSP_AMR_CURRENT	OSPAMRMethod sampling method. Supported methods are: OSP_AMR_CURRENT OSP_AMR_FINEST OSP_AMR_OCTANT
float[]	cellWidth	NULL	array of each level's cell width
box3i[]	block.bounds	NULL	data array of grid sizes (in voxels) for each AMR block
int[]	block.level	NULL	array of each block's refinement level
OSPData[]	block.data	NULL	data array of OSPData containing the actual scalar voxel data, only OSP_FLOAT is supported as OSPDataType
vec3f	gridOrigin	(0, 0, 0)	origin of the grid in world-space
vec3f	gridSpacing	(1, 1, 1)	size of the grid cells in world-space

1. M.J. Berger and P. Colella, “Local adaptive mesh refinement for shock hydrodynamics.” Journal of Computational Physics 82.1 (1989): 64-84. DOI: 10.1016/0021-9991(89)90035-1
2. M. Adams, P. Colella, D.T. Graves, J.N. Johnson, N.D. Keen, T.J. Ligocki, D.F. Martin, P.W. McCorquodale, D. Modiano, P.O. Schwartz, T.D. Sternberg, and B. Van Straalen, “Chombo Software Package for AMR Applications – Design Document”, Lawrence Berkeley National Laboratory Technical Report LBNL-6616E.
3. I. Wald, C. Brownlee, W. Usher, and A. Knoll, “CPU volume rendering of adaptive mesh refinement data”. SIGGRAPH Asia 2017 Symposium on Visualization – SA ’17, 18(8), 1–8. DOI: 10.1145/3139295.3139305

3.3.4 Unstructured Volume

Unstructured volumes can have their topology and geometry freely defined. Geometry can be composed of tetrahedral, hexahedral, wedge or pyramid cell types. The data format used is compatible with VTK and consists of multiple arrays: vertex positions and values, vertex indices, cell start indices, cell types, and cell values. An unstructured volume type is created by passing the type string “unstructured” to `ospNewVolume`.

Sampled cell values can be specified either per-vertex (`vertex.data`) or per-cell (`cell.data`). If both arrays are set, `cell.data` takes precedence.

Similar to a mesh, each cell is formed by a group of indices into the vertices. For each vertex, the corresponding (by array index) data value will be used for sampling when rendering, if specified. The index order for a tetrahedron is the same as VTK_TETRA: bottom triangle counterclockwise, then the top vertex.

For hexahedral cells, each hexahedron is formed by a group of eight indices into the vertices and data values. Vertex ordering is the same as VTK_HEXAHEDRON: four bottom vertices counterclockwise, then top four counterclockwise.

For wedge cells, each wedge is formed by a group of six indices into the vertices and data values. Vertex ordering is the same as VTK_WEDGE: three bottom vertices counterclockwise, then top three counterclockwise.

For pyramid cells, each cell is formed by a group of five indices into the vertices and data values. Vertex ordering is the same as VTK_PYRAMID: four bottom vertices counterclockwise, then the top vertex.

To maintain VTK data compatibility, the index array may be specified with cell sizes interleaved with vertex indices in the following format: $n, id_1, \dots, id_n, m, id_1, \dots, id_m$.

This alternative index array layout can be enabled through the `indexPrefixed` flag (in which case, the `cell.type` parameter must be omitted).

Table 3.9 – Configuration parameters for unstructured volumes.

Type	Name	Default	Description
<code>vec3f[]</code>	<code>vertex.position</code>		<code>data</code> array of vertex positions
<code>float[]</code>	<code>vertex.data</code>		<code>data</code> array of vertex data values to be sampled
<code>uint32[] / uint64[]</code>	<code>index</code>		<code>data</code> array of indices (into the vertex array(s)) that form cells
<code>bool</code>	<code>indexPrefixed</code>	<code>false</code>	indicates that the <code>index</code> array is compatible to VTK, where the indices of each cell are prefixed with the number of vertices
<code>uint32[] / uint64[]</code>	<code>cell.index</code>		<code>data</code> array of locations (into the <code>index</code> array), specifying the first index of each cell
<code>float[]</code>	<code>cell.data</code>		<code>data</code> array of cell data values to be sampled
<code>uint8[]</code>	<code>cell.type</code>		<code>data</code> array of cell types (VTK compatible), only set if <code>indexPrefixed = false</code> . Supported types are: <code>OSP_TETRAHEDRON</code> <code>OSP_HEXAHEDRON</code> <code>OSP_WEDGE</code> <code>OSP_PYRAMID</code>
<code>bool</code>	<code>hexIterative</code>	<code>false</code>	hexahedron interpolation method, defaults to fast non-iterative version which could have rendering inaccuracies may appear if hex is not parallelepiped
<code>bool</code>	<code>precomputedNormals</code>	<code>false</code>	whether to accelerate by precomputing, at a cost of 12 bytes/face

3.3.5 VDB Volume

VDB volumes implement a data structure that is very similar to the data structure outlined in Museth [1], they are created by passing the type string “vdb” to `ospNewVolume`.

The data structure is a hierarchical regular grid at its core: Nodes are regular grids, and each grid cell may either store a constant value (this is called a tile), or child pointers. Nodes in VDB trees are wide: Nodes on the first level have a resolution of 32^3 voxels, on the next level 16^3 , and on the leaf level 8^3 voxels. All nodes on a given level have the same resolution. This makes it easy to find the node containing a coordinate using shift operations (see [1]). VDB leaf nodes are implicit in OSPRay / Open VKL: they are stored as pointers to user-provided data.

VDB volumes interpret input data as constant cells (which are then potentially filtered). This is in contrast to `structuredRegular` volumes, which have a vertex-centered interpretation.

The VDB implementation in OSPRay / Open VKL follows the following goals:

- Efficient data structure traversal on vector architectures.
- Enable the use of industry-standard .vdb files created through the OpenVDB library.
- Compatibility with OpenVDB on a leaf data level, so that .vdb file may be loaded with minimal overhead.

VDB volumes have the following parameters:

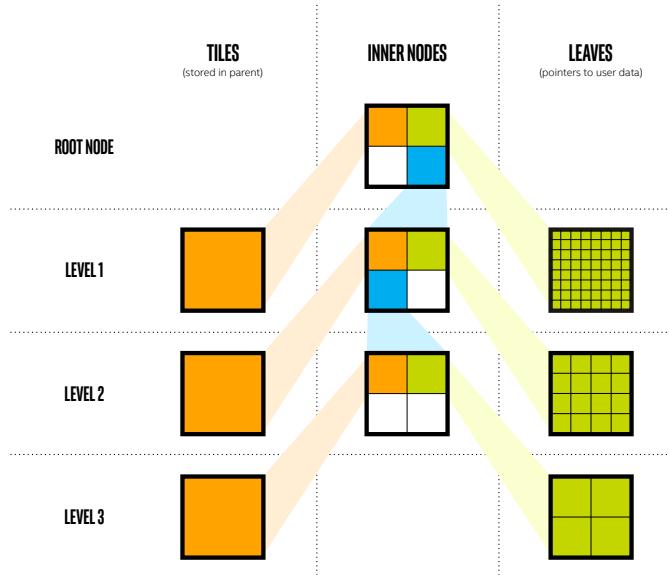


Figure 3.2 – Topology of VDB volumes.

Table 3.10 – Configuration parameters for VDB volumes.

Type	Name	Description
int	maxIteratorDepth	do not descend further than to this depth during interval iteration, the maximum value and the default is 3
int	maxSamplingDepth	do not descend further than to this depth during sampling, the maximum value and the default is 3
uint32[]	node.level	level on which each input node exists, may be 1, 2 or 3 (levels are counted from the root level = 0 down)
vec3i[]	node.origin	the node origin index (per input node)
OSPData[]	node.data	data arrays with the node data (per input node). Nodes that are tiles are expected to have single-item arrays. Leaf-nodes with grid data expected to have compact 3D arrays in zyx layout (z changes most quickly) with the correct number of voxels for the level. Only OSP_FLOAT is supported as field OSPDataType.
int	filter	filter used for reconstructing the field, default is OSP_VOLUME_FILTER_TRILINEAR, alternatively OSP_VOLUME_FILTER_NEAREST.
int	gradientFilter	filter used for reconstructing the field during gradient computations, default same as filter

1. Museth, K. VDB: High-Resolution Sparse Volumes with Dynamic Topology. ACM Transactions on Graphics 32(3), 2013. DOI: 10.1145/2487228.2487235

3.3.6 Particle Volume

Particle volumes consist of a set of points in space. Each point has a position, a radius, and a weight typically associated with an attribute. Particle volumes are created by passing the type string “particle” to `ospNewVolume`.

A radial basis function defines the contribution of that particle. Currently, we use the Gaussian radial basis function

$$\phi(P) = w \exp\left(-\frac{(P - p)^2}{2r^2}\right),$$

where P is the particle position, p is the sample position, r is the radius and w is

the weight. At each sample, the scalar field value is then computed as the sum of each radial basis function ϕ , for each particle that overlaps it.

The OSPRay / Open VKL implementation is similar to direct evaluation of samples in Reda et al. [2]. It uses an Embree-built BVH with a custom traversal, similar to the method in [1].

Table 3.11 – Configuration parameters for particle volumes.

Type	Name	Default	Description
vec3f[]	particle.position		data array of particle positions
float[]	particle.radius		data array of particle radii
float[]	particle.weight	NULL	optional data array of particle weights, specifying the height of the kernel.
float	radiusSupportFactor	3.0	The multiplier of the particle radius required for support. Larger radii ensure smooth results at the cost of performance. In the Gaussian kernel, the radius is one standard deviation (σ), so a value of 3 corresponds to 3σ .
float	clampMaxCumulativeValue	0	The maximum cumulative value possible, set by user. All cumulative values will be clamped to this, and further traversal (RBF summation) of particle contributions will halt when this value is reached. A value of zero or less turns this off.
bool	estimateValueRanges	true	Enable heuristic estimation of value ranges which are used in internal acceleration structures as well as for determining the volume's overall value range. When set to <code>false</code> , the user <i>must</i> specify <code>clampMaxCumulativeValue</code> , and all value ranges will be assumed <code>[0, clampMaxCumulativeValue]</code> . Disabling this switch may improve volume commit time, but will make volume rendering less efficient.

1. A. Knoll, I. Wald, P. Navratil, A. Bowen, K. Reda, M.E., Papka, and K. Gaither, “RBF Volume Ray Casting on Multicore and Manycore CPUs”, 2014, Computer Graphics Forum, 33: 71–80. doi:10.1111/cgf.12363
2. K. Reda, A. Knoll, K. Nomura, M. E. Papka, A. E. Johnson and J. Leigh, “Visualizing large-scale atomistic simulations in ultra-resolution immersive environments”, 2013 IEEE Symposium on Large-Scale Data Analysis and Visualization (LDAV), Atlanta, GA, 2013, pp. 59–65.

3.3.7 Transfer Function

Transfer functions map the scalar values of volumes to color and opacity and thus they can be used to visually emphasize certain features of the volume. To create a new transfer function of given type `type` use

```
OSPRTransferFunction ospNewTransferFunction(const char *type);
```

The returned handle can be assigned to a volumetric model (described below) as parameter “`transferFunction`” using `ospSetObject`.

One type of transfer function that is supported by OSPRay is the linear transfer function, which interpolates between given equidistant colors and opacities. It is created by passing the string “`piecewiseLinear`” to `ospNewTransferFunction` and it is controlled by these parameters:

The arrays `color` and `opacity` can be of different length.

Type	Name	Description
vec3f[]	color	data array of RGB colors
float[]	opacity	data array of opacities
vec2f	valueRange	domain (scalar range) this function maps from

[Table 3.12](#) – Parameters accepted by the linear transfer function.

3.3.8 VolumetricModels

Volumes in OSPRay are given volume rendering appearance information through VolumetricModels. This decouples the physical representation of the volume (and possible acceleration structures it contains) to rendering-specific parameters (where more than one set may exist concurrently). To create a volume instance, call

```
OSPVolumetricModel ospNewVolumetricModel(OSPVolume volume);
```

[Table 3.13](#) – Parameters understood by VolumetricModel.

Type	Name	Default	Description
OSPTTransferFunction	transferFunction		transfer function to use
float	densityScale	1.0	makes volumes uniformly thinner or thicker
float	anisotropy	0.0	anisotropy of the (Henyey-Greenstein) phase function in [-1, 1] (path tracer only), default to isotropic scattering

3.4 Geometries

Geometries in OSPRay are objects that describe intersectable surfaces. To create a new geometry object of given type `type` use

```
OSPGeometry ospNewGeometry(const char *type);
```

Note that in the current implementation geometries are limited to a maximum of 2^{32} primitives.

3.4.1 Mesh

A mesh consisting of either triangles or quads is created by calling `ospNewGeometry` with type string “mesh”. Once created, a mesh recognizes the following parameters:

Type	Name	Description
vec3f[]	vertex.position	data array of vertex positions
vec3f[]	vertex.normal	data array of vertex normals
vec4f[] / vec3f[]	vertex.color	data array of vertex colors (RGBA/RGB)
vec2f[]	vertex.texcoord	data array of vertex texture coordinates
vec3ui[] / vec4ui[]	index	data array of (either triangle or quad) indices (into the vertex array(s))

[Table 3.14](#) – Parameters defining a mesh geometry.

The data type of index arrays differentiates between the underlying geometry, triangles are used for a index with `vec3ui` type and quads for `vec4ui` type. Quads are internally handled as a pair of two triangles, thus mixing triangles and quads is supported by encoding some triangle as a quad with the last two vertex indices being identical ($w=z$).

The `vertex.position` and `index` arrays are mandatory to create a valid mesh.

3.4.2 Subdivision

A mesh consisting of subdivision surfaces, created by specifying a geometry of type “subdivision”. Once created, a subdivision recognizes the following parameters:

Table 3.15 – Parameters defining a Subdivision geometry.

Type	Name	Description
<code>vec3f[]</code>	<code>vertex.position</code>	<code>data</code> array of vertex positions
<code>vec4f[]</code>	<code>vertex.color</code>	optional <code>data</code> array of vertex colors (RGBA)
<code>vec2f[]</code>	<code>vertex.texcoord</code>	optional <code>data</code> array of vertex texture coordinates
<code>float</code>	<code>level</code>	global level of tessellation, default 5
<code>uint[]</code>	<code>index</code>	<code>data</code> array of indices (into the vertex array(s))
<code>float[]</code>	<code>index.level</code>	optional <code>data</code> array of per-edge levels of tessellation, overrides global level
<code>uint[]</code>	<code>face</code>	optional <code>data</code> array holding the number of indices/edges (3 to 15) per face, defaults to 4 (a pure quad mesh)
<code>vec2i[]</code>	<code>edgeCrease.index</code>	optional <code>data</code> array of edge crease indices
<code>float[]</code>	<code>edgeCrease.weight</code>	optional <code>data</code> array of edge crease weights
<code>uint[]</code>	<code>vertexCrease.index</code>	optional <code>data</code> array of vertex crease indices
<code>float[]</code>	<code>vertexCrease.weight</code>	optional <code>data</code> array of vertex crease weights
<code>int</code>	<code>mode</code>	subdivision edge boundary mode, supported modes are: <code>OSP_SUBDIVISION_NO_BOUNDARY</code> <code>OSP_SUBDIVISION_SMOOTH_BOUNDARY</code> (default) <code>OSP_SUBDIVISION_PIN_CORNERS</code> <code>OSP_SUBDIVISION_PIN_BOUNDARY</code> <code>OSP_SUBDIVISION_PIN_ALL</code>

The `vertex` and `index` arrays are mandatory to create a valid subdivision surface. If no `face` array is present then a pure quad mesh is assumed (the number of indices must be a multiple of 4). Optionally supported are edge and vertex creases.

3.4.3 Spheres

A geometry consisting of individual spheres, each of which can have an own radius, is created by calling `ospNewGeometry` with type string “sphere”. The spheres will not be tessellated but rendered procedurally and are thus perfectly round. To allow a variety of sphere representations in the application this geometry allows a flexible way of specifying the data of center position and radius within a `data` array:

Table 3.16 – Parameters defining a spheres geometry.

Type	Name	Default	Description
vec3f[]	sphere.position		data array of center positions
float[]	sphere.radius	NULL	optional data array of the per-sphere radius
vec2f[]	sphere.texcoord	NULL	optional data array of texture coordinates (constant per sphere)
float	radius	0.01	default radius for all spheres (if <code>sphere.radius</code> is not set)

3.4.4 Curves

A geometry consisting of multiple curves is created by calling `ospNewGeometry` with type string “curve”. The parameters defining this geometry are listed in the table below.

Table 3.17 – Parameters defining a curves geometry.

Type	Name	Description
vec4f[]	vertex.position_radius	data array of vertex position and per-vertex radius
vec3f[]	vertex.position	data array of vertex position
float	radius	global radius of all curves (if per-vertex radius is not used), default 0.01
vec2f[]	vertex.texcoord	data array of per-vertex texture coordinates
vec4f[]	vertex.color	data array of corresponding vertex colors (RGBA)
vec3f[]	vertex.normal	data array of curve normals (only for “ribbon” curves)
vec4f[]	vertex.tangent	data array of curve tangents (only for “hermite” curves)
uint32[]	index	data array of indices to the first vertex or tangent of a curve segment
int	type	OSPCurveType for rendering the curve. Supported types are: <code>OSP_FLAT</code> <code>OSP_ROUND</code> <code>OSP_RIBBON</code>
int	basis	OSPCurveBasis for defining the curve. Supported bases are: <code>OSP_LINEAR</code> <code>OSP_BEZIER</code> <code>OSP_BSPLINE</code> <code>OSP_HERMITE</code> <code>OSP_CATMULL_ROM</code>

Depending upon the specified data type of vertex positions, the curves will be implemented Embree curves or assembled from rounded and linearly-connected segments.

Positions in `vertex.position_radius` format supports per-vertex varying radii with data type `vec4f[]` and instantiate Embree curves internally for the relevant type/basis mapping.

If a constant `radius` is used and positions are specified in a `vec3f[]` type of `vertex.position` format, then type/basis defaults to `OSP_ROUND` and `OSP_LINEAR` (this is the fastest and most memory efficient mode). Implementation is with round linear segments where each segment corresponds to a link between two vertices.

The following section describes the properties of different curve basis' and how they use the data provided in data buffers:

OSP_LINEAR The indices point to the first of 2 consecutive control points in the vertex buffer. The first control point is the start and the second control point the end of the line segment. The curve goes through all control points listed in the vertex buffer.

OSP_BEZIER The indices point to the first of 4 consecutive control points in the vertex buffer. The first control point represents the start point of the curve, and the 4th control point the end point of the curve. The Bézier basis is interpolating, thus the curve does go exactly through the first and fourth control vertex.

OSP_BSPLINE The indices point to the first of 4 consecutive control points in the vertex buffer. This basis is not interpolating, thus the curve does in general not go through any of the control points directly. Using this basis, 3 control points can be shared for two continuous neighboring curve segments, e.g., the curves (p_0, p_1, p_2, p_3) and (p_1, p_2, p_3, p_4) are C1 continuous. This feature make this basis a good choice to construct continuous multi-segment curves, as memory consumption can be kept minimal.

OSP_HERMITE It is necessary to have both vertex buffer and tangent buffer for using this basis. The indices point to the first of 2 consecutive points in the vertex buffer, and the first of 2 consecutive tangents in the tangent buffer. This basis is interpolating, thus does exactly go through the first and second control point, and the first order derivative at the begin and end matches exactly the value specified in the tangent buffer. When connecting two segments continuously, the end point and tangent of the previous segment can be shared.

OSP_CATMULL_ROM The indices point to the first of 4 consecutive control points in the vertex buffer. If (p_0, p_1, p_2, p_3) represent the points then this basis goes through p_1 and p_2 , with tangents as $(p_2 - p_0)/2$ and $(p_3 - p_1)/2$.

The following section describes the properties of different curve types' and how they define the geometry of a curve:

OSP_FLAT This type enables faster rendering as the curve is rendered as a connected sequence of ray facing quads.

OSP_ROUND This type enables rendering a real geometric surface for the curve which allows closeup views. This mode renders a sweep surface by sweeping a varying radius circle tangential along the curve.

OSP_RIBBON The type enables normal orientation of the curve and requires a normal buffer be specified along with vertex buffer. The curve is rendered as a flat band whose center approximately follows the provided vertex buffer and whose normal orientation approximately follows the provided normal buffer.

3.4.5 Boxes

OSPRay can directly render axis-aligned bounding boxes without the need to convert them to quads or triangles. To do so create a boxes geometry by calling `ospNewGeometry` with type string “box”.

Type	Name	Description
<code>box3f[]</code>	<code>box</code>	<code>data</code> array of boxes

Table 3.18 – Parameters defining a boxes geometry.

3.4.6 Planes

OSPRay can directly render planes defined by plane equation coefficients in its implicit form $ax + by + cz + d = 0$. By default planes are infinite but their extents

can be limited by defining optional bounding boxes. A planes geometry can be created by calling `ospNewGeometry` with type string “plane”.

Type	Name	Description
<code>vec4f[]</code>	<code>plane.coefficients</code>	<code>data</code> array of plane coefficients (a, b, c, d)
<code>box3f[]</code>	<code>plane.bounds</code>	optional <code>data</code> array of bounding boxes

Table 3.19 – Parameters defining a planes geometry.

3.4.7 Isosurfaces

OSPRay can directly render multiple isosurfaces of a volume without first tesselating them. To do so create an isosurfaces geometry by calling `ospNewGeometry` with type string “isosurface”. The appearance information of the surfaces is set through the Geometric Model. Per-isosurface colors can be set by passing per-primitive colors to the Geometric Model, in order of the isosurface array.

Type	Name	Description
<code>float</code>	<code>isovalue</code>	single isovalue
<code>float[]</code>	<code>isovalue</code>	<code>data</code> array of isovalue
<code>OSPVolume</code>	<code>volume</code>	handle of the <code>Volume</code> to be isosurfaced

Table 3.20 – Parameters defining an isosurfaces geometry.

3.4.8 GeometricModels

Geometries are matched with surface appearance information through `GeometricModel`s. These take a geometry, which defines the surface representation, and applies either full-object or per-primitive color and material information. To create a geometric model, call

```
OSPGeometricModel ospNewGeometricModel(OSPGeometry geometry);
```

Color and material are fetched with the primitive ID of the hit (clamped to the valid range, thus a single color or material is fine), or mapped first via the index array (if present). All parameters are optional, however, some renderers (notably the `path tracer`) require a material to be set. Materials are either handles of `OSPMaterial`, or indices into the `material` array on the `renderer`, which allows to build a `world` which can be used by different types of renderers.

An `invertNormals` flag allows to invert (shading) normal vectors of the rendered geometry. That is particularly useful for clipping. By changing normal vectors orientation one can control whether inside or outside of the clipping geometry is being removed. For example, a clipping geometry with normals oriented outside clips everything what's inside.

3.5 Lights

To create a new light source of given type `type` use

```
OSPLight ospNewLight(const char *type);
```

All light sources accept the following parameters:

The following light types are supported by most OSPRay renderers.

Table 3.21 – Parameters understood by GeometricModel.

Type	Name	Description
OSPMaterial / uint32	material	optional material applied to the geometry, may be an index into the material parameter on the renderer (if it exists)
vec4f	color	optional color assigned to the geometry
OSPMaterial[] / uint32[]	material	optional data array of (per-primitive) materials, may be an index into the material parameter on the renderer (if it exists)
vec4f[]	color	optional data array of (per-primitive) colors
uint8[]	index	optional data array of per-primitive indices into color and material
bool	invertNormals	inverts all shading normals (Ns), default false

Type	Name	Default	Description
vec3f	color	white	color of the light
float	intensity	1	intensity of the light (a factor)
bool	visible	true	whether the light can be directly seen

Table 3.22 – Parameters accepted by all lights.

3.5.1 Directional Light / Distant Light

The distant light (or traditionally the directional light) is thought to be far away (outside of the scene), thus its light arrives (almost) as parallel rays. It is created by passing the type string “distant” to `ospNewLight`. In addition to the [general parameters](#) understood by all lights the distant light supports the following special parameters:

Type	Name	Description
vec3f	direction	main emission direction of the distant light
float	angularDiameter	apparent size (angle in degree) of the light

Table 3.23 – Special parameters accepted by the distant light.

Setting the angular diameter to a value greater than zero will result in soft shadows when the renderer uses stochastic sampling (like the [path tracer](#)). For instance, the apparent size of the sun is about 0.53°.

3.5.2 Point Light / Sphere Light

The sphere light (or the special case point light) is a light emitting uniformly in all directions from the surface toward the outside. It does not emit any light toward the inside of the sphere. It is created by passing the type string “sphere” to `ospNewLight`. In addition to the [general parameters](#) understood by all lights the sphere light supports the following special parameters:

Type	Name	Description
vec3f	position	the center of the sphere light, in world-space
float	radius	the size of the sphere light

Table 3.24 – Special parameters accepted by the sphere light.

Setting the radius to a value greater than zero will result in soft shadows when the renderer uses stochastic sampling (like the [path tracer](#)).

3.5.3 Spotlight / Photometric Light

The spotlight is a light emitting into a cone of directions. It is created by passing the type string “spot” to `ospNewLight`. In addition to the [general parameters](#) understood by all lights the spotlight supports the special parameters listed in the table.

Table 3.25 – Special parameters accepted by the spotlight.

Type	Name	Default	Description
<code>vec3f</code>	<code>position</code>	<code>(0, 0, 0)</code>	the center of the spotlight, in world-space
<code>vec3f</code>	<code>direction</code>	<code>(0, 0, 1)</code>	main emission direction of the spot
<code>float</code>	<code>openingAngle</code>	180	full opening angle (in degree) of the spot; outside of this cone is no illumination
<code>float</code>	<code>penumbraAngle</code>	5	size (angle in degree) of the “penumbra”, the region between the rim (of the illumination cone) and full intensity of the spot; should be smaller than half of <code>openingAngle</code>
<code>float</code>	<code>radius</code>	0	the size of the spotlight, the radius of a disk with normal <code>direction</code>
<code>float</code>	<code>innerRadius</code>	0	in combination with <code>radius</code> turns the disk into a ring
<code>float[]</code>	<code>intensityDistribution</code>		luminous intensity distribution for photometric lights; can be 2D for asymmetric illumination; values are assumed to be uniformly distributed
<code>vec3f</code>	<code>c0</code>		orientation, i.e., direction of the C0-(half)plane (only needed if illumination via <code>intensityDistribution</code> is asymmetric)

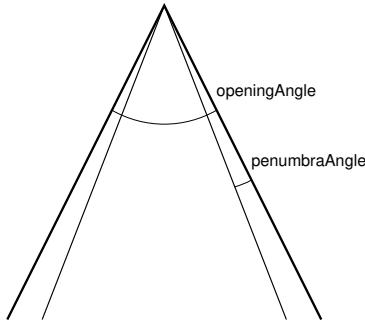


Figure 3.3 – Angles used by the spotlight.

Setting the radius to a value greater than zero will result in soft shadows when the renderer uses stochastic sampling (like the [path tracer](#)). Additionally setting the inner radius will result in a ring instead of a disk emitting the light.

Measured light sources (IES, EULUMDAT, ...) are supported by providing an `intensityDistribution` [data](#) array to modulate the intensity per direction. The mapping is using the C-γ coordinate system (see also below figure): the values of the first (or only) dimension of `intensityDistribution` are uniformly mapped to γ in [0–π]; the first intensity value to 0, the last value to π, thus at least two values need to be present. If the array has a second dimension then the intensities are not rotational symmetric around `direction`, but are accordingly mapped to the C-halfplanes in [0–2π]; the first “row” of values to 0 and 2π, the other rows such that they have uniform distance to its neighbors. The orientation of the C0-plane is specified via `c0`.

3.5.4 Quad Light

The quad³ light is a planar, procedural area light source emitting uniformly on one side into the half-space. It is created by passing the type string “quad” to

³ actually a parallelogram

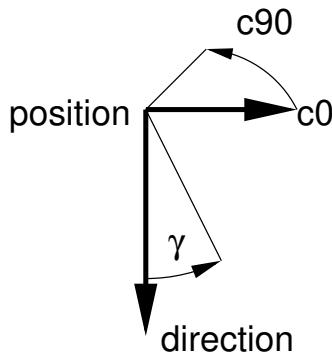


Figure 3.4 – C- γ coordinate system for the mapping of `intensityDistribution` to the spotlight.

`ospNewLight`. In addition to the [general parameters](#) understood by all lights the quad light supports the following special parameters:

Type	Name	Description
vec3f	position	world-space position of one vertex of the quad light
vec3f	edge1	vector to one adjacent vertex
vec3f	edge2	vector to the other adjacent vertex

Table 3.26 – Special parameters accepted by the quad light.

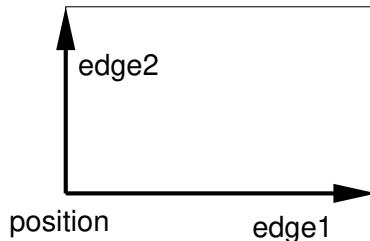


Figure 3.5 – Defining a quad light which emits toward the reader.

The emission side is determined by the cross product of $\text{edge1} \times \text{edge2}$. Note that only renderers that use stochastic sampling (like the path tracer) will compute soft shadows from the quad light. Other renderers will just sample the center of the quad light, which results in hard shadows.

3.5.5 HDRI Light

The HDRI light is a textured light source surrounding the scene and illuminating it from infinity. It is created by passing the type string “`hdri`” to `ospNewLight`. In addition to the [general parameters](#) the HDRI light supports the following special parameters:

Table 3.27 – Special parameters accepted by the HDRI light.

Type	Name	Description
vec3f	up	up direction of the light in world-space
vec3f	direction	direction to which the center of the texture will be mapped to (analog to panoramic camera)
OSPTexture	map	environment map in latitude / longitude format

Note that the currently only the [path tracer](#) supports the HDRI light.

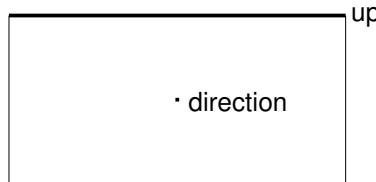


Figure 3.6 – Orientation and Mapping of an HDRI Light.

3.5.6 Ambient Light

The ambient light surrounds the scene and illuminates it from infinity with constant radiance (determined by combining the parameters `color` and `intensity`). It is created by passing the type string “ambient” to `ospNewLight`.

Note that the `SciVis renderer` uses ambient lights to control the color and intensity of the computed ambient occlusion (AO).

3.5.7 Sun-Sky Light

The sun-sky light is a combination of a distant light for the sun and a procedural `hdri` light for the sky. It is created by passing the type string “`sunSky`” to `ospNewLight`. The sun-sky light surrounds the scene and illuminates it from infinity and can be used for rendering outdoor scenes. The radiance values are calculated using the Hošek-Wilkie sky model and solar radiance function. In addition to the [general parameters](#) the following special parameters are supported:

Type	Name	Default	Description
<code>vec3f</code>	<code>up</code>	<code>(0, 1, 0)</code>	zenith of sky in world-space
<code>vec3f</code>	<code>direction</code>	<code>(0, -1, 0)</code>	main emission direction of the sun
<code>float</code>	<code>turbidity</code>	3	atmospheric turbidity due to particles, in [1–10]
<code>float</code>	<code>albedo</code>	0.3	ground reflectance, in [0–1]

Table 3.28 – Special parameters accepted by the `sunSky` light.

The lowest elevation for the sun is restricted to the horizon.

3.5.8 Emissive Objects

The `path tracer` will consider illumination by `geometries` which have a light emitting material assigned (for example the `Luminous` material).

3.6 Scene Hierarchy

3.6.1 Groups

Groups in OSPRay represent collections of `GeometricModels` and `VolumetricModels` which share a common local-space coordinate system. To create a group call

```
OSPGroup ospNewGroup();
```

Groups take arrays of geometric models, volumetric models and clipping geometric models, but they are optional. In other words, there is no need to create empty arrays if there are no geometries or volumes in the group.

By adding `OSPGeometricModels` to the `clippingGeometry` array a clipping geometry feature is enabled. Geometries assigned to this parameter will be used as clipping geometries. Any supported geometry can be used for clipping. The

only requirement is that it has to distinctly partition space into clipping and non-clipping one. These include: spheres, boxes, infinite planes, closed meshes, closed subdivisions and curves. All geometries and volumes assigned to `geometry` or `volume` will be clipped. Use of clipping geometry that is not closed (or infinite) will result in rendering artifacts. User can decide which part of space is clipped by changing shading normals orientation with the `invertNormals` flag of the `GeometricModel`. When more than single clipping geometry is defined all clipping areas will be “added” together – an union of these areas will be applied.

Table 3.29 – Parameters understood by groups.

Type	Name	Default	Description
<code>OSPGeometricModel[]</code>	<code>geometry</code>	<code>NULL</code>	<code>data</code> array of <code>GeometricModels</code>
<code>OSPVolumetricModel[]</code>	<code>volume</code>	<code>NULL</code>	<code>data</code> array of <code>VolumetricModels</code>
<code>OSPGeometricModel[]</code>	<code>clippingGeometry</code>	<code>NULL</code>	<code>data</code> array of <code>GeometricModels</code> used for clipping
<code>bool</code>	<code>dynamicScene</code>	<code>false</code>	use <code>RTC_SCENE_DYNAMIC</code> flag (faster BVH build, slower ray traversal), otherwise uses <code>RTC_SCENE_STATIC</code> flag (faster ray traversal, slightly slower BVH build)
<code>bool</code>	<code>compactMode</code>	<code>false</code>	tell Embree to use a more compact BVH in memory by trading ray traversal performance
<code>bool</code>	<code>robustMode</code>	<code>false</code>	tell Embree to enable more robust ray intersection code paths (slightly slower)

Note that groups only need to re-commit if a geometry or volume changes (surface/scalar field representation). Appearance information on `OSPGeometricModel` and `OSPVolumetricModel` can be changed freely, as internal acceleration structures do not need to be reconstructed.

3.6.2 Instances

Instances in OSPRay represent a single group’s placement into the world via a transform. To create an instance call

```
OSPIstance ospNewInstance(OSPGroup);
```

Table 3.30 – Parameters understood by instances.

Type	Name	Default	Description
<code>affine3f</code>	<code>xfm</code>	<code>identity</code>	world-space transform for all attached geometries and volumes

3.6.3 World

Worlds are a container of scene data represented by `instances`. To create an (empty) world call

```
OSPWorld ospNewWorld();
```

Objects are placed in the world through an array of instances. Similar to `groups`, the array of instances is optional: there is no need to create empty arrays if there are no instances (though there will be nothing to render).

Applications can query the world (axis-aligned) bounding box after the world has been committed. To get this information, call

```
OSPBounds ospGetBounds(OSPObject);
```

The result is returned in the provided `OSPBounds`⁴ struct:

```
typedef struct {
    float lower[3];
    float upper[3];
} OSPBounds;
```

⁴ `OSPBounds` has essentially the same layout as the `OSP_BOX3F OSPDataType`.

This call can also take `OSPGroup` and `OSPIstance` as well: all other object types will return an empty bounding box.

Finally, Worlds can be configured with parameters for making various feature/performance trade-offs (similar to groups).

Table 3.31 – Parameters understood by worlds.

Type	Name	Default	Description
<code>OSPIstance[]</code>	<code>instance</code>	<code>NULL</code>	<code>data</code> array with handles of the <code>instances</code>
<code>OSPLight[]</code>	<code>light</code>	<code>NULL</code>	<code>data</code> array with handles of the <code>lights</code>
<code>bool</code>	<code>dynamicScene</code>	<code>false</code>	use <code>RTC_SCENE_DYNAMIC</code> flag (faster BVH build, slower ray traversal), otherwise uses <code>RTC_SCENE_STATIC</code> flag (faster ray traversal, slightly slower BVH build)
<code>bool</code>	<code>compactMode</code>	<code>false</code>	tell Embree to use a more compact BVH in memory by trading ray traversal performance
<code>bool</code>	<code>robustMode</code>	<code>false</code>	tell Embree to enable more robust ray intersection code paths (slightly slower)

3.7 Renderers

A renderer is the central object for rendering in OSPRay. Different renderers implement different features and support different materials. To create a new renderer of given type `type` use

```
OSPRenderer ospNewRenderer(const char *type);
```

General parameters of all renderers are

OSPRay's renderers support a feature called adaptive accumulation, which accelerates progressive `rendering` by stopping the rendering and refinement of image regions that have an estimated variance below the `varianceThreshold`. This feature requires a `framebuffer` with an `OSP_FB_VARIANCE` channel.

Per default the background of the rendered image will be transparent black, i.e., the alpha channel holds the opacity of the rendered objects. This eases transparency-aware blending of the image with an arbitrary background image by the application. The parameter `backgroundColor` or `map_backplate` can be used to already blend with a constant background color or backplate texture, respectively, (and alpha) during rendering.

OSPRay renderers support depth composition with images of other renderers, for example to incorporate help geometries of a 3D UI that were rendered with OpenGL. The screen-sized `texture` `map_maxDepth` must have format `OSP_TEXTURE_R32F` and flag `OSP_TEXTURE_FILTER_NEAREST`. The fetched values are used to limit the distance of primary rays, thus objects of other renderers can hide objects rendered by OSPRay.

OSPRay supports antialiasing in image space by using pixel filters, which are centered around the center of a pixel. The size $w \times w$ of the filter depends on

Table 3.32 – Parameters understood by all renderers.

Type	Name	Default	Description
int	pixelSamples	1	samples per pixel
int	maxPathLength	20	maximum ray recursion depth
float	minContribution	0.001	sample contributions below this value will be neglected to speedup rendering
float	varianceThreshold	0	threshold for adaptive accumulation
float / vec3f / vec4f	backgroundColor	black, transparent	background color and alpha (RGBA), if no <code>map_backplate</code> is set
OSPTexture	map_backplate		optional <code>texture</code> image used as background (use texture type <code>texture2d</code>)
OSPTexture	map_maxDepth		optional screen-sized float <code>texture</code> with maximum far distance per pixel (use texture type <code>texture2d</code>)
OSPMaterial[]	material		optional <code>data</code> array of <code>materials</code> which can be indexed by a <code>GeometricModel</code> 's <code>material</code> parameter
int	pixelFilter	<code>OSP_PIXELFILTER_GAUSS</code>	<code>OSPPixelFilterType</code> to select the pixel filter used by the renderer for antialiasing. Possible pixel filters are listed below.

the selected filter type. The types of supported pixel filters are defined by the `OSPPixelFilterType` enum and can be set using the `pixelFilter` parameter.

Table 3.33 – Pixel filter types supported by OSPRay for antialiasing in image space.

Name	Description
<code>OSP_PIXELFILTER_POINT</code>	a point filter only samples the center of the pixel, therefore the filter width is $w = 0$
<code>OSP_PIXELFILTER_BOX</code>	a uniform box filter with a width of $w = 1$
<code>OSP_PIXELFILTER_GAUSS</code>	a truncated, smooth Gaussian filter with a standard deviation of $\sigma = 0.5$ and a filter width of $w = 3$
<code>OSP_PIXELFILTER_MITCHELL</code>	the Mitchell-Netravali filter with a width of $w = 4$
<code>OSP_PIXELFILTER_BLACKMAN_HARRIS</code>	the Blackman-Harris filter with a width of $w = 3$

3.7.1 SciVis Renderer

The SciVis renderer is a fast ray tracer for scientific visualization which supports volume rendering and ambient occlusion (AO). It is created by passing the type string “scivis” to `ospNewRenderer`. In addition to the `general parameters` understood by all renderers, the SciVis renderer supports the following parameters:

3.7.2 Path Tracer

The path tracer supports soft shadows, indirect illumination and realistic materials. This renderer is created by passing the type string “pathtracer” to `ospNewRenderer`. In addition to the `general parameters` understood by all renderers the path tracer supports the following special parameters:

Table 3.34 – Special parameters understood by the SciVis renderer.

Type	Name	Default	Description
int	aoSamples	0	number of rays per sample to compute ambient occlusion
float	aoRadius	10^{20}	maximum distance to consider for ambient occlusion
float	aoIntensity	1	ambient occlusion strength
float	volumeSamplingRate	1	sampling rate for volumes

Table 3.35 – Special parameters understood by the path tracer.

Type	Name	Default	Description
int	lightSamples	all	number of random light samples per path vertex, per default all light sources are sampled
bool	geometryLights	true	whether geometries with an emissive material (e.g., Luminous) illuminate the scene
int	roulettePathLength	5	ray recursion depth at which to start Russian roulette termination
float	maxContribution	∞	samples are clamped to this value before they are accumulated into the framebuffer

The path tracer requires that [materials](#) are assigned to [geometries](#), otherwise surfaces are treated as completely black.

The path tracer supports [volumes](#) with multiple scattering. The scattering albedo can be specified using the [transfer function](#). Extinction is assumed to be spectrally constant.

3.7.3 Materials

Materials describe how light interacts with surfaces, they give objects their distinctive look. To let the given renderer create a new material of given type `type` call

```
OSPMaterial ospNewMaterial(const char *renderer_type, const char *material_type);
```

The returned handle can then be used to assign the material to a given geometry with

```
void ospSetObject(OSPGeometricModel, "material", OSPMaterial);
```

3.7.3.1 OBJ Material

The OBJ material is the workhorse material supported by both the [SciVis renderer](#) and the [path tracer](#). It offers widely used common properties like diffuse and specular reflection and is based on the [MTL material format](#) of Lightwave's OBJ scene files. To create an OBJ material pass the type string "obj" to `ospNewMaterial`. Its main parameters are

In particular when using the path tracer it is important to adhere to the principle of energy conservation, i.e., that the amount of light reflected by a surface is not larger than the light arriving. Therefore the path tracer issues a warning and renormalizes the color parameters if the sum of K_d , K_s , and T_f is larger than one in any color channel. Similarly important to mention is that almost all materials of the real world reflect at most only about 80% of the incoming light. So even for a white sheet of paper or white wall paint do better not set K_d larger than 0.8; otherwise rendering times are unnecessary long and the contrast in the

Type	Name	Default	Description
vec3f	kd	white 0.8	diffuse color
vec3f	ks	black	specular color
float	ns	10	shininess (Phong exponent), usually in [2–10 ⁴]
float	d	opaque	opacity
vec3f	tf	black	transparency filter color
OSPTexture	map_bump	NULL	normal map

Table 3.36 – Main parameters of the OBJ material.

final images is low (for example, the corners of a white room would hardly be discernible, as can be seen in the figure below).

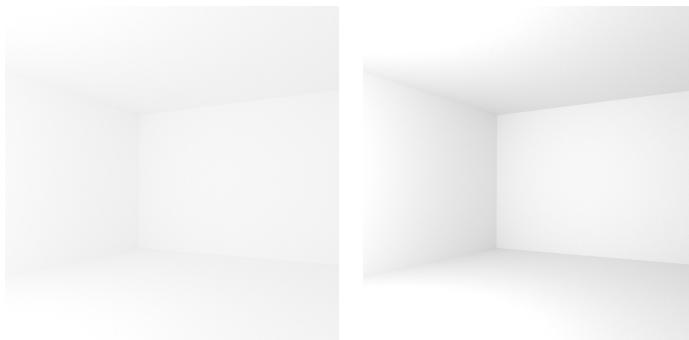


Figure 3.7 – Comparison of diffuse rooms with 100% reflecting white paint (left) and realistic 80% reflecting white paint (right), which leads to higher overall contrast. Note that exposure has been adjusted to achieve similar brightness levels.

If present, the color component of [geometries](#) is also used for the diffuse color Kd and the alpha component is also used for the opacity d.

Note that currently only the path tracer implements colored transparency with Tf.

Normal mapping can simulate small geometric features via the texture map_Bump. The normals n in the normal map are with respect to the local tangential shading coordinate system and are encoded as $\frac{1}{2}(n + 1)$, thus a texel $(0.5, 0.5, 1)^5$ represents the unperturbed shading normal $(0, 0, 1)$. Because of this encoding an sRGB gamma [texture](#) format is ignored and normals are always fetched as linear from a normal map. Note that the orientation of normal maps is important for a visually consistent look: by convention OSPRay uses a coordinate system with the origin in the lower left corner; thus a convexity will look green toward the top of the texture image (see also the example image of a normal map). If this is not the case flip the normal map vertically or invert its green channel.

⁵ respectively $(127, 127, 255)$ for 8 bit textures and $(32767, 32767, 65535)$ for 16 bit textures

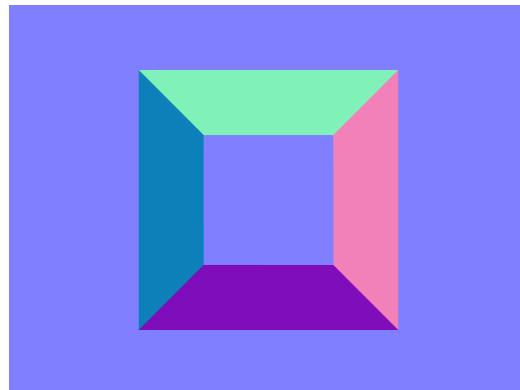
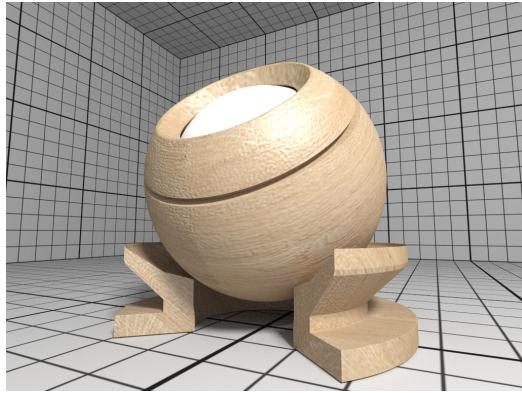


Figure 3.8 – Normal map representing an exalted square pyramidal frustum.

All parameters (except Tf) can be textured by passing a [texture](#) handle, pre-

fixed with “`map_`”. The fetched texels are multiplied by the respective parameter value. If only the texture is given (but not the corresponding parameter), only the texture is used (the default value of the parameter is *not* multiplied). The color textures `map_Kd` and `map_Ks` are typically in one of the sRGB gamma encoded formats, whereas textures `map_Ns` and `map_d` are usually in a linear format (and only the first component is used). Additionally, all textures support [texture transformations](#).

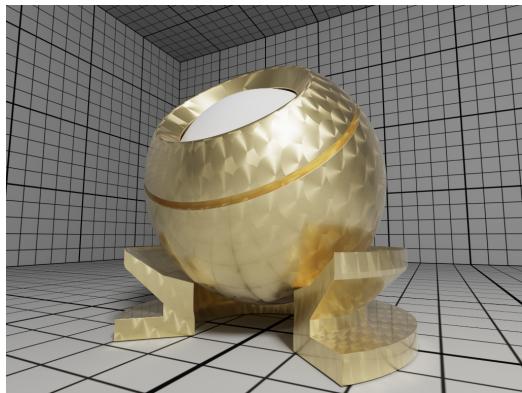


[Figure 3.9](#) – Rendering of a OBJ material with wood textures.

3.7.3.2 Principled

The Principled material is the most complex material offered by the [path tracer](#), which is capable of producing a wide variety of materials (e.g., plastic, metal, wood, glass) by combining multiple different layers and lobes. It uses the GGX microfacet distribution with approximate multiple scattering for dielectrics and metals, uses the Oren-Nayar model for diffuse reflection, and is energy conserving. To create a Principled material, pass the type string “principled” to `ospNewMaterial`. Its parameters are listed in the table below.

All parameters can be textured by passing a [texture](#) handle, prefixed with “`map_`” (e.g., “`map_baseColor`”). [texture transformations](#) are supported as well.



[Figure 3.10](#) – Rendering of a Principled coated brushed metal material with textured anisotropic rotation and a dust layer (sheen) on top.

3.7.3.3 CarPaint

The CarPaint material is a specialized version of the Principled material for rendering different types of car paints. To create a CarPaint material, pass the type string “`carPaint`” to `ospNewMaterial`. Its parameters are listed in the table below.

All parameters can be textured by passing a [texture](#) handle, prefixed with “`map_`” (e.g., “`map_baseColor`”). [texture transformations](#) are supported as well.

Table 3.37 – Parameters of the Principled material.

Type	Name	Default	Description
vec3f	baseColor	white 0.8	base reflectivity (diffuse and/or metallic)
vec3f	edgeColor	white	edge tint (metallic only)
float	metallic	0	mix between dielectric (diffuse and/or specular) and metallic (specular only with complex IOR) in [0–1]
float	diffuse	1	diffuse reflection weight in [0–1]
float	specular	1	specular reflection/transmission weight in [0–1]
float	ior	1	dielectric index of refraction
float	transmission	0	specular transmission weight in [0–1]
vec3f	transmissionColor	white	attenuated color due to transmission (Beer's law)
float	transmissionDepth	1	distance at which color attenuation is equal to transmissionColor
float	roughness	0	diffuse and specular roughness in [0–1], 0 is perfectly smooth
float	anisotropy	0	amount of specular anisotropy in [0–1]
float	rotation	0	rotation of the direction of anisotropy in [0–1], 1 is going full circle
float	normal	1	default normal map/scale for all layers
float	baseNormal	1	base normal map/scale (overrides default normal)
bool	thin	false	flag specifying whether the material is thin or solid
float	thickness	1	thickness of the material (thin only), affects the amount of color attenuation due to specular transmission
float	backlight	0	amount of diffuse transmission (thin only) in [0–2], 1 is 50% reflection and 50% transmission, 2 is transmission only
float	coat	0	clear coat layer weight in [0–1]
float	coatIor	1.5	clear coat index of refraction
vec3f	coatColor	white	clear coat color tint
float	coatThickness	1	clear coat thickness, affects the amount of color attenuation
float	coatRoughness	0	clear coat roughness in [0–1], 0 is perfectly smooth
float	coatNormal	1	clear coat normal map/scale (overrides default normal)
float	sheen	0	sheen layer weight in [0–1]
vec3f	sheenColor	white	sheen color tint
float	sheenTint	0	how much sheen is tinted from sheenColor toward baseColor
float	sheenRoughness	0.2	sheen roughness in [0–1], 0 is perfectly smooth
float	opacity	1	cut-out opacity/transparency, 1 is fully opaque

3.7.3.4 Metal

The [path tracer](#) offers a physical metal, supporting changing roughness and realistic color shifts at edges. To create a Metal material pass the type string “metal” to `ospNewMaterial`. Its parameters are

The main appearance (mostly the color) of the Metal material is controlled by the physical parameters `eta` and `k`, the wavelength-dependent, complex index of refraction. These coefficients are quite counter-intuitive but can be found in [published measurements](#). For accuracy the index of refraction can be given as an array of spectral samples in `ior`, each sample a triplet of wavelength (in nm), `eta`, and `k`, ordered monotonically increasing by wavelength; OSPRay will then calculate the Fresnel in the spectral domain. Alternatively, `eta` and `k` can also be specified as approximated RGB coefficients; some examples are given in below

Table 3.38 – Parameters of the CarPaint material.

Type	Name	Default	Description
vec3f	baseColor	white 0.8	diffuse base reflectivity
float	roughness	0	diffuse roughness in [0–1], 0 is perfectly smooth
float	normal	1	normal map/scale
vec3f float	flakeColor flakeDensity	Aluminium 0	color of metallic flakes density of metallic flakes in [0–1], 0 disables flakes, 1 fully covers the surface with flakes
float	flakeScale	100	scale of the flake structure, higher values increase the amount of flakes
float	flakeSpread	0.3	flake spread in [0–1]
float	flakeJitter	0.75	flake randomness in [0–1]
float	flakeRoughness	0.3	flake roughness in [0–1], 0 is perfectly smooth
float	coat	1	clear coat layer weight in [0–1]
float	coatIor	1.5	clear coat index of refraction
vec3f	coatColor	white	clear coat color tint
float	coatThickness	1	clear coat thickness, affects the amount of color attenuation
float	coatRoughness	0	clear coat roughness in [0–1], 0 is perfectly smooth
float	coatNormal	1	clear coat normal map/scale
vec3f	flipflopColor	white	reflectivity of coated flakes at grazing angle, used together with coatColor produces a pearlescent paint
float	flipflopFalloff	1	flip flop color falloff, 1 disables the flip flop effect

Table 3.39 – Parameters of the Metal material.

Type	Name	Default	Description
vec3f[]	ior	Aluminium	data array of spectral samples of complex refractive index, each entry in the form (wavelength, eta, k), ordered by wavelength (which is in nm)
vec3f	eta		RGB complex refractive index, real part
vec3f	k		RGB complex refractive index, imaginary part
float	roughness	0.1	roughness in [0–1], 0 is perfect mirror

table.

Metal	eta	k
Ag, Silver	(0.051, 0.043, 0.041)	(5.3, 3.6, 2.3)
Al, Aluminium	(1.5, 0.98, 0.6)	(7.6, 6.6, 5.4)
Au, Gold	(0.07, 0.37, 1.5)	(3.7, 2.3, 1.7)
Cr, Chromium	(3.2, 3.1, 2.3)	(3.3, 3.3, 3.1)
Cu, Copper	(0.1, 0.8, 1.1)	(3.5, 2.5, 2.4)

Table 3.40 – Index of refraction of selected metals as approximated RGB coefficients, based on data from <https://refractiveindex.info/>.

The roughness parameter controls the variation of microfacets and thus how polished the metal will look. The roughness can be modified by a [texture map_roughness](#) ([texture transformations](#) are supported as well) to create notable edging effects.

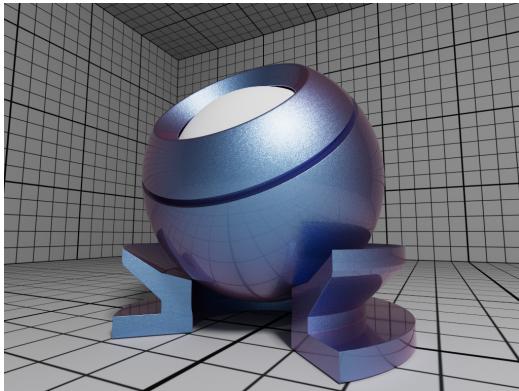


Figure 3.11 – Rendering of a pearlescent CarPaint material.

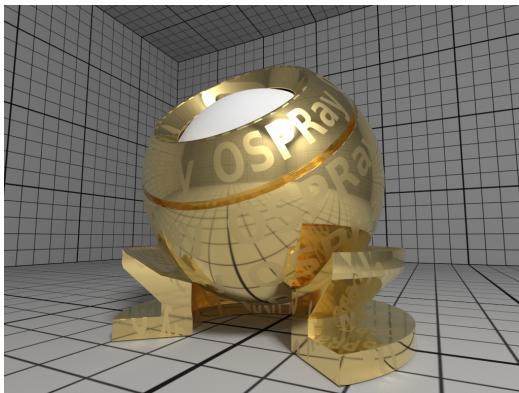


Figure 3.12 – Rendering of golden Metal material with textured roughness.

3.7.3.5 Alloy

The [path tracer](#) offers an alloy material, which behaves similar to [Metal](#), but allows for more intuitive and flexible control of the color. To create an Alloy material pass the type string “alloy” to `ospNewMaterial`. Its parameters are

Type	Name	Default	Description
vec3f	color	white 0.9	reflectivity at normal incidence (0 degree)
vec3f	edgeColor	white	reflectivity at grazing angle (90 degree)
float	roughness	0.1	roughness, in [0–1], 0 is perfect mirror

Table 3.41 – Parameters of the Alloy material.

The main appearance of the Alloy material is controlled by the parameter `color`, while `edgeColor` influences the tint of reflections when seen at grazing angles (for real metals this is always 100% white). If present, the color component of [geometries](#) is also used for reflectivity at normal incidence `color`. As in [Metal](#) the `roughness` parameter controls the variation of microfacets and thus how polished the alloy will look. All parameters can be textured by passing a [texture](#) handle, prefixed with “`map_`”; [texture transformations](#) are supported as well.

3.7.3.6 Glass

The [path tracer](#) offers a realistic a glass material, supporting refraction and volumetric attenuation (i.e., the transparency color varies with the geometric thickness). To create a Glass material pass the type string “glass” to `ospNewMaterial`. Its parameters are

For convenience, the rather counter-intuitive physical attenuation coefficients will be calculated from the user inputs in such a way, that the `attenuationColor` will be the result when white light traveled trough a glass of thickness

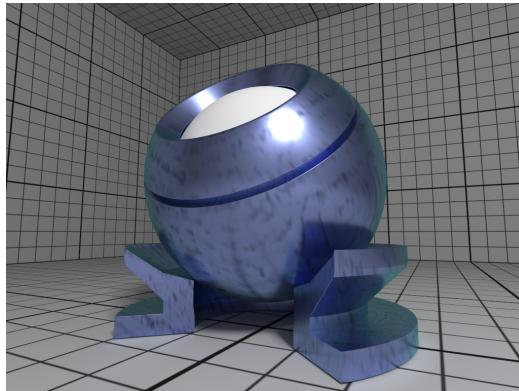


Figure 3.13 – Rendering of a fictional Alloy material with textured color.

Type	Name	Default	Description
float	eta	1.5	index of refraction
vec3f	attenuationColor	white	resulting color due to attenuation
float	attenuationDistance	1	distance affecting attenuation

Table 3.42 – Parameters of the Glass material.

attenuationDistance.

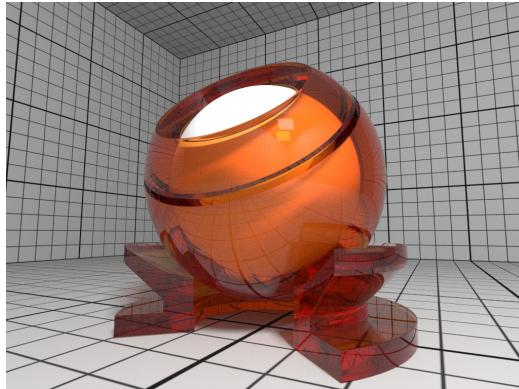


Figure 3.14 – Rendering of a Glass material with orange attenuation.

3.7.3.7 ThinGlass

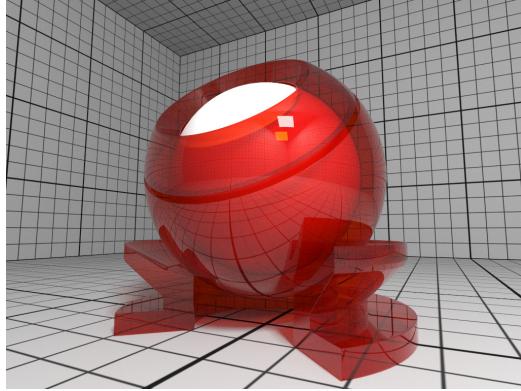
The [path tracer](#) offers a thin glass material useful for objects with just a single surface, most prominently windows. It models a thin, transparent slab, i.e., it behaves as if a second, virtual surface is parallel to the real geometric surface. The implementation accounts for multiple internal reflections between the interfaces (including attenuation), but neglects parallax effects due to its (virtual) thickness. To create a such a thin glass material pass the type string “thinGlass” to `ospNewMaterial`. Its parameters are

Type	Name	Default	Description
float	eta	1.5	index of refraction
vec3f	attenuationColor	white	resulting color due to attenuation
float	attenuationDistance	1	distance affecting attenuation
float	thickness	1	virtual thickness

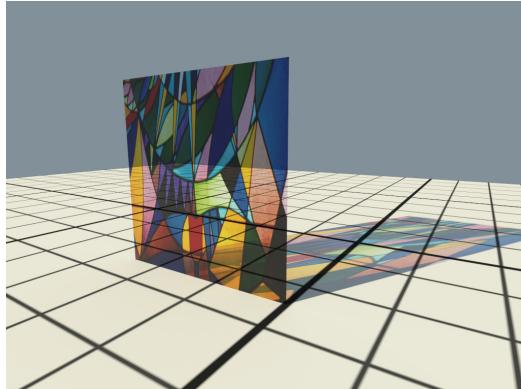
Table 3.43 – Parameters of the ThinGlass material.

For convenience the attenuation is controlled the same way as with the [Glass](#) material. Additionally, the color due to attenuation can be modulated with a [tex-](#)

`ture map_attenuationColor` ([texture transformations](#) are supported as well). If present, the color component of [geometries](#) is also used for the attenuation color. The `thickness` parameter sets the (virtual) thickness and allows for easy exchange of parameters with the (real) [Glass](#) material; internally just the ratio between `attenuationDistance` and `thickness` is used to calculate the resulting attenuation and thus the material appearance.



[Figure 3.15](#) – Rendering of a [ThinGlass](#) material with red attenuation.



[Figure 3.16](#) – Example image of a coloured window made with textured attenuation of the [ThinGlass](#) material.

3.7.3.8 MetallicPaint

The [path tracer](#) offers a metallic paint material, consisting of a base coat with optional flakes and a clear coat. To create a [MetallicPaint](#) material pass the type string “`metallicPaint`” to `ospNewMaterial`. Its parameters are listed in the table below.

Type	Name	Default	Description
<code>vec3f</code>	<code>baseColor</code>	<code>white 0.8</code>	color of base coat
<code>float</code>	<code>flakeAmount</code>	0.3	amount of flakes, in [0–1]
<code>vec3f</code>	<code>flakeColor</code>	<code>Aluminium</code>	color of metallic flakes
<code>float</code>	<code>flakeSpread</code>	0.5	spread of flakes, in [0–1]
<code>float</code>	<code>eta</code>	1.5	index of refraction of clear coat

[Table 3.44](#) – Parameters of the [MetallicPaint](#) material.

The color of the base coat `baseColor` can be textured by a `texture map_baseColor`, which also supports [texture transformations](#). If present, the color component of [geometries](#) is also used for the color of the base coat. Parameter `flakeAmount` controls the proportion of flakes in the base coat, so when setting it to 1 the `baseColor` will not be visible. The shininess of the metallic component

is governed by `flakeSpread`, which controls the variation of the orientation of the flakes, similar to the `roughness` parameter of `Metal`. Note that the effect of the metallic flakes is currently only computed on average, thus individual flakes are not visible.

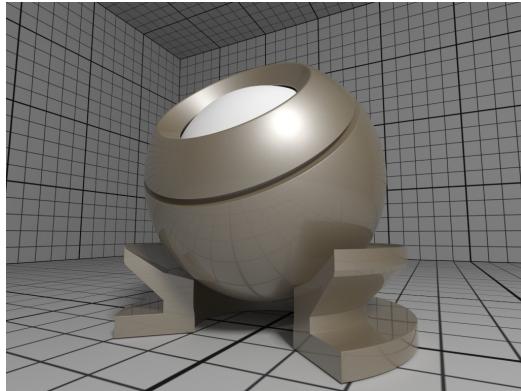


Figure 3.17 – Rendering of a Metallic-Paint material.

3.7.3.9 Luminous

The `path tracer` supports the Luminous material which emits light uniformly in all directions and which can thus be used to turn any geometric object into a light source⁶. It is created by passing the type string “luminous” to `ospNewMaterial`. The amount of constant radiance that is emitted is determined by combining the general parameters of lights: [color and intensity](#).

⁶If `geometryLights` is enabled in the `path tracer`.

Type	Name	Default	Description
<code>vec3f</code>	<code>color</code>	<code>white</code>	color of the emitted light
<code>float</code>	<code>intensity</code>	1	intensity of the light (a factor)
<code>float</code>	<code>transparency</code>	1	material transparency

Table 3.45 – Parameters accepted by the Luminous material.

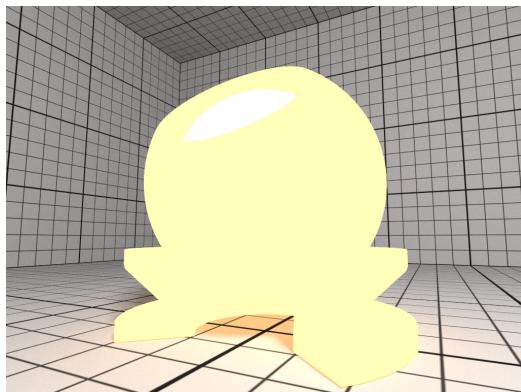


Figure 3.18 – Rendering of a yellow Luminous material.

3.7.4 Texture

OSPRay currently implements two texture types (`texture2d` and `volume`) and is open for extension to other types by applications. More types may be added in future releases.

To create a new texture use

```
OSPTexture ospNewTexture(const char *type);
```

3.7.4.1 Texture2D

The `texture2d` texture type implements an image-based texture, where its parameters are as follows

Type	Name	Description
int	format	<code>OSPTextureFormat</code> for the texture
int	filter	default <code>OSP_TEXTURE_FILTER_BILINEAR</code> , alternatively <code>OSP_TEXTURE_FILTER_NEAREST</code>
OSPData	data	the actual texel 2D <code>data</code>

Table 3.46 – Parameters of `texture2d` texture type.

The supported texture formats for `texture2d` are:

Name	Description
<code>OSP_TEXTURE_RGBA8</code>	8 bit [0–255] linear components red, green, blue, alpha
<code>OSP_TEXTURE_SRGBA</code>	8 bit sRGB gamma encoded color components, and linear alpha
<code>OSP_TEXTURE_RGBA32F</code>	32 bit float components red, green, blue, alpha
<code>OSP_TEXTURE_RGB8</code>	8 bit [0–255] linear components red, green, blue
<code>OSP_TEXTURE_SRGB</code>	8 bit sRGB gamma encoded components red, green, blue
<code>OSP_TEXTURE_RGB32F</code>	32 bit float components red, green, blue
<code>OSP_TEXTURE_R8</code>	8 bit [0–255] linear single component red
<code>OSP_TEXTURE_RA8</code>	8 bit [0–255] linear two components red, alpha
<code>OSP_TEXTURE_L8</code>	8 bit [0–255] gamma encoded luminance (replicated into red, green, blue)
<code>OSP_TEXTURE_LA8</code>	8 bit [0–255] gamma encoded luminance, and linear alpha
<code>OSP_TEXTURE_R32F</code>	32 bit float single component red
<code>OSP_TEXTURE_RGBA16</code>	16 bit [0–65535] linear components red, green, blue, alpha
<code>OSP_TEXTURE_RGB16</code>	16 bit [0–65535] linear components red, green, blue
<code>OSP_TEXTURE_RA16</code>	16 bit [0–65535] linear two components red, alpha
<code>OSP_TEXTURE_R16</code>	16 bit [0–65535] linear single component red

Table 3.47 – Supported texture formats by `texture2d`, i.e., valid constants of type `OSPTextureFormat`.

The size of the texture is inferred from the size of the 2D array `data`, which also needs have a compatible type to `format`. The texel data in `data` starts with the texels in the lower left corner of the texture image, like in OpenGL. Per default a texture fetch is filtered by performing bi-linear interpolation of the nearest 2×2 texels; if instead fetching only the nearest texel is desired (i.e., no filtering) then pass the `OSP_TEXTURE_FILTER_NEAREST` flag.

Texturing with `texture2d` image textures requires `geometries` with texture coordinates, e.g., a `mesh` with `vertex.texcoord` provided.

3.7.4.2 TextureVolume

The volume texture type implements texture lookups based on 3D object coordinates of the surface hit point on the associated geometry. If the given hit point is within the attached volume, the volume is sampled and classified with the transfer function attached to the volume. This implements the ability to visualize volume values (as colored by its transfer function) on arbitrary surfaces inside the volume (as opposed to an isosurface showing a particular value in the volume). Its parameters are as follows

Type	Name	Description
OSPVolumeModel	volume	VolumetricModel used to generate color lookups

TextureVolume can be used for implementing slicing of volumes with any geometry type. It enables coloring of the slicing geometry with a different transfer function than that of the sliced volume.

3.7.4.3 Texture Transformations

All materials with textures also offer to manipulate the placement of these textures with the help of texture transformations. If so, this convention shall be used: the following parameters are prefixed with “texture_name.”).

Type	Name	Description
linear2f	transform	linear transformation (rotation, scale)
float	rotation	angle in degree, counterclockwise, around center
vec2f	scale	enlarge texture, relative to center (0.5, 0.5)
vec2f	translation	move texture in positive direction (right/up)

Above parameters are combined into a single `affine2d` transformation matrix and the transformations are applied in the given order. Rotation, scale and translation are interpreted “texture centric”, i.e., their effect seen by an user are relative to the texture (although the transformations are applied to the texture coordinates).

Type	Name	Description
affine3f	transform	linear transformation (rotation, scale) plus translation

Similarly, volume texture placement can also be modified by an `affine3f` transformation matrix.

3.7.5 Cameras

To create a new camera of given type type use

```
OSPCamera ospNewCamera(const char *type);
```

All cameras accept these parameters:

The camera is placed and oriented in the world with `position`, `direction` and `up`. OSPRay uses a right-handed coordinate system. The region of the camera sensor that is rendered to the image can be specified in normalized screen-space coordinates with `imageStart` (lower left corner) and `imageEnd` (upper

Table 3.48 – Parameters of volume texture type.

Table 3.49 – Parameters to define 2D texture coordinate transformations.

Table 3.50 – Parameter to define 3D volume texture transformations.

Type	Name	Description
vec3f	position	position of the camera in world-space
vec3f	direction	main viewing direction of the camera
vec3f	up	up direction of the camera
float	nearClip	near clipping distance
vec2f	imageStart	start of image region (lower left corner)
vec2f	imageEnd	end of image region (upper right corner)

Table 3.51 – Parameters accepted by all cameras.

right corner). This can be used, for example, to crop the image, to achieve asymmetrical view frusta, or to horizontally flip the image to view scenes which are specified in a left-handed coordinate system. Note that values outside the default range of [0–1] are valid, which is useful to easily realize overscan or film gate, or to emulate a shifted sensor.

3.7.5.1 Perspective Camera

The perspective camera implements a simple thin lens camera for perspective rendering, supporting optionally depth of field and stereo rendering, but no motion blur. It is created by passing the type string “perspective” to `ospNewCamera`. In addition to the [general parameters](#) understood by all cameras the perspective camera supports the special parameters listed in the table below.

Table 3.52 – Additional parameters accepted by the perspective camera.

Type	Name	Description
float	fovy	the field of view (angle in degree) of the frame's height
float	aspect	ratio of width by height of the frame (and image region)
float	apertureRadius	size of the aperture, controls the depth of field
float	focusDistance	distance at where the image is sharpest when depth of field is enabled
bool	architectural	vertical edges are projected to be parallel
int	stereoMode	OSPStereoMode for stereo rendering, possible values are: <code>OSP_STEREO_NONE</code> (default) <code>OSP_STEREO_LEFT</code> <code>OSP_STEREO_RIGHT</code> <code>OSP_STEREO_SIDE_BY_SIDE</code> <code>OSP_STEREO_TOP_BOTTOM</code> (left eye at top half)
float	interpupillaryDistance	distance between left and right eye when stereo is enabled, default 0.0635

Note that when computing the aspect ratio a potentially set image region (using `imageStart` & `imageEnd`) needs to be regarded as well.

In architectural photography it is often desired for aesthetic reasons to display the vertical edges of buildings or walls vertically in the image as well, regardless of how the camera is tilted. Enabling the `architectural` mode achieves this by internally leveling the camera parallel to the ground (based on the `up` direction) and then shifting the lens such that the objects in direction `dir` are centered in the image. If finer control of the lens shift is needed use `imageStart` & `imageEnd`. Because the camera is now effectively leveled its image plane and thus the plane of focus is oriented parallel to the front of buildings, the whole façade appears sharp, as can be seen in the example images below. The resolution of

the `framebuffer` is not altered by `imageStart`/`imageEnd`.

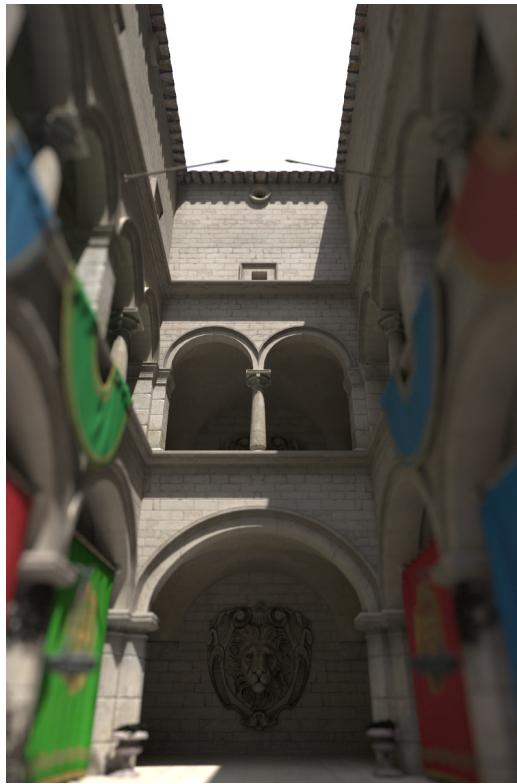


Figure 3.19 – Example image created with the perspective camera, featuring depth of field.

3.7.5.2 Orthographic Camera

The orthographic camera implements a simple camera with orthographic projection, without support for depth of field or motion blur. It is created by passing the type string “orthographic” to `ospNewCamera`. In addition to the [general parameters](#) understood by all cameras the orthographic camera supports the following special parameters:

Type	Name	Description
float	height	size of the camera’s image plane in y, in world coordinates
float	aspect	ratio of width by height of the frame

Table 3.53 – Additional parameters accepted by the orthographic camera.

For convenience the size of the camera sensor, and thus the extent of the scene that is captured in the image, can be controlled with the `height` parameter. The same effect can be achieved with `imageStart` and `imageEnd`, and both methods can be combined. In any case, the aspect ratio needs to be set accordingly to get an undistorted image.

3.7.5.3 Panoramic Camera

The panoramic camera implements a simple camera with support for stereo rendering. It captures the complete surrounding with a latitude / longitude mapping and thus the rendered images should best have a ratio of 2:1. A panoramic camera is created by passing the type string “panoramic” to `ospNewCamera`. It is placed and oriented in the scene by using the [general parameters](#) understood by all cameras.



Figure 3.20 – Enabling the architectural flag corrects the perspective projection distortion, resulting in parallel vertical edges.

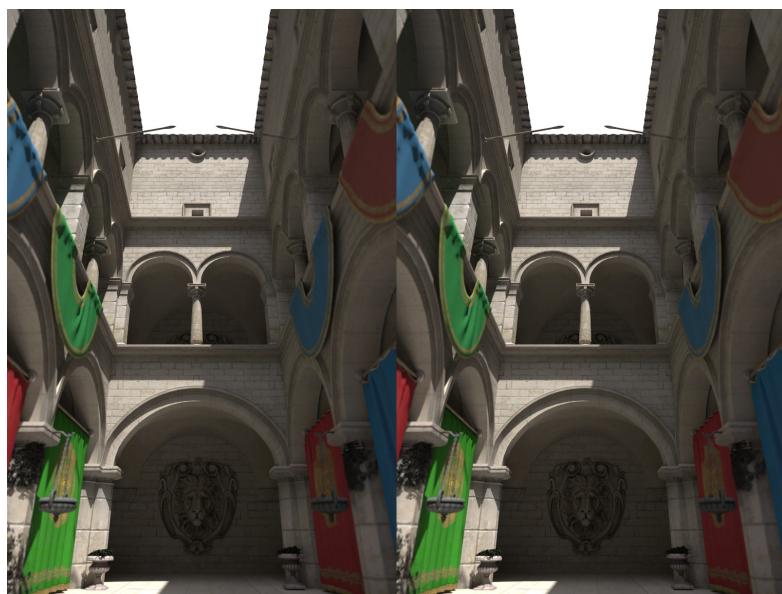


Figure 3.21 – Example 3D stereo image using `stereoMode = OSP_STEREO_SIDE_BY_SIDE`.

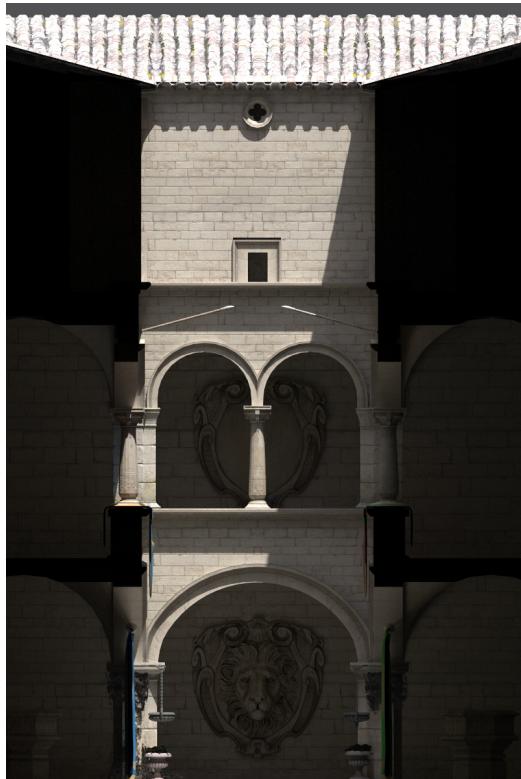


Figure 3.22 – Example image created with the orthographic camera.



Figure 3.23 – Latitude / longitude map created with the panoramic camera.

Table 3.54 – Additional parameters accepted by the panoramic camera.

Type	Name	Description
int	stereoMode	OSPStereoMode for stereo rendering, possible values are: OSP_STEREO_NONE (default) OSP_STEREO_LEFT OSP_STEREO_RIGHT OSP_STEREO_SIDE_BY_SIDE OSP_STEREO_TOP_BOTTOM (left eye at top half)
float	interpupillaryDistance	distance between left and right eye when stereo is enabled, default 0.0635

3.7.6 Picking

To get the world-space position of the geometry (if any) seen at [0–1] normalized screen-space pixel coordinates `screenPos` use

```
void ospPick(OSPPickResult *,
    OSPFrameBuffer,
    OSPRenderer,
    OSPCamera,
    OSPWorld,
    osp_vec2f screenPos);
```

The result is returned in the provided `OSPPickResult` struct:

```
typedef struct {
    int hasHit;
    osp_vec3f worldPosition;
    OSPGeometricModel GeometricModel;
    uint32_t primID;
} OSPPickResult;
```

Note that `ospPick` considers exactly the same camera of the given renderer that is used to render an image, thus matching results can be expected. If the camera supports depth of field then the center of the lens and thus the center of the circle of confusion is used for picking.

3.8 Framebuffer

The framebuffer holds the rendered 2D image (and optionally auxiliary information associated with pixels). To create a new framebuffer object of given size `size` (in pixels), color format, and channels use

```
OSPFrameBuffer ospNewFrameBuffer(int size_x, int size_y,
    OSPFrameBufferFormat format = OSP_FB_SRGB,
    uint32_t frameBufferChannels = OSP_FB_COLOR);
```

The parameter `format` describes the format the color buffer has *on the host*, and the format that `ospMapFrameBuffer` will eventually return. Valid values are:

The parameter `frameBufferChannels` specifies which channels the framebuffer holds, and can be combined together by bitwise OR from the values of `OSPFrameBufferChannel` listed in the table below.

If a certain channel value is *not* specified, the given buffer channel will not be present. Note that OSPRay makes a clear distinction between the *external*

Name	Description
OSP_FB_NONE	framebuffer will not be mapped by the application
OSP_FB_RGBA8	8 bit [0–255] linear component red, green, blue, alpha
OSP_FB_SRGBA	8 bit sRGB gamma encoded color components, and linear alpha
OSP_FB_RGBA32F	32 bit float components red, green, blue, alpha

Table 3.55 – Supported color formats of the framebuffer that can be passed to `ospNewFrameBuffer`, i.e., valid constants of type `OSPFrameBufferFormat`.

Name	Description
OSP_FB_COLOR	RGB color including alpha
OSP_FB_DEPTH	euclidean distance to the camera (<i>not</i> to the image plane), as linear 32 bit float
OSP_FB_ACCUM	accumulation buffer for progressive refinement
OSP_FB_VARIANCE	for estimation of the current noise level if <code>OSP_FB_ACCUM</code> is also present, see rendering
OSP_FB_NORMAL	accumulated world-space normal of the first hit, as <code>vec3f</code>
OSP_FB_ALBEDO	accumulated material albedo (color without illumination) at the first hit, as <code>vec3f</code>

Table 3.56 – Framebuffer channels constants (of type `OSPFrameBufferChannel`), naming optional information the framebuffer can store. These values can be combined by bitwise OR when passed to `ospNewFrameBuffer`.

format of the framebuffer and the internal one: The external format is the format the user specifies in the `format` parameter; it specifies what color format OSPRay will eventually *return* the framebuffer to the application (when calling `ospMapFrameBuffer`): no matter what OSPRay uses internally, it will simply return a 2D array of pixels of that format, with possibly all kinds of reformatting, compression/decompression, etc., going on in-between the generation of the *internal* framebuffer and the mapping of the externally visible one.

In particular, `OSP_FB_NONE` is a perfectly valid pixel format for a framebuffer that an application will never map. For example, an application driving a display wall may well generate an intermediate framebuffer and eventually transfer its pixel to the individual displays using an `OSPIImageOperation` [image operation](#).

The application can map the given channel of a framebuffer – and thus access the stored pixel information – via

```
const void *ospMapFrameBuffer(OSPFrameBuffer, OSPFrameBufferChannel = OSP_FB_COLOR);
```

Note that `OSP_FB_ACCUM` or `OSP_FB_VARIANCE` cannot be mapped. The origin of the screen coordinate system in OSPRay is the lower left corner (as in OpenGL), thus the first pixel addressed by the returned pointer is the lower left pixel of the image.

A previously mapped channel of a framebuffer can be unmapped by passing the received pointer mapped to

```
void ospUnmapFrameBuffer(const void *mapped, OSPFrameBuffer);
```

The individual channels of a framebuffer can be cleared with

```
void ospResetAccumulation(OSPFrameBuffer);
```

This function will clear *all* accumulating buffers (`OSP_FB_VARIANCE`, `OSP_FB_NORMAL`, and `OSP_FB_ALBEDO`, if present) and resets the accumulation counter `accumID`. It is unspecified if the existing color and depth buffers are physically cleared when `ospResetAccumulation` is called.

If OSP_FB_VARIANCE is specified, an estimate of the variance of the last accumulated frame can be queried with

```
float ospGetVariance(OSPFrameBuffer);
```

Note this value is only updated after synchronizing with OSP_FRAME_FISHED, as further described in [asynchronous rendering](#). The estimated variance can be used by the application as a quality indicator and thus to decide whether to stop or to continue progressive rendering.

The framebuffer takes a list of pixel operations to be applied to the image in sequence as an OSPData. The pixel operations will be run in the order they are in the array.

Type	Name	Description
OSPImageOperation[]	imageOperation	ordered sequence of image operations

Table 3.57 – Parameters accepted by the framebuffer.

3.8.1 Image Operation

Image operations are functions that are applied to every pixel of a frame. Examples include post-processing, filtering, blending, tone mapping, or sending tiles to a display wall. To create a new pixel operation of given type use

```
OSPImageOperation ospNewImageOperation(const char *type);
```

3.8.1.1 Tone Mapper

The tone mapper is a pixel operation which implements a generic filmic tone mapping operator. Using the default parameters it approximates the Academy Color Encoding System (ACES). The tone mapper is created by passing the type string “tonemapper” to `ospNewImageOperation`. The tone mapping curve can be customized using the parameters listed in the table below.

Table 3.58 – Parameters accepted by the tone mapper.

Type	Name	Default	Description
float	exposure	1.0	amount of light per unit area
float	contrast	1.6773	contrast (toe of the curve); typically is in [1–2]
float	shoulder	0.9714	highlight compression (shoulder of the curve); typically is in [0.9–1]
float	midIn	0.18	mid-level anchor input; default is 18% gray
float	midOut	0.18	mid-level anchor output; default is 18% gray
float	hdrMax	11.0785	maximum HDR input that is not clipped
bool	acesColor	true	apply the ACES color transforms

To use the popular “Uncharted 2” filmic tone mapping curve instead, set the parameters to the values listed in the table below.

3.8.1.2 Denoiser

OSPRay comes with a module that adds support for Intel® Open Image Denoise. This is provided as an optional module as it creates an additional project dependency at compile time. The module implements a “denoiser” frame operation, which denoises the entire frame before the frame is completed.

Name	Value
contrast	1.1759
shoulder	0.9746
midIn	0.18
midOut	0.18
hdrMax	6.3704
acesColor	false

Table 3.59 – Filmic tone mapping curve parameters. Note that the curve includes an exposure bias to match 18% middle gray.

3.9 Rendering

3.9.1 Asynchronous Rendering

Rendering is by default asynchronous (non-blocking), and is done by combining a framebuffer, renderer, camera, and world.

What to render and how to render it depends on the renderer's parameters. If the framebuffer supports accumulation (i.e., it was created with `OSP_FB_ACCUM`) then successive calls to `ospRenderFrame` will progressively refine the rendered image.

To start an render task, use

```
OSPFuture ospRenderFrame(OSPFrameBuffer, OSPRenderer, OSPCamera, OSPWorld);
```

This returns an `OSPFuture` handle, which can be used to synchronize with the application, cancel, or query for progress of the running task. When `ospRenderFrame` is called, there is no guarantee when the associated task will begin execution.

Progress of a running frame can be queried with the following API function

```
float ospGetProgress(OSPFuture);
```

This returns the progress of the task in [0-1].

Applications can wait on the result of an asynchronous operation, or choose to only synchronize with a specific event. To synchronize with an `OSPFuture` use

```
void ospWait(OSPFuture, OSPSyncEvent = OSP_TASK_FINISHED);
```

The following are values which can be synchronized with the application

Table 3.60 – Supported events that can be passed to `ospWait`.

Name	Description
<code>OSP_NONE_FINISHED</code>	Do not wait for anything to be finished (immediately return from <code>ospWait</code>)
<code>OSP_WORLD_COMMITTED</code>	Wait for the world to be committed (not yet implemented)
<code>OSP_WORLD_RENDERED</code>	Wait for the world to be rendered, but not post-processing operations (Pixel/Tile/Frame Op)
<code>OSP_FRAME_FINISHED</code>	Wait for all rendering operations to complete
<code>OSP_TASK_FINISHED</code>	Wait on full completion of the task associated with the future. The underlying task may involve one or more of the above synchronization events

Currently only rendering can be invoked asynchronously. However, future releases of OSPRay may add more asynchronous versions of API calls (and thus return `OSPFuture`).

Applications can query whether particular events are complete with

```
int ospIsReady(OSPFuture, OSPSyncEvent = OSP_TASK_FINISHED);
```

As the given running task runs (as tracked by the OSPFuture), applications can query a boolean [0,1] result if the passed event has been completed.

Applications can query how long an async task ran with

```
float ospGetTaskDuration(OSPFuture);
```

This returns the wall clock execution time of the task in seconds. If the task is still running, this will block until the task is completed. This is useful for applications to query exactly how long an asynchronous task executed without the overhead of measuring both task execution + synchronization by the calling application.

3.9.2 Asynchronously Rendering and `ospCommit()`

The use of either `ospRenderFrame` or `ospRenderFrame` requires that all objects in the scene being rendered have been committed before rendering occurs. If a call to `ospCommit()` happens while a frame is rendered, the result is undefined behavior and should be avoided.

3.9.3 Synchronous Rendering

For convenience in certain use cases, `ospray_util.h` provides a synchronous version of `ospRenderFrame`:

```
float ospRenderFrameBlocking(OSPFrameBuffer, OSPRenderer, OSPCamera, OSPWorld);
```

This version is the equivalent of:

```
ospRenderFrame  
ospWait(f, OSP_TASK_FINISHED)  
return ospGetVariance(fb)
```

This version is closest to `ospRenderFrame` from OSPRay v1.x.

3.10 Distributed rendering with MPI

The OSPRay MPI module is now a stand alone repository. It can be found on GitHub [here](#), where all code and documentation can be found.

Chapter 4

Examples

4.1 Tutorial

A minimal working example demonstrating how to use OSPRay can be found at `apps/tutorials/ospTutorial.c`¹.

An example of building `ospTutorial.c` with CMake can be found in `apps/tutorials/ospTutorialFindospray/`.

To build the tutorial on Linux, build it in a build directory with

```
gcc -std=c99 .../apps/ospTutorial/ospTutorial.c \
-I ..\ospray\include -L . -lospray -Wl,-rpath,. -o ospTutorial
```

On Windows build it can be build manually in a “`build_directory\$Configuration`” directory with

```
cl ..\..\apps\ospTutorial\ospTutorial.c -I ..\..\ospray\include -I ..\..\ospray.lib
```

Running `ospTutorial` will create two images of two triangles, rendered with the Scientific Visualization renderer with full Ambient Occlusion. The first image `firstFrame.ppm` shows the result after one call to `ospRenderFrame` – jagged edges and noise in the shadow can be seen. Calling `ospRenderFrame` multiple times enables progressive refinement, resulting in antialiased edges and converged shadows, shown after ten frames in the second image `accumulated-Frames.ppm`.

¹ A C++ version that uses the C++ convenience wrappers of OSPRay’s C99 API via `include/ospray/ospray_cpp.h` is available at `apps/tutorials/ospTutorial.cpp`.



Figure 4.1 – First frame.

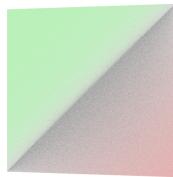


Figure 4.2 – After accumulating ten frames.

4.2 ospExamples

Apart from tutorials, OSPRay comes with a C++ app called `ospExamples` which is an elaborate easy-to-use tutorial, with a single interface to try various OSPRay features. It is aimed at providing users with multiple simple scenes composed of basic geometry types, lights, volumes etc. to get started with OSPRay quickly.

`ospExamples` app runs a `GLFWOSPRayWindow` instance that manages instances of the camera, framebuffer, renderer and other OSPRay objects necessary to render an interactive scene. The scene is rendered on a `GLFW` window with an `imgui` GUI controls panel for the user to manipulate the scene at runtime.

The application is located in `apps/ospExamples/` directory and can be built with CMake. It can be run from the build directory via:

```
./ospExamples <command-line-parameter>
```

The command line parameter is optional however.

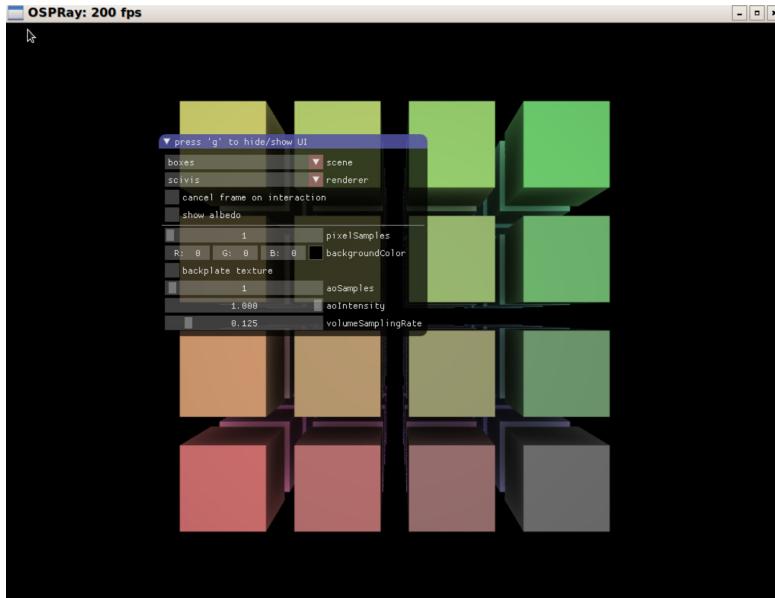


Figure 4.3 – `ospExamples` application with default boxes scene.

4.2.1 Scenes

Different scenes can be selected from the `scenes` dropdown and each scene corresponds to an instance of a special `detail::Builder` struct. Example builders are located in `apps/common/ospray_testing/builders/`. These builders provide a usage guide for the OSPRay scene hierarchy and OSPRay API in the form of cpp wrappers. They instantiate and manage objects for the specific scene like `cpp::Geometry`, `cpp::Volume`, `cpp::Light` etc.

The `detail::Builder` base struct is mostly responsible for setting up OS-PRay world and objects common in all scenes (for example lighting and ground plane), which can be conveniently overridden in the derived builders.

Given below are different scenes listed with their string identifiers:

`boxes` A simple scene with box geometry type.

`cornell_box` A scene depicting a classic cornell box with quad mesh geometry type for rendering two cubes and a quad light type.

`curves` A simple scene with curve geometry type and options to change `curveBasis`. For details on different basis' please check documentation of `curves`.

`gravity_spheres_volume` A scene with `structuredRegular` type of `volume`.

`gravity_spheres_isosurface` A scene depicting iso-surface rendering of `gravity_spheres_volume` using geometry type `isosurface`.

`perlin_noise_volumes` An example scene with `structuredRegular` volume type depicting perlin noise.

`random_spheres` A simple scene depicting sphere geometry type.

`streamlines` A scene showcasing streamlines geometry derived from curve geometry type.

`subdivision_cube` A scene with a cube of subdivision geometry type to showcase subdivision surfaces.

`unstructured_volume` A simple scene with a volume of unstructured volume type.

4.2.2 Renderer

This app comes with three `renderer` options: `scivis`, `pathtracer` and `debug`. The app provides some common rendering controls like `pixelSamples` and other more specific to the renderer type like `aoIntensity` for `scivis` renderer.

The sun-sky lighting can be used in a sample scene by enabling the `renderSunSky` option of the `pathtracer` renderer. It allows the user to change `turbidity` and `sunDirection`.

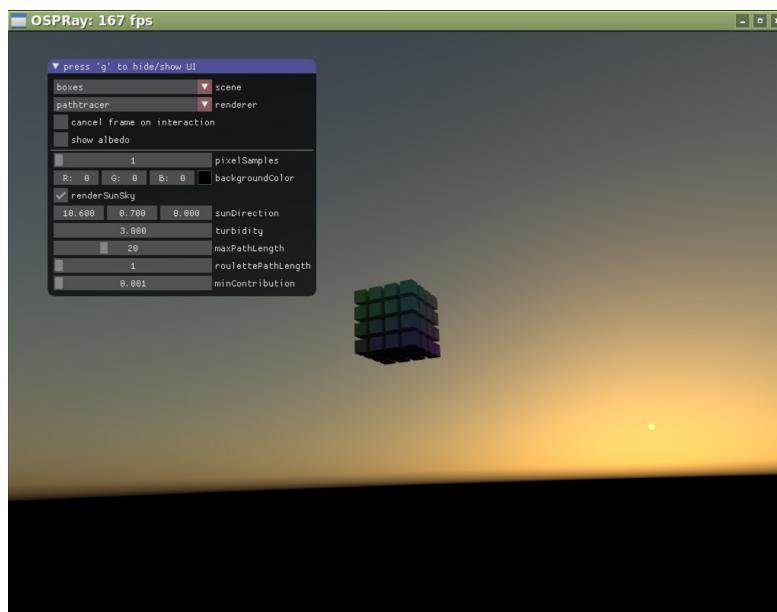


Figure 4.4 – Rendering an evening sky with the `renderSunSky` option.

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