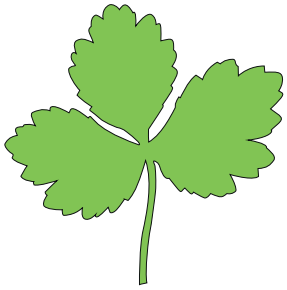

Mitsuba Documentation

Version 0.3.0

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Contents

Part I.
Using Mitsuba

Disclaimer: This is manual documents the usage, file format, and internal design of the Mitsuba rendering system. It is currently a work in progress, hence some parts may still be incomplete or missing.

1. About Mitsuba

Mitsuba is a research-oriented rendering system in the style of PBRT (`www.pbrt.org`), from which it derives much inspiration. It is written in portable C++, implements unbiased as well as biased techniques, and contains heavy optimizations targeted towards current CPU architectures. Mitsuba is extremely modular: it consists of a small set of core libraries and over 100 different plugins that implement functionality ranging from materials and light sources to complete rendering algorithms.

In comparison to other open source renderers, Mitsuba places a strong emphasis on experimental rendering techniques, such as path-based formulations of Metropolis Light Transport and volumetric modeling approaches. Thus, it may be of genuine interest to those who would like to experiment with such techniques that haven't yet found their way into mainstream renderers, and it also provides a solid foundation for research in this domain.

Other design considerations are are:

Performance: One important goal of Mitsuba is to provide optimized implementations of the most commonly used rendering algorithms. By virtue of running on a shared foundation, comparisons between them can better highlight the merits and limitations of different approaches. This is in contrast to, say, comparing two completely different rendering products, where technical information on the underlying implementation is often intentionally not provided.

Robustness: In many cases, physically-based rendering packages force the user to model scenes with the underlying algorithm (specifically: its convergence behavior) in mind. For instance, glass windows are routinely replaced with light portals, photons must be manually guided to the relevant parts of a scene, and interactions with complex materials are taboo, since they cannot be importance sampled exactly. One focus of Mitsuba will be to develop path-space light transport algorithms, which handle such cases more gracefully.

Scalability: Mitsuba instances can be merged into large clusters, which transparently distribute and jointly execute tasks assigned to them using only node-to-node communcation. It has successfully scaled to large-scale renderings that involved more than 1000 cores working on a single image. Most algorithms in Mitsuba are written using a generic parallelization layer, which can tap into this cluster-wide parallelism. The principle is that if any component of the renderer produces work that takes longer than a second or so, it at least ought to use all of the processing power it can get.

The renderer also tries to be very conservative in its use of memory, which allows it to handle large scenes (>30 million triangles) and multi-gigabyte heterogeneous volumes on consumer hardware.

Realism and accuracy: Mitsuba comes with a large repository of physically-based reflectance models for surfaces and participating media. These implementations are designed so that they can be used to build complex shader networks, while providing enough flexibility to be compatible with

a wide range of different rendering techniques, including path tracing, photon mapping, hardware-accelerated rendering and bidirectional methods.

The unbiased path tracers in Mitsuba are battle-proven and produce reference-quality results that can be used for predictive rendering, and to verify implementations of other rendering methods.

Usability: Mitsuba comes with a graphical user interface to interactively explore scenes. Once a suitable viewpoint has been found, it is straightforward to perform renderings using any of the implemented rendering techniques, while tweaking their parameters to find the most suitable settings. Experimental integration into Blender 2.5 is also available.

2. License

3. Compiling the renderer

To compile Mitsuba, you will need a recent C++ compiler (e.g. GCC 4.1+ or Visual Studio 2008+) and some additional libraries, which Mitsuba uses internally. Builds on all supported platforms are done using a unified system based on SCons (http://www.scons.org), which is a Python-based software construction tool. There are some differences between the different operating systems—for more details, please refer to one of the next sections depending on which one you use.

3.1. Common steps

To get started, you will need to download a recent version of Mitsuba. Make sure that you have the Mercurial (http://mercurial.selenic.com/) versioning system installed[1] and enter the following at the command prompt:

```
$ hg clone https://www.mitsuba-renderer.org/hg/mitsuba
```

Afterwards, you will need to download the precompiled dependencies into a new subdirectory named `mitsuba/dependencies`:

```
$ cd mitsuba
$ hg clone https://www.mitsuba-renderer.org/hg/dependencies
```

Common to all platforms is that a build configuration file must be chosen: amongst the following, please copy the best matching file into a new file to the root of the Mitsuba directory and rename it into `config.py`.

```
build/config-linux.py
build/config-darwin-x86_64.py
build/config-darwin-x86.py
build/config-darwin-universal.py
build/config-msvc2008-win32.py
build/config-msvc2008-win64.py
build/config-msvc2010-win32.py
build/config-msvc2010-win64.py
build/config-icl12-msvc2010-win32.py
build/config-icl12-msvc2010-win64.py
build/config-icl12-darwin-x86_64.py
build/config-icl12-darwin-x86.py
```

3.2. Compilation flags

Usually, you will not have to make any modification to this file, but sometimes a few minor edits may be necessary. In particular, you might want to add or remove certain compilation flags from the `CXXFLAGS` parameter. The following settings affect the behavior of Mitsuba:

`MTS_DEBUG` Enable assertions etc. Usually a good idea, and enabled by default.

`MTS_KD_DEBUG` Enable additional checks in the kd-Tree. This is quite slow and mainly useful to track down bugs when they are suspected.

[1] On Windows, you might want to use the convenient TortoiseHG shell extension (http://tortoisehg.bitbucket.org/) to run the subsequent steps directly from the Explorer.

MTS_KD_CONSERVE_MEMORY Use a more compact representation for triangle geometry (at the cost of speed). This flag causes Mitsuba to use the somewhat slower Moeller-Trumbore triangle intersection method instead of the default Wald intersection test, which has an overhead of 48 bytes per triangle. Off by default.

MTS_SSE Activate optimized SSE routines. On by default.

MTS_HAS_COHERENT_RT Include coherent ray tracing support (depends on `MTS_SSE`). This flag is activated by default.

MTS_DEBUG_FP Generated NaNs and overflows will cause floating point exceptions, which can be caught in a debugger. This is slow and mainly meant as a debugging tool for developers. Off by default.

SPECTRUM_SAMPLES=⟨..⟩ This setting defines the number of spectral samples (in the 368-830 *nm* range) that are used to render scenes. The default is 3 samples, in which case the renderer automatically turns into an RGB-based system. For high-quality spectral rendering, this should be set to 30 or higher.

SINGLE_PRECISION Do all computation in single precision. This is normally sufficient and therefore used as the default setting.

DOUBLE_PRECISION Do all computation in double precision. This flag is incompatible with `MTS_SSE`, `MTS_HAS_COHERENT_RT`, and `MTS_DEBUG_FP`.

MTS_GUI_SOFTWARE_FALLBACK Forces the GUI to use a software fallback mode, which is considerably slower and removes the realtime preview. This is useful when running the interface on a remote Windows machine accessed via the Remote Desktop Protocol (RDP).

All of the default configurations files located in the `build` directory use the flags `SINGLE_PRECISION`, `SPECTRUM_SAMPLES=3`, `MTS_DEBUG`, `MTS_SSE`, as well as `MTS_HAS_COHERENT_RT`.

3.3. Building on Ubuntu Linux

You'll first need to install a number of dependencies. It is assumed here that you are using Ubuntu Linux (Maverick Meerkat / 10.10 or later), hence some of the package may be named differently if you are using another version.

First, run

```
$ sudo apt-get install build-essential scons mercurial qt4-dev-tools libpng12-dev
    libjpeg62-dev libilmbase-dev libxerces-c3-dev libboost1.42-all-dev
    libopenexr-dev libglewmx1.5-dev libxxf86vm-dev libpcrecpp0
    libboost-system-dev libboost-filesystem-dev libboost-python-dev libboost-dev
```

Please ensure that the installed version of the boost libraries is 1.42 or later. To get COLLADA support, you will also need to install the `collada-dom` packages or build it from scratch. Here, we install the `x86_64` binaries and development headers that can be found in the `dependencies/linux` directory[2]:

[2] The directory also contains source packages in case these binaries don't work for you.

```
$ sudo dpkg --install collada-dom_2.3.1-1_amd64.deb collada-dom-dev_2.3.1-1_amd64.
    deb
```

Afterwards, simply run

```
$ scons
```

inside the Mitsuba directory. In the case that you have multiple processors, you might want to parallelize the build by appending `-j` *core count* to the command. If all goes well, SCons should finish successfully within a few minutes:

```
scons: done building targets.
```

To be able to run the renderer from the command line, you will first have to import it into your path:

```
$ . setpath.sh
```

(note the period at the beginning – this assumes that you are using `bash`). Having set up everything, you can now move on to Section 4.

3.3.1. Creating Ubuntu packages

For Ubuntu, the preferred way of redistristributing executables is to create `.deb` package files. To create Mitsuba packages, it is strongly recommended that you work with a pristine Ubuntu installation[3]. This can be done as follows: first, install `debootstrap` and download the latest version of Ubuntu to a subdirectory (here, we use Maverick Meerkat, or version 10.10)

```
$ sudo apt-get install debootstrap
$ sudo debootstrap --arch amd64 maverick maverick-pristine
```

Next, `chroot` into the created directory, enable the `multiverse` package repository, and install the necessary tools for creating package files:

```
$ sudo chroot maverick-pristine
$ echo "deb http://archive.ubuntu.com/ubuntu maverick universe" >> /etc/apt/
    sources.list
$ apt-get update
$ apt-get install debhelper dpkg-dev pkg-config
```

Now, you should be able to set up the remaining dependencies as described in Section 3.3. Once this is done, check out a copy of Mitsuba to the root directory of the `chroot` environment, e.g.

```
$ hg clone https://www.mitsuba-renderer.org/hg/mitsuba
```

To start the compilation process, enter

```
$ cd mitsuba
$ cp -R data/linux/debian debian
$ dpkg-buildpackage -nc
```

After everything has been built, you should find the created package files in the root directory.

[3] Several commercial graphics drivers "pollute" the OpenGL setup so that the compiled Mitsuba binaries can only be used on machines using the same drivers. For this reason, it is better to work from a clean boostrapped install.

3.3.2. Releasing Ubuntu packages

To redistribute Ubuntu packages over the Internet, it is convenient to put them into an `apt`-compatible repository. To prepare such a repository, put the two `deb`-files built in the last section, as well as the `collada-dom` `deb`-files into a public directory made available by a HTTP server and inside it, run

```
path – to – htdocs$ dpkg-scanpackages path/to/deb-directory /dev/null | gzip -9c >
    path/to/deb-directory/Packages.gz
```

This will create a respository index file named `Packages.gz`. Note that you must execute this command in the root directory of the HTTP server's web directory and provide the relative path to the package files – otherwise, the index file will specify the wrong package paths. Finally, the whole directory can be uploaded to some public location and then referenced by placing a line following the pattern

```
deb http://<path-to-deb-directory> ./
```

into the `/etc/apt/sources.list` file.

3.4. Building on Fedora Core

You'll first need to install a number of dependencies. It is assumed here that you are using FC15, hence some of the package may be named differently if you are using another version.

First, run

```
$ yum install mercurial gcc-c++ scons boost-devel qt4-devel OpenEXR-devel xerces-c-
    devel python-devel glew-devel collada-dom-devel
```

Afterwards, simply run

```
$ scons
```

inside the Mitsuba directory. In the case that you have multiple processors, you might want to parallelize the build by appending `-j` *core count* to the command. If all goes well, SCons should finish successfully within a few minutes:

```
scons: done building targets.
```

To be able to run the renderer from the command line, you will first have to import it into your path:

```
$ . setpath.sh
```

(note the period at the beginning – this assumes that you are using `bash`). Having set up everything, you can now move on to Section 4.

3.4.1. Creating Fedora Core packages

To create `RPM` packages, you will need to install the `RPM` development tools:

```
$ yum install rpmdevtools
```

Once this is done, run the following command in your home directory:

```
$ rpmdev-setuptree
```

and create a Mitsuba source package in the appropriate directory:

```
$ ln -s mitsuba mitsuba-0.3.0
$ tar czvf rpmbuild/SOURCES/mitsuba-0.3.0.tar.gz mitsuba-0.3.0/.
```

Finally, `rpmbuilder` can be invoked to create the package:

```
$ rpmbuild -bb mitsuba-0.3.0/data/linux/fedora/mitsuba.spec
```

After this command finishes, its output can be found in the directory `rpmbuild/RPMS`.

3.5. Building on Arch Linux

You'll first need to install a number of dependencies:

```
$ sudo pacman -S gcc xerces-c glew openexr boost libpng libjpeg qt scons mercurial
    python
```

For COLLADA support, you will also have to install the `collada-dom` library. For this, you can either install the binary package available on the Mitsuba website, or you can compile it yourself using the `PKGBUILD` supplied with Mitsuba, i.e.

```
$ cd <some-temporary-directory>
$ cp <path-to-mitsuba>/data/linux/arch/collada-dom/PKGBUILD .
$ makepkg PKGBUILD
<..compiling..>
$ sudo pacman -U <generated package file>
```

Once all dependencies are taken care of, simply run

```
$ scons
```

inside the Mitsuba directory. In the case that you have multiple processors, you might want to parallelize the build by appending `-j` *core count* to the command. If all goes well, SCons should finish successfully within a few minutes:

```
scons: done building targets.
```

To be able to run the renderer from the command line, you will first have to import it into your path:

```
$ . setpath.sh
```

(note the period at the beginning – this assumes that you are using `bash`). Having set up everything, you can now move on to Section 4.

3.5.1. Creating Arch Linux packages

Mitsuba ships with a `PKGBUILD` file, which automatically builds a package from the most recent repository version:

```
$ makepkg data/linux/arch/mitsuba/PKGBUILD
```

3.6. Building on Windows

On the Windows platform, Mitsuba already includes most of the dependencies in precompiled form. You will still need to set up a few things though: first, you need to install Python 2.6.x [4] (`www.python.org`) and SCons [5] (`http://www.scons.org`, any 2.x version will do) and ensure that they are contained in the `%PATH%` environment variable so that entering `scons` on the command prompt (`cmd.exe`) launches the build system.

Next, you will either need to compile Qt 4.7 (or a newer version) from source or grab pre-built binaries (e.g. from `http://code.google.com/p/qt-msvc-installer`). It is crucial that the Qt build configuration *exactly* matches that of Mitsuba: for instance, if you were planning to use the 64-bit compiler in Visual Studio 2010, both projects must be built with that exact same compiler.

When building Qt from source, an important point is to install any Visual Studio service packs prior to this step—for instance, 64-bit Qt binaries always crash when built with a Visual Studio 2010 installation that is missing SP1. Once that is taken care of, start the correct Visual Studio command prompt, and enter

```
C:\Qt>configure.exe -release -no-webkit -no-phonon -no-phonon-backend -no-script
      -no-scripttools -no-qt3support -no-multimedia -no-ltcg
..(configuration messages)..
C:\Qt>nmake
```

inside the Qt source directory.

Having installed all dependencies, run the "Visual Studio *2008/2010* Command Prompt" from the Start Menu (`x86` for 32-bit or `x64` for 64bit). Afterwards, navigate to the Mitsuba directory. Depending on whether or not the Qt binaries are on the `%PATH%` environment variable, you might have to explicitly specify the Qt path:

```
C:\Mitsuba\>set QTDIR=C:\Qt
```

where `C:\Qt` is the path to your Qt installation. Afterwards, simply run

```
C:\Mitsuba\>scons
```

In the case that you have multiple processors, you might want to parallelize the build by appending the option `-j` *core count* to the `scons` command.

If all goes well, the build process will finish successfully after a few minutes. In comparison to the other platforms, you don't have to run the `setpath.sh` script at this point. All binaries are now located in the `dist` directory, and they should be executed directly from there.

3.6.1. Integration with the Visual Studio interface

Basic Visual Studio 2008 and 2010 integration with support for code completion exists for those who develop Mitsuba code on Windows. To use the supplied projects, simply double-click on one of the two files `build/mitsuba-msvc2008.sln` and `build/mitsuba-msvc2010.sln`. These Visual Studio projects still internally use the SCons-based build system to compile Mitsuba; whatever build

[4] Please make sure that you get a Python binary matching the architecture, for which you plan to compile Mitsuba (i.e. `x86` or `x86_64`) – this is needed for the Python bindings. If you wish to use another Python version, you will have to change `config.py` and supply your own Boost boost binaries linked against that version of Python.

[5] Note that on some Windows machines, the SCons installer generates a warning about not finding Python in the registry. In this case, you can instead run `python setup.py install` within the source release of SCons.

configuration is selected within Visual Studio will be used to pick a matching configuration file from the `build` directory. Note that you will potentially have to add a `QTDIR=..\..` line to each of the used configuration files when building directly from Visual Studio.

3.7. Building on Mac OS X

On Mac OS X, you will need to install both SCons (>2.0.0, available at `www.scons.org`) and a recent release of XCode. You will also need to get Qt 4.7.0 or a newer version — make sure that you get the normal Cocoa release (i.e. *not* the one based on Carbon). All of the other dependencies are already included in precompiled form. Now open a Terminal and run

```
$ scons
```

inside the Mitsuba directory. In the case that you have multiple processors, you might want to parallelize the build by appending `-j` *core count* to the command. If all goes well, SCons should finish successfully within a few minutes:

```
scons: done building targets.
```

To be able to run the renderer from the command line, you will have to import it into your path:

```
$ . setpath.sh
```

(note the period at the beginning – this assumes that you are using `bash`).

4. Basic usage

The rendering functionality of Mitsuba can be accessed through a command line interface and an interactive Qt-based frontend. This section provides some basic instructions on how to use them.

4.1. Interactive frontend

To launch the interactive frontend, run `Mitsuba.app` on MacOS, `mtsgui.exe` on Windows, and `mtsgui` on Linux (after sourcing `setpath.sh`). You can also drag and drop scene files onto the application icon or the running program to open them. A quick video tutorial on using the GUI can be found here: http://vimeo.com/13480342.

4.2. Command line interface

The `mitsuba` binary is an alternative non-interactive rendering frontend for command-line usage and batch job operation. To get a listing of the parameters it supports, run the executable without parameters:

```
$ mitsuba
```

Listing 1 shows the output resulting from this command. The most common mode of operation is to render a single scene, which is provided as a parameter, e.g.

```
$ mitsuba path-to/my-scene.xml
```

It is also possible to connect to network render nodes, which essentially lets Mitsuba parallelize over additional cores. To do this, pass a semicolon-separated list of machines to the `-c` parameter.

```
$ mitsuba -c machine1;machine2;... path-to/my-scene.xml
```

There are two different ways in which you can access render nodes:

- **Direct**: Here, you create a direct connection to a running `mtssrv` instance on another machine (`mtssrv` is the Mitsuba server process). From the the performance standpoint, this approach should always be preferred over the SSH method described below when there is a choice between them. There are some disadvantages though: first, you need to manually start `mtssrv` on every machine you want to use.

  And perhaps more importantly: the direct communication protocol makes no provisions for a malicious user on the remote side. It is too costly to constantly check the communication stream for illegal data sequences, so Mitsuba simply doesn't do it. The consequence of this is that you should only use the direct communication approach within trusted networks.

  For direct connections, you can specify the remote port as follows:

  ```
  $ mitsuba -c machine:1234 path-to/my-scene.xml
  ```

  When no port is explicitly specified, Mitsuba uses default value of 7554.

- **SSH**: This approach works as follows: The renderer creates a SSH connection to the remote side, where it launches a Mitsuba worker instance. All subsequent communication then passes

```
Mitsuba version 0.3.0, Copyright (c) 2011 Wenzel Jakob
Usage: mitsuba [options] <One or more scene XML files>
Options/Arguments:
   -h          Display this help text

   -D key=val  Define a constant, which can referenced as "$key" in the scene

   -o fname    Write the output image to the file denoted by "fname"

   -a p1;p2;.. Add one or more entries to the resource search path

   -p count    Override the detected number of processors. Useful for reducing
               the load or creating scheduling-only nodes in conjunction with
               the -c and -s parameters, e.g. -p 0 -c host1;host2;host3,...

   -q          Quiet mode - do not print any log messages to stdout

   -c hosts    Network rendering: connect to mtssrv instances over a network.
               Requires a semicolon-separated list of host names of the form
                       host.domain[:port] for a direct connection
                 or
                       user@host.domain[:path] for a SSH connection (where
                       "path" denotes the place where Mitsuba is checked
                       out -- by default, "~/mitsuba" is used)

   -s file     Connect to additional Mitsuba servers specified in a file
               with one name per line (same format as in -c)

   -j count    Simultaneously schedule several scenes. Can sometimes accelerate
               rendering when large amounts of processing power are available
               (e.g. when running Mitsuba on a cluster. Default: 1)

   -n name     Assign a node name to this instance (Default: host name)

   -t          Test case mode (see Mitsuba docs for more information)

   -x          Skip rendering of files where output already exists

   -r sec      Write (partial) output images every 'sec' seconds

   -b res      Specify the block resolution used to split images into parallel
               workloads (default: 32). Only applies to some integrators.

   -v          Be more verbose

   -w          Treat warnings as errors

   -z          Disable progress bars

 For documentation, please refer to http://www.mitsuba-renderer.org/docs.html
```

Listing 1: Command line options of the `mitsuba` binary

through the encrypted link. This is completely secure but slower due to the encryption overhead. If you are rendering a complex scene, there is a good chance that it won't matter much since most time is spent doing computations rather than communicating

Such an SSH link can be created simply by using a slightly different syntax:

```
$ mitsuba -c username@machine path-to/my-scene.xml
```

The above line assumes that the remote home directory contains a Mitsuba source directory named `mitsuba`, which contains the compiled Mitsuba binaries. If that is not the case, you need to provide the path to such a directory manually, e.g:

```
$ mitsuba -c username@machine:/opt/mitsuba path-to/my-scene.xml
```

For the SSH connection approach to work, you *must* enable passwordless authentication. Try opening a terminal window and running the command `ssh username@machine` (replace with the details of your remote connection). If you are asked for a password, something is not set up correctly — please see http://www.debian-administration.org/articles/152 for instructions.

On Windows, the situation is a bit more difficult since there is no suitable SSH client by default. To get SSH connections to work, Mitsuba requires `plink.exe` (from PuTTY) to be on the path. For passwordless authentication with a Linux/OSX-based server, convert your private key to PuTTY's format using `puttygen.exe`. Afterwards, start `pageant.exe` to load and authenticate the key. All of these binaries are available from the PuTTY website.

It is possible to mix the two approaches to access some machines directly and others over SSH.

When doing many network-based renders over the command line, it can become tedious to specify the connections every time. They can alternatively be loaded from a text file where each line contains a separate connection description as discussed previously:

```
$ mitsuba -s servers.txt path-to/my-scene.xml
```

where `servers.txt` e.g. contains

```
user1@machine1.domain.org:/opt/mitsuba
machine2.domain.org
machine3.domain.org:7346
```

4.2.1. Passing parameters

Any attribute in the XML-based scene description language can be parameterized from the command line. For instance, you can render a scene several times with different reflectance values on a certain material by changing its description to something like

```
<bsdf type="diffuse">
    <spectrum name="reflectance" value="$reflectance"/>
</bsdf>
```

and running Mitsuba as follows:

```
$ mitsuba -Dreflectance=0.1 -o ref_0.1.exr scene.xml
$ mitsuba -Dreflectance=0.2 -o ref_0.2.exr scene.xml
$ mitsuba -Dreflectance=0.5 -o ref_0.5.exr scene.xml
```

4.2.2. Writing partial images to disk

When doing lengthy command line renders on Linux or OSX, it is possible to send a signal to the process using

```
$ killall -HUP mitsuba
```

This causes the renderer to write out the partially finished image, after which it continues rendering. This can sometimes be useful to check if everything is working correctly.

4.2.3. Rendering an animation

The command line interface is ideally suited for rendering large amounts of files in batch operation. You can simply pass in the files using a wildcard in the filename.

If you've already rendered a subset of the frames and you only want to complete the remainder, add the `-x` flag, and all files with existing output will be skipped. You can also let the scheduler work on several scenes at once using the `-j` parameter — this is especially useful when parallelizing over multiple machines: as some of the participating machines finish rendering the current frame, they can immediately start working on the next one instead of having to wait for all other cores to finish. Altogether, you might start the with parameters such as the following

```
$ mitsuba -xj 2 -c machine1;machine2;...  animation/frame_*.xml
```

4.3. Direct connection server

A Mitsuba compute node can be created using the `mtssrv` executable. By default, it will listen on port 7554:

```
$ mtssrv
..
maxwell: Listening on port 7554.. Send Ctrl-C or SIGTERM to stop.
```

Type `mtssrv -h` to see a list of available options. If you find yourself unable to connect to the server, `mtssrv` is probably listening on the wrong interface. In this case, please specify an explicit IP address or hostname:

```
$ mtssrv -i maxwell.cs.cornell.edu
```

As advised in Section 4.2, it is advised to run `mtssrv` *only* in trusted networks.

One nice feature of `mtssrv` is that it (like the `mitsuba` executable) also supports the `-c` and `-s` parameters, which create connections to additional compute servers. Using this feature, one can create hierarchies of compute nodes. For instance, the root `mttsrv` instance of such a hierarchy could share its work with a number of other machines running `mtssrv`, and each of these might also share their work with further machines, and so on...

The parallelization over such hierarchies happens transparently—when connecting a renderering process to the root node, it sees a machine with hundreds or thousands of cores, to which it can submit work without needing to worry about how exactly it is going to be spread out in the hierarchy.

Such hierarchies are mainly useful to reduce communication bottlenecks when distributing large resources (such as scenes) to remote machines. Imagine the following hypothetical scenario: you would like to render a 50MB-sized scene while at home, but rendering is too slow. You decide to tap into some extra machines available at your workplace, but this usually doesn't make things much

faster because of the relatively slow broadband connection and the need to transmit your scene to every single compute node involved.

Using `mtssrv`, you can instead designate a central scheduling node at your workplace, which accepts connections and delegates rendering tasks to the other machines. In this case, you will only have to transmit the scene once, and the remaining distribution happens over the fast local network at your workplace.

4.4. Utility launcher

When working on a larger project, one often needs to implement various utility programs that perform simple tasks, such as applying a filter to an image or processing a matrix stored in a file. In a framework like Mitsuba, this unfortunately involves a significant coding overhead in initializing the necessary APIs on all supported platforms. To reduce this tedious work on the side of the programmer, Mitsuba comes with a utility launcher called `mtsutil`.

The general usage of this command is

```
$ mtsutil [options] <utility name> [arguments]
```

For a listing of all supported options and utilities, enter the command without parameters.

5. Scene file format

Mitsuba uses a very simple and general XML-based format to represent scenes. Since the framework's philosophy is to represent discrete blocks of functionality as plugins, a scene file can essentially be interpreted as description that determines which plugins should be instantiated and how they should interface with each other. In the following, we'll look at a few examples to get a feeling for the scope of the format.

An simple scene with a single mesh and the default lighting and camera setup might look something like this:

```
<?xml version="1.0" encoding="utf-8"?>
<scene version="0.3.0">
    <shape type="obj">
        <string name="filename" value="dragon.obj"/>
    </shape>
</scene>
```

The scene version attribute denotes the release of Mitsuba that was used to create the scene. This information allows Mitsuba to always correctly process the file irregardless of any potential future changes in the scene description language.

This example already contains the most important things to know about format: you can have *objects* (such as the objects instantiated by the `scene` or `shape` tags), which are allowed to be nested within each other. Each object optionally accepts *properties* (such as the `string` tag), which further characterize its behavior. All objects except for the root object (the `scene`) cause the renderer to search and load a plugin from disk, hence you must provide the plugin name using `type=".."` parameter.

The object tags also let the renderer know *what kind* of object is to be instantiated: for instance, any plugin loaded using the `shape` tag must conform to the *Shape* interface, which is certainly the case for the plugin named `obj` (it contains a WaveFront OBJ loader). Similarly, you could write

```
<?xml version="1.0" encoding="utf-8"?>
<scene version="0.3.0">
    <shape type="sphere">
        <float name="radius" value="10"/>
    </shape>
</scene>
```

This loads a different plugin (`sphere`) which is still a *Shape*, but instead represents a sphere configured with a radius of 10 world-space units. Mitsuba ships with a large number of plugins; please refer to the next chapter for a detailed overview of them.

The most common scene setup is to declare an integrator, some geometry, a camera, a film, a sampler and one or more luminaires. Here is a more complex example:

```
<?xml version="1.0" encoding="utf-8"?>

<scene version="0.3.0">
    <integrator type="path">
        <!-- Path trace with a max. path length of 8 -->
        <integer name="maxDepth" value="8"/>
    </integrator>
```

```
    <!-- Instantiate a perspective camera with 45 degrees field of view -->
    <camera type="perspective">
        <!-- Rotate the camera around the Y axis by 180 degrees -->
        <transform name="toWorld">
            <rotate y="1" angle="180"/>
        </transform>
        <float name="fov" value="45"/>

        <!-- Render with 32 samples per pixel using a basic
             independent sampling strategy -->
        <sampler type="independent">
            <integer name="sampleCount" value="32"/>
        </sampler>

        <!-- Generate an EXR image at HD resolution -->
        <film type="exrfilm">
            <integer name="width" value="1920"/>
            <integer name="height" value="1080"/>
        </film>
    </camera>

    <!-- Add a dragon mesh made of rough glass (stored as OBJ file) -->
    <shape type="obj">
        <string name="filename" value="dragon.obj"/>

        <bsdf type="roughdielectric">
            <!-- Tweak the roughness parameter of the material -->
            <float name="alpha" value="0.01"/>
        </bsdf>
    </shape>

    <!-- Add another mesh -- this time, stored using Mitsuba's own
         (compact) binary representation -->
    <shape type="serialized">
        <string name="filename" value="lightsource.serialized"/>
        <transform name="toWorld">
            <translate x="5" x="-3" z="1"/>
        </transform>

        <!-- This mesh is an area luminaire -->
        <luminaire type="area">
            <rgb name="intensity" value="100,400,100"/>
        </luminaire>
    </shape>
</scene>
```

This example introduces several new object types (`integrator`, `camera`, `bsdf`, `sampler`, `film`, and `luminaire`) and property types (`integer`, `transform`, and `rgb`). As you can see in the example, objects are usually declared at the top level except if there is some inherent relation that links them to another object. For instance, BSDFs are usually specific to a certain geometric object, so they appear as a child object of a shape. Similarly, the sampler and film affect the way in which rays are

generated from the camera and how it records the resulting radiance samples, hence they are nested inside it.

5.1. Property types

This section documents all of the ways in which properties can be supplied to objects. If you are more interested in knowing which properties a certain plugin accepts, you should look at the next section instead.

5.1.1. Numbers

Integer and floating point values can be passed as follows:

```
<integer name="intProperty" value="1234"/>
<float name="floatProperty" value="1.234"/>
<float name="floatProperty2" value="-1.5e3"/>
```

Note that you must adhere to the format expected by the object, i.e. you can't pass an integer property to an object, which expects a floating-point value associated with that name.

5.1.2. Strings

Passing strings is straightforward:

```
<string name="stringProperty" value="This is a string"/>
```

5.1.3. Color spectra

Depending on the compilation flags of Mitsuba (see Section 3.2 for details), the renderer internally either represents colors using discretized color spectra (when `SPECTRUM_SAMPLES` is set to a value other than 3), or it uses a basic linear RGB representation[6]. Irrespective of which internal representation is used, Mitsuba supports several different ways of specifying color information, which is then converted appropriately.

The preferred way of passing color spectra to the renderer is to explicitly denote the associated wavelengths of each value:

```
<spectrum name="spectrumProperty" value="400:0.56, 500:0.18, 600:0.58, 700:0.24"/>
```

This is a mapping from wavelength in nanometers (before the colon) to a reflectance or intensity value (after the colon). Values in between are linearly interpolated from the two closest neighbors. A useful shortcut to get a completely uniform spectrum, it is to provide only a single value:

```
<spectrum name="spectrumProperty" value="0.56"/>
```

Another (discouraged) option is to directly provide the spectrum in Mitsuba's internal representation, avoiding the need for any kind of conversion. However, this is problematic, since the associated scene will likely not work anymore when Mitsuba is compiled with a different value of `SPECTRUM_SAMPLES`. For completeness, the possibility is explained nonetheless. Assuming that the 360-830nm range is discretized into ten 47nm-sized blocks (i.e. `SPECTRUM_SAMPLES` is set to 10), their values can be specified as follows:

[6] The official releases all use linear RGB—to do spectral renderings, you will have to compile Mitsuba yourself.

```
<spectrum name="spectrumProperty" value=".2, .2, .8, .4, .6, .5, .1, .9, .4, .2"/>
```

Another convenient way of providing color spectra is by specifying linear RGB or sRGB values using floating-point triplets or hex values:

```
<rgb name="spectrumProperty" value="0.2, 0.8, 0.4"/>
<srgb name="spectrumProperty" value="0.4, 0.3, 0.2"/>
<srgb name="spectrumProperty" value="#f9aa34"/>
```

When Mitsuba is compiled with the default settings, it internally uses linear RGB to represent colors, so these values can directly be used. However, when configured for doing spectral rendering, a suitable color spectrum with the requested RGB reflectance must be found. This is a tricky problem, since there is an infinite number of spectra with this property.

Mitsuba uses a method by Smits et al. [19] to find a "plausible" spectrum that is as smooth as possible. To do so, it uses one of two methods depending on whether the spectrum contains a unitless reflectance value, or a radiance-valued intensity.

```
<rgb name="spectrumProperty" intent="reflectance" value="0.2, 0.8, 0.4"/>
<rgb name="spectrumProperty" intent="illuminant" value="0.2, 0.8, 0.4"/>
```

The `reflectance` intent is used by default, so remember to set it to `illuminant` when defining the brightness of a light source with the <rgb> tag.

When spectral power or reflectance distributions are obtained from measurements (e.g. at $10nm$ intervals), they are usually quite unwiedy and can clutter the scene description. For this reason, there is yet another way to pass a spectrum by loading it from an external file:

```
<spectrum name="spectrumProperty" filename="measuredSpectrum.spd"/>
```

The file should contain a single measurement per line, with the corresponding wavelength in nanometers and the measured value separated by a space. Comments are allowed. Here is an example:

```
# This file contains a measured spectral power/reflectance distribution
406.13 0.703313
413.88 0.744563
422.03 0.791625
430.62 0.822125
435.09 0.834000
...
```

Finally, it is also possible to specify the spectral distribution of a black body emitter, where the temperature is given in Kelvin.

```
<blackbody name="spectrumProperty" temperature="5000K"/>
```

Note that attaching a black body spectrum to the `intensity` property of a luminaire introduces physical units into the rendering process of Mitsuba, which is ordinarily a unitless system[7].

Specifically, the black body spectrum has units of power (W) per unit area (m^{-2}) per steradian (sr^{-1}) per unit wavelength (nm^{-1}). Assuming that the scene is modeled in units of meters, the spectral power distribution of pixels rendered by a perspective camera will then have the exact same units (i.e. $W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}$).

If these units are inconsistent with your scene, you may use the optional `multiplier` attribute:

[7] This means that the units of pixel values in a rendering are completely dependent on the units of the user input, including the unit of world-space distance and the units of the light source emission profile.

```
<!-- Oops, the scene is modeled in centimeters, not meters -->
<blackbody name="spectrumProperty" temperature="5000K" multiplier="0.01"/>
```

5.1.4. Vectors, Positions

Points and vectors can be specified as follows:

```
<point name="pointProperty" x="3" y="4" z="5"/>
<vector name="vectorProperty" x="3" y="4" z="5"/>
```

It is important that whatever you choose as world-space units (meters, inches, etc.) is used consistently in all places.

5.1.5. Transformations

Transformations are the only kind of property that require more than a single tag. The idea is that, starting with the identity, one can build up a transformation using a sequence of commands. For instance, a transformation that does a translation followed by a rotation might be written like this:

```
<transform name="trafoProperty">
    <translate x="-1" y="3" z="4"/>
    <rotate y="1" angle="45"/>
</transform>
```

Mathematically, each incremental transformation in the sequence is left-multiplied onto the current one. The following choices are available:

- Translations, e.g.

  ```
  <translate x="-1" y="3" z="4"/>
  ```

- Rotations around a specified direction. The angle is given in degrees, e.g.

  ```
  <rotate x="0.701" y="0.701" z="0" angle="180"/>
  ```

- Scaling operations. The coefficients may also be negative to obtain a flip, e.g.

  ```
  <scale value="5"/>           <!-- uniform scale -->
  <scale x="2" y="1" z="-1"/>  <!-- non-unform scale -->
  ```

- Explicit 4×4 matrices, e.g

  ```
  <matrix value="0 -0.53 0 -1.79 0.92 0 0 8.03 0 0 0.53 0 0 0 0 1"/>
  ```

- LookAt transformations — this is primarily useful for setting up cameras (and spot lights). The `origin` coordinates specify the camera origin, `target` is the point that the camera will look at, and the (optional) `up` parameter determines the "upward" direction in the final rendered image. The `up` parameter is not needed for spot lights.

  ```
  <lookAt origin="10, 50, -800" target="0, 0, 0" up="0, 1, 0"/>
  ```

Cordinates that are zero (for `translate` and `rotate`) or one (for `scale`) do not explicitly have to be specified.

5.2. Instancing

Quite often, you will find yourself using an object (such as a material) in many places. To avoid having to declare it over and over again, which wastes memory, you can make use of references. Here is an example of how this works:

```
<scene version="0.3.0">
    <texture type="bitmap" id="myImage">
        <string name="filename" value="textures/myImage.jpg"/>
    </texture>

    <bsdf type="diffuse" id="myMaterial">
        <!-- Reference the texture named myImage and pass it
            to the BRDF as the reflectance parameter -->
        <ref name="reflectance" id="myImage"/>
    </bsdf>

    <shape type="obj">
        <string name="filename" value="meshes/myShape.obj"/>

        <!-- Reference the material named myMaterial -->
        <ref id="myMaterial"/>
    </shape>
</scene>
```

By providing a unique `id` attribute in the object declaration, the object is bound to that identifier upon instantiation. Referencing this identifier at a later point (using the `<ref id="..."/>` tag) will add the instance to the parent object, with no further memory allocation taking place. Note that some plugins expect their child objects to be named[8]. For this reason, a name can also be associated with the reference.

Note that while this feature is meant to efficiently handle materials, textures, and participating media that are referenced from multiple places, it cannot be used to instantiate geometry—if this functionality is needed, take a look at the `instance` plugin.

5.3. Including external files

A scene can be split into multiple pieces for better readability. to include an external file, please use the following command:

```
<include filename="nested-scene.xml"/>
```

In this case, the file `nested-scene.xml` must be a proper scene file with a `<scene>` tag at the root. This feature is sometimes very convenient in conjunction with the `-D key=value` flag of the `mitsuba` command line renderer (see the previous section for details). This lets you include different parts of a scene configuration by changing the command line parameters (and without having to touch the XML file):

```
<include filename="nested-scene-$version.xml"/>
```

[8] For instance, material plugins such as `diffuse` require that nested texture instances explicitly specify the parameter to which they want to bind (e.g. "`reflectance`").

6. Plugin reference

6.1. Shapes

This section presents an overview of the shape plugins that are released along with the renderer.

In Mitsuba, shapes define surfaces that mark transitions between different types of materials. For instance, a shape could describe a boundary between air and a solid object, such as a piece of rock. Alternatively, a shape can mark the beginning of a region of space that isn't solid at all, but rather contains a participating medium, such as smoke or steam. Finally, a shape can be used to create an object that emits light on its own.

Shapes are usually declared along with a surface scattering model (named "BSDF", see Section 6.2 for details). This BSDF characterizes what happens *at the surface*. In the XML scene description language, this might look like the following:

```
<scene version="0.3.0">
    <shape type="... shape type ...">
        ... shape parameters ...

        <bsdf type="... bsdf type ...">
            ... bsdf parameters ..
        </bsdf>

        <!-- Alternatively: reference a named BSDF that
             has been declared previously

             <ref id="myBSDF"/>
        -->
    </shape>
</scene>
```

When a shape marks the transition to a participating medium (e.g. smoke, fog, ..), it is furthermore necessary to provide information about the two media that lie at the *interior* and *exterior* of the shape. This informs the renderer about what happens in the region of space *surrounding the surface*.

```
<scene version="0.3.0">
    <shape type="... shape type ...">
        ... shape parameters ...

        <medium name="interior" type="... medium type ...">
            ... medium parameters ...
        </medium>

        <medium name="exterior" type="... medium type ...">
            ... medium parameters ...
        </medium>

        <!-- Alternatively: reference named media that
             have been declared previously

             <ref name="interior" id="myMedium1"/>
             <ref name="exterior" id="myMedium2"/>
        -->
    </shape>
</scene>
```

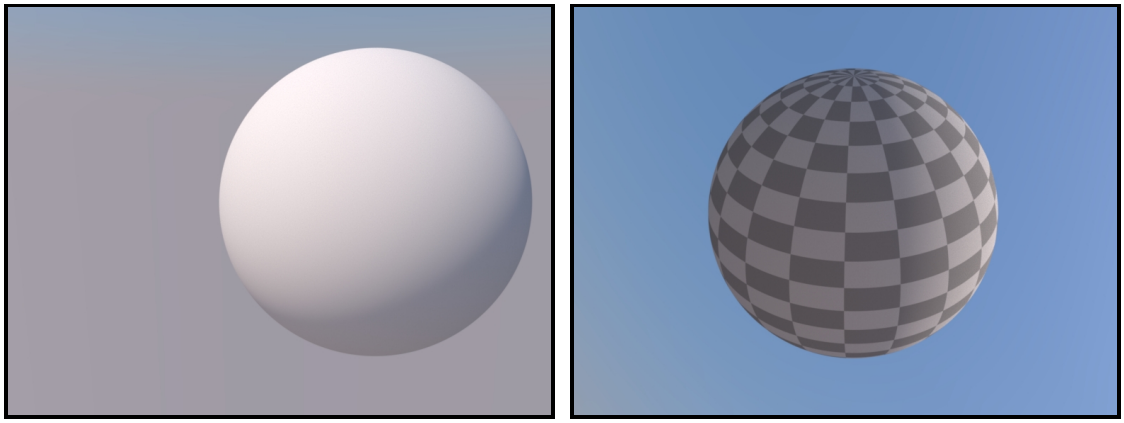
You may have noticed that the previous XML example dit not make any mention of surface scattering models (BSDFs). In Mitsuba, such a shape declaration creates an *index-matched* boundary. This means that incident illumination will pass through the surface without undergoing any kind of interaction. However, the renderer will still uses the information available in the shape to correctly account for the medium change.

It is also possible to create *index-mismatched* boundaries between media, where some of the light is affected by the boundary transition:

```
<scene version="0.3.0">
    <shape type="... shape type ...">
        ... shape parameters ...

        <bsdf type="... bsdf type ...">
            ... bsdf parameters ..
        </bsdf>

        <medium name="interior" type="... medium type ...">
            ... medium parameters ...
        </medium>

        <medium name="exterior" type="... medium type ...">
            ... medium parameters ...
        </medium>

        <!-- Alternatively: reference named media and BSDF
             instances that have been declared previously

             <ref id="myBSDF"/>
             <ref name="interior" id="myMedium1"/>
             <ref name="exterior" id="myMedium2"/>
        -->
    </shape>
</scene>
```

6.1.1. Sphere intersection primitive (`sphere`)

Parameter	Type	Description
`center`	`point`	Center of the sphere in object-space (Default: (0, 0, 0))
`radius`	`float`	Radius of the sphere in object-space units (Default: 1)
`toWorld`	`transform`	Specifies an optional linear object-to-world transformation. Note that non-uniform scales are not permitted! (Default: none (i.e. object space = world space))
`flipNormals`	`boolean`	Is the sphere inverted, i.e. should the normal vectors be flipped? (Default: `false`, i.e. the normals point outside)



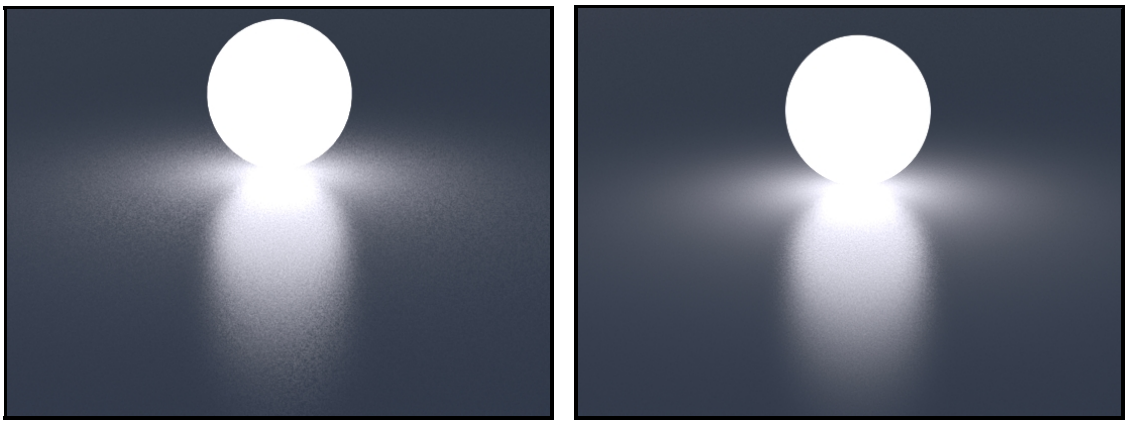
(a) Basic example, see Listing 2 (b) A textured sphere with the default parameterization

This shape plugin describes a simple sphere intersection primitive. It should always be preferred over sphere approximations modeled using triangles.

When using a sphere as the base object of an `area` luminaire, Mitsuba will switch to a special sphere luminaire sampling strategy [18] that works much better than the default approach. The resulting variance reduction makes it preferable to model most light sources as sphere luminaires (Figure 1).

```
<shape type="sphere">
    <transform name="toWorld">
        <scale value="2"/>
        <translate x="1" y="0" z="0"/>
    </transform>
    <bsdf type="diffuse"/>
</shape>

<shape type="sphere">
    <point name="center" x="1" y="0" z="0"/>
    <float name="radius" value="2"/>
    <bsdf type="diffuse"/>
</shape>
```

Listing 2: A sphere can either be configured using a linear `toWorld` transformation or the `center` and `radius` parameters (or both). The above two declarations are equivalent.



(a) Spherical area light modeled using triangles (b) Spherical area light modeled using the `sphere` plugin

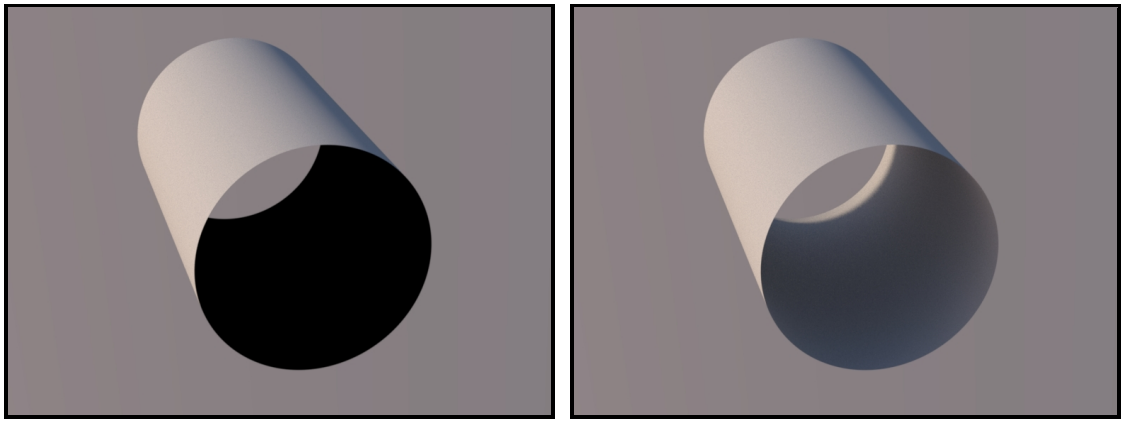
Figure 1: Area lights built from the combination of the `area` and `sphere` plugins produce renderings that have an overall lower variance.

```
<shape type="sphere">
    <point name="center" x="0" y="1" z="0"/>
    <float name="radius" value="1"/>

    <luminaire type="area">
        <blackbody name="intensity" temperature="7000K"/>
    </luminaire>
</shape>
```

Listing 3: Instantiation of a sphere luminaire

6.1.2. Cylinder intersection primitive (`cylinder`)

Parameter	Type	Description
`p0`	`point`	Object-space starting point of the cylinder's centerline (Default: (0, 0, 0))
`p1`	`point`	Object-space endpoint of the cylinder's centerline (Default: (0, 0, 1))
`radius`	`float`	Radius of the cylinder in object-space units (Default: 1)
`toWorld`	`transform`	Specifies an optional linear object-to-world transformation. Note that non-uniform scales are not permitted! (Default: none (i.e. object space = world space))



(a) Cylinder with the default one-sided shading (b) Cylinder with two-sided shading, see Listing 4

This shape plugin describes a simple cylinder intersection primitive. It should always be preferred over approximations modeled using triangles. Note that the cylinder does not have endcaps – also, it's interior has inward-facing normals, which most scattering models in Mitsuba will treat as fully absorbing. If this is not desirable, consider using the `twosided` plugin.

```
<shape type="cylinder">
    <float name="radius" value="0.3"/>
    <bsdf type="twosided">
        <bsdf type="diffuse"/>
    </bsdf>
</shape>
```

Listing 4: A simple example for instantiating a cylinder, whose interior is visible

6.1.3. Wavefront OBJ mesh loader (`obj`)

Parameter	Type	Description
`filename`	`string`	Filename of the OBJ file that should be loaded
`faceNormals`	`boolean`	When set to `true`, Mitsuba will use face normals when rendering the object, which will give it a faceted apperance. (Default: `false`)
`flipNormals`	`boolean`	Optional flag to flip all normals. (Default: `false`, i.e. the normals are left unchanged).
`toWorld`	`transform`	Specifies an optional linear object-to-world transformation. Note that non-uniform scales are not permitted! (Default: none (i.e. object space = world space))
`recenter`	`boolean`	When set to `true`, the geometry will be uniformly scaled and shifted to so that its object-space footprint fits into $[-1,1]^3$.

6.1.4. Shape group for geometry instancing (shapegroup)

Parameter	Type	Description
(Nested plugin)	shape	One or more shapes that should be made available for geometry instancing

This plugin implements a container for shapes that should be made available for geometry instancing. Any shapes placed in a `shapegroup` will not be visible on their own—instead, the renderer will precompute ray intersection acceleration data structures so that they can efficiently be referenced many times using the `instance` plugin. This is useful for rendering things like forests, where only a few distinct types of trees have to be kept in memory.

```
<!-- Declare a named shape group containing two objects -->
<shape type="shapegroup" id="myShapeGroup">
    <shape type="ply">
        <string name="filename" value="data.ply"/>
        <bsdf type="roughconductor"/>
    </shape>

    <shape type="sphere">
        <transform name="toWorld">
            <scale value="5"/>
            <translate y="20"/>
        </transform>
        <bsdf type="diffuse"/>
    </shape>
</shape>

<!-- Instantiate the shape group without
     any kind of transformation -->
<shape type="instance">
    <ref id="myShapeGroup"/>
</shape>

<!-- Instantiate another version of the shape
     group, but rotated, scaled, and translated -->
<shape type="instance">
    <ref id="myShapeGroup"/>

    <transform name="toWorld">
        <rotate x="1" angle="45"/>
        <scale value="1.5"/>
        <translate z="10"/>
    </transform>
</shape>
```

Listing 5: An example of geometry instancing

6.1.5. Geometry instance (`instance`)

Parameter	Type	Description
(Nested plugin)	shapegroup	A reference to a shape group that should be instantiated
toWorld	transform	Specifies an optional linear instance-to-world transformation. (Default: none (i.e. instance space = world space))

This plugin implements a geometry instance used to efficiently replicate geometry many times. For details, please refer to the `shapegroup` plugin.

6.1.6. Animated geometry instance (`animatedinstance`)

Parameter	Type	Description
`filename`	`string`	Filename of an animated transformation
`(Nested plugin)`	`shapegroup`	A reference to a shape group that should be instantiated

This plugin implements an *animated* geometry instance, i.e. one or more shapes that are undergoing *ridgid* transformations over time.

The input file should contain a binary / serialized `AnimatedTransform` data structure – for details, please refer to the C++ implementation of this class.

6.1.7. Serialized mesh loader (`serialized`)

Parameter	Type	Description
`filename`	`string`	Filename of the gemoetry file that should be loaded
`faceNormals`	`boolean`	When set to `true`, Mitsuba will use face normals when rendering the object, which will give it a faceted apperance. (Default: `false`)
`flipNormals`	`boolean`	Optional flag to flip all normals. (Default: `false`, i.e. the normals are left unchanged).
`toWorld`	`transform`	Specifies an optional linear object-to-world transformation. Note that non-uniform scales are not permitted! (Default: none (i.e. object space = world space))

This plugin represents the most space and time-efficient way of getting geometry into Mitsuba. It uses a highly efficient lossless compressed format for geometry storage. Th format will be explained on this page in a subsequent revision of the documentation.

6.1.8. Hair intersection shape (`hair`)

Parameter	Type	Description
`filename`	`string`	Filename of the hair data file that should be loaded
`radius`	`float`	Radius of the hair segments (Default: 0.05).
`angleThreshold`	`float`	For performance reasons, the plugin will merge adjacent hair segments when the angle of their tangent directions is below than this value (in degrees). (Default: 1).
`toWorld`	`transform`	Specifies an optional linear object-to-world transformation. Note that non-uniform scales are not permitted! (Default: none (i.e. object space = world space))

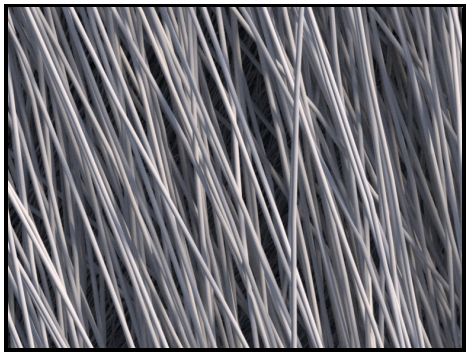


Figure 2: A close-up of the hair shape rendered with a diffuse scattering model (an actual hair scattering model will be needed for realistic apperance)

The plugin implements a space-efficient acceleration structure for hairs made from many straight cylindrical hair segments with miter joints. The underlying idea is that intersections with straight cylindrical hairs can be found quite efficiently, and curved hairs are easily approximated using a series of such segments.

The plugin supports two different input formats: a simple (but not particularly efficient) ASCII format containing the coordinates of a hair vertex on every line. An empty line marks the beginning of a new hair, e.g.

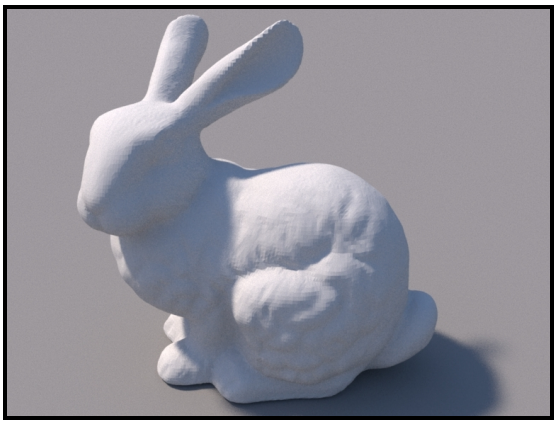
```
.....
-18.5498 -21.7669 22.8138
-18.6358 -21.3581 22.9262
-18.7359 -20.9494 23.0256

-30.6367 -21.8369 6.78397
-30.7289 -21.4145 6.76688
-30.8226 -20.9933 6.73948
.....
```

There is also a binary format, which starts with the identifier "`BINARY_HAIR`" (11 bytes), followed by the number of vertices as a 32-bit little endian integer. The remainder of the file consists of the vertex positions stored as single-precision XYZ coordinates (again in little-endian byte ordering). To mark the beginning of a new hair strand, a single $+\infty$ floating point value can be inserted between the vertex data.

6.1.9. PLY (Stanford Triangle Format) mesh loader (`ply`)

Parameter	Type	Description
`filename`	`string`	Filename of the PLY file that should be loaded
`faceNormals`	`boolean`	When set to `true`, Mitsuba will use face normals when rendering the object, which will give it a faceted apperance. (Default: `false`)
`flipNormals`	`boolean`	Optional flag to flip all normals. (Default: `false`, i.e. the normals are left unchanged).
`toWorld`	`transform`	Specifies an optional linear object-to-world transformation. Note that non-uniform scales are not permitted! (Default: none (i.e. object space = world space))
`srgb`	`boolean`	When set to `true`, any vertex colors will be interpreted as sRGB, instead of linear RGB (Default: `true`).

(a) The PLY plugin is useful for loading heavy geometry. (Thai statue courtesy of XYZ RGB)



(b) The Stanford bunny loaded with `faceNormals=true`. Note the faceted appearance.

This plugin is based on the library `libply` by Ares Lagae (`http://people.cs.kuleuven.be/~ares.lagae/libply`).

6.2. Surface scattering models

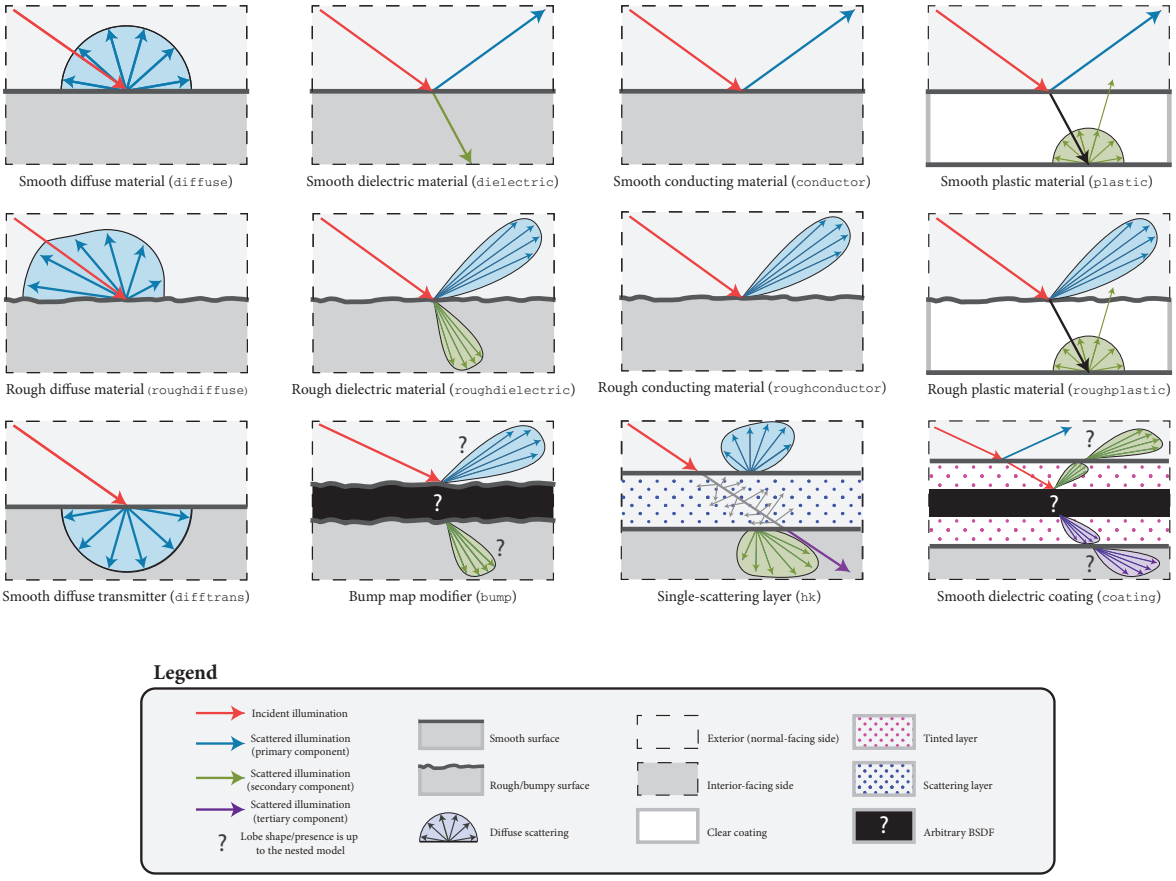


Figure 3: Schematic overview of the most important surface scattering models in Mitsuba (shown in the style of Weidlich and Wilkie [23]). The arrows indicate possible outcomes of an interaction with a surface that has the respective model applied to it.

Surface scattering models describe the manner in which light interacts with surfaces in the scene. They conveniently summarize the mesoscopic scattering processes that take place within the material and cause it to look the way it does. This represents one central component of the material system in Mitsuba—another part of the renderer concerns itself with what happens *in between* surface interactions. For more information on this aspect, please refer to Sections 6.5 and 6.4. This section presents an overview of all surface scattering models that are supported, along with their parameters.

BSDFs

To achieve realistic results, Mitsuba comes with a library of both general-purpose surface scattering models (smooth or rough glass, metal, plastic, etc.) and specializations to particular materials (woven cloth, masks, etc.). Some model plugins fit neither category and can best be described as *modifiers* that are applied on top of one or more scattering models.

Throughout the documentation and within the scene description language, the word *BSDF* is used synonymously with the term "surface scattering model". This is an abbreviation for *Bidirectional Scat-*

tering Distribution Function, a more precise technical term.

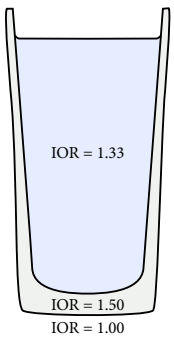
In Mitsuba, BSDFs are assigned to *shapes*, which describe the visible surfaces in the scene. In the scene description language, this assignment can either be performed by nesting BSDFs within shapes, or they can be named and then later referenced by their name. The following fragment shows an example of both kinds of usages:

```
<scene version="0.3.0">
    <!-- Creating a named BSDF for later use -->
    <bsdf type=".. BSDF type .." id="myNamedMaterial">
        <!-- BSDF parameters go here -->
    </bsdf>

    <shape type="sphere">
        <!-- Example of referencing a named material -->
        <ref id="myNamedMaterial"/>
    </shape>

    <shape type="sphere">
        <!-- Example of instantiating an unnamed material -->
        <bsdf type=".. BSDF type ..">
            <!-- BSDF parameters go here -->
        </bsdf>
    </shape>
</scene>
```

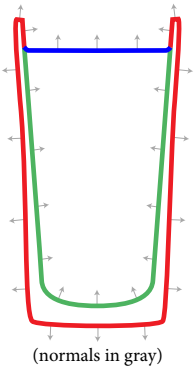
It is generally more economical to use named BSDFs when they are used in several places, since this reduces Mitsuba's internal memory usage.

Correctness considerations

A vital consideration when modeling a scene in a physically-based rendering system is that the used materials do not violate physical properties, and that their arrangement is meaningful. For instance,



(a) Slice through a glass filled with water



(b) Description using surfaces in Mitsuba

Surface	Interior IOR	Exterior IOR
	1.50	1.00
	1.50	1.33
	1.33	1.00

(c) Detailed IOR transitions

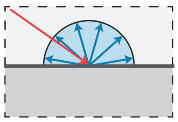
Figure 4: Some of the scattering models in Mitsuba need to know the indices of refraction on the exterior and interior-facing side of a surface. It is therefore important to decompose the mesh into meaningful separate surfaces corresponding to each index of refraction change. The example here shows such a decomposition for a water-filled Glass.

imagine having designed an architectural interior scene that looks good except for a white desk that seems a bit too dark. A closer inspection reveals that it uses a Lambertian material with a diffuse reflectance of 0.9.

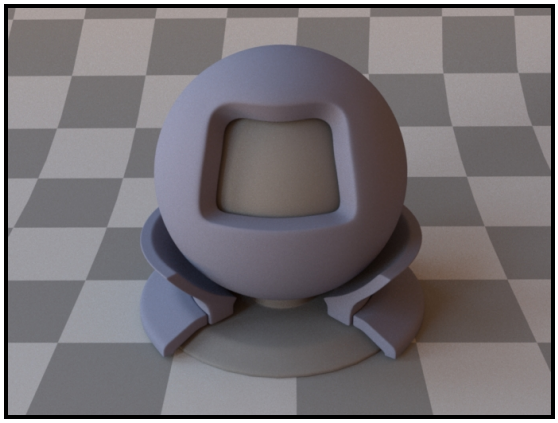
In many rendering systems, it would be feasible to increase the reflectance value above 1.0 in such a situation. But in Mitsuba, even a small surface that reflects a little more light than it receives will likely break the available rendering algorithms, or cause them to produce otherwise unpredictable results. In fact, we should rather change the lighting setup and then *reduce* the material's reflectance, since it is quite unlikely that we could find a real-world desk with a reflectance as high as 0.9.

As an example of the necessity for a meaningful material arrangement, consider the glass model illustrated in Figure 4. Here, careful thinking is needed to decompose the object into boundaries that mark index of refraction-changes. If this is done incorrectly and a beam of light can potentially pass through a sequence of incompatible index of refraction changes (e.g. 1.00 → 1.33 followed by 1.50 → 1.33), the output is undefined and will quite likely even contain inaccuracies in parts of the scene that are some distance away from the glass.

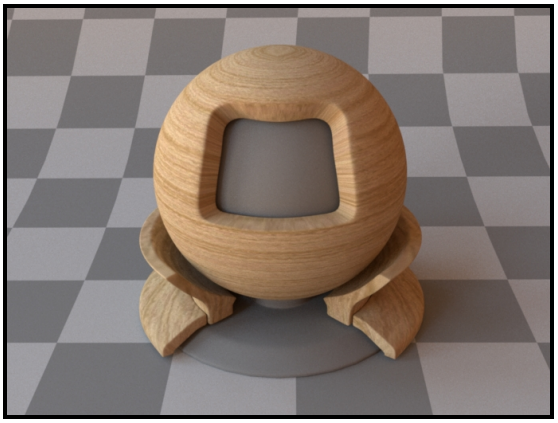
6.2.1. Smooth diffuse material (`diffuse`)



Parameter	Type	Description
`reflectance`	`spectrum` or `texture`	Specifies the diffuse albedo of the material (Default: 0.5)



(a) Homogeneous reflectance, see Listing 6



(b) Textured reflectance, see Listing 7

The smooth diffuse material (also referred to as "Lambertian") represents an ideally diffuse material with a user-specified amount of reflectance. Any received illumination is scattered so that the surface looks the same independently of the direction of observation.

Apart from a homogeneous reflectance value, the plugin can also accept a nested or referenced texture map to be used as the source of reflectance information, which is then mapped onto the shape based on its UV parameterization. When no parameters are specified, the model uses the default of 50% reflectance.

Note that this material is one-sided—that is, observed from the back side, it will be completely black. If this is undesirable, consider using the `twosided` BRDF adapter plugin.

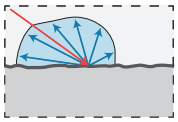
```
<bsdf type="diffuse">
    <srgb name="reflectance" value="#6d7185"/>
</bsdf>
```

Listing 6: A diffuse material, whose reflectance is specified as an sRGB color

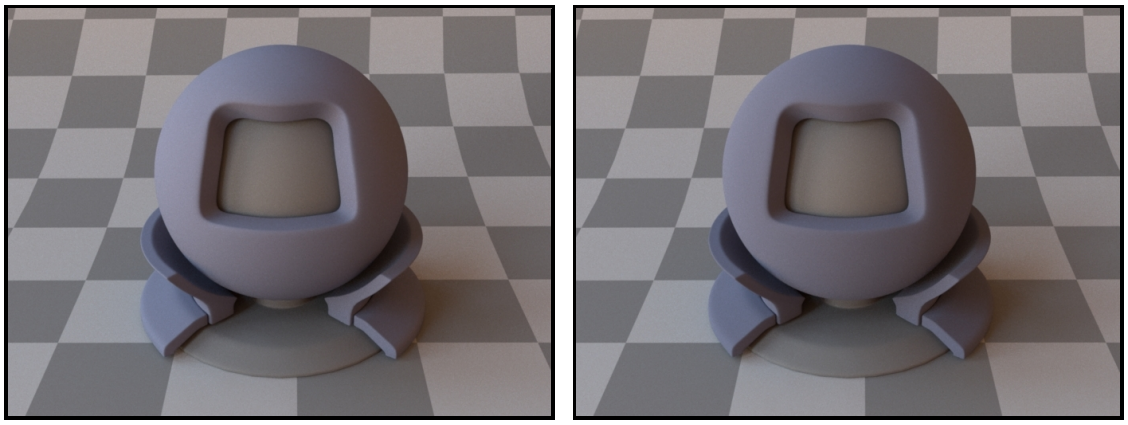
```
<bsdf type="diffuse">
    <texture type="bitmap" name="reflectance">
        <string name="filename" value="wood.jpg"/>
    </texture>
</bsdf>
```

Listing 7: A diffuse material with a texture map

6.2.2. Rough diffuse material (`roughdiffuse`)



Parameter	Type	Description
`reflectance`	`spectrum` or `texture`	Specifies the diffuse albedo of the material. (Default: 0.5)
`alpha`	`spectrum` or `texture`	Specifies the roughness of the unresolved surface microgeometry using the *root mean square* (RMS) slope of the microfacets. (Default: 0.2)
`useFastApprox`	`boolean`	This parameter selects between the full version of the model or a fast approximation that still retains most qualitative features. (Default: `false`, i.e. use the high-quality version)



(a) Smooth diffuse surface ($\alpha = 0$) (b) Very rough diffuse surface ($\alpha = 0.7$)

Figure 5: The effect of switching from smooth to rough diffuse scattering is fairly subtle on this model—generally, there will be higher reflectance at grazing angles, as well as an overall reduced contrast.

This reflectance model describes the interaction of light with a *rough* diffuse material, such as plaster, sand, clay, or concrete, or "powdery" surfaces. The underlying theory was developed by Oren and Nayar [13], who model the microscopic surface structure as unresolved planar facets arranged in V-shaped grooves, where each facet is an ideal diffuse reflector. The model takes into account shadowing, masking, as well as interreflections between the facets.

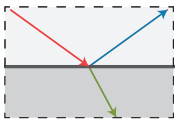
Since the original publication, this approach has been shown to be a good match for many real-world materials, particularly compared to Lambertian scattering, which does not take surface roughness into account.

The implementation in Mitsuba uses a surface roughness parameter α that is slightly different from the slope-area variance in the original 1994 paper. The reason for this change is to make the parameter α portable across different models (i.e. `roughdielectric`, `roughplastic`, `roughconductor`).

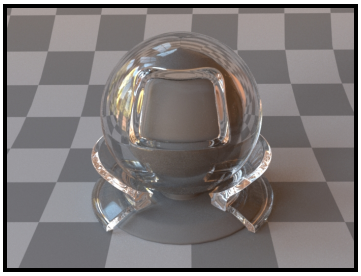
To get an intuition about the effect of the parameter α, consider the following approximate differentiation: a value of $\alpha = 0.001 - 0.01$ corresponds to a material with slight imperfections on an otherwise smooth surface (for such small values, the model will behave identically to `diffuse`), $\alpha = 0.1$ is relatively rough, and $\alpha = 0.3 - 0.7$ is *extremely* rough (e.g. an etched or ground surface).

Note that this material is one-sided—that is, observed from the back side, it will be completely black. If this is undesirable, consider using the `twosided` BRDF adapter plugin.

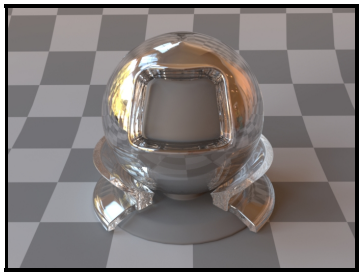
6.2.3. Smooth dielectric material (`dielectric`)



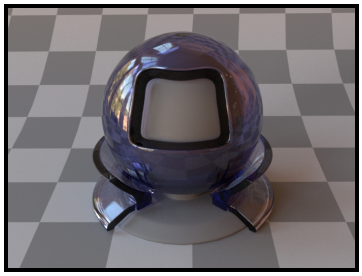
Parameter	Type	Description
`intIOR`	`float` or `string`	Interior index of refraction specified numerically or using a known material name. (Default: `bk7` / 1.5046)
`extIOR`	`float` or `string`	Exterior index of refraction specified numerically or using a known material name. (Default: `air` / 1.000277)
`specular↙ Reflectance`	`spectrum` or `texture`	Optional factor used to modulate the reflectance component (Default: 1.0)
`specular↙ Transmittance`	`spectrum` or `texture`	Optional factor used to modulate the transmittance component (Default: 1.0)



(a) Air↔Water (IOR: 1.33) interface. See Listing 8.



(b) Air↔Diamond (IOR: 2.419)



(c) Air↔Glass (IOR: 1.504) interface with absorption. See Listing 9.

This plugin models an interface between two dielectric materials having mismatched indices of refraction (for instance, water and air). Exterior and interior IOR values can be specified independently, where "exterior" refers to the side that contains the surface normal. When no parameters are given, the plugin activates the defaults, which describe a borosilicate glass BK7/air interface.

In this model, the microscopic structure of the surface is assumed to be perfectly smooth, resulting in a degenerate[9] BSDF described by a Dirac delta distribution. For a similar model that instead describes a rough surface microstructure, take a look at the `roughdielectric` plugin.

```
<shape type="...">
    <bsdf type="dielectric">
        <string name="intIOR" value="water"/>
        <string name="extIOR" value="air"/>
    </bsdf>
<shape>
```

Listing 8: A simple air-to-water interface

When using this model, it is crucial that the scene contains meaningful and mutually compatible indices of refraction changes—see Figure 4 for a description of what this entails.

In many cases, we will want to additionally describe the *medium* within a dielectric material. This requires the use of a rendering technique that is aware of media (e.g. the volumetric path tracer). An example of how one might describe a slightly absorbing piece of glass is given on the next page:

[9] Meaning that for any given incoming ray of light, the model always scatters into a discrete set of directions, as opposed to a continuum.

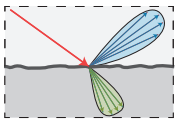
```
<shape type="...">
    <bsdf type="dielectric">
        <float name="intIOR" value="1.504"/>
        <float name="extIOR" value="1.0"/>
    </bsdf>

    <medium type="homogeneous" name="interior">
        <rgb name="sigmaS" value="0, 0, 0"/>
        <rgb name="sigmaA" value="4, 4, 2"/>
    </medium>
<shape>
```

Listing 9: A glass material with absorption (based on the Beer-Lambert law). This material can only be used by an integrator that is aware of participating media.

Name	Value	Name	Value
vacuum	1.0	bromine	1.661
helium	1.00004	water ice	1.31
hydrogen	1.00013	fused quartz	1.458
air	1.00028	pyrex	1.470
carbon dioxide	1.00045	acrylic glass	1.49
water	1.3330	polypropylene	1.49
acetone	1.36	bk7	1.5046
ethanol	1.361	sodium chloride	1.544
carbon tetrachloride	1.461	amber	1.55
glycerol	1.4729	pet	1.575
benzene	1.501	diamond	2.419
silicone oil	1.52045		

Table 1: This table lists all supported material names along with along with their associated index of refraction at standard conditions. These material names can be used with the plugins `dielectric`, `roughdielectric`, `plastic`, `roughplastic`, as well as `coating`.

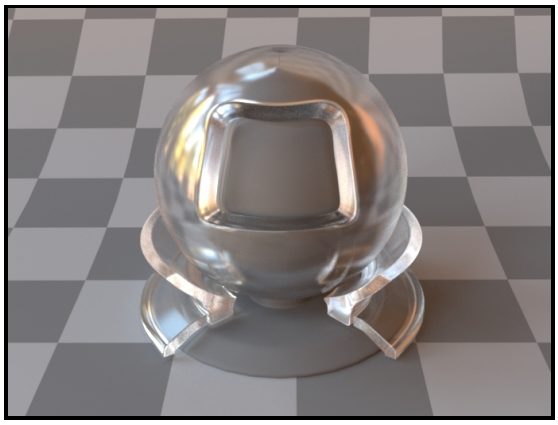
6.2.4. Rough dielectric material (`roughdielectric`)



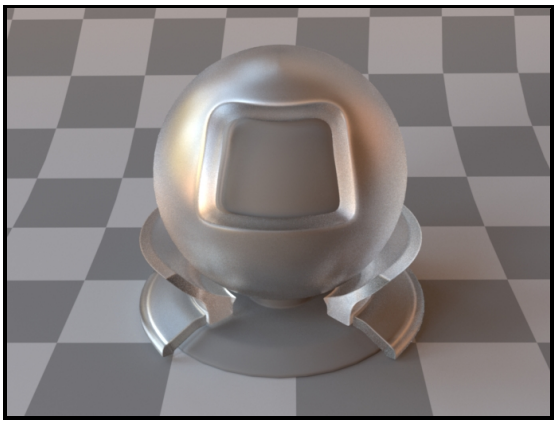
Parameter	Type	Description
`distribution`	`string`	Specifies the type of microfacet normal distribution used to model the surface roughness. (i) `beckmann`: Physically-based distribution derived from Gaussian random surfaces. This is the default. (ii) `ggx`: New distribution proposed by Walter et al. [21], which is meant to better handle the long tails observed in measurements of ground surfaces. Renderings with this distribution may converge slowly. (iii) `phong`: Classical $\cos^p\theta$ distribution. Due to the underlying microfacet theory, the use of this distribution here leads to more realistic behavior than the separately available phong plugin. (iv) `as`: Anisotropic Phong-style microfacet distribution proposed by Ashikhmin and Shirley [1].
`alpha`	`float` or `texture`	Specifies the roughness of the unresolved surface microgeometry. When the Beckmann distribution is used, this parameter is equal to the *root mean square* (RMS) slope of the microfacets. This parameter is only valid when `distribution=beckmann/phong/ggx`. (Default: 0.1).
`alphaU, alphaV`	`float` or `texture`	Specifies the anisotropic roughness values along the tangent and bitangent directions. These parameter are only valid when `distribution=as`. (Default: 0.1).
`intIOR`	`float` or `string`	Interior index of refraction specified numerically or using a known material name. (Default: `bk7` / 1.5046)
`extIOR`	`float` or `string`	Exterior index of refraction specified numerically or using a known material name. (Default: `air` / 1.000277)
`specular↙Reflectance`	`spectrum` or `texture`	Optional factor used to modulate the reflectance component (Default: 1.0)
`specular↙Transmittance`	`spectrum` or `texture`	Optional factor used to modulate the transmittance component (Default: 1.0)

This plugin implements a realistic microfacet scattering model for rendering rough interfaces between dielectric materials, such as a transition from air to ground glass. Microfacet theory describes rough surfaces as an arrangement of unresolved and ideally specular facets, whose normal directions are given by a specially chosen *microfacet distribution*. By accounting for shadowing and masking effects between these facets, it is possible to reproduce the important off-specular reflections peaks observed in real-world measurements of such materials.

This plugin is essentially the "roughened" equivalent of the (smooth) plugin `dielectric`. For very low values of α, the two will be very similar, though scenes using this plugin will take longer to render due to the additional computational burden of tracking surface roughness.



(a) Anti-glare glass (Beckmann, $\alpha = 0.02$)



(b) Rough glass (Beckmann, $\alpha = 0.1$)

The implementation is based on the paper "Microfacet Models for Refraction through Rough Surfaces" by Walter et al. [21]. It supports several different types of microfacet distributions and has a texturable roughness parameter. Exterior and interior IOR values can be specified independently, where "exterior" refers to the side that contains the surface normal. Similar to the `dielectric` plugin, IOR values can either be specified numerically, or based on a list of known materials (see Table 1 for an overview). When no parameters are given, the plugin activates the default settings, which describe a borosilicate glass BK7/air interface with a light amount of roughness modeled using a Beckmann distribution.

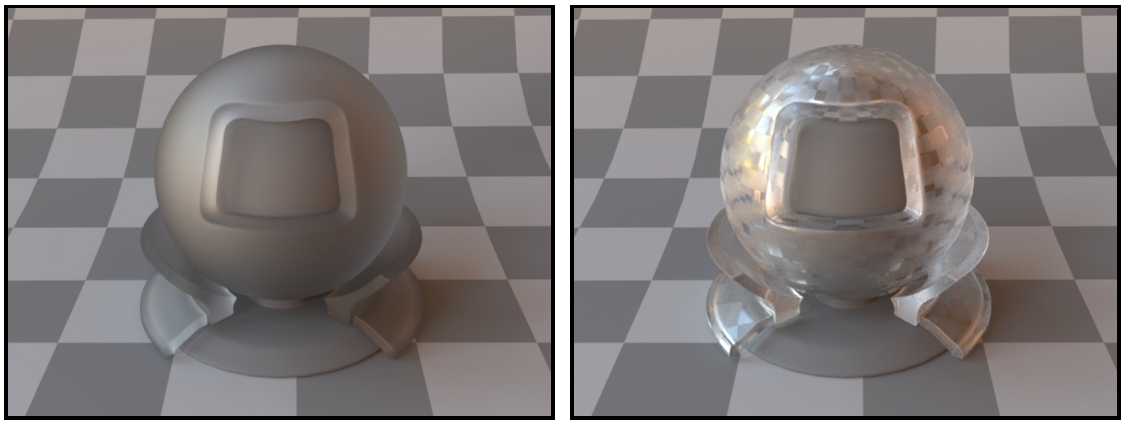
To get an intuition about the effect of the surface roughness parameter α, consider the following approximate differentiation: a value of $\alpha = 0.001 - 0.01$ corresponds to a material with slight imperfections on an otherwise smooth surface finish, $\alpha = 0.1$ is relatively rough, and $\alpha = 0.3 - 0.7$ is *extremely* rough (e.g. an etched or ground finish).

Please note that when using this plugin, it is crucial that the scene contains meaningful and mutually compatible index of refraction changes—see Figure 4 for an example of what this entails. Also, note that the importance sampling implementation of this model is close, but not always a perfect a perfect match to the underlying scattering distribution, particularly for high roughness values and when the `ggx` microfacet distribution is used. Hence, such renderings may converge slowly.

Technical details

When rendering with the Ashikhmin-Shirley or Phong microfacet distributions, a conversion is used to turn the specified α roughness value into the exponents of these distributions. This is done in a way, such that the different distributions all produce a similar appearance for the same value of α.

The Ashikhmin-Shirley microfacet distribution allows the specification of two distinct roughness values along the tangent and bitangent directions. This can be used to provide a material with a "brushed" appearance. The alignment of the anisotropy will follow the UV parameterization of the underlying mesh in this case. This also means that such an anisotropic material cannot be applied to triangle meshes that are missing texture coordinates.



(a) Ground glass (GGX, α=0.304, Listing 10) (b) Textured roughness (Listing 11)

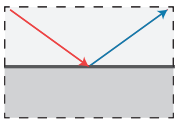
```
<bsdf type="roughdielectric">
    <string name="distribution" value="ggx"/>
    <float name="alpha" value="0.304"/>
    <string name="intIOR" value="bk7"/>
    <string name="extIOR" value="air"/>
</bsdf>
```

Listing 10: A material definition for ground glass

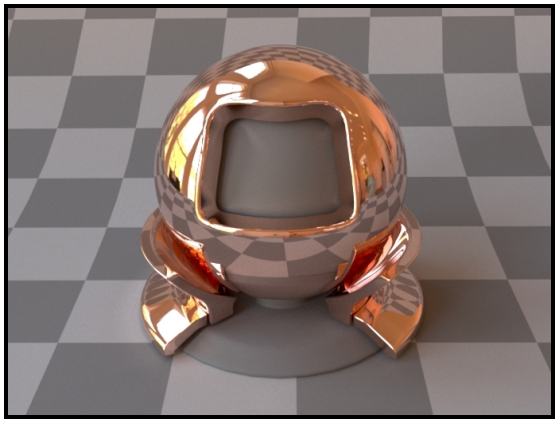
```
<bsdf type="roughdielectric">
    <string name="distribution" value="beckmann"/>
    <float name="intIOR" value="1.5046"/>
    <float name="extIOR" value="1.0"/>

    <texture name="alpha" type="bitmap">
        <string name="filename" value="roughness.exr"/>
    </texture>
</bsdf>
```

Listing 11: A texture can be attached to the roughness parameter

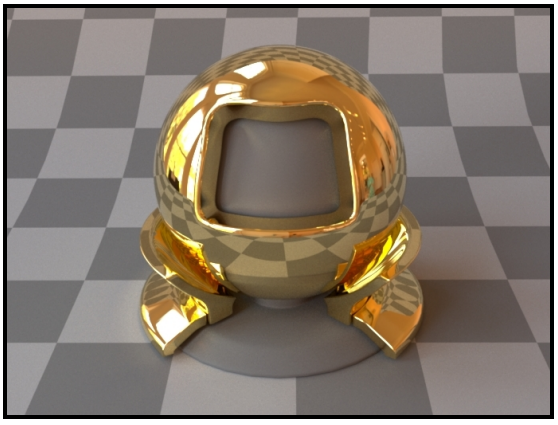
6.2.5. Smooth conductor (`conductor`)



Parameter	Type	Description
`material`	`string`	Name of a material preset, see Table 2. (Default: `Cu` / copper)
`eta`	`spectrum`	Real part of the material's index of refraction (Default: based on the value of `material`)
`k`	`spectrum`	Imaginary part of the material's index of refraction, also known as absorption coefficient. (Default: based on the value of `material`)
`specular↙ Reflectance`	`spectrum` or `texture`	Optional factor used to modulate the reflectance component (Default: 1.0)



(a) Measured copper material (the default), rendered using 30 spectral samples between 360 and 830nm



(b) Measured gold material (Listing 12)

This plugin implements a perfectly smooth interface to a conducting material, such as a metal. For a similar model that instead describes a rough surface microstructure, take a look at the separately available `roughconductor` plugin.

In contrast to dielectric materials, conductors do not transmit any light. Their index of refraction is complex-valued and tends to undergo considerable changes throughout the visible color spectrum.

To facilitate the tedious task of specifying spectrally-varying index of refraction information, Mitsuba ships with a set of measured data for several materials, where visible-spectrum information was publicly available[10].

Note that Table 2 also includes several popular optical coatings, which are not actually conductors. These materials can also be used with this plugin, though note that the plugin will ignore any refraction component that the actual material might have had. The table also contains a few birefingent materials, which are split into separate measurements corresponding to their two indices of refraction (named "ordinary" and "extraordinary ray").

When using this plugin, you should ideally compile Mitsuba with support for spectral rendering to get the most accurate results. While it also works in RGB mode, the computations will be much more

[10] These index of refraction values are identical to the data distributed with PBRT. They are originally from the Luxpop database (`www.luxpop.com`) and are based on data by Palik et al. [14] and measurements of atomic scattering factors made by the Center For X-Ray Optics (CXRO) at Berkeley and the Lawrence Livermore National Laboratory (LLNL).

approximate in this case. Also note that this material is one-sided—that is, observed from the back side, it will be completely black. If this is undesirable, consider using the `twosided` BRDF adapter plugin.

```
<shape type="...">
    <bsdf type="conductor">
        <string name="material" value="Au"/>
    </bsdf>
<shape>
```

Listing 12: A material configuration for a smooth conductor with measured gold data

It is also possible to load spectrally varying index of refraction data from two external files containing the real and imaginary components, respectively (see Section 5.1.3 for details on the file format):

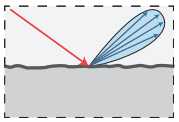
```
<shape type="...">
    <bsdf type="conductor">
        <spectrum name="eta" filename="conductorIOR.eta.spd"/>
        <spectrum name="k" filename="conductorIOR.k.spd"/>
    </bsdf>
<shape>
```

Listing 13: Rendering a smooth conductor with custom data

Preset(s)	Description	Preset(s)	Description
a-C	Amorphous carbon	Na_palik	Sodium
Ag	Silver	Nb, Nb_palik	Niobium
Al	Aluminium	Ni_palik	Nickel
AlAs, AlAs_palik	Cubic aluminium arsenide	Rh, Rh_palik	Rhodium
AlSb, AlSb_palik	Cubic aluminium antimonide	Se, Se_palik	Selenium (ord. ray)
Au	Gold	Se-e, Se-e_palik	Selenium (extr. ray)
Be, Be_palik	Polycrystalline beryllium	SiC, SiC_palik	Hexagonal silicon carbide
Cr	Chromium	SnTe, SnTe_palik	Tin telluride
CsI, CsI_palik	Cubic caesium iodide	Ta, Ta_palik	Tantalum
Cu, Cu_palik	Copper	Te, Te_palik	Trigonal tellurium (ord. ray)
Cu2O, Cu2O_palik	Copper (I) oxide	Te-e, Te-e_palik	Trigonal tellurium (extr. ray)
CuO, CuO_palik	Copper (II) oxide	ThF4, ThF4_palik	Polycryst. thorium (IV) fluoride
d-C, d-C_palik	Cubic diamond	TiC, TiC_palik	Polycrystalline titanium carbide
Hg, Hg_palik	Mercury	TiN, TiN_palik	Titanium nitride
HgTe, HgTe_palik	Mercury telluride	TiO2, TiO2_palik	Tetragonal titan. dioxide (ord. ray)
Ir, Ir_palik	Iridium	TiO2-e, TiO2-e_palik	Tetragonal titan. dioxide (extr. ray)
K, K_palik	Polycrystalline potassium	VC, VC_palik	Vanadium carbide
Li, Li_palik	Lithium	V_palik	Vanadium
MgO, MgO_palik	Magnesium oxide	VN, VN_palik	Vanadium nitride
Mo, Mo_palik	Molybdenum	W	Tungsten

Table 2: This table lists all supported materials that can be passed into the `conductor` and `roughconductor` plugins. Note that some of them are not actually conductors—this is not a problem, they can be used regardless (though only the reflection component and no transmission will be simulated). In most cases, there are multiple entries for each material, which represent measurements by different authors.

6.2.6. Rough conductor material (`roughconductor`)

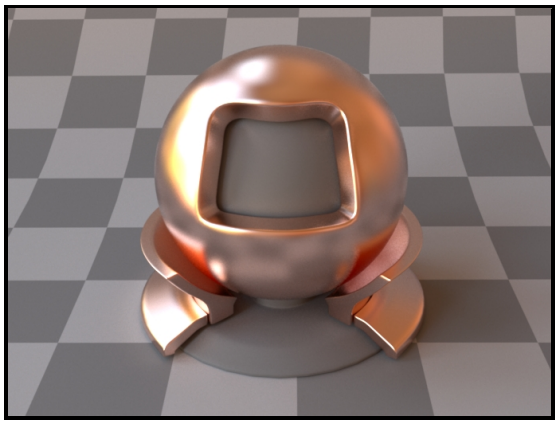


Parameter	Type	Description
`distribution`	`string`	Specifies the type of microfacet normal distribution used to model the surface roughness. (i) `beckmann`: Physically-based distribution derived from Gaussian random surfaces. This is the default. (ii) `ggx`: New distribution proposed by Walter et al. [21], which is meant to better handle the long tails observed in measurements of ground surfaces. Renderings with this distribution may converge slowly. (iii) `phong`: Classical $\cos^p\theta$ distribution. Due to the underlying microfacet theory, the use of this distribution here leads to more realistic behavior than the separately available phong plugin. (iv) `as`: Anisotropic Phong-style microfacet distribution proposed by Ashikhmin and Shirley [1].
`alpha`	`float` or `texture`	Specifies the roughness of the unresolved surface microgeometry. When the Beckmann distribution is used, this parameter is equal to the *root mean square* (RMS) slope of the microfacets. This parameter is only valid when `distribution=beckmann/phong/ggx`. (Default: 0.1).
`alphaU, alphaV`	`float` or `texture`	Specifies the anisotropic roughness values along the tangent and bitangent directions. These parameter are only valid when `distribution=as`. (Default: 0.1).
`material`	`string`	Name of a material preset, see Table 2. (Default: `Cu` / copper)
`eta`	`spectrum`	Real part of the material's index of refraction (Default: based on the value of `material`)
`k`	`spectrum`	Imaginary part of the material's index of refraction (the absorption coefficient). (Default: based on `material`)
`specular↙ Reflectance`	`spectrum` or `texture`	Optional factor used to modulate the reflectance component (Default: 1.0)

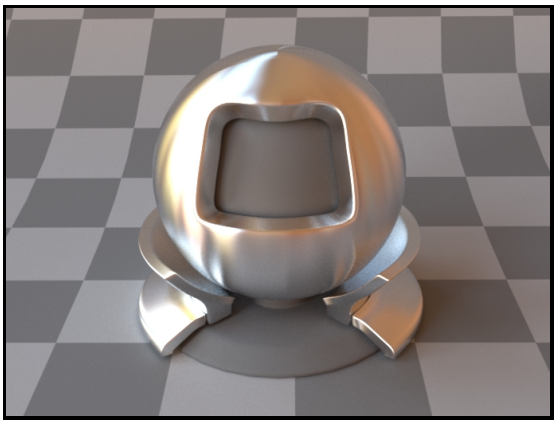
This plugin implements a realistic microfacet scattering model for rendering rough conducting materials, such as metals. It can be interpreted as a fancy version of the Cook-Torrance model and should be preferred over empirical models like phong and ward when possible.

Microfacet theory describes rough surfaces as an arrangement of unresolved and ideally specular facets, whose normal directions are given by a specially chosen *microfacet distribution*. By accounting for shadowing and masking effects between these facets, it is possible to reproduce the important off-specular reflections peaks observed in real-world measurements of such materials.

This plugin is essentially the "roughened" equivalent of the (smooth) plugin `conductor`. For very low values of α, the two will be very similar, though scenes using this plugin will take longer to render due to the additional computational burden of tracking surface roughness.



(a) Rough copper (Beckmann, $\alpha = 0.1$)



(b) Vertically brushed aluminium (Ashikhmin-Shirley, $\alpha_u = 0.05$, $\alpha_v = 0.3$), see Listing 14

The implementation is based on the paper "Microfacet Models for Refraction through Rough Surfaces" by Walter et al. [21]. It supports several different types of microfacet distributions and has a texturable roughness parameter. To facilitate the tedious task of specifying spectrally-varying index of refraction information, this plugin can access a set of measured materials for which visible-spectrum information was publicly available (see Table 2 for the full list).

When no parameters are given, the plugin activates the default settings, which describe copper with a light amount of roughness modeled using a Beckmann distribution.

To get an intuition about the effect of the surface roughness parameter α, consider the following approximate differentiation: a value of $\alpha = 0.001 - 0.01$ corresponds to a material with slight imperfections on an otherwise smooth surface finish, $\alpha = 0.1$ is relatively rough, and $\alpha = 0.3 - 0.7$ is *extremely* rough (e.g. an etched or ground finish). Values significantly above that are probably not too realistic.

Technical details

When rendering with the Ashikhmin-Shirley or Phong microfacet distributions, a conversion is used to turn the specified α roughness value into the exponents of these distributions. This is done in a way, such that the different distributions all produce a similar appearance for the same value of α.

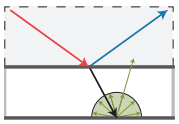
The Ashikhmin-Shirley microfacet distribution allows the specification of two distinct roughness values along the tangent and bitangent directions. This can be used to provide a material with a "brushed" appearance. The alignment of the anisotropy will follow the UV parameterization of the underlying mesh in this case. This also means that such an anisotropic material cannot be applied to triangle meshes that are missing texture coordinates.

When using this plugin, you should ideally compile Mitsuba with support for spectral rendering to get the most accurate results. While it also works in RGB mode, the computations will be much more approximate in this case. Also note that this material is one-sided—that is, observed from the back side, it will be completely black. If this is undesirable, consider using the `twosided` BRDF adapter.

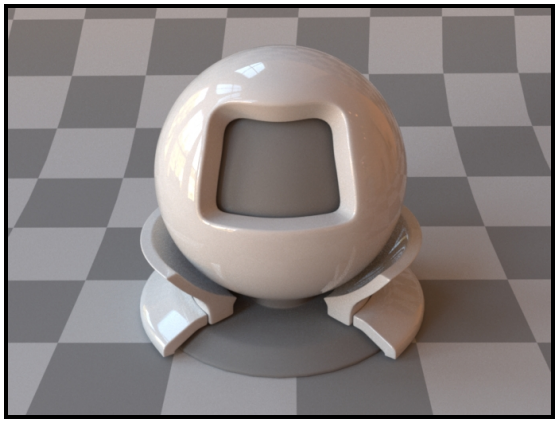
```
<bsdf type="roughconductor">
    <string name="material" value="Al"/>
    <string name="distribution" value="as"/>
    <float name="alphaU" value="0.05"/>
    <float name="alphaV" value="0.3"/>
</bsdf>
```

Listing 14: A material definition for brushed aluminium

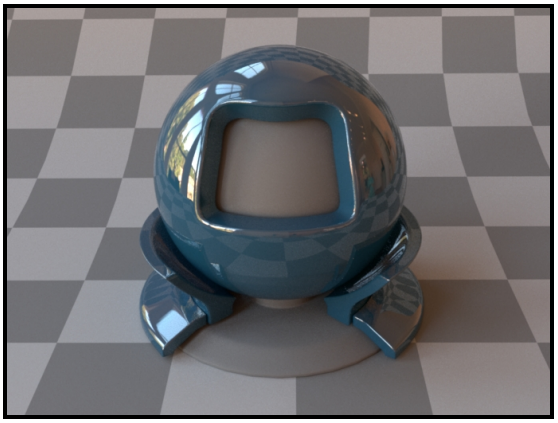
6.2.7. Smooth plastic material (`plastic`)



Parameter	Type	Description
`intIOR`	`float` or `string`	Interior index of refraction specified numerically or using a known material name. (Default: `polypropylene` / 1.49)
`extIOR`	`float` or `string`	Exterior index of refraction specified numerically or using a known material name. (Default: `air` / 1.000277)
`specular↙ Reflectance`	`spectrum` or `texture`	Optional factor used to modulate the specular component (Default: 1.0)
`diffuse↙ Reflectance`	`spectrum` or `texture`	Optional factor used to modulate the diffuse component (Default: 0.5)



(a) A rendering with the default parameters



(b) A rendering with custom parameters (Listing 15)

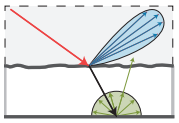
This plugin describes a perfectly smooth plastic-like dielectric material with internal scattering. The model interpolates between ideally specular and ideally diffuse reflection based on the Fresnel reflectance (i.e. it does so in a way that depends on the angle of incidence). Similar to the `dielectric` plugin, IOR values can either be specified numerically, or based on a list of known materials (see Table 1 for an overview).

Since it is very simple and fast, this model is often a better choice than the `phong`, `ward`, and `roughplastic` plugins when rendering very smooth plastic-like materials.

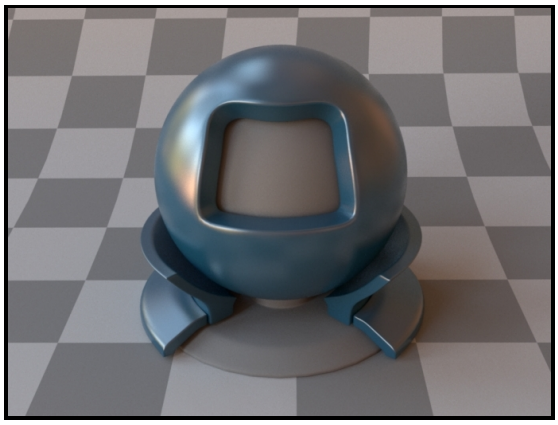
```
<bsdf type="plastic">
    <srgb name="diffuseReflectance" value="#18455c"/>
    <float name="intIOR" value="1.9"/>
</bsdf>
```

Listing 15: A shiny material whose diffuse reflectance is specified using sRGB

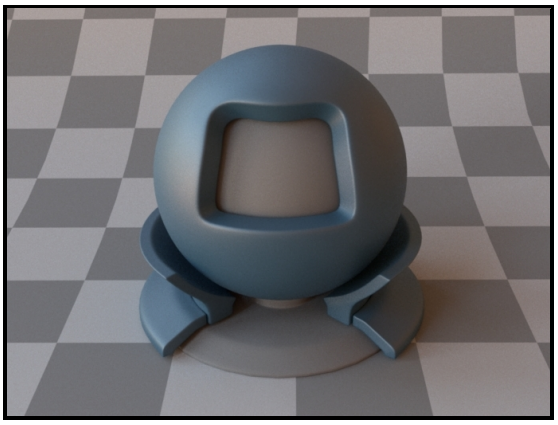
6.2.8. Rough plastic material (`roughplastic`)



Parameter	Type	Description
`distribution`	`string`	Specifies the type of microfacet normal distribution used to model the surface roughness. (i) `beckmann`: Physically-based distribution derived from Gaussian random surfaces. This is the default. (ii) `ggx`: New distribution proposed by Walter et al. [21], which is meant to better handle the long tails observed in measurements of ground surfaces. Renderings with this distribution may converge slowly. (iii) `phong`: Classical $\cos^p\theta$ distribution. Due to the underlying microfacet theory, the use of this distribution here leads to more realistic behavior than the separately available phong plugin.
`alpha`	`float`	Specifies the roughness of the unresolved surface microgeometry. When the Beckmann distribution is used, this parameter is equal to the *root mean square* (RMS) slope of the microfacets. (Default: 0.1).
`intIOR`	`float` or `string`	Interior index of refraction specified numerically or using a known material name. (Default: `polypropylene` / 1.49)
`extIOR`	`float` or `string`	Exterior index of refraction specified numerically or using a known material name. (Default: `air` / 1.000277)
`specular↙Reflectance`	`spectrum` or `texture`	Optional factor used to modulate the specular reflectance component (Default: 1.0)
`diffuse↙Reflectance`	`spectrum` or `texture`	Optional factor used to modulate the diffuse reflectance component (Default: 0.5)

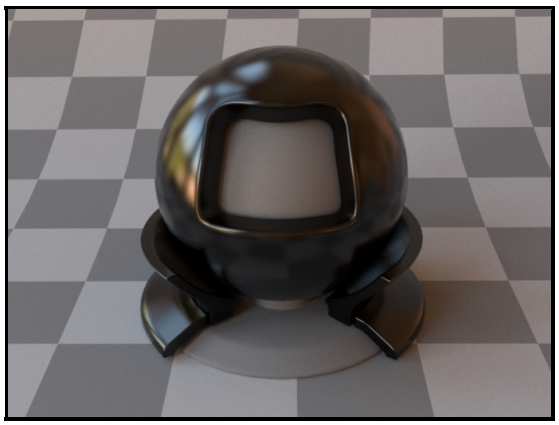


(a) Beckmann, $\alpha = 0.1$



(b) GGX, $\alpha = 0.3$

This plugin implements a realistic microfacet scattering model for rendering rough dielectric materials with internal scattering, such as plastic. It can be interpreted as a fancy version of the Cook-Torrance model and should be preferred over empirical models like phong and ward when possible.



(c) Beckmann, $\alpha = 0.05$, diffuseReflectance=0

Microfacet theory describes rough surfaces as an arrangement of unresolved and ideally specular facets, whose normal directions are given by a specially chosen *microfacet distribution*. By accounting for shadowing and masking effects between these facets, it is possible to reproduce the important off-specular reflections peaks observed in real-world measurements of such materials.

This plugin is essentially the "roughened" equivalent of the (smooth) plugin `plastic`. For very low values of α, the two will be very similar, though scenes using this plugin will take longer to render due to the additional computational burden of tracking surface roughness.

The model uses the integrated specular reflectance to interpolate between the specular and diffuse components (i.e. any light that is not scattered specularly is assumed to contribute to the diffuse component). Similar to the `dielectric` plugin, IOR values can either be specified numerically, or based on a list of known materials (see Table 1 for an overview).

The implementation is based on the paper "Microfacet Models for Refraction through Rough Surfaces" by Walter et al. [21]. It supports several different types of microfacet distributions. Note that the choices are a bit more restricted here—in comparison to other rough scattering models in Mitsuba, the roughness cannot be textured, and anisotropic microfacet distributions are not allowed.

When no parameters are given, the plugin activates the defaults, which describe a white polypropylene plastic material with a light amount of roughness modeled using the Beckmann distribution.

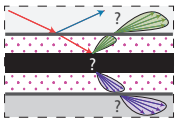
To get an intuition about the effect of the surface roughness parameter α, consider the following approximate differentiation: a value of $\alpha = 0.001 - 0.01$ corresponds to a material with slight imperfections on an otherwise smooth surface finish, $\alpha = 0.1$ is relatively rough, and $\alpha = 0.3 - 0.7$ is *extremely* rough (e.g. an etched or ground finish). Values significantly above that are probably not too realistic.

When rendering with the Phong microfacet distributions, a conversion is used to turn the specified α roughness value into the Phong exponent. This is done in a way, such that the different distributions all produce a similar appearance for the same value of α.

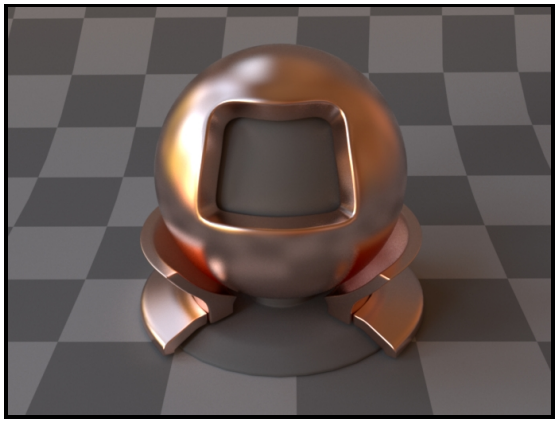
```
<bsdf type="roughplastic">
    <string name="distribution" value="beckmann"/>
    <float name="alpha" value="0.05"/>
    <float name="intIOR" value="1.61"/>
    <specturm name="diffuseReflectance" value="0"/>
</bsdf>
```

Listing 16: A material definition for rough, black laquer.

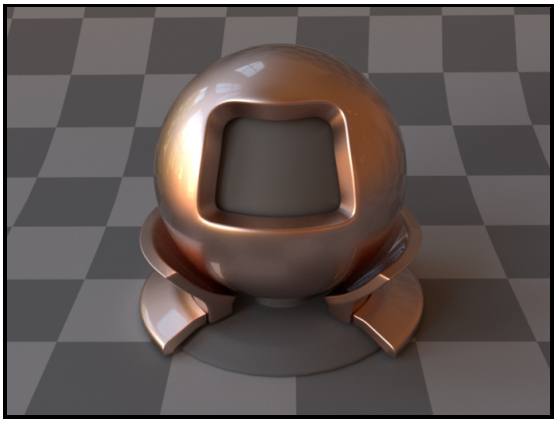
6.2.9. Smooth dielectric coating (`coating`)



Parameter	Type	Description
`intIOR`	`float` or `string`	Interior index of refraction specified numerically or using a known material name. (Default: `bk7` / 1.5046)
`extIOR`	`float` or `string`	Exterior index of refraction specified numerically or using a known material name. (Default: `air` / 1.000277)
`thickness`	`float`	Denotes the thickness of the layer (to model absorption — should be specified in inverse units of `sigmaA`) (Default: 1)
`sigmaA`	`spectrum` or `texture`	The absorption coefficient of the coating layer. (Default: 0, i.e. there is no absorption)
`(Nested plugin)`	`bsdf`	A nested BSDF model that should be coated.



(a) Rough copper

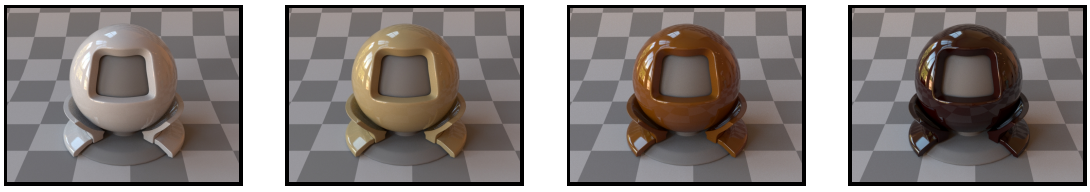


(b) The same material coated with a single layer of clear varnish (see Listing 17)

This plugin implements a smooth dielectric coating (e.g. a layer of varnish) in the style of the paper "Arbitrarily Layered Micro-Facet Surfaces" by Weidlich and Wilkie [23]. Any BSDF in Mitsuba can be coated using this plugin, and multiple coating layers can even be applied in sequence. This allows designing interesting custom materials like car paint or glazed metal foil. The coating layer can optionally be tinted (i.e. filled with an absorbing medium), in which case this model also accounts for the directionally dependent absorption within the layer.

Note that the plugin discards illumination that undergoes internal reflection within the coating. This can lead to a noticeable energy loss for materials that reflect much of their energy near or below the critical angle (i.e. diffuse or very rough materials). Therefore, users are discouraged to use this plugin to coat smooth diffuse materials, since there is a separately available plugin named `plastic`, which covers the same case and does not suffer from energy loss.

Evaluating the internal component of this model entails refracting the incident and exitant rays through the dielectric interface, followed by querying the nested material with this modified direction pair. The result is attenuated by the two Fresnel transmittances and the absorption, if any.

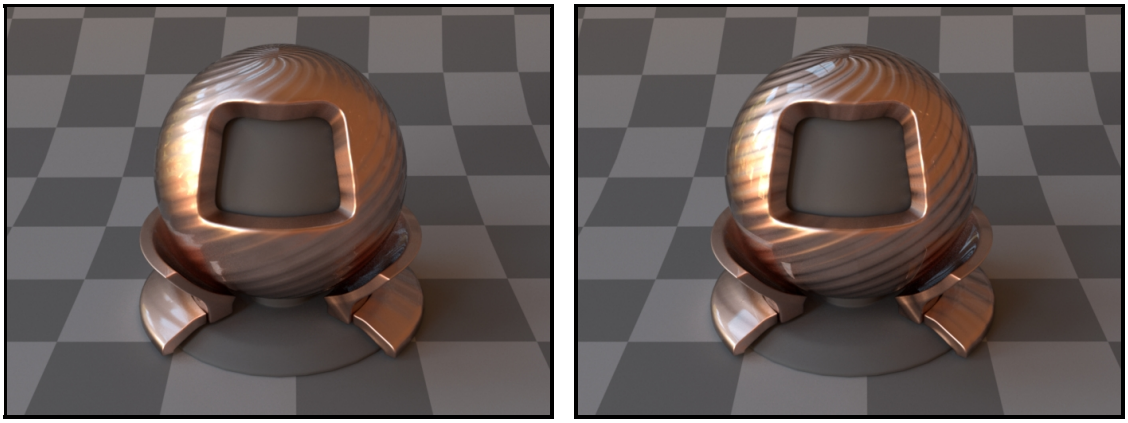


(a) `thickness` = 0 (b) `thickness` = 1 (c) `thickness` = 5 (d) `thickness` = 15

Figure 6: The effect of the layer thickness parameter on a tinted coating (`sigmaT` = (0.1, 0.2, 0.5))

```
<bsdf type="coating">
    <float name="intIOR" value="1.7"/>

    <bsdf type="roughconductor">
        <string name="material" value="Cu"/>
        <float name="alpha" value="0.1"/>
    </bsdf>
</bsdf>
```

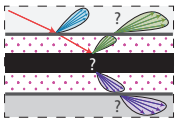
Listing 17: Rough copper coated with a transparent layer of varnish



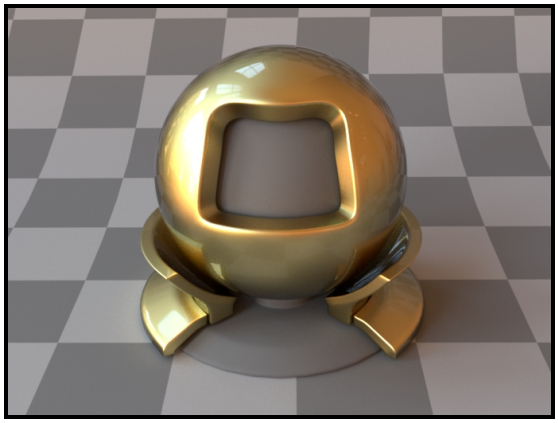
(a) Coated rough copper with a bump map applied on top (b) Bump mapped rough copper with a coating on top

Figure 7: Some interesting materials can be created simply by applying Mitsuba's material modifiers in different orders.

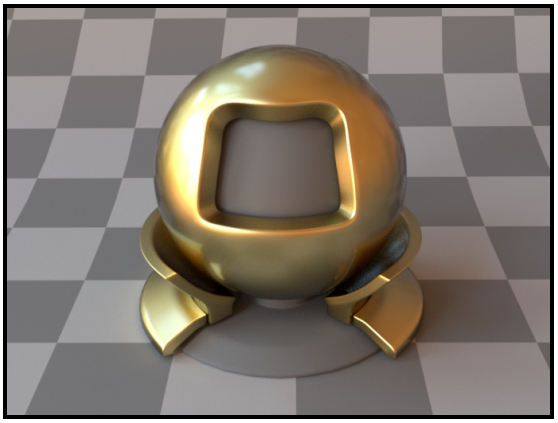
6.2.10. Rough dielectric coating (`roughcoating`)



Parameter	Type	Description
`distribution`	`string`	Specifies the type of microfacet normal distribution used to model the surface roughness. (i) `beckmann`: Physically-based distribution derived from Gaussian random surfaces. This is the default. (ii) `ggx`: New distribution proposed by Walter et al. [21], which is meant to better handle the long tails observed in measurements of ground surfaces. Renderings with this distribution may converge slowly. (iii) `phong`: Classical $\cos^p\theta$ distribution. Due to the underlying microfacet theory, the use of this distribution here leads to more realistic behavior than the separately available phong plugin.
`alpha`	`float`	Specifies the roughness of the unresolved surface microgeometry. When the Beckmann distribution is used, this parameter is equal to the *root mean square* (RMS) slope of the microfacets. (Default: 0.1).
`intIOR`	`float` or `string`	Interior index of refraction specified numerically or using a known material name. (Default: `bk7` / 1.5046)
`extIOR`	`float` or `string`	Exterior index of refraction specified numerically or using a known material name. (Default: `air` / 1.000277)
`sigmaA`	`spectrum` or `texture`	The absorption coefficient of the coating layer. (Default: 0, i.e. there is no absorption)
`(Nested plugin)`	`bsdf`	A nested BSDF model that should be coated.



(a) Rough gold coated with a *smooth* varnish layer



(b) Rough gold coated with a *rough* ($\alpha = 0.03$) varnish layer

This plugin implements a *very* approximate[11] model that simulates a rough dielectric coating. It is

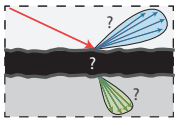
[11] The model only accounts for roughness in the specular reflection and Fresnel transmittance through the interface. The interior model receives incident illumination that is transformed *as if* the coating was smooth. While that's not quite correct, it is a convenient workaround when the `coating` plugin produces specular highlights that are too sharp.

essentially the roughened version of `coating`. Any BSDF in Mitsuba can be coated using this plugin, and multiple coating layers can even be applied in sequence. This allows designing interesting custom materials. The coating layer can optionally be tinted (i.e. filled with an absorbing medium), in which case this model also accounts for the directionally dependent absorption within the layer.

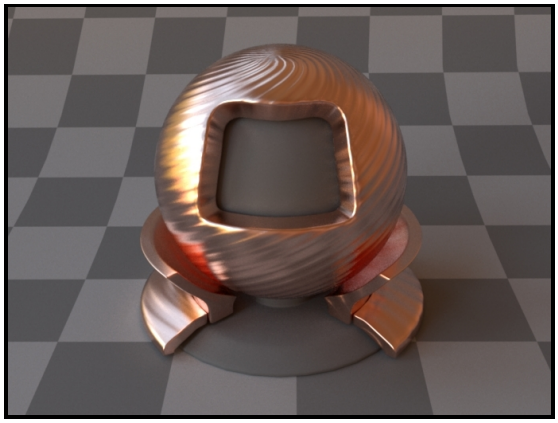
Note that the plugin discards illumination that undergoes internal reflection within the coating. This can lead to a noticeable energy loss for materials that reflect much of their energy near or below the critical angle (i.e. diffuse or very rough materials).

The implementation here is influenced by the paper "Arbitrarily Layered Micro-Facet Surfaces" by Weidlich and Wilkie [23].

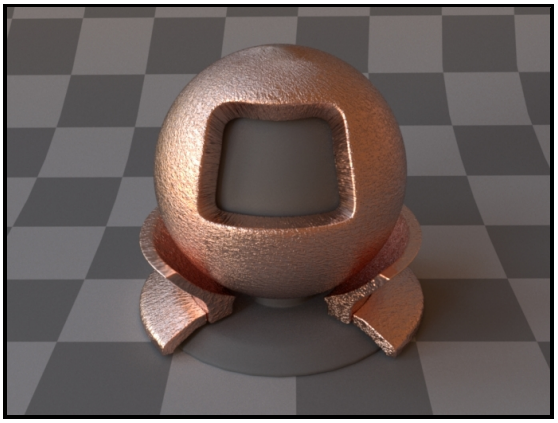
6.2.11. Bump map modifier (bump)



Parameter	Type	Description
(Nested plugin)	texture	The luminance of this texture specifies the amount of displacement. The implementation ignores any constant offset—only changes in the luminance matter.
(Nested plugin)	bsdf	A BSDF model that should be affected by the bump map



(a) Bump map based on tileable diagonal lines



(b) An irregular bump map

Bump mapping [2] is a simple technique for cheaply adding surface detail to a rendering. This is done by perturbing the shading coordinate frame based on a displacement height field provided as a texture. This method can lend objects a highly realistic and detailed appearance (e.g. wrinkled or covered by scratches and other imperfections) without requiring any changes to the input geometry.

The implementation in Mitsuba uses the common approach of ignoring the usually negligible texture-space derivative of the base mesh surface normal. As side effect of this decision, it is invariant to constant offsets in the height field texture—only variations in its luminance cause changes to the shading frame.

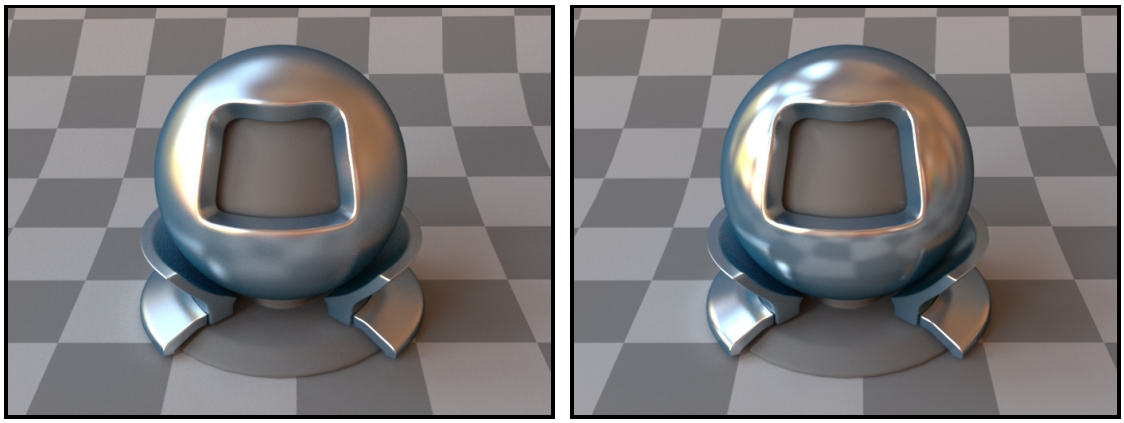
Note that the magnitude of the height field variations influences the strength of the displacement. If desired, the `scale` texture plugin can be used to magnify or reduce the effect of a bump map texture.

```
<bsdf type="bump">
    <!-- The bump map is applied to a rough metal BRDF -->
    <bsdf type="roughconductor"/>

    <texture type="scale">
        <!-- The scale of the displacement gets multiplied by 10x -->
        <float name="scale" value="10"/>

        <texture type="bitmap">
            <string name="filename" value="bumpmap.png"/>
        </texture>
    </texture>
</bsdf>
```

Listing 18: A rough metal model with a scaled image-based bump map

6.2.12. Modified Phong BRDF (phong)

Parameter	Type	Description
exponent	float or texture	Specifies the Phong exponent (Default: 30).
specular↙ Reflectance	spectrum or texture	Specifies the weight of the specular reflectance component. (Default: 0.2)
diffuse↙ Reflectance	spectrum or texture	Specifies the weight of the diffuse reflectance component (Default: 0.5)



(a) Exponent = 60 (b) Exponent = 300

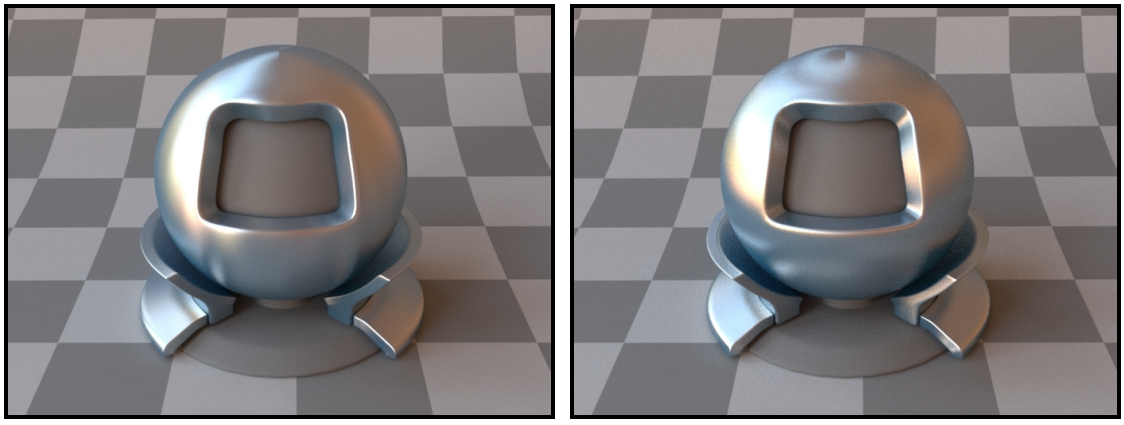
This plugin implements the modified Phong reflectance model as described in [15] and [11]. This empirical model is mainly included for historical reasons—its use in new scenes is discouraged, since significantly more realistic models have been developed since 1975.

If possible, it is recommended to switch to a BRDF that is based on microfacet theory and includes knowledge about the material's index of refraction. In Mitsuba, two good alternatives to phong are the plugins roughconductor and roughplastic (depending on the material type).

When using this plugin, note that the diffuse and specular reflectance components should add up to a value less than or equal to one (for each color channel). Otherwise, they will automatically be scaled appropriately to ensure energy conservation.

6.2.13. Anisotropic Ward BRDF (`ward`)

Parameter	Type	Description
`variant`	`string`	Determines the variant of the Ward model to use: (i) `ward`: The original model by Ward [22] — suffers from energy loss at grazing angles. (ii) `ward-duer`: Corrected Ward model with lower energy loss at grazing angles [3]. Does not always conserve energy. (iii) `balanced`: Improved version of the `ward-duer` model with energy balance at all angles [4].
`alphaU, alphaV`	`float` or `texture`	Specifies the anisotropic roughness values along the tangent and bitangent directions. (Default: 0.1).
`specular↙ Reflectance`	`spectrum` or `texture`	Specifies the weight of the specular reflectance component. (Default: 0.2)
`diffuse↙ Reflectance`	`spectrum` or `texture`	Specifies the weight of the diffuse reflectance component (Default: 0.5)



(a) $\alpha_u = 0.1,\ \alpha_v = 0.3$ (b) $\alpha_u = 0.3,\ \alpha_v = 0.1$

This plugin implements the anisotropic Ward reflectance model and several extensions. They are described in the papers

(i) "Measuring and Modeling Anisotropic Reflection" by Greg Ward [22]

(ii) "Notes on the Ward BRDF" by Bruce Walter [20]

(iii) "An Improved Normalization for the Ward Reflectance Model" by Arne Dür [3]

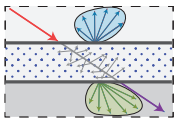
(iv) "A New Ward BRDF Model with Bounded Albedo" by Geisler-Moroder et al. [4]

Like the Phong BRDF, the Ward model does not take the Fresnel reflectance of the material into account. In an experimental study by Ngan et al. [12], the Ward model performed noticeably worse than models based on microfacets.

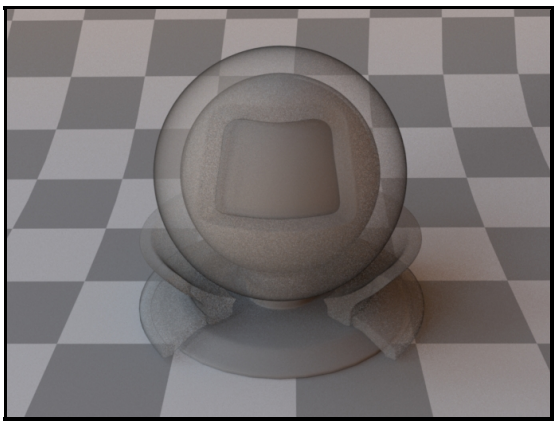
For this reason, it is usually preferable to switch to a microfacet model that incorporates knowledge about the material's index of refraction. In Mitsuba, two such alternatives to `ward` are given by the plugins `roughconductor` and `roughplastic` (depending on the material type).

When using this plugin, note that the diffuse and specular reflectance components should add up to a value less than or equal to one (for each color channel). Otherwise, they will automatically be scaled appropriately to ensure energy conservation.

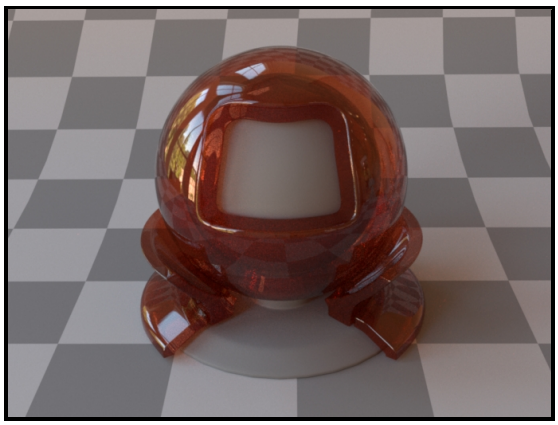
6.2.14. Hanrahan-Krueger BSDF (hk)



Parameter	Type	Description
material	string	Name of a material preset, see Table 3. (Default: skin1)
sigmaS	spectrum or texture	Specifies the scattering coefficient of the internal layer. (Default: based on material)
sigmaA	spectrum or texture	Specifies the absorption coefficient of the internal layer. (Default: based on material)
sigmaT & albedo	spectrum or texture	Optional: Alternatively, the scattering and absorption coefficients may also be specified using the extinction coefficient sigmaT and the single-scattering albedo. Note that only one of the parameter passing conventions can be used at a time (i.e. use either sigmaS&sigmaA *or* sigmaT&albedo)
thickness	float	Denotes the thickness of the layer. (should be specified in inverse units of sigmaA and sigmaS) (Default: 1)
(Nested plugin)	phase	A nested phase function instance that represents the type of scattering interactions occurring within the layer



(a) An index-matched scattering layer with parameters $\sigma_s = 2$, $\sigma_a = 0.1$, thickness= 0.1



(b) Example of the HK model with a dielectric coating (and the ketchup material preset, see Listing 19)

Figure 8: Renderings using the uncoated and coated form of the Hanrahan-Krueger model.

This plugin provides an implementation of the Hanrahan-Krueger BSDF [5] for simulating single scattering in thin index-matched layers filled with a random scattering medium. In addition, the implementation also accounts for attenuated light that passes through the medium without undergoing any scattering events.

This BSDF requires a phase function to model scattering interactions within the random medium. When no phase function is explicitly specified, it uses an isotropic one ($g = 0$) by default. A sample usage for instantiating the plugin is given on the next page:

```
<bsdf type="hk">
    <spectrum name="sigmaS" value="2"/>
    <spectrum name="sigmaA" value="0.1"/>
    <float name="thickness" value="0.1"/>

    <phase type="hg">
        <float name="g" value="0.8"/>
    </phase>
</bsdf>
```

When used in conjuction with the `coating` plugin, it is possible to model refraction and reflection at the layer boundaries when the indices of refraction are mismatched. The combination of these two plugins then reproduces the full model as it was originally proposed by Hanrahan and Krueger [5].

Note that this model does not account for light that undergoes multiple scattering events within the layer. This leads to energy loss, particularly at grazing angles, which can be seen in the left-hand image of Figure 8. A solution is to use the `sssbrdf` plugin, which adds an approximate multiple scattering component.

```
<bsdf type="coating">
    <float name="extIOR" value="1.0"/>
    <float name="intIOR" value="1.5"/>

    <bsdf type="hk">
        <string name="material" value="ketchup"/>
        <float name="thickness" value="0.01"/>
    </bsdf>
</bsdf>
```

Listing 19: A thin dielectric layer with measured ketchup scattering parameters

Note that when `sigmaS` = `sigmaA` = 0, or when `thickness=0`, any geometry associated with this BSDF becomes invisible, as light will pass through unchanged.

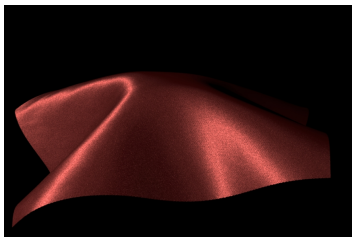
The implementation in Mitsuba is based on code by Tom Kazimiers and Marios Papas. Marios Papas has kindly verified the implementation of the coated and uncoated variants against both a path tracer and a separate reference implementation.

6.2.15. Irawan & Marschner woven cloth BRDF (`irawan`)

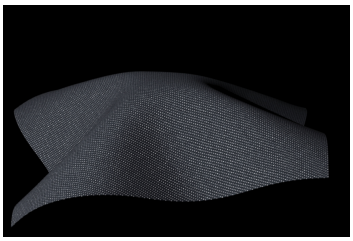
Parameter	Type	Description
`filename`	`string`	Path to a weave pattern description
`repeatU, repeatV`	`float`	Specifies the number of weave pattern repetitions over a $[0,1]^2$ region of the UV parameterization
`ksFactor`	`float`	Multiplicative factor of the specular component
`kdFactor`	`float`	Multiplicative factor of the diffuse component

This plugin implements the Irawan & Marschner BRDF, a realistic model for rendering woven materials. This spatially-varying reflectance model uses an explicit description of the underlying weave pattern to create fine-scale texture and realistic reflections across a wide range of different weave types. To use the model, you must provide a special weave pattern file—for an example of what these look like, see the examples scenes available on the Mitsuba website.

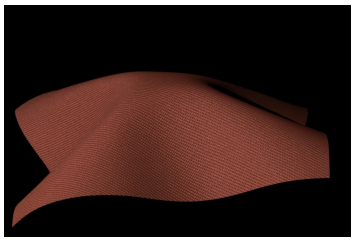
A detailed explanation of the model is beyond the scope of this manual. For reference, it is described in detail in the PhD thesis of Piti Irawan ("The Appearance of Woven Cloth" [7]). The code in Mitsuba a modified port of a previous Java implementation by Piti, which has been extended with a simple domain-specific weave pattern description language.



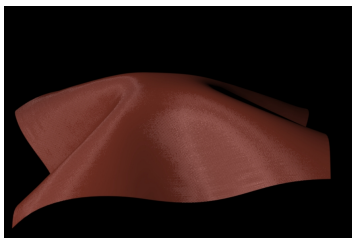
(a) Silk charmeuse



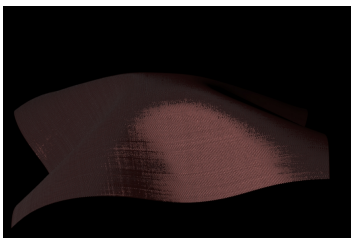
(b) Cotton denim



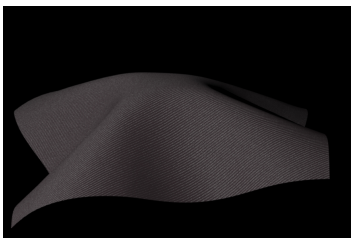
(c) Wool gabardine



(d) Polyester lining cloth



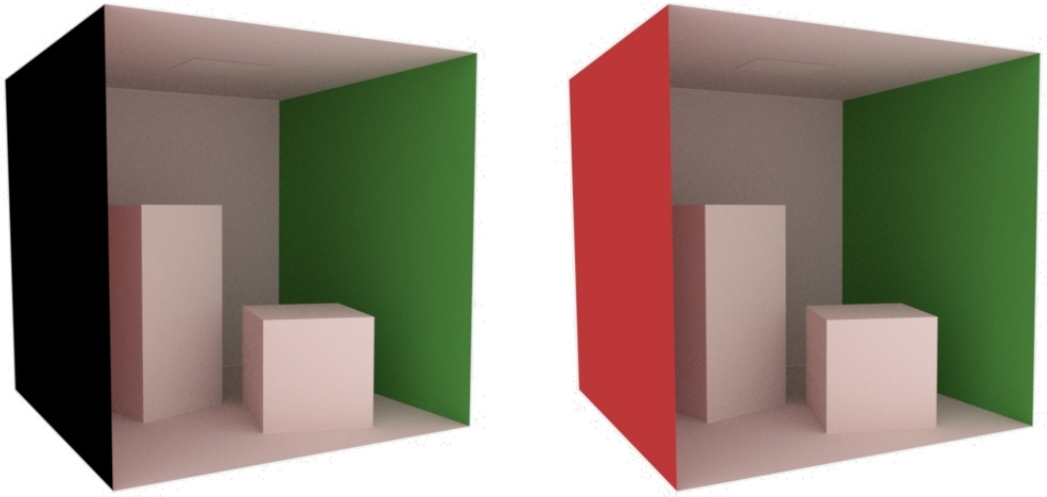
(e) Silk shantung



(f) Cotton twill

6.2.16. Two-sided BRDF adapter (`twosided`)

Parameter	Type	Description
(Nested plugin)	bsdf	A nested BRDF that should be turned into a two-sided scattering model.



(a) From this angle, the Cornell box scene shows visible back-facing geometry

(b) Applying the `twosided` plugin fixes the rendering

By default, all non-transmissive scattering models in Mitsuba are *one-sided* — in other words, they absorb all light that is received on the interior-facing side of any associated surfaces. Holes and visible back-facing parts are thus exposed as black regions.

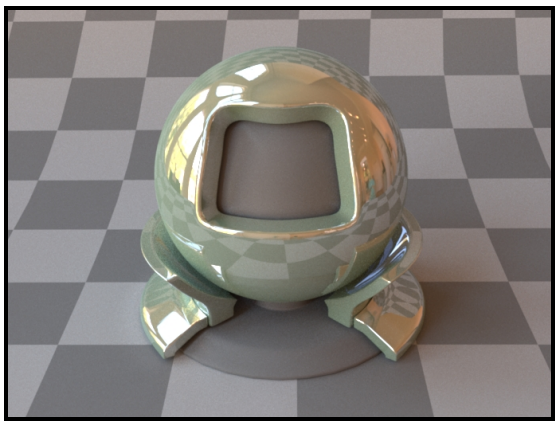
Usually, this is a good idea, since it will reveal modeling issues early on. But sometimes one is forced to deal with improperly closed geometry, where the one-sided behavior is bothersome. In that case, this plugin can be used to turn one-sided scattering models into proper two-sided versions of themselves. The plugin has no parameters other than a required nested BSDF specification.

```
<bsdf type="twosided">
    <bsdf type="diffuse">
        <spectrum name="reflectance" value="0.4"/>
    </bsdf>
</bsdf>
```

Listing 20: A two-sided diffuse material

6.2.17. Mixture material (`mixturebsdf`)

Parameter	Type	Description
`weights`	`string`	A comma-separated list of BSDF weights
(Nested plugin)	`bsdf`	Multiple BSDF instances that should be mixed according to the specified weights



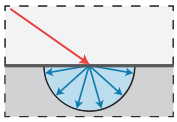
(a) An admittedly not particularly realistic linear combination of diffuse and specular BSDFs (Listing 21)

This plugin implements a "mixture" material, which represents linear combinations of multiple BSDF instances. Any surface scattering model in Mitsuba (be it smooth, rough, reflecting, or transmitting) can be mixed with others in this manner to synthesize new models. There is no limit on how many models can be mixed, but their combination weights must be non-negative and sum to a value of one or less to ensure energy balance.

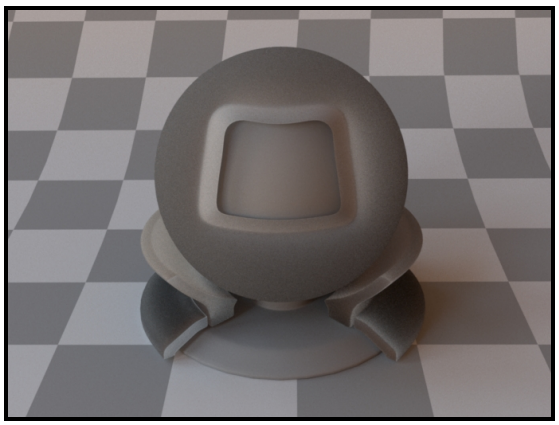
```
<bsdf type="mixturebsdf">
    <string name="weights" value="0.7, 0.2"/>

    <bsdf type="conductor">
        <string name="material" value="Cr"/>
    </bsdf>

    <bsdf type="roughdiffuse">
        <rgb name="reflectance" value=".7 1 .7"/>
        <float name="alpha" value="0.4"/>
    </bsdf>
</bsdf>
```

Listing 21: A material definition for a mixture of 70% smooth chromium, 20% of a greenish rough diffuse material (and 10% absorption)

6.2.18. Diffuse transmitter (`difftrans`)



Parameter	Type	Description
`transmittance`	`spectrum` or `texture`	Specifies the diffuse transmittance of the material (Default: 0.5)



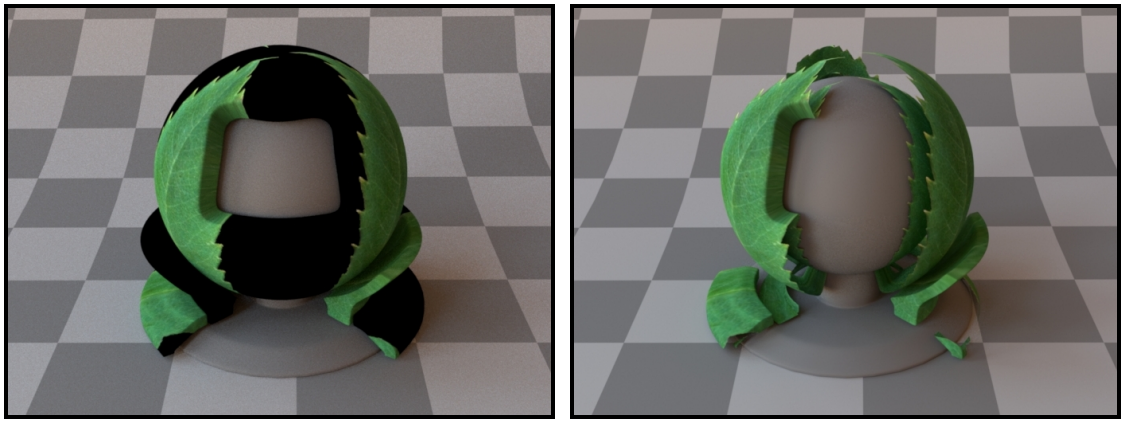
(a) The model with default parameters

This BSDF models a non-reflective material, where any entering light loses its directionality and is diffusely scattered from the other side. This model can be combined[12] with a surface reflection model to describe translucent substances that have internal multiple scattering processes (e.g. plant leaves).

[12] For instance using the `mixturebsdf` plugin.

6.2.19. Opacity mask (`mask`)

Parameter	Type	Description
`opacity`	`spectrum` or `texture`	Specifies the per-channel opacity (where 1 = completely opaque) (Default: 0.5).
(Nested plugin)	`bsdf`	A base BSDF model that represents the non-transparent portion of the scattering



(a) Rendering without an opacity mask (b) Rendering *with* an opacity mask (Listing 22)

This plugin applies an opacity mask to add nested BSDF instance. It interpolates between perfectly transparent and completely opaque based on the `opacity` parameter.

The transparency is implemented as a forward-facing Dirac delta distribution.

```
<bsdf type="mask">
    <!-- Base material: a two-sided textured diffuse BSDF -->
    <bsdf type="twosided">
        <bsdf type="diffuse">
            <texture name="reflectance" type="bitmap">
                <string name="filename" value="leaf.jpg"/>
            </texture>
        </bsdf>
    </bsdf>

    <!-- Fetch the opacity mask from a bitmap -->
    <texture name="opacity" type="bitmap">
        <string name="filename" value="leaf_opacity.jpg"/>
        <float name="gamma" value="1"/>
    </texture>
</bsdf>
```

Listing 22: Material configuration for a transparent leaf

6.2.20. Subsurface scattering BRDF (`sssbrdf`)

Parameter	Type	Description
`material`	`string`	Name of a material preset, see Table 3. (Default: `skin1`)
`sigmaS`	`spectrum` or `texture`	Specifies the scattering coefficient of the layer. (Default: based on `material`)
`sigmaA`	`spectrum` or `texture`	Specifies the absorption coefficient of the layer. (Default: based on `material`)
`sigmaT & albedo`	`spectrum` or `texture`	Optional: Alternatively, the scattering and absorption coefficients may also be specified using the extinction coefficient `sigmaT` and the single-scattering albedo. Note that only one of the parameter passing conventions can be used at a time (i.e. use either `sigmaS&sigmaA` *or* `sigmaT&albedo`)
`intIOR`	`float` or `string`	Interior index of refraction specified numerically or using a known material name. (Default: based on `material`)
`extIOR`	`float` or `string`	Exterior index of refraction specified numerically or using a known material name. (Default: `air` / 1.000277)
`g`	`float` or `string`	Specifies the phase function anisotropy — see the `hg` plugin for details (Default: 0, i.e. isotropic)
`alpha`	`float`	Specifies the roughness of the unresolved surface microgeometry. (Default: 0.0, i.e. the surface has a smooth finish)

This plugin implements a BRDF scattering model that emulates interactions with a participating medium embedded inside a dielectric layer. By approximating these events using a BRDF, any scattered illumination is assumed to exit the material *directly* at the original point of incidence. To account for internal light transport with *different* incident and exitant positions, please refer to Sections 6.5 and 6.4.

Internally, the model is implemented by instantiating a Hanrahan-Krueger BSDF for single scattering in an infinitely thick layer together with an approximate multiple scattering component based on Jensen's [9] integrated dipole BRDF. These are then embedded into a dielectric layer using either the `coating` or `roughcoating` plugins depending on whether or not `alpha`=0. This yields a very convenient parameterization of a scattering model that behaves similarly to a coated diffuse material, but expressed in terms of the scattering and absorption coefficients `sigmaS` and `sigmaA`.

6.3. Textures

The following section describes the available texture sources. In Mitsuba, textures are objects that can be attached to scattering model parameters supporting the "`texture`" type (see Section 6.2 for examples).

6.3.1. Vertex color passthrough texture (`vertexcolors`)

When rendering with a mesh that contains vertex colors, this plugin exposes the underlying color data as a texture. Currently, this is only supported by the PLY file format loader.

Here is an example:

```
<shape type="ply">
    <string name="filename" value="mesh.ply"/>

    <bsdf type="diffuse">
        <texture type="vertexcolors" name="reflectance"/>
    </bsdf>
</shape>
```

Listing 23: Rendering a PLY file with vertex colors

6.3.2. Bitmap texture (`bitmap`)

Parameter	Type	Description
`filename`	`string`	Filename of the bitmap to be loaded
`gamma`	`float`	Gamma value of the source bitmap file (Default: *automatic*, i.e. linear for EXR input, and sRGB for everything else.)
`filterType`	`string`	Specifies the texture filtering that should be used for lookups (i) `ewa`: Elliptically weighted average (a.k.a. anisotropic filtering). This produces the best quality (ii) `trilinear`: Simple trilinear (isotropic) filtering. (iii) `none`: No filtering, do nearest neighbor lookups. Default: `ewa`.
`wrapMode`	`string`	This parameter defines the behavior of the texture outside of the $[0,1]$ *uv* range. (i) `repeat`: Repeat the texture (i.e. *uv* coordinates are taken modulo 2) (ii) `clamp`: Clamp *uv* coordinates to $[0,1]$ (iii) `black`: Switch to a zero-valued texture (iv) `white`: Switch to a one-valued texture Default: `repeat`.
`maxAnisotropy`	`float`	Specifies an upper limit on the amount of anisotropy of `ewa` lookups (Default: 8)
`uscale, vscale`	`float`	Multiplicative factors that should be applied to UV values before a lookup
`uoffset, voffset`	`float`	Numerical offset that should be applied to UV values before a lookup

This plugin implements a bitmap-based texture, which supports the following file formats:

- OpenEXR
- JPEG
- PNG (Portable Network Graphics)
- TGA (Targa)
- BMP (Windows bitmaps)

The plugin internally converts all bitmap data into a *linear* space to ensure a proper workflow.

6.3.3. Procedural grid texture (`gridtexture`)

Parameter	Type	Description
`color0`	`spectrum`	Color values of the background (Default: 0.2)
`color1`	`spectrum`	Color value of the lines (Default: 0.4)
`lineWidth`	`float`	Width of the grid lines in UV space (Default: 0.01)
`uscale, vscale`	`float`	Multiplicative factors that should be applied to UV values before a lookup
`uoffset, voffset`	`float`	Numerical offset that should be applied to UV values before a lookup

This plugin implements a simple procedural grid texture.

6.3.4. Checkerboard (`checkerboard`)

Parameter	Type	Description
`color0, color1`	`spectrum`	Color values for the two differently-colored patches (Default: 0.4 and 0.2)
`uscale, vscale`	`float`	Multiplicative factors that should be applied to UV values before a lookup
`uoffset, voffset`	`float`	Numerical offset that should be applied to UV values before a lookup

This plugin implements a simple procedural checkerboard texture.

6.4. Subsurface scattering

TBD

6.5. Participating media

TBD

6.5.1. Heterogeneous participating medium (`heterogeneous`)

Parameter	Type	Description
`method`	`string`	Specifies the sampling method that is used to generate scattering events within the medium. (i) `simpson`: Sampling is done by inverting a deterministic quadrature rule based on composite Simpson integration over small ray segments. (ii) `woodcock`: Generate samples using Woodcock tracking. This is usually faster and guaranteed to be unbiased, but has the disadvantage of not providing certain information that is required by bidirectional rendering techniques. Default: `woodcock`
`density`	`volume`	Volumetric data source that supplies the medium densities (in inverse scene units)
`albedo`	`volume`	Volumetric data source that supplies the single-scattering albedo
`orientation`	`volume`	Optional: volumetric data source that supplies the local particle orientations throughout the medium
`densityMultiplier`	`float`	Optional multiplier that will be applied to the `density` parameter. Provided for convenience when accomodating data based on different units, or to simply tweak the density of the medium. (Default: 1)
(Nested plugin)	`phase`	A nested phase function that describes the directional scattering properties of the medium. When none is specified, the renderer will automatically use an instance of `isotropic`.

This plugin provides a flexible heterogeneous medium implementation, which acquires its data from nested `volume` instances. These can be constant, use a procedural function, or fetch data from disk, e.g. using a memory-mapped density grid. See Section 6.7 for details.

Instead of allowing separate volumes to be provided for the scattering absorption parameters `sigmaS` and `sigmaA` (as is done in `homogeneous`, this class instead takes the approach of enforcing a spectrally uniform value of `sigmaT`, which must be provided using a nested scalar-valued volume named `density`.

Another nested spectrum-valued `albedo` volume must also be provided, which is used to compute the scattering coefficient σ_s using the expression σ_s = `density` $*$ `albedo` (i.e. 'albedo' contains the single-scattering albedo of the medium.

Optionally, one can also provide an vector-valued `orientation` volume, which contains local particle orientation that will be passed to scattering models that support this, such as a the Microflake or Kajiya-Kay phase functions.

6.5.2. Homogeneous participating medium (homogeneous)

Parameter	Type	Description
material	string	Name of a material preset, see Table 3. (Default: skin1)
sigmaA, sigmaS	spectrum	Absorption and scattering coefficients of the medium in inverse scene units. These parameters are mutually exclusive with sigmaT and albedo (Default: configured based on material)
sigmaT, albedo	spectrum	Extinction coefficient in inverse scene units and a (unitless) single-scattering albedo. These parameters are mutually exclusive with sigmaA and sigmaS (Default: configured based on material)
densityMultiplier	float	Optional multiplier that will be applied to the sigma* parameters. Provided for convenience when accomodating data based on different units, or to simply tweak the density of the medium. (Default: 1)
(Nested plugin)	phase	A nested phase function that describes the directional scattering properties of the medium. When none is specified, the renderer will automatically use an instance of isotropic.

This class implements a flexible homogeneous participating medium with support for arbitrary phase functions and various medium sampling methods. It provides several ways of configuring the medium properties. Either, a material preset can be loaded using the material parameter—see Table 3 for details. Alternatively, when specifying parameters by hand, they can either be provided using the scattering and absorption coefficients, or by declaring the extinction coefficient and single scattering albedo (whichever is more convenient). Mixing these parameter initialization methods is not allowed.

All scattering parameters (named sigma*) should be provided in inverse scene units. For instance, when a world-space distance of 1 unit corresponds to a meter, the scattering coefficents should have units of inverse meters. For convenience, the densityMultiplier parameter can be used to correct the units. For instance, when the scene is in meters and the coefficients are in inverse millimeters, set densityMultiplier to 1000.

```
<medium id="myMedium" type="homogeneous">
    <spectrum name="sigmaS" value="1"/>
    <spectrum name="sigmaA" value="0.05"/>

    <phase type="hg">
        <float name="g" value="0.7"/>
    </phase>
</medium>
```

Listing 24: Declaration of a forward scattering medium with high albedo

Note: Rendering media that have a spectrally varying extinction coefficient can be tricky, since all commonly used medium sampling methods suffer from high variance in that case. Here, it may often make more sense to render several monochromatic images separately (using only the coefficients for

a single channel) and then merge them back into a RGB image. There is a `mtsutil` (Section 4.4) plugin named `joinrgb` that will perform this RGB merging process.

Name	Name
apple	potato
chicken1	skimmilk
chicken2	skin1
cream	skin2
ketchup	spectralon
marble	wholemilk

Table 3: This table lists all supported medium material presets. The values are from Jensen et al. [9] using units of $\frac{1}{mm}$, so remember to set `densityMultiplier` appropriately when your scene is not in units of millimeters. These material names can be used with the plugins `homogeneous`, `dipole`, `hk`, and `sssbrdf`.

6.6. Phase functions

This section contains a description of all implemented medium scattering models, which are also known as *phase functions*. These are very similar in principle to surface scattering models (or *BSDF*s), and essentially describe where light travels after hitting a particle within the medium.

The most commonly used models for smoke, fog, and other homogeneous media are isotropic scattering (`isotropic`) and the Henyey-Greenstein phase function (`hg`). Mitsuba also supports *anisotropic* media, where the behavior of the medium changes depending on the direction of light propagation (e.g. in volumetric representations of fabric). These are the Kajiya-Kay (`kkay`) and Microflake (`microflake`) models.

Finally, there is also a phase function for simulating scattering in planetary atmospheres (`rayleigh`).

6.6.1. Isotropic phase function (`isotropic`)

(a) Isotropic (b) Anisotropic micro-flakes

Figure 9: Heterogeneous volume renderings of a scarf model with isotropic and anisotropic phase functions.

This phase function simulates completely uniform scattering, where all directionality is lost after a single scattering interaction. It does not have any parameters.

6.6.2. Henyey-Greenstein phase function (`hg`)

Parameter	Type	Description
`g`	`float`	This parameter must be somewhere in the range −1 to 1 (but not equal to −1 or 1). It denotes the *mean cosine* of scattering interactions. A value greater than zero indicates that medium interactions predominantly scatter incident light into a similar direction (i.e. the medium is *forward-scattering*), whereas values smaller than zero cause the medium to be scatter more light in the opposite direction.

This plugin implements the phase function model proposed by Henyey and Greenstein [6]. It is parameterizable from backward- ($g < 0$) through isotropic- ($g = 0$) to forward ($g > 0$) scattering.

6.6.3. Rayleigh phase function (`rayleigh`)

Scattering by particles that are much smaller than the wavelength of light (e.g. individual molecules in the atmosphere) is well-approximated by the Rayleigh phase function. This plugin implements an unpolarized version of this scattering model (i.e the effects of polarization are ignored). This plugin is useful for simulating scattering in planetary atmospheres.

This model has no parameters.

6.6.4. Kajiya-Kay phase function (kkay)

This plugin implements the Kajiya-Kay [10] phase function for volumetric rendering of fibers, e.g. hair or cloth.

The function is normalized so that it has no energy loss when ş=1 and illumination arrives perpendicularly to the surface.

6.6.5. Micro-flake phase function (`microflake`)

Parameter	Type	Description
`stddev`	`float`	Standard deviation of the micro-flake normals. This specifies the roughness of the fibers in the medium.

(a) `stddev=0.2` (b) `stddev=0.05`

This plugin implements the anisotropic micro-flake phase function described in "A radiative transfer framework for rendering materials with anisotropic structure" by Wenzel Jakob, Adam Arbree, Jonathan T. Moon, Kavita Bala, and Steve Marschner [8].

The implementation in this plugin is specific to rough fibers and uses a Gaussian-type flake distribution. It is much faster than the spherical harmonics approach proposed in the original paper. This distribution, as well as the implemented sampling method, are described in the paper "Building Volumetric Appearance Models of Fabric using Micro CT Imaging" by Shuang Zhao, Wenzel Jakob, Steve Marschner, and Kavita Bala [24].

Note: this phase function must be used with a medium that specifies the local fiber orientation at different points in space. Please refer to `heterogeneous` for details.

6.6.6. Mixture phase function (`mixturephase`)

Parameter	Type	Description
`weights`	`string`	A comma-separated list of phase function weights
`(Nested plugin)`	`phase`	Multiple phase function instances that should be mixed according to the specified weights

This plugin implements a "mixture" scattering model, which represents linear combinations of multiple phase functions. There is no limit on how many phase function can be mixed, but their combination weights must be non-negative and sum to a value of one or less to ensure energy balance.

6.7. Volume data sources

This section covers the different types of volume data sources included with Mitsuba. These plugins are intended to be used together with the `heterogeneous` medium plugin and provide three-dimensional spatially varying density, albedo, and orientation fields.

6.7.1. Grid-based volume data source (`gridvolume`)

Parameter	Type	Description
`filename`	`string`	Specifies the filename of the volume data file to be loaded
`sendData`	`boolean`	When this parameter is set to `true`, the implementation will send all volume data to other network render nodes. Otherwise, they are expected to have access to an identical volume data file that can be mapped into memory. (Default: `false`)
`toWorld`	`transform`	Optional linear transformation that should be applied to the data
`min, max`	`point`	Optional parameter that can be used to re-scale the data so that it lies in the bounding box between `min` and `max`.

This class implements access to memory-mapped volume data stored on a 3D grid using a simple binary exchange format. The format uses a little endian encoding and is specified as follows:

Position	Content
Bytes 1-3	ASCII Bytes 'V', '0', and 'L'
Byte 4	File format version number (currently 3)
Bytes 5-8	Encoding identifier (32-bit integer). The following choices are available: 1. Dense `float32`-based representation 2. Dense `float16`-based representation (*currently not supported by this implementation*) 3. Dense `uint8`-based representation (The range 0..255 will be mapped to 0..1) 4. Dense quantized directions. The directions are stored in spherical coordinates with a total storage cost of 16 bit per entry.
Bytes 9-12	Number of cells along the X axis (32 bit integer)
Bytes 13-16	Number of cells along the Y axis (32 bit integer)
Bytes 17-20	Number of cells along the Z axis (32 bit integer)
Bytes 21-24	Number of channels (32 bit integer, supported values: 1 or 3)
Bytes 25-48	Axis-aligned bounding box of the data stored in single precision (order: xmin, ymin, zmin, xmax, ymax, zmax)
Bytes 49-*	Binary data of the volume stored in the specified encoding. The data are ordered so that the following C-style indexing operation makes sense after the file has been mapped into memory: `data[((zpos*yres + ypos)*xres + xpos)*channels + chan]` where `(xpos, ypos, zpos, chan)` denotes the lookup location.

Note that Mitsuba expects that entries in direction volumes are either zero or valid unit vectors.

When using this data source to represent floating point density volumes, please ensure that the values are all normalized to lie in the range $[0,1]$—otherwise, the Woocock-Tracking integration method in `heterogeneous` will produce incorrect results.

6.7.2. Caching volume data source (`volcache`)

Parameter	Type	Description
`blockSize`	`integer`	Size of the individual cache blocks (Default: 8, i.e. $8 \times 8 \times 8$)
`voxelWidth`	`float`	Width of a voxel (in a cache block) expressed in world-space units. (Default: set to the ray marching step size of the nested medium)
`memoryLimit`	`integer`	Maximum allowed memory usage in MiB. (Default: 1024, i.e. 1 GiB)
`toWorld`	`transform`	Optional linear transformation that should be applied to the volume data
`(Nested plugin)`	`volume`	A nested volume data source

This plugin can be added between the renderer and another data source, for which it caches all data lookups using a LRU scheme. This is useful when the nested volume data source is expensive to evaluate.

The cache works by performing on-demand rasterization of subregions of the nested volume into blocks ($8 \times 8 \times 8$ by default). These are kept in memory until a user-specifiable threshold is exeeded, after which point a *least recently used* (LRU) policy removes records that haven't been accessed in a long time.

6.7.3. Constant-valued volume data source (`constvolume`)

Parameter	Type	Description
`value`	`float` or `spectrum` or `vector`	Specifies the value of the volume

This plugin provides a volume data source that is constant throughout its domain. Depending on how it is used, its value can either be a scalar, a color spectrum, or a 3D vector.

```
<medium type="heterogeneous">
    <volume type="constvolume" name="density">
        <float name="value" value="1"/>
    </volume>
    <volume type="constvolume" name="albedo">
        <rgb name="value" value="0.9 0.9 0.7"/>
    </volume>
    <volume type="constvolume" name="orientation">
        <vector name="value" x="0" y="1" z="0"/>
    </volume>

    <!-- .... remaining parameters for
         the 'heterogeneous' plugin .... -->
</medium>
```

Listing 25: Definition of a heterogeneous medium with homogeneous contents

6.8. Luminaires

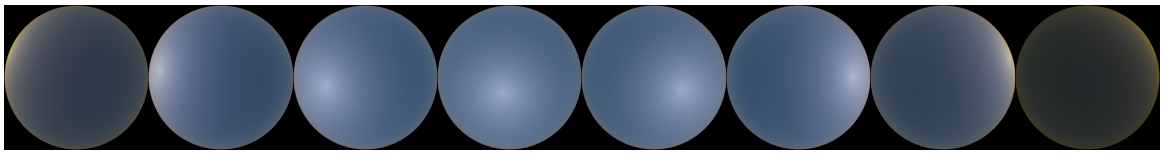
TBD

6.8.1. Sun luminaire (sun)

Parameter	Type	Description
turbidity	float	This parameter determines the amount of scattering particles (or 'haze') in the atmosphere. Smaller values (~ 2) produce a clear blue sky, larger values (~ 8) lead to an overcast sky, and a very high values (~ 20) cause a color shift towards orange and red. (Default: 3)
day	integer	Solar day used to compute the sun's position. Must be in the range between 1 and 365. (Default: 180)
time	float	Fractional time used to compute the sun's position. A time of 4:15 PM corresponds to 16.25. (Default: 15.00)
latitude, longitude	float	These two parameters specify the oberver's latitude and longitude in degrees, which are required to compute the sun's position. (Default: 35.6894, 139.6917 — Tokyo, Japan)
standardMeridian	integer	Denotes the standard meridian of the time zone for finding the sun's position (Default: 135 — Japan standard time)
sunDirection	vector	Allows to manually override the sun direction in world space. When this value is provided, parameters pertaining to the computation of the sun direction (day, time, latitude, longitude, and standardMeridian) are unnecessary. (Default: none)
resolution	integer	Specifies the resolution of the precomputed image that is used to represent the sun environment map (Default: 256)
sunScale	float	This parameter can be used to scale the the amount of illumination emitted by the sun luminaire, for instance to change its units. To switch from photometric ($W/m^2 \cdot sr$) to arbitrary but convenient units in the $[0,1]$ range, set this parameter to 1e-5. (Default: 1)

6.8.2. Skylight luminaire (`sky`)

Parameter	Type	Description
`turbidity`	`float`	This parameter determines the amount of scattering particles (or 'haze') in the atmosphere. Smaller values (~ 2) produce a clear blue sky, larger values (~ 8) lead to an overcast sky, and a very high values (~ 20) cause a color shift towards orange and red. (Default: 3)
`day`	`integer`	Solar day used to compute the sun's position. Must be in the range between 1 and 365. (Default: 180)
`time`	`float`	Fractional time used to compute the sun's position. A time of 4:15 PM corresponds to 16.25. (Default: 15.00)
`latitude`, `longitude`	`float`	These two parameters specify the oberver's latitude and longitude in degrees, which are required to compute the sun's position. (Default: 35.6894, 139.6917 — Tokyo, Japan)
`standardMeridian`	`integer`	Denotes the standard meridian of the time zone for finding the sun's position (Default: 135 — Japan standard time)
`sunDirection`	`vector`	Allows to manually override the sun direction in world space. When this value is provided, parameters pertaining to the computation of the sun direction (`day`, `time`, `latitude`, `longitude`, and `standardMeridian`) are unnecessary. (Default: none)
`extend`	`boolean`	Extend luminaire below the horizon? (Default: `false`)
`resolution`	`integer`	Specifies the resolution of the precomputed image that is used to represent the sky environment map (Default: 256)
`skyScale`	`float`	This parameter can be used to scale the the amount of illumination emitted by the sky luminaire, for instance to change its units. To switch from photometric ($W/m^2 \cdot sr$) to arbitrary but convenient units in the $[0,1]$ range, set this parameter to `1e-5`. (Default: 1)

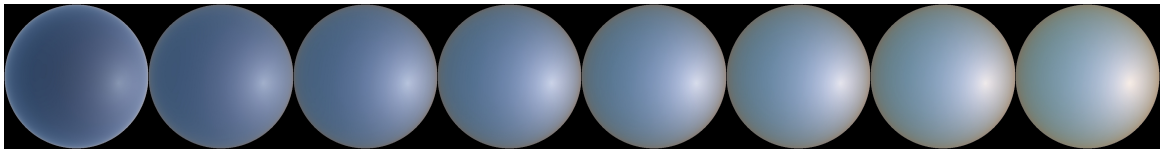


(a) 6AM (b) 8AM (c) 10AM (d) 12PM (e) 2PM (f) 4PM (g) 6PM (h) 8PM

Figure 10: Time series with the default settings (shown by projecting the sky onto a disk. East is left.)

This plugin implements the physically-based skylight model proposed by Preetham et al. [16]. It can be used for realistic daylight renderings of scenes under clear and overcast skies, assuming that the sky is observed from a position either on or close to the surface of the earth.

Numerous parameters allow changing the both the position on Earth, as well as the time of observation. These are used to compute the sun direction which, together with `turbidity`, constitutes the main parameter of the model. If desired, the sun direction can also be specified manually.



(a) 2 (b) 3 (c) 4 (d) 5 (e) 6 (f) 7 (g) 8 (h) 9

Figure 11: Sky light for different turbidity values (fixed time & location)

Turbidity, the other important parameter, specifies the amount of atmospheric extinction due to larger particles (t_l), as opposed to molecules (t_m). Lower values correspond to a clear sky, and higher values produce illumination resembling that of a hazy, overcast sky. Formally, the turbidity is defined as the ratio between the combined extinction cross-section and the cross-section only due to molecules, i.e. $T = \frac{t_m + t_l}{t_m}$. Values between 1 and 30 are possible, though the model will be most accurate for values between 2 and 6, to which it was fit using numerical optimization.

The default coordinate system of the luminaire associates the up direction with the $+Y$ axis. The east direction is associated with $+X$ and the north direction is equal to $+Z$. To change this coordinate system, rotations can be applied using the `toWorld` parameter.

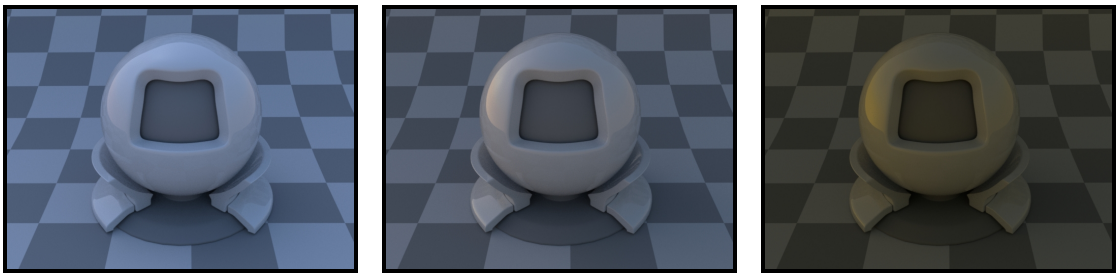
By default, the luminaire will not emit any light below the horizon, which means that these regions will be black when they are observed directly. By setting the `extend` parameter to `true`, the emitted radiance at the horizon will be extended to the entire bottom hemisphere. Note that this will significantly increase the amount of illumination present in the scene.

For performance reasons, the implementation precomputes an environment map of the entire sky that is then forwarded to the `envmap` plugin. The resolution of this environment map can affect the quality of the result. Due to the smoothness of the sky illumination, `resolution` values of around 256 (the default) are usually more than sufficient.

Note that while the model encompasses sunrise and sunset configurations, it does not extend to the night sky, where illumination from stars, galaxies, and the moon dominate. The model also currently does not handle cloudy skies. The implementation in Mitsuba is based on code by Preetham et al. It was ported by Tom Kazimiers.

```
<luminaire type="sky">
    <transform name="toWorld">
        <rotate x="1" angle="90"/>
    </transform>
</luminaire>
```

Listing 26: Rotating the sky luminaire for scenes that use Z as the "up" direction



(a) 3 PM (b) 6 PM (c) 8 PM

Figure 12: Renderings with the `plastic` material under default conditions

6.8.3. Sun and sky luminaire (sunsky)

Parameter	Type	Description
turbidity	float	This parameter determines the amount of scattering particles (or 'haze') in the atmosphere. Smaller values (~ 2) produce a clear blue sky, larger values (~ 8) lead to an overcast sky, and a very high values (~ 20) cause a color shift towards orange and red. (Default: 3)
day	integer	Solar day used to compute the sun's position. Must be in the range between 1 and 365. (Default: 180)
time	float	Fractional time used to compute the sun's position. A time of 4:15 PM corresponds to 16.25. (Default: 15.00)
latitude, longitude	float	These two parameters specify the oberver's latitude and longitude in degrees, which are required to compute the sun's position. (Default: 35.6894, 139.6917 — Tokyo, Japan)
standardMeridian	integer	Denotes the standard meridian of the time zone for finding the sun's position (Default: 135 — Japan standard time)
sunDirection	vector	Allows to manually override the sun direction in world space. When this value is provided, parameters pertaining to the computation of the sun direction (day, time, latitude, longitude, and standardMeridian) are unnecessary. (Default: none)
extend	boolean	Extend luminaire below the horizon? (Default: false)
resolution	integer	Specifies the resolution of the precomputed image that is used to represent the sky environment map (Default: 256)
skyScale	float	This parameter can be used to scale the the amount of illumination emitted by the sky.
sunScale	float	This parameter can be used to scale the the amount of illumination emitted by the sun.

This plugin implements the physically-based skylight model proposed by Preetham et al. [16]. It can be used for realistic daylight renderings of scenes under clear and overcast skies, assuming that the sky is observed from a position either on or close to the surface of the earth.

This is a convenience plugin, which has the sole purpose of instantiating sun and sky at the same time. Please refer to these plugins individually for more detail

6.8.4. Environment map luminaire (`envmap`)

Parameter	Type	Description
`intensityScale`	`float`	This parameter can be used to scale the the amount of illumination emitted by the luminaire. (Default: 1)

This plugin implements a simple environment map luminaire with importance sampling. It uses the scene's bounding sphere to simulate an infinitely far-away light source and expects an EXR image in latitude-longitude (equirectangular) format.

6.9. Integrators

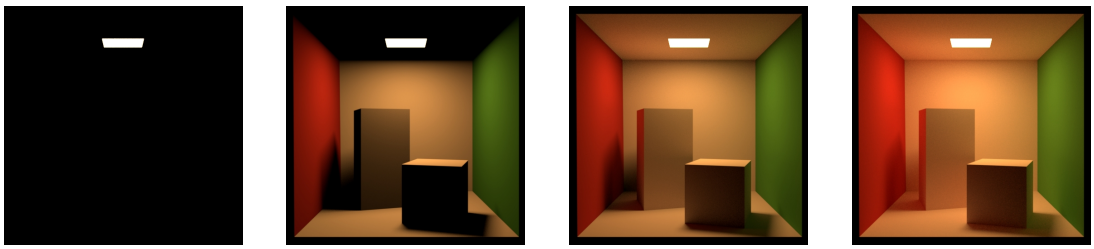
In Mitsuba, the different rendering techniques are collectively referred to as *integrators*, since they perform integration over a high-dimensional space. Each integrator represents a specific approach for solving the light transport equation—usually favored in certain scenarios, but at the same time affected by its own set of intrinsic limitations. Therefore, it is important to carefully select an integrator based on user-specified accuracy requirements and properties of the scene to be rendered.

In Mitsuba's XML description language, a single integrator is usually instantiated by declaring it at the top level within the scene, e.g.

```
<scene version="0.3.0">
    <!-- Instantiate a unidirectional path tracer,
         which renders paths up to a depth of 5 -->
    <integrator type="path">
        <integer name="maxDepth" value="5"/>
    </integrator>

    <!-- Some geometry to be rendered -->
    <shape type="sphere">
        <bsdf type="diffuse"/>
    </shape>
</scene>
```

This section gives a brief overview of the available choices along with their parameters.

Path length



(a) Max. length = 1 (b) Max. length = 2 (c) Max. length = 3 (d) Max. length = ∞

Figure 13: These Cornell box renderings demonstrate the visual effect of a maximum path length. As the paths are allowed to grow longer, the color saturation increases due to multiple scattering interactions with the colored surfaces. At the same time, the computation time increases.

Almost all integrators use the concept of *path length*. Here, a path refers to a chain of scattering events that starts at the light source and ends at the eye or camera. It is often useful to limit the path length (Figure 13) when rendering scenes for preview purposes, since this reduces the amount of computation that is necessary per pixel. Furthermore, such renderings usually converge faster and therefore need fewer samples per pixel. When reference-quality is desired, one should always leave the path length unlimited.

Mitsuba counts lengths starting at 1, which correspond to visible light sources (i.e. a path that starts at the light source and ends at the eye or camera without any scattering interaction in between). A length-2 path (also known as "direct illumination") includes a single scattering event (Figure 14).

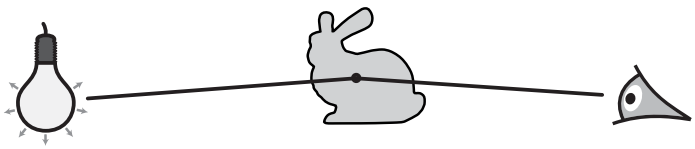


Figure 14: A ray of emitted light is scattered by an object and subsequently reaches the eye/camera. In Mitsuba, this is a *length-2* path, since it has two edges.

Progressive versus non-progressive

Some of the rendering techniques in Mitsuba are *progressive*. What this means is that they display a rough preview, which improves over time. Leaving them running indefinitely will continually reduce noise (e.g. in Metropolis Light Transport) or both noise and bias (e.g. in Progressive Photon Mapping).

6.9.1. Path tracer with multiple importance sampling (`path`)

Parameter	Type	Description
`maxDepth`	`integer`	Maximum path depth (Default: -1)
`strictNormals`	`boolean`	Strict normals?

Extended path tracer – uses multiple importance sampling to combine two sampling strategies, namely BSDF and luminaire sampling. This class does not attempt to solve the full radiative transfer equation (see <tt>volpath</tt> if this is needed).

6.10. Films

This section contains a reference of the film plugins that come with Mitsuba. A film defines how conducted measurements are stored and coverted into a final output format.

6.10.1. OpenEXR-based film (`exrfilm`)

Parameter	Type	Description
`width, height`	`integer`	Width and height of the camera sensor in pixels (Default: 768, 576)
`cropOffsetX, cropOffsetY, cropWidth, cropHeight`	`integer`	These parameter can optionally be provided to render a sub-rectangle of the output (Default: Unused)
`alpha`	`boolean`	Include an alpha channel in the output image? (Default: `true`)
`banner`	`boolean`	Include a small Mitsuba banner in the output image? (Default: `true`)

This plugin implements a simple camera film that stores the captured image as an RGBA-based high dynamic-range EXR file. It does not perform any gamma correction (i.e. the EXR file will contain linear radiance values).

The measured spectral power distributions are converted to linear RGB based on CIE 1931 XYZ color matching functions and ITU-R Rec. BT.709.

6.10.2. MATLAB M-file film (`mfilm`)

Parameter	Type	Description
`width, height`	`integer`	Width and height of the camera sensor in pixels (Default: 768, 576)
`cropOffsetX, cropOffsetY, cropWidth, cropHeight`	`integer`	These parameter can optionally be provided to render a sub-rectangle of the output (Default: Unused)
`alpha`	`boolean`	Include an alpha channel in the output image? (Default: `true`)
`banner`	`boolean`	Include a small Mitsuba banner in the output image? (Default: `true`)

This plugin provides a camera film that exports luminance values as a matrix using the MATLAB M-file format. This is useful when running Mitsuba as simulation step as part of a larger virtual experiment. It can also come in handy when verifying parts of the renderer using a test suite.

When Mitsuba is started with the "test case mode" parameter (`-t`), this class will write triples consisting of the luminance, variance, and sample count for every pixel (instead of just the luminance).

6.10.3. PNG-based film (`pngfilm`)

Parameter	Type	Description
`width, height`	`integer`	Width and height of the camera sensor in pixels (Default: 768, 576)
`cropOffsetX, cropOffsetY, cropWidth, cropHeight`	`integer`	These parameter can optionally be provided to render a sub-rectangle of the output (Default: Unused)
`alpha`	`boolean`	Include an alpha channel in the output image? (Default: `true`)
`banner`	`boolean`	Include a small Mitsuba banner in the output image? (Default: `true`)
`toneMappingMethod`	`string`	Specifies the tonemapping method that should be used to convert high-dynamic range images to 8 bits per channel. 1. `gamma`: Use a basic Gamma conversion 2. `reinhard`: Use a global version of the Reinhard [17] tonemapping method
`reinhardKey, reinhardBurn`	`float`	When `toneMappingMethod=reinhard`, these two parameters specify the *key* and *burn* parameters of that model. (Default: `reinhardKey`=0.18 and `reinhardBurn`=0)

This plugin implements a simple camera film that stores the captured image as an RGBA-based low dynamic-range PNG file with gamma correction. The measured spectral power distributions are converted to linear RGB based on CIE 1931 XYZ color matching functions and ITU-R Rec. BT.709. If desired, the class can optionally apply a global version of the Reinhard tonemapping algorithm.

Part II.
Development guide

This chapter and the subsequent ones will provide an overview of the the coding conventions and general architecture of Mitsuba. You should only read them if if you wish to interface with the API in some way (e.g. by developing your own plugins). The coding style section is only relevant if you plan to submit patches that are meant to become part of the main codebase.

7. Code structure

Mitsuba is split into four basic support libraries:

- The core library (`libcore`) implements basic functionality such as cross-platform file and bitmap I/O, data structures, scheduling, as well as logging and plugin management.
- The rendering library (`librender`) contains abstractions needed to load and represent scenes containing light sources, shapes, materials, and participating media.
- The hardware acceleration library (`libhw`) implements a cross-platform display library, an object-oriented OpenGL wrapper, as well as support for rendering interactive previews of scenes.
- Finally, the bidirectional library (`libbidir`) contains a support layer that is used to implement bidirectional rendering algorithms such as Bidirectional Path Tracing and Metropolis Light Transport.

A detailed reference of these APIs is available at `http://www.mitsuba-renderer.org/api`. The next sections present a few basic examples to get familiar with them.

8. Coding style

Indentation: The Mitsuba codebase uses tabs for indentation, which expand to *four* spaces. Please make sure that you configure your editor this way, otherwise the source code layout will look garbled.

Placement of braces: Opening braces should be placed on the same line to make the best use of vertical space, i.e.

```
if (x > y) {
    x = y;
}
```

Placement of spaces: Placement of spaces follows K&R, e.g.

```
if (x == y) {
    ..
} else if (x > y) {
    ..
```

```
} else {
    ..
}
```

rather than things like this

```
if ( x==y ){
}
..
```

Name format: Names are always written in camel-case. Classes and structures start with a capital letter, whereas member functions and attributes start with a lower-case letter. Attributes of classes have the prefix `m_`. Here is an example:

```
class MyClass {
public:
    MyClass(int value) : m_value(value) { }

    inline void setValue(int value) { m_value = value; }
    inline int getValue() const { return m_value; }
private:
    int m_value;
};
```

Enumerations: For clarity, both enumerations types and entries start with a capital **E**, e.g.

```
enum ETristate {
    ENo = 0,
    EYes,
    EMaybe
};
```

Constant methods and parameters: Declare member functions and their parameters as `const` whenever this is possible and properly conveys the semantics.

Inline methods: Always inline trivial pieces of code, such as getters and setters.

Documentation: Headers files should contain Doxygen-compatible documentation. It is also a good idea to add comments to a `.cpp` file to explain subtleties of an implemented algorithm. However, anything pertaining to the API should go into the header file.

Boost: Use the boost libraries whenever this helps to save time or write more compact code.

Classes vs structures: In Mitsuba, classes usually go onto the heap, whereas structures may be allocated both on the stack and the heap.

Classes that derive from `Object` implement a protected virtual deconstructor, which explicitly prevents them from being allocated on the stack. The only way they can be deallocated is using the built-in reference counting. This is done using the `ref<>` template, e.g.

```
if (..) {
    ref<MyClass> instance = new MyClass();
    instance->doSomething()
}   // reference expires, instance will be deallocated
```

Separation of plugins: Mitsuba encourages that plugins are only used via the generic interface they implement. You will find that almost all plugins (e.g. luminaires) don't actually provide a header file, hence they can only be accessed using the generic `Luminaire` interface they implement. If any kind of special interaction between plugins is needed, this is usually an indication that the generic interface should be extended to accomodate this.

9. Designing a custom integrator plugin

Suppose you want to design a custom integrator to render scenes in Mitsuba. There are two general ways you can do this, and which one you should take mostly depends on the characteristics of your particular integrator.

The framework distinguishes between *sampling-based* integrators and *generic* ones. A sampling-based integrator is able to generate (usually unbiased) estimates of the incident radiance along a specified rays, and this is done a large number of times to render a scene. A generic integrator is more like a black box, where no assumptions are made on how the the image is created. For instance, the VPL renderer uses OpenGL to rasterize the scene using hardware acceleration, which certainly doesn't fit into the sampling-based pattern. For that reason, it must be implemented as a generic integrator.

Generally, if you can package up your code to fit into the `SampleIntegrator` interface, you should do it, because you'll get parallelization and network rendering essentially for free. This is done by transparently sending instances of your integrator class to all participating cores and assigning small image blocks for each one to work on. Also, sampling-based integrators can be nested within some other integrators, such as an irradiance cache or an adaptive integrator. This cannot be done with generic integrators due to their black-box nature. Note that it is often still possible to parallelize generic integrators, but this involves significantly more work.

In this section, we'll design a rather contrived sampling-based integrator, which renders a monochromatic image of your scene, where the intensity denotes the distance to the camera. But to get a feel for the overall framework, we'll start with an even simpler one, that just renders a solid-color image.

9.1. Basic implementation

In Mitsuba's `src/integrators` directory, create a file named `myIntegrator.cpp`.

```
#include <mitsuba/render/scene.h>

MTS_NAMESPACE_BEGIN

class MyIntegrator : public SampleIntegrator {
public:
    MTS_DECLARE_CLASS()
};

MTS_IMPLEMENT_CLASS_S(MyIntegrator, false, SampleIntegrator)
MTS_EXPORT_PLUGIN(MyIntegrator, "A contrived integrator");
MTS_NAMESPACE_END
```

The `scene.h` header file contains all of the dependencies we'll need for now. To avoid conflicts with other libraries, the whole framework is located in a separate namespace named `mitsuba`, and the lines starting with `MTS_NAMESPACE` ensure that our integrator is placed there as well.

The two lines starting with `MTS_DECLARE_CLASS` and `MTS_IMPLEMENT_CLASS` ensure that this class is recognized as a native Mitsuba class. This is necessary to get things like run-time type information, reference counting, and serialization/unserialization support. Let's take a look at the second of these lines, because it contains several important pieces of information:

The suffix `S` in `MTS_IMPLEMENT_CLASS_S` specifies that this is a serializable class, which means that it can be sent over the network or written to disk and later restored. That also implies that certain methods need to be provided by the implementation — we'll add those in a moment.

The three following parameters specify the name of this class (`MyIntegrator`), the fact that it is *not* an abstract class (`false`), and the name of its parent class (`SampleIntegrator`).

Just below, you can see a line that starts with `MTS_EXPORT_PLUGIN`. As the name suggests, this line is only necessary for plugins, and it ensures that the specified class (`MyIntegrator`) is what you want to be instantiated when somebody loads this plugin. It is also possible to supply a short descriptive string.

Let's add an instance variable and a constructor:

```
public:
    /// Initialize the integrator with the specified properties
    MyIntegrator(const Properties &props) : SampleIntegrator(props) {
        Spectrum defaultColor;
        defaultColor.fromLinearRGB(0.2f, 0.5f, 0.2f);
        m_color = props.getSpectrum("color", defaultColor);
    }

private:
    Spectrum m_color;
```

This code fragment sets up a default color (a light shade of green), which can be overridden from the scene file. For example, one could instantiate the integrator from an XML document like this

```
<integrator type="myIntegrator">
    <spectrum name="color" value="1.0"/>
</integrator>
```

in which case white would take preference.

Next, we need to add serialization and unserialization support:

```
    /// Unserialize from a binary data stream
    MyIntegrator(Stream *stream, InstanceManager *manager)
     : SampleIntegrator(stream, manager) {
        m_color = Spectrum(stream);
    }

    /// Serialize to a binary data stream
    void serialize(Stream *stream, InstanceManager *manager) const {
        SampleIntegrator::serialize(stream, manager);
        m_color.serialize(stream);
    }
```

This makes use of a *stream* abstraction similar in style to Java. A stream can represent various things, such as a file, a console session, or a network communication link. Especially when dealing with multiple machines, it is important to realize that the machines may use different binary representations related to their respective *endianness*. To prevent issues from arising, the `Stream` interface provides many methods for writing and reading small chunks of data (e.g. `writeShort`, `readFloat`, ..), which automatically perform endianness translation. In our case, the `Spectrum` class already provides serialization/unserialization support, so we don't really have to do anything.

Note that it is crucial that your code calls the serialization and unserialization implementations of the superclass, since it will also read/write some information to the stream.

We haven't used the `manager` parameter yet, so here is a quick overview of what it does: if many cases, we don't just want to serialize a single class, but a whole graph of objects. Some may be referenced many times from different places, and potentially there are even cycles. If we just naively called the serialization and unserialization implementation of members recursively within each class, we'd waste much bandwitdth and potentially end up stuck in an infinite recursion.

This is where the instance manager comes in. Every time you want to serialize a heap-allocated object (suppose it is of type `SomeClass`), instead of calling its serialize method, write

```
ref<SomeClass> myObject = ...;
manager->serialize(stream, myObject.get());
```

Later, to unserialize the object from a stream again, write

```
ref<SomeClass> myObject = static_cast<SomeClass *>(manager->getInstance(stream));
```

Behind the scenes, the object manager adds annotations to the data stream, which ensure that you will end up with the exact same reference graph on the remote side, while only one copy of every object is transmitted and no infinite recursion can occur. But we digress – let's go back to our integrator.

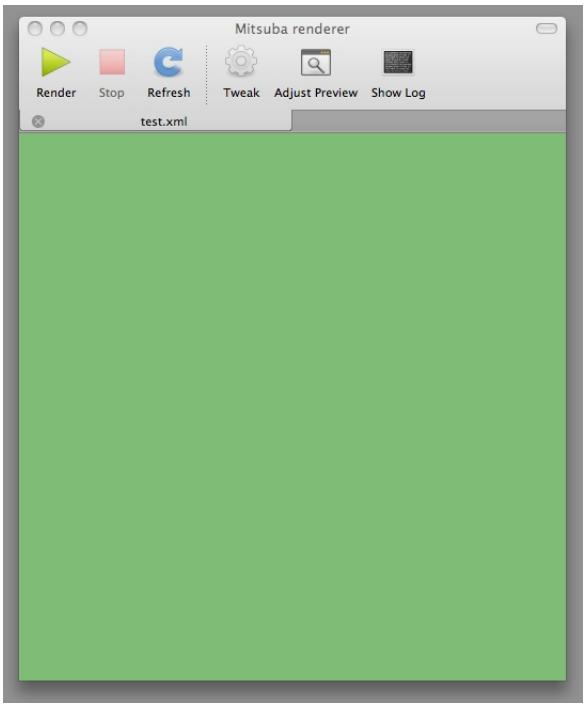
The last thing to add is a function, which returns an estimate for the radiance along a ray differential: here, we simply return the stored color

```
    /// Query for an unbiased estimate of the radiance along <tt>r</tt>
   Spectrum Li(const RayDifferential &r, RadianceQueryRecord &rRec) const {
       return m_color;
   }
```

Let's try building the plugin: edit the `SConstruct` file in the main directory, and add the following line after the comment "`# Integrators`":

```
plugins += env.SharedLibrary('plugins/myIntegrator', ['src/integrators/
    myIntegrator.cpp'])
```

After calling, `scons`, you should be able to use your new integrator in parallel rendering jobs and you'll get something like this:



That is admittedly not very exciting — so let's do some actual computation.

9.2. Visualizing depth

Add an instance variable `Float m_maxDist;` to the implementation. This will store the maximum distance from the camera to any object, which is needed to map distances into the $[0,1]$ range. Note the upper-case `Float` — this means that either a single- or a double-precision variable is substituted based the compilation flags. This variable constitutes local state, thus it must not be forgotten in the serialization- and unserialization routines: append

```
    m_maxDist = stream->readFloat();
```

and

```
    stream->writeFloat(m_maxDist);
```

to the unserialization constructor and the `serialize` method, respectively.

We'll conservatively bound the maximum distance by measuring the distance to all corners of the bounding box, which encloses the scene. To avoid having to do this every time `Li()` is called, we can override the `preprocess` function:

```
    /// Preprocess function -- called on the initiating machine
    bool preprocess(const Scene *scene, RenderQueue *queue,
            const RenderJob *job, int sceneResID, int cameraResID,
            int samplerResID) {
        SampleIntegrator::preprocess(scene, queue, job, sceneResID,
            cameraResID, samplerResID);

        const AABB &sceneAABB = scene->getAABB();
        Point cameraPosition = scene->getCamera()->getPosition();
```

```
        m_maxDist = - std::numeric_limits<Float>::infinity();

        for (int i=0; i<8; ++i)
            m_maxDist = std::max(m_maxDist,
                (cameraPosition - sceneAABB.getCorner(i)).length());

        return true;
    }
```

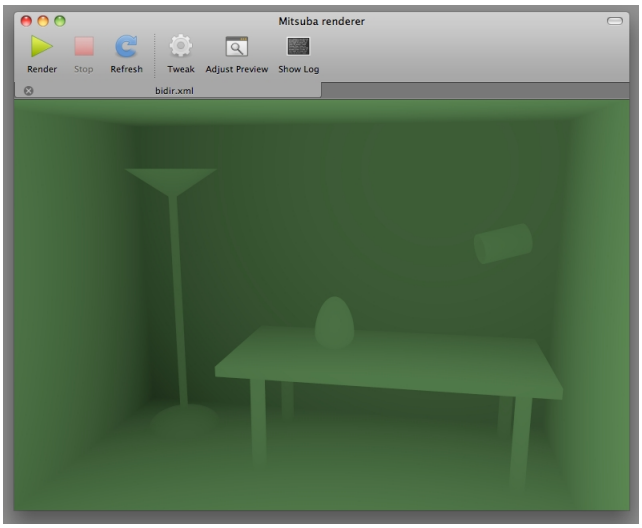
The bottom of this function should be relatively self-explanatory. The numerous arguments at the top are related to the parallelization layer, which will be considered in more detail in the next section. Briefly, the render queue provides synchronization facilities for render jobs (e.g. one can wait for a certain job to terminate). And the integer parameters are global resource identifiers. When a network render job runs, many associated pieces of information (the scene, the camera, etc.) are wrapped into global resource chunks shared amongst all nodes, and these can be referenced using such identifiers.

One important aspect of the `preprocess` function is that it is executed on the initiating node and before any of the parallel rendering begins. This can be used to compute certain things only once. Any information updated here (such as `m_maxDist`) will be forwarded to the other nodes before the rendering begins.

Now, replace the body of the `Li` method with

```
    if (rRec.rayIntersect(r)) {
        Float distance = rRec.its.t;
        return Spectrum(1.0f - distance/m_maxDist) * m_color;
    }
    return Spectrum(0.0f);
```

and the distance renderer is done!



There are a few more noteworthy details: first of all, the "usual" way to intersect a ray against the scene actually works like this:

```
    Intersection its;
    Ray ray = ...;
    if (scene->rayIntersect(ray, its)) {
```

```
        /* Do something with the intersection stored in 'its' */
    }
```

As you can see, we did something slightly different in the distance renderer fragment above (we called `RadianceQueryRecord::rayIntersect()` on the supplied parameter `rRec`), and the reason for this is *nesting*.

9.3. Nesting

The idea of of nesting is that sampling-based rendering techniques can be embedded within each other for added flexibility: for instance, one might concoct a 1-bounce indirect rendering technique complete with irradiance caching and adaptive integration simply by writing the following into a scene XML file:

```
<!-- Adaptively integrate using the nested technique -->
<integrator type="errctrl">
    <!-- Irradiance caching + final gathering with the nested technique -->
    <integrator type="irrcache">
        <!-- Simple direct illumination technique -->
        <integrator type="direct">
    </integrator>
</integrator>
```

To support this kind of complex interaction, some information needs to be passed between the integrators, and the `RadianceQueryRecord` parameter of the function `SampleIntegrator::Li` is used for this.

This brings us back to the odd way of computing an intersection a moment ago: the reason why we didn't just do this by calling `scene->rayIntersect()` is that our technique might actually be nested within a parent technique, which has already computed this intersection. To avoid wasting resources, the function `rRec.rayIntersect` first determines whether an intersection record has already been provided. If yes, it does nothing. Otherwise, it takes care of computing one.

The radiance query record also lists the particular *types* of radiance requested by the parent integrator – your implementation should respect these as much as possible. Your overall code might for example be structured like this:

```
Spectrum Li(const RayDifferential &r, RadianceQueryRecord &rRec) const {
    Spectrum result;
    if (rRec.type & RadianceQueryRecord::EEmittedRadiance) {
        // Emitted surface radiance contribution was requested
        result += ...;
    }
    if (rRec.type & RadianceQueryRecord::EDirectRadiance) {
        // Direct illumination contribution was requested
        result += ...;
    }
    ...
    return result;
}
```

10. Parallelization layer

Mitsuba is built on top of a flexible parallelization layer, which spreads out various types of computation over local and remote cores. The guiding principle is that if an operation can potentially take longer than a few seconds, it ought to use all the cores it can get.

Here, we will go through a basic example, which will hopefully provide sufficient intuition to realize more complex tasks. To obtain good (i.e. close to linear) speedups, the parallelization layer depends on several key assumptions of the task to be parallelized:

- The task can easily be split up into a discrete number of *work units*, which requires a negligible amount of computation.
- Each work unit is small in footprint so that it can easily be transferred over the network or shared memory.
- A work unit constitutes a significant amount of computation, which by far outweighs the cost of transmitting it to another node.
- The *work result* obtained by processing a work unit is again small in footprint, so that it can easily be transferred back.
- Merging all work results to a solution of the whole problem requires a negligible amount of additional computation.

This essentially corresponds to a parallel version of *Map* (one part of *Map&Reduce*) and is ideally suited for most rendering workloads.

The example we consider here computes a `ROT13` "encryption" of a string, which most certainly violates the "significant amount of computation" assumption. It was chosen due to the inherent parallelism and simplicity of this task. While of course over-engineered to the extreme, the example hopefully communicates how this framework might be used in more complex scenarios.

We will implement this program as a plugin for the utility launcher `mtsutil`, which frees us from having to write lots of code to set up the framework, prepare the scheduler, etc.

We start by creating the utility skeleton file `src/utils/rot13.cpp`:

```
#include <mitsuba/render/util.h>

MTS_NAMESPACE_BEGIN

class ROT13Encoder : public Utility {
public:
    int run(int argc, char **argv) {
        cout << "Hello world!" << endl;
        return 0;
    }

    MTS_DECLARE_UTILITY()
};

MTS_EXPORT_UTILITY(ROT13Encoder, "Perform a ROT13 encryption of a string")
MTS_NAMESPACE_END
```

The file must also be added to the build system: insert the line

```
plugins += env.SharedLibrary('plugins/rot13', ['src/utils/rot13.cpp'])
```

into the SConscript (near the comment "`Build the plugins - utilities`"). After compiling using `scons`, the `mtsutil` binary should automatically pick up your new utility plugin:

```
$ mtsutil
..
The following utilities are available:

    addimages             Generate linear combinations of EXR images
    rot13                 Perform a ROT13 encryption of a string
```

It can be executed as follows:

```
$ mtsutil rot13
2010-08-16 18:38:27 INFO  main [src/mitsuba/mtsutil.cpp:276] Mitsuba version 0.1.1,
     Copyright (c) 2010 Wenzel Jakob
2010-08-16 18:38:27 INFO  main [src/mitsuba/mtsutil.cpp:350] Loading utility "
    rot13" ..
Hello world!
```

Our approach for implementing distributed ROT13 will be to treat each character as an indpendent work unit. Since the ordering is lost when sending out work units, we must also include the position of the character in both the work units and the work results.

All of the relevant interfaces are contained in `include/mitsuba/core/sched.h`. For reference, here are the interfaces of `WorkUnit` and `WorkResult`:

```
/**
 * Abstract work unit. Represents a small amount of information
 * that encodes part of a larger processing task.
 */
class MTS_EXPORT_CORE WorkUnit : public Object {
public:
    /// Copy the content of another work unit of the same type
    virtual void set(const WorkUnit *workUnit) = 0;

    /// Fill the work unit with content acquired from a binary data stream
    virtual void load(Stream *stream) = 0;

    /// Serialize a work unit to a binary data stream
    virtual void save(Stream *stream) const = 0;

    /// Return a string representation
    virtual std::string toString() const = 0;

    MTS_DECLARE_CLASS()
protected:
    /// Virtual destructor
    virtual ~WorkUnit() { }
};
/**
 * Abstract work result. Represents the information that encodes
```

```
 * the result of a processed <tt>WorkUnit</tt> instance.
 */
class MTS_EXPORT_CORE WorkResult : public Object {
public:
    /// Fill the work result with content acquired from a binary data stream
    virtual void load(Stream *stream) = 0;

    /// Serialize a work result to a binary data stream
    virtual void save(Stream *stream) const = 0;

    /// Return a string representation
    virtual std::string toString() const = 0;

    MTS_DECLARE_CLASS()
protected:
    /// Virtual destructor
    virtual ~WorkResult() { }
};
```

In our case, the `WorkUnit` implementation then looks like this:

```
class ROT13WorkUnit : public WorkUnit {
public:
    void set(const WorkUnit *workUnit) {
        const ROT13WorkUnit *wu =
            static_cast<const ROT13WorkUnit *>(workUnit);
        m_char = wu->m_char;
        m_pos = wu->m_pos;
    }

    void load(Stream *stream) {
        m_char = stream->readChar();
        m_pos = stream->readInt();
    }

    void save(Stream *stream) const {
        stream->writeChar(m_char);
        stream->writeInt(m_pos);
    }

    std::string toString() const {
        std::ostringstream oss;
        oss << "ROT13WorkUnit[" << endl
            << "  char = '" << m_char << "'," << endl
            << "  pos = " << m_pos << endl
            << "]";
        return oss.str();
    }

    inline char getChar() const { return m_char; }
    inline void setChar(char value) { m_char = value; }
    inline int getPos() const { return m_pos; }
```

```
    inline void setPos(int value) { m_pos = value; }

    MTS_DECLARE_CLASS()
private:
    char m_char;
    int m_pos;
};

MTS_IMPLEMENT_CLASS(ROT13WorkUnit, false, WorkUnit)
```

The `ROT13WorkResult` implementation is not reproduced since it is almost identical (except that it doesn't need the `set` method). The similarity is not true in general: for most algorithms, the work unit and result will look completely different.

Next, we need a class, which does the actual work of turning a work unit into a work result (a subclass of `WorkProcessor`). Again, we need to implement a range of support methods to enable the various ways in which work processor instances will be submitted to remote worker nodes and replicated amongst local threads.

```
class ROT13WorkProcessor : public WorkProcessor {
public:
    /// Construct a new work processor
    ROT13WorkProcessor() : WorkProcessor() { }

    /// Unserialize from a binary data stream (nothing to do in our case)
    ROT13WorkProcessor(Stream *stream, InstanceManager *manager)
        : WorkProcessor(stream, manager) { }

    /// Serialize to a binary data stream (nothing to do in our case)
    void serialize(Stream *stream, InstanceManager *manager) const {
    }

    ref<WorkUnit> createWorkUnit() const {
        return new ROT13WorkUnit();
    }

    ref<WorkResult> createWorkResult() const {
        return new ROT13WorkResult();
    }

    ref<WorkProcessor> clone() const {
        return new ROT13WorkProcessor(); // No state to clone in our case
    }

    /// No internal state, thus no preparation is necessary
    void prepare() { }

    /// Do the actual computation
    void process(const WorkUnit *workUnit, WorkResult *workResult,
                 const bool &stop) {
        const ROT13WorkUnit *wu
            = static_cast<const ROT13WorkUnit *>(workUnit);
        ROT13WorkResult *wr = static_cast<ROT13WorkResult *>(workResult);
```

```
        wr->setPos(wu->getPos());
        wr->setChar((std::toupper(wu->getChar()) - 'A' + 13) % 26 + 'A');
    }
    MTS_DECLARE_CLASS()
};
MTS_IMPLEMENT_CLASS_S(ROT13WorkProcessor, false, WorkProcessor)
```

Since our work processor has no state, most of the implementations are rather trivial. Note the `stop` field in the `process` method. This field is used to abort running jobs at the users requests, hence it is a good idea to periodically check its value during lengthy computations.

Finally, we need a so-called *parallel process* instance, which is responsible for creating work units and stitching work results back into a solution of the whole problem. The `ROT13` implementation might look as follows:

```
class ROT13Process : public ParallelProcess {
public:
    ROT13Process(const std::string &input) : m_input(input), m_pos(0) {
        m_output.resize(m_input.length());
    }

    ref<WorkProcessor> createWorkProcessor() const {
        return new ROT13WorkProcessor();
    }

    std::vector<std::string> getRequiredPlugins() {
        std::vector<std::string> result;
        result.push_back("rot13");
        return result;
    }

    EStatus generateWork(WorkUnit *unit, int worker /* unused */) {
        if (m_pos >= (int) m_input.length())
            return EFailure;
        ROT13WorkUnit *wu = static_cast<ROT13WorkUnit *>(unit);

        wu->setPos(m_pos);
        wu->setChar(m_input[m_pos++]);

        return ESuccess;
    }

    void processResult(const WorkResult *result, bool cancelled) {
        if (cancelled) // indicates a work unit, which was
            return;    // cancelled partly through its execution
        const ROT13WorkResult *wr =
            static_cast<const ROT13WorkResult *>(result);
        m_output[wr->getPos()] = wr->getChar();
    }

    inline const std::string &getOutput() {
        return m_output;
    }
```

```
    MTS_DECLARE_CLASS()
public:
    std::string m_input;
    std::string m_output;
    int m_pos;
};
MTS_IMPLEMENT_CLASS(ROT13Process, false, ParallelProcess)
```

The `generateWork` method produces work units until we have moved past the end of the string, after which it returns the status code `EFailure`. Note the method `getRequiredPlugins()`: this is necessary to use the utility across machines. When communicating with another node, it ensures that the remote side loads the `ROT13*` classes at the right moment.

To actually use the `ROT13` encoder, we must first launch the newly created parallel process from the main utility function (the 'Hello World' code we wrote earlier). We can adapt it as follows:

```
    int run(int argc, char **argv) {
        if (argc < 2) {
            cout << "Syntax: mtsutil rot13 <text>" << endl;
            return -1;
        }

        ref<ROT13Process> proc = new ROT13Process(argv[1]);
        ref<Scheduler> sched = Scheduler::getInstance();

        /* Submit the encryption job to the scheduler */
        sched->schedule(proc);

        /* Wait for its completion */
        sched->wait(proc);

        cout << "Result: " << proc->getOutput() << endl;

        return 0;
    }
```

After compiling everything using `scons`, an simple example involving the utility would be to encode a string (e.g. `SECUREBYDESIGN`), while forwarding all computation to a network machine. (`-p0` disables all local worker threads). Adding a verbose flag (`-v`) shows some additional scheduling information:

```
$ mtsutil -vc feynman -p0 rot13 SECUREBYDESIGN
2010-08-17 01:35:46 INFO  main [src/mitsuba/mtsutil.cpp:201] Mitsuba version 0.1.1,
     Copyright (c) 2010 Wenzel Jakob
2010-08-17 01:35:46 INFO  main [SocketStream] Connecting to "feynman:7554"
2010-08-17 01:35:46 DEBUG main [Thread] Spawning thread "net0_r"
2010-08-17 01:35:46 DEBUG main [RemoteWorker] Connection to "feynman" established
    (2 cores).
2010-08-17 01:35:46 DEBUG main [Scheduler] Starting ..
2010-08-17 01:35:46 DEBUG main [Thread] Spawning thread "net0"
2010-08-17 01:35:46 INFO  main [src/mitsuba/mtsutil.cpp:275] Loading utility "
    rot13" ..
```

```
2010-08-17 01:35:46 DEBUG main [Scheduler] Scheduling process 0: ROT13Process[
    unknown]..
2010-08-17 01:35:46 DEBUG main [Scheduler] Waiting for process 0
2010-08-17 01:35:46 DEBUG net0 [Scheduler] Process 0 has finished generating work
2010-08-17 01:35:46 DEBUG net0_r[Scheduler] Process 0 is complete.
Result: FRPHEROLQRFVTA
2010-08-17 01:35:46 DEBUG main [Scheduler] Pausing ..
2010-08-17 01:35:46 DEBUG net0 [Thread] Thread "net0" has finished
2010-08-17 01:35:46 DEBUG main [Scheduler] Stopping ..
2010-08-17 01:35:46 DEBUG main [RemoteWorker] Shutting down
2010-08-17 01:35:46 DEBUG net0_r[Thread] Thread "net0_r" has finished
```

11. Python integration

A recent feature of Mitsuba is a simple Python interface to the renderer API. While the interface is still limited at this point, it can already be used for many useful purposes. To access the API, start your Python interpreter and enter

```
import mitsuba
```

For this to work on MacOS X, you will first have to run the "*Apple Menu→Command-line access*" menu item from within Mitsuba. On Windows and non-packaged Linux builds, you may have to update the extension search path before issuing the `import` command, e.g.:

```
import sys

# Update the extension search path
# (may vary depending on your setup)
sys.path.append('dist/python')

import mitsuba
```

For an overview of the currently exposed API subset, please refer to the following page: http://www.mitsuba-renderer.org/api/group__libpython.html.

11.1. Basics

Generally, the Python API tries to mimic the C++ API as closely as possible. Where applicable, the Python classes and methods replicate overloaded operators, overridable virtual function calls, and default arguments. Under rare circumstances, some features are inherently non-portable due to fundamental differences between the two programming languages. In this case, the API documentation will contain further information.

Mitsuba's linear algebra-related classes are usable with essentially the same syntax as their C++ versions — for example, the following snippet creates and rotates a unit vector.

```
import mitsuba
from mitsuba.core import *

# Create a normalized direction vector
myVector = normalize(Vector(1.0, 2.0, 3.0))

# 90 deg. rotation around the Y axis
trafo = Transform.rotate(Vector(0, 1, 0), 90)

# Apply the rotation and display the result
print(trafo * myVector)
```

11.2. Recipes

The following section contains a series of "recipes" on how to do certain things with the help of the Python bindings.

11.2.1. Loading a scene

The following script demonstrates how to use the `FileResolver` and `SceneHandler` classes to load a Mitsuba scene from an XML file:

```
import mitsuba

from mitsuba.core import *
from mitsuba.render import SceneHandler

# Get a reference to the thread's file resolver
fileResolver = Thread.getThread().getFileResolver()

# Add the search path needed to load plugins
fileResolver.addPath('<path to mitsuba directory>')

# Add the search path needed to load scene resources
fileResolver.addPath('<path to scene directory>')

# Optional: supply parameters that can be accessed
# by the scene (e.g. as $myParameter)
paramMap = StringMap()
paramMap['myParameter'] = 'value'

# Load the scene from an XML file
scene = SceneHandler.loadScene(fileResolver.resolve("scene.xml"), paramMap)

# Display a textual summary of the scene's contents
print(scene)
```

11.2.2. Rendering a loaded scene

Once a scene has been loaded, it can be rendered as follows:

```
from mitsuba.core import *
from mitsuba.render import RenderQueue, RenderJob
import multiprocessing

scheduler = Scheduler.getInstance()

# Start up the scheduling system with one worker per local core
for i in range(0, multiprocessing.cpu_count()):
    scheduler.registerWorker(LocalWorker('wrk%i' % i))
scheduler.start()

# Create a queue for tracking render jobs
queue = RenderQueue()

scene.setDestinationFile('renderedResult')

# Create a render job and insert it into the queue
job = RenderJob('myRenderJob', scene, queue)
```

```
job.start()

# Wait for all jobs to finish and release resources
queue.waitLeft(0)
queue.join()

# Print some statistics about the rendering process
print(Statistics.getInstance().getStats())
```

11.2.3. Rendering over the network

To render over the network, you must first set up one or more machines that run the `mtssrv` server (see Section 4.3). A network node can then be registered with the scheduler as follows:

```
# Connect to a socket on a named host or IP address
# 7554 is the default port of 'mtssrv'
stream = SocketStream('128.84.103.222', 7554)

# Create a remote worker instance that communicates over the stream
remoteWorker = RemoteWorker('netWorker', stream)

scheduler = Scheduler.getInstance()
# Register the remote worker (and any other potential workers)
scheduler.registerWorker(remoteWorker)
scheduler.start()
```

11.2.4. Constructing custom scenes from Python

Dynamically constructing Mitsuba scenes entails loading a series of external plugins, instantiating them with custom parameters, and finally assembling them into an object graph. For instance, the following snippet shows how to create a basic perspective camera with a film that writes PNG images:

```
from mitsuba.core import *
pmgr = PluginManager.getInstance()

# Encodes parameters on how to instantiate the 'perspective' plugin
cameraProps = Properties('perspective')
cameraProps['toWorld'] = Transform.lookAt(
    Point(0, 0, -10),  # Camera origin
    Point(0, 0, 0),    # Camera target
    Vector(0, 1, 0)    # 'up' vector
)
cameraProps['fov'] = 45.0

# Encodes parameters on how to instantiate the 'pngfilm' plugin
filmProps = Properties('pngfilm')
filmProps['width'] = 1920
filmProps['height'] = 1080

# Load and instantiate the plugins
camera = pmgr.createObject(cameraProps)
```

```
film = pmgr.createObject(filmProps)

# First configure the film and then add it to the camera
film.configure()
camera.addChild('film', film)

# Now, the camera can be configured
camera.configure()
```

The above code fragment uses the plugin manager to construct a `Camera` instance from an external plugin named `perspective.so/dll/dylib` and adds a child object named `film`, which is a `Film` instance loaded from the plugin `pngfilm.so/dll/dylib`. Each time after instantiating a plugin, all child objects are added, and finally the plugin's `configure()` method must be called.

Creating scenes in this manner ends up being rather laborious. Since Python comes with a powerful dynamically-typed dictionary primitive, Mitsuba additionally provides a more "pythonic" alternative that makes use of this facility:

```
from mitsuba.core import *

pmgr = PluginManager.getInstance()
camera = pmgr.create({
    'type' : 'perspective',
    'toWorld' : Transform.lookAt(
        Point(0, 0, -10),
        Point(0, 0, 0),
        Vector(0, 1, 0)
    ),
    'film' : {
        'type' : 'pngfilm',
        'width' : 1920,
        'height' : 1080
    }
})
```

This code does exactly the same as the previous snippet. By the time `PluginManager.create` returns, the object hierarchy has already been assembled, and the `configure()` method of every object has been called.

Finally, here is an full example that creates a basic scene which can be rendered. It describes a sphere lit by a point light, rendered using the direct illumination integrator.

```
from mitsuba.core import *
from mitsuba.render import Scene

scene = Scene()

# Create a camera, film & sample generator
scene.addChild(pmgr.create({
    'type' : 'perspective',
    'toWorld' : Transform.lookAt(
        Point(0, 0, -10),
        Point(0, 0, 0),
        Vector(0, 1, 0)
```

```
    ),
    'film' : {
        'type' : 'pngfilm',
        'width' : 1920,
        'height' : 1080
    },
    'sampler' : {
        'type' : 'ldsampler',
        'sampleCount' : 2
    }
}))

# Set the integrator
scene.addChild(pmgr.create({
    'type' : 'direct'
}))

# Add a light source
scene.addChild(pmgr.create({
    'type' : 'point',
    'position' : Point(5, 0, -10),
    'intensity' : Spectrum(100)
}))

# Add a shape
scene.addChild(pmgr.create({
    'type' : 'sphere',
    'center' : Point(0, 0, 0),
    'radius' : 1.0,
    'bsdf' : {
        'type' : 'diffuse',
        'reflectance' : Spectrum(0.4)
    }
}))

scene.configure()
```

11.2.5. Taking control of the logging system

Many operations in Mitsuba will print one or more log messages during their execution. By default, they will be printed to the console, which may be undesirable. Similar to the C++ side, it is possible to define custom `Formatter` and `Appender` classes to interpret and direct the flow of these messages.

Roughly, a `Formatter` turns detailed information about a logging event into a human-readable string, and a `Appender` routes it to some destination (e.g. by appending it to a file or a log viewer in a graphical user interface). Here is an example of how to activate such extensions:

```
import mitsuba
from mitsuba.core import *

class MyFormatter(Formatter):
```

```
    def format(self, logLevel, sourceClass, sourceThread, message, filename, line):

        return '%s (log level: %s, thread: %s, class %s, file %s, line %i)' % \
                (message, str(logLevel), sourceThread.getName(), sourceClass,
                 filename, line)

class MyAppender(Appender):
    def append(self, logLevel, message):
        print(message)

    def logProgress(self, progress, name, formatted, eta):
        print('Progress message: ' + formatted)

# Get the logger associated with the current thread
logger = Thread.getThread().getLogger()
logger.setFormatter(MyFormatter())
logger.clearAppenders()
logger.addAppender(MyAppender())
logger.setLogLevel(EDebug)

Log(EInfo, 'Test message')
```

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