

Embree
High Performance Ray Tracing Kernels

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Chapter 1

Embree Overview

Embree is a collection of high-performance ray tracing kernels, developed at Intel. The target user of Embree are graphics application engineers that want to improve the performance of their application by leveraging the optimized ray tracing kernels of Embree. The kernels are optimized for photo-realistic rendering on the latest Intel[®] processors with support for SSE, AVX, AVX2, and the 16-wide Intel[®] Xeon Phi™ coprocessor vector instructions. Embree supports runtime code selection to choose the traversal and build algorithms that best matches the instruction set of your CPU. We recommend using Embree through its API to get the highest benefit from future improvements. Embree is released as Open Source under the [Apache 2.0 license](#).

Embree supports applications written with the Intel SPMD Programm Compiler (ISPC, <https://ispc.github.io/>) by also providing an ISPC interface to the core ray tracing algorithms. This makes it possible to write a renderer in ISPC that leverages SSE, AVX, AVX2, and Xeon Phi instructions without any code change. ISPC also supports runtime code selection, thus ISPC will select the best code path for your application, while Embree selects the optimal code path for the ray tracing algorithms.

Embree contains algorithms optimized for incoherent workloads (e.g. Monte Carlo ray tracing algorithms) and coherent workloads (e.g. primary visibility and hard shadow rays). For standard CPUs, the single-ray traversal kernels in Embree provide the best performance for incoherent workloads and are very easy to integrate into existing rendering applications. For Xeon Phi, a renderer written in ISPC using the default hybrid ray/packet traversal algorithms have shown to perform best, but requires writing the renderer in ISPC. In general for coherent workloads, ISPC outperforms the single ray mode on each platform. Embree also supports dynamic scenes by implementing high performance two-level spatial index structure construction algorithms.

In addition to the ray tracing kernels, Embree provides some tutorials to demonstrate how to use the [Embree API](#). The example photorealistic renderer that was originally included in the Embree kernel package is now available in a separate GIT repository (see [Embree Example Renderer](#)).

1.1 Version History

1.1.1 New Features in Embree 2.5.1

- On dual socket workstations, the initial BVH build performance almost doubled through a better memory allocation scheme.
- Reduced memory usage for subdivision surface objects with crease features

- `rtcCommit` performance is robust against unset “flush to zero” and “denormals are zero” flags. However, enabling these flags in your application is still recommended.
- Internal cleanups and bugfixes.

1.1.2 New Features in Embree 2.5.0

- Improved hierarchy build performance on both Intel® Xeon® and Intel® Xeon Phi™
- Vastly improved tessellation cache for ray tracing subdivision surfaces
- Added `rtcGetUserData` API call to query per geometry user pointer set through `rtcSetUserData`.
- Added support for memory monitor callback functions to track and limit memory consumption.
- Added support for progress monitor callback functions to track build progress and cancel long build operations.
- BVH builders can be used to build user defined hierarchies inside the application (see tutorial11)
- Switched to TBB as default tasking system on Xeon to get even faster hierarchy build times and better integration for applications that also use TBB.
- `rtcCommit` can get called from multiple TBB threads to join the hierarchy build operations

1.1.3 New Features in Embree 2.4

- Support for Catmull Clark subdivision surfaces (triangle/quad base primitives)
- Support for vector displacements on Catmull Clark subdivision surfaces
- Various bugfixes (e.g. 4-byte alignment of vertex buffers works)

1.1.4 New Features in Embree 2.3.3

- BVH builders more robustly handle invalid input data (Intel Xeon processor family)
- Motion blur support for hair geometry (Xeon)
- Improved motion blur performance for triangle geometry (Xeon)
- Improved robust ray tracing mode (Xeon)
- Added `rtcCommitThread` API call for easier integration into existing tasking systems (Xeon and Intel Xeon Phi coprocessor)
- Added support for recording and replaying all `rtcIntersect/rtcOccluded` calls (Xeon and Xeon Phi)

1.1.5 New Features in Embree 2.3.2

- Improved mixed AABB/OBB-BVH for hair geometry (Xeon Phi)
- Reduced amount of pre-allocated memory for BVH builders (Xeon Phi)
- New 64 bit Morton code-based BVH builder (Xeon Phi)
- (Enhanced) Morton code-based BVH builders use now tree rotations to improve BVH quality (Xeon Phi)
- Bug fixes (Xeon and Xeon Phi)

1.1.6 New Features in Embree 2.3.1

- High quality BVH mode improves spatial splits which result in up to 30% performance improvement for some scenes (Xeon).
- Compile time enabled intersection filter functions do not reduce performance if no intersection filter is used in the scene (Xeon and Xeon Phi)
- Improved ray tracing performance for hair geometry by >20% on Xeon Phi. BVH for hair geometry requires 20% less memory
- BVH8 for AVX/AVX2 targets improves performance for single ray tracing on Haswell by up to 12% and by up to 5% for hybrid (Xeon)
- Memory conservative BVH for Xeon Phi now uses BVH node quantization to lower memory footprint (requires half the memory footprint of the default BVH)

1.1.7 New Features in Embree 2.3

- Support for ray tracing hair geometry (Xeon and Xeon Phi)
- Catching errors through error callback function
- Faster hybrid traversal (Xeon and Xeon Phi)
- New memory conservative BVH for Xeon Phi
- Faster Morton code-based builder on Xeon
- Faster binned-SAH builder on Xeon Phi
- Lots of code cleanups/simplifications/improvements (Xeon and Xeon Phi)

1.1.8 New Features in Embree 2.2

- Support for motion blur on Xeon Phi
- Support for intersection filter callback functions
- Support for buffer sharing with the application
- Lots of AVX2 optimizations, e.g. ~20% faster 8-wide hybrid traversal
- Experimental support for 8-wide (AVX/AVX2) and 16-wide BVHs (Xeon Phi)

1.1.9 New Features in Embree 2.1

- New future proof API with a strong focus on supporting dynamic scenes
- Lots of optimizations for 8-wide AVX2 (Haswell architecture)
- Automatic runtime code selection for SSE, AVX, and AVX2
- Support for user-defined geometry
- New and improved BVH builders:
 - Fast adaptive Morton code-based builder (without SAH-based top-level rebuild)
 - Both the SAH and Morton code-based builders got faster (Xeon Phi)
 - New variant of the SAH-based builder using triangle pre-splits (Xeon Phi)

1.1.10 Example Performance Numbers for Embree 2.1

BVH rebuild performance (including triangle accel generation, excluding memory allocation) for scenes with 2–12 million triangles:

- Intel® Core™ i7 (Haswell-based CPU, 4 cores @ 3.0 GHz)
 - 7–8 million triangles/s for the SAH-based BVH builder
 - 30–36 million triangles/s for the Morton code-based BVH builder

- Intel® Xeon Phi™ 7120
 - 37–40 million triangles/s for the SAH-based BVH builder
 - 140–160 million triangles/s for the Morton code-based BVH builder

Rendering of the Crown model (`crown.ecs`) with 4 samples per pixel (`- spp 4`):

- Intel® Core™ i7 (Haswell-based CPU, 4 cores CPU @ 3.0 GHz)
 - 1024×1024 resolution: 7.8 million rays per sec
 - 1920×1080 resolution: 9.9 million rays per sec
- Intel® Xeon Phi™ 7120
 - 1024×1024 resolution: 47.1 million rays per sec
 - 1920×1080 resolution: 61.1 million rays per sec

1.1.11 New Features in Embree 2.0

- Support for the Intel® Xeon Phi™ coprocessor platform
- Support for high-performance “packet” kernels on SSE, AVX, and Xeon Phi
- Integration with the Intel® SPMD Program Compiler (ISPC)
- Instantiation and fast BVH reconstruction
- Example photo-realistic rendering engine for both C++ and ISPC

1.2 Supported Platforms

Embree supports Windows (32 bit and 64 bit), Linux (64 bit) and Mac OS X (64 bit). The code compiles with the Intel Compiler, GCC, CLANG and the Microsoft Compiler. Embree is tested with Intel Compiler 15.0.2, CLANG 3.4.2, GCC 4.8.2, and Visual Studio 12 2013. Using the Intel Compiler improves performance by approximately 10%.

Performance also varies across different operating systems. Embree is optimized for Intel CPUs supporting SSE, AVX, and AVX2 instructions, and requires at least a CPU with support for SSE2.

The Xeon Phi version of Embree only works under Linux in 64 bit mode. For compilation of the the Xeon Phi code the Intel Compiler is required. The host side code compiles with GCC, CLANG, and the Intel Compiler.

1.3 Embree Support and Contact

If you encounter bugs please report them via [Embree’s GitHub Issue Tracker](#).

For questions please write us at embree_support@intel.com.

To receive notifications of updates and new features of Embree please subscribe to the [Embree mailing list](#).

Chapter 2

Installation of Embree

This section describes how to install Embree. You can download the referenced installers from the embree webpage <https://embree.github.com/>.

2.1 Windows Installer

You can install the 64 bit version of the Embree library using the Windows installer application `embree-2.5.1.x64.exe`. This will install the 64 bit Embree version by default in `Program Files\Intel\Embree 2.5.1`. To install the 32 bit Embree library use the `embree-2.5.1.win32.exe` installer. This will install the 32 bit Embree version by default in `Program Files\Intel\Embree 2.5.1` on 32 bit systems and `Program Files (x86)\Intel\Embree 2.5.1` on 64 bit systems.

You have to set the path to the `lib` folder manually to your `PATH` environment variable for applications to find Embree. To compile applications with Embree you also have to set the `Include Directories` path in Visual Studio to the `include` folder of the Embree installation.

To uninstall Embree again open `Programs and Features` by clicking the `Start` button, clicking `Control Panel`, clicking `Programs`, and then clicking `Programs and Features`. Select `Embree 2.5.1` and uninstall it.

2.2 Windows ZIP File

Embree is also delivered as a ZIP file `embree-2.5.1.x64.windows.zip`. After unpacking this ZIP file you should set the path to the `lib` folder manually to your `PATH` environment variable for applications to find Embree. To compile applications with Embree you also have to set the `Include Directories` path in Visual Studio to the `include` folder of the Embree installation.

If you plan to ship Embree with your application, best use the Embree version from this ZIP file.

2.3 Linux RPMs

Use the provided RPMs to install Embree on your Linux system:

```
sudo rpm --install embree-devel-2.5.1-1.x86_64.rpm
sudo rpm --install embree-examples-2.5.1-1.x86_64.rpm
```

To also install the Intel® Xeon Phi™ version of Embree additionally install the following Xeon Phi™ RPMs:

```
sudo rpm --install embree-devel_xeonphi-2.5.1-1.x86_64.rpm
sudo rpm --install embree-examples_xeonphi-2.5.1-1.x86_64.rpm
```

You also have to install the Intel® Threading Building Blocks (TBB) of at least version 4.3 either using yum:

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

or via apt-get:

```
sudo apt-get install libtbb-dev
```

Alternatively you can download the latest TBB version from <https://www.threadingbuildingblocks.org/download> and set the LD_LIBRARY_PATH environment variable to point to the TBB library.

Under Linux Embree is installed by default in the /usr/lib and /usr/include directories. This way applications will find Embree automatically. The Embree tutorials are installed into the /usr/bin/embree-2.5.1 folder. Specify the full path to the tutorials to start them.

To uninstall Embree again just execute the following:

```
sudo rpm --erase embree-devel-2.5.1-1.x86_64
sudo rpm --erase embree-examples-2.5.1-1.x86_64
```

If you also installed the Xeon Phi™ RPMs you have to uninstall them too:

```
sudo rpm --erase embree-devel_xeonphi-2.5.1-1.x86_64
sudo rpm --erase embree-examples_xeonphi-2.5.1-1.x86_64
```

2.4 Linux tar.gz files

The Linux version of Embree is also delivered as a tar.gz file embree-2.5.1.x64.linux.tar.gz. Unpack this file using tar and source the provided embree-vars.sh to setup the environment properly:

```
tar xzf embree-2.5.1.x64.linux.tar.gz
source embree-2.5.1.x64.linux/embree-vars.sh
```

If you want to ship Embree with your application best use the Embree version provided through the tar.gz file.

2.5 Mac OS X PKG Installer

To install the Embree library on your Mac OS X system use the provided package installer inside embree-2.5.1.x86_64.dmg. This will install Embree by default into /opt/local/lib and /opt/local/include directories. The Embree tutorials are installed into the /Applications/embree-2.5.1 folder.

You also have to install the Intel® Threading Building Blocks (TBB) using [MacPorts](#):

```
sudo port install tbb
```

Alternatively you can download the latest TBB version from <https://www.threadingbuildingblocks.org/download> and set the DYLD_LIBRARY_PATH environment variable to point to the TBB library.

To uninstall Embree again execute the uninstaller script /Applications/embree-2.5.1/uninstall.command.

2.6 Mac OS X tar.gz file

The Mac OS X version of Embree is also delivered as a tar.gz file `embree-2.5.1.x64.macosx.tar.gz`. Unpack this file using `tar` and source the provided `embree-vars.sh` to setup the environment properly:

```
tar xzf embree-2.5.1.x64.macosx.tar.gz
source embree-2.5.1.x64.macosx/embree-vars.sh
```

If you want to ship Embree with your application please use the Embree library of the provided tar.gz file. The library name of that Embree library does not contain any global path and also links against TBB without global path. This ensures that the Embree (and TBB) library that you put next to your application executable is used.

2.7 Linking ISPC applications with Embree

The precompiled Embree library uses the multi-target mode of ISPC. For your ISPC application to properly link against Embree you also have to enable this mode. You can do this by specifying multiple targets when compiling your application with ISPC, e.g.:

```
ispc --target sse2,sse4,avx,avx2 -o code.o code.ispc
```

Chapter 3

Compiling Embree

3.1 Linux and Mac OS X

To compile Embree you need a modern C++ compiler that supports C++11. Embree is tested with Intel® Compiler 15.0.2, CLANG 3.4.2, and GCC 4.8.2. If the GCC that comes with your Fedora/Redhat/CentOS distribution is too old then you can run the provided script `scripts/install_linux_gcc.sh` to locally install a recent GCC into `$HOME/devtools-2`.

Embree supports to use the Intel® Threading Building Blocks (TBB) as tasking system. For performance and flexibility reasons we recommend to use Embree with the Intel® Threading Building Blocks (TBB) and best also use TBB inside your application. Optionally you can disable TBB in Embree through the `RT-CORE_TASKING_SYSTEM` CMake variable.

Embree supported the Intel® SPMD Program Compiler (ISPC), which allows straight forward parallelization of an entire renderer. If you do not want to use ISPC then you can disable `ENABLE_ISPC_SUPPORT` in CMake. Otherwise, download and install the ISPC binaries (we have tested ISPC version 1.8.0) from ispc.github.io. After installation, put the path to `ispc` permanently into your `PATH` environment variable or you need to correctly set the `ISPC_EXECUTABLE` variable during CMake configuration.

You additionally have to install CMake 2.8.11 or higher and the developer version of GLUT.

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

```
sudo port install cmake tbb freeglut
```

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

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

```
sudo yum install cmake.x86_64
sudo yum install tbb.x86_64 tbb-devel.x86_64
sudo yum install freeglut.x86_64 freeglut-devel.x86_64
sudo yum install libXmu.x86_64 libXi.x86_64
sudo yum install libXmu-devel.x86_64 libXi-devel.x86_64
```

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

```
sudo apt-get install cmake-curses-gui
sudo apt-get install libtbb-dev
sudo apt-get install freeglut3-dev
sudo apt-get install libxmu-dev libxi-dev
```

Finally you can compile Embree using CMake. Create a build directory inside the Embree root directory and execute “cmake ..” inside this build directory.

```
mkdir build
cd build
cmake ..
```

This will open a configuration dialog where you can perform various configurations as described below. After having configured Embree, press c (for configure) and g (for generate) to generate a Makefile and leave the configuration. The code can be compiled by executing make.

```
make
```

The executables will be generated inside the build folder. We recommend to finally install the Embree library and header files on your system. Therefore set the CMAKE_INSTALL_PREFIX to /usr in cmake and type:

```
sudo make install
```

If you keep the default CMAKE_INSTALL_PREFIX of /usr/local then you have to make sure the path /usr/local/lib is in your LD_LIBRARY_PATH.

You can also uninstall Embree again by executing:

```
sudo make uninstall
```

If you cannot install Embree on your system (e.g. when you don't have administrator rights) you need to add embree_root_directory/build to your LD_LIBRARY_PATH (and SINK_LD_LIBRARY_PATH in case you want to use Embree on Intel® Xeon Phi™ coprocessors).

3.1.1 Intel® Xeon Phi™ coprocessor

Embree supports the Intel® Xeon Phi™ coprocessor under Linux. To compile Embree for Xeon Phi you need to enable the XEON_PHI_ISA option in CMake and have the Intel Compiler and the Intel® [Manycore Platform Software Stack](#) (Intel® MPSS) installed.

Enabling the buffer stride feature reduces performance for building spatial hierarchies on Xeon Phi. Under Xeon Phi the Intel® Threading Building Blocks (TBB) tasking system is not supported, and the implementation will always use some internal tasking system.

3.2 Windows

To compile Embree under Windows you need a recent version of Visual Studio that supports C++11. We have tested Visual Studio 2013, Visual Studio 2012, and Visual Studio 2010. Under Visual Studio 2013 you can enable AVX2 in CMake, however, Visual Studio 2012 supports at most AVX, and Visual Studio 2010 at most the SSE4.2 CMake configuration.

Embree supports to use the Intel® Threading Building Blocks (TBB) as tasking system. For performance and flexibility reasons we recommend to use Embree with the Intel® Threading Building Blocks (TBB) and best also use TBB inside your application. Optionally you can disable TBB in Embree through the RT-CORE_TASKING_SYSTEM CMake variable.

Embree will either find the Intel® Threading Building Blocks (TBB) installation that comes with the Intel® Compiler, or you can install the binary distribution of TBB directly from www.threadingbuildingblocks.org into a folder

named `tbb` into your Embree root directory. You also have to make sure that the libraries `tbb.dll` and `tbb_malloc.dll` can be found when executing your Embree applications, e.g. by putting the path to these libraries into your `PATH` environment variable.

Embree supported the Intel® SPMD Program Compiler (ISPC), which allows straight forward parallelization of an entire renderer. If you do not want to use ISPC then you can disable `ENABLE_ISPC_SUPPORT` in CMake. Otherwise, download and install the ISPC binaries (we have tested ISPC version 1.8.0) from ispc.github.io. After installation, put the path to `ispc.exe` permanently into your `PATH` environment variable or you need to correctly set the `ISPC_EXECUTABLE` variable during CMake configuration.

You additionally have to install CMake (version 2.8.11 or higher). Note that you need a native Windows CMake installation, because CMake under Cygwin cannot generate solution files for Visual Studio.

3.2.1 Using the IDE

Run `cmake-gui`, browse to the Embree sources, set the build directory and click Configure. Now you can select the Generator, e.g. “Visual Studio 12 2013” for a 32 bit build or “Visual Studio 12 2013 Win64” for a 64 bit build. Most configuration parameters described for the [Linux build](#) can be set under Windows as well. Finally, click “Generate” to create the Visual Studio solution files.

Option	Description	Default
<code>CMAKE_CONFIGURATION_TYPES</code>	Generated configurations.	Debug;Release;RelWithDebInfo
<code>USE_STATIC_RUNTIME</code>	Use the static version of the C/C++ runtime library.	OFF

Table 3.1 – Windows-specific CMake build options for Embree.

For compilation of Embree under Windows use the generated Visual Studio solution file `embree2.sln`. The solution is by default setup to use the Microsoft Compiler. You can switch to the Intel Compiler by right clicking onto the solution in the Solution Explorer and then selecting the Intel Compiler. We recommend using 64 bit mode and the Intel Compiler for best performance.

To build Embree with support for the AVX2 instruction set you need at least Visual Studio 2013 Update 4. When switching to the Intel Compiler to build with AVX2 you currently need to manually *remove* the switch `/arch:AVX2` from the `embree_avx2` project, which can be found under Properties ⇒ C/C++ ⇒ All Options ⇒ Additional Options.

To build all projects of the solution it is recommend to build the CMake utility project `ALL_BUILD`, which depends on all projects. Using “Build Solution” would also build all other CMake utility projects (such as `INSTALL`), which is usually not wanted.

We recommend enabling syntax highlighting for the `.ispc` source and `.isph` header files. To do so open Visual Studio, go to Tools ⇒ Options ⇒ Text Editor ⇒ File Extension and add the `isph` and `ispc` extension for the “Microsoft Visual C++” editor.

3.2.2 Using the Command Line

Embree can also be configured and built without the IDE using the Visual Studio command prompt:

```
cd path\to\embree
mkdir build
cd build
cmake -G "Visual Studio 12 2013 Win64" ..
cmake --build . --config Release
```

You can also build only some projects with the `--target` switch. Additional parameters after “`--`” will be passed to `msbuild`. For example, to build the Embree library in parallel use

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

3.3 CMake configuration

The default CMake configuration in the configuration dialog should be appropriate for most usages. The following table describes all parameters that can be configured in CMake:

Option	Description	Default
CMAKE_BUILD_TYPE	Can be used to switch between Debug mode (Debug), Release mode (Release), and Release mode with enabled assertions and debug symbols (RelWithDebInfo).	Release
COMPILER	Select either GCC, ICC, or CLANG as compiler.	GCC
ENABLE_ISPC_SUPPORT	Enables ISPC support of Embree.	ON
ENABLE_STATIC_LIB	Builds Embree as a static library.	OFF
ENABLE_TUTORIALS	Enables build of Embree tutorials.	ON
ENABLE_XEON_PHI_SUPPORT	Enables generation of the Xeon Phi version of Embree.	OFF
RTCORE_BACKFACE_CULLING	Enables backface culling, i.e. only surfaces facing a ray can be hit.	OFF
RTCORE_BUFFER_STRIDE	Enables the buffer stride feature.	ON
RTCORE_INTERSECTION_FILTER	Enables the intersection filter feature.	ON
RTCORE_RAY_MASK	Enables the ray masking feature.	OFF
RTCORE_RETURN_SUBDIV_NORMAL	Instead of the triangle normal the ray returns a smooth normal based on evaluating the subdivision surface patch.	OFF
RTCORE_TASKING_SYSTEM	Chooses between Intel® Threading Building Blocks (TBB) or an internal tasking system (INTERNAL).	TBB
XEON_ISA	Select highest supported ISA on Intel® Xeon® CPUs (SSE2, SSE3, SSSE3, SSE4.1, SSE4.2, AVX, AVX-I, or AVX2).	AVX2

Table 3.2 – CMake build options for Embree.

Chapter 4

Embree API

The Embree API is a low level ray tracing API that supports defining and committing of geometry and performing ray queries of different types. Static and dynamic scenes are supported, that may contain triangular geometry (including linear motions for motion blur), instanced geometry, and user defined geometry. Supported ray queries are, finding the closest scene intersection along a ray, and testing a ray segment for any intersection with the scene. Single rays, as well as packets of rays in a struct of array layout can be used for packet sizes of 1, 4, 8, and 16 rays. Filter callback functions are supported, that get invoked for every intersection encountered during traversal.

The Embree API exists in a C++ and ISPC version. This document describes the C++ version of the API, the ISPC version is almost identical. The only differences are that the ISPC version needs some ISPC specific uniform type modifiers, and limits the ray packets to the native SIMD size the ISPC code is compiled for.

The user is supposed to include the `embree2/rtcore.h`, and the `embree2/rtcore_ray.h` file, but none of the other header files. If using the ISPC version of the API, the user should include `embree2/rtcore.isph` and `embree2/rtcore_ray.isph`.

```
#include <embree2/rtcore.h>
#include <embree2/rtcore_ray.h>
```

All API calls carry the prefix `rtc` which stands for ray tracing core. Before invoking any API call, the Embree ray tracing core has to get initialized through the `rtcInit` call. Before the application exits it should call `rtcExit`. Initializing Embree again after an `rtcExit` is allowed.

```
rtcInit(NULL);
...
rtcExit();
```

It is strongly recommended to have the `Flush to Zero` and `Denormals are Zero` mode of the `MXCSR` control and status register enabled for each thread before calling the `rtcIntersect` and `rtcOccluded` functions. Otherwise, under some circumstances special handling of denormalized floating point numbers can significantly reduce application and Embree performance. When using Embree together with the Intel® Threading Building Blocks, it is sufficient to execute the following code at the beginning of the application main thread (before the creation of the `tbb::task_scheduler_init` object):

```
#include <xmmintrin.h>
#include <pmmintrin.h>
...
_MM_SET_FLUSH_ZERO_MODE(_MM_FLUSH_ZERO_ON);
_MM_SET_DENORMALS_ZERO_MODE(_MM_DENORMALS_ZERO_ON);
```

Embree processes some implementation specific configuration from the following locations in the specified order:

- 1) configuration string passed to the `rtcInit` function
- 2) `.embree2` file in the application folder
- 3) `.embree2` file in the home folder

This way the configuration for the application can be changed globally (either through the `rtcInit` call or through the `.embree2` file in the application folder) and each user has the option to modify the configuration to fit its needs.

The threads calling the API functions should have at least 4MB of stack space allocated. Also every Intel® Threading Building Blocks (TBB) worker thread needs at least 4MB of stack space (which is the default for TBB).

API calls that access geometries are only thread safe as long as different geometries are accessed. Accesses to one geometry have to get sequenced by the application. All other API calls are thread safe. The API calls are re-entrant, it is thus safe to trace new rays and create new geometry when intersecting a user defined object.

Each user thread has its own error flag in the API. If an error occurs when invoking some API function, this flag is set to an error code if it stores no previous error. The `rtcGetError` function reads and returns the currently stored error and clears the error flag again.

Possible error codes returned by `rtcGetError` are:

Error Code	Description
<code>RTC_NO_ERROR</code>	No error occurred.
<code>RTC_UNKNOWN_ERROR</code>	An unknown error has occurred.
<code>RTC_INVALID_ARGUMENT</code>	An invalid argument was specified.
<code>RTC_INVALID_OPERATION</code>	The operation is not allowed for the specified object.
<code>RTC_OUT_OF_MEMORY</code>	There is not enough memory left to complete the operation.
<code>RTC_UNSUPPORTED_CPU</code>	The CPU is not supported as it does not support SSE2.
<code>RTC_CANCELLED</code>	The operation got cancelled by an Memory Monitor Callback or Progress Monitor Callback function.

Table 4.1 – Return values of `rtcGetError`.

Using the `rtcSetErrorFunction` call, it is also possible to set a callback function that is called whenever an error occurs. The callback function gets passed the error code, as well as some string that describes the error further. Passing `NULL` to `rtcSetErrorFunction` disables the set callback function again. The previously described error flags are also set if an error callback function is present.

4.1 Scene

A scene is a container for a set of geometries of potentially different types. A scene is created using the `rtcNewScene` function call, and destroyed using the `rtcDeleteScene` function call. Two types of scenes are supported, dynamic and static scenes. Different flags specify the type of scene to create and the type of ray query operations that can later be performed on the scene. The following example creates a scene that supports dynamic updates and the single ray `rtcIntersect` and `rtcOccluded` calls.

```
RTCScene scene = rtcNewScene(RTC_SCENE_DYNAMIC, RTC_INTERSECT1);
...
rtcDeleteScene(scene);
```

Using the following scene flags the user can select between creating a static and dynamic scene.

Scene Flag	Description
RTC_SCENE_STATIC	Scene is optimized for static geometry.
RTC_SCENE_DYNAMIC	Scene is optimized for dynamic geometry.

Table 4.2 – Dynamic type flags for `rtcNewScene`.

A dynamic scene is created by invoking `rtcNewScene` with the `RTC_SCENE_DYNAMIC` flag. Different geometries can now be created inside that scene. Geometries are enabled by default. Once the scene geometry is specified, an `rtcCommit` call will finish the scene description and trigger building of internal data structures. After the `rtcCommit` call it is safe to perform ray queries of the type specified at scene construction time. Geometries can get disabled (`rtcDisable` call), enabled again (`rtcEnable` call), and deleted (`rtcDeleteGeometry` call). Geometries can also get modified, including their vertex and index arrays. After the modification of some geometry, `rtcUpdate` or `rtcUpdateBuffer` has to get called for that geometry to specify which buffers got modified. Each modified buffer can be specified separately using the `rtcUpdateBuffer` function. In contrast the `rtcUpdate` function simply tags each buffer of some geometry as modified. If geometries got enabled, disabled, deleted, or modified an `rtcCommit` call has to get invoked before performing any ray queries for the scene, otherwise the effect of the ray query is undefined. During an `rtcCommit` call modifications to the scene are not allowed.

A static scene is created by the `rtcNewScene` call with the `RTC_SCENE_STATIC` flag. Geometries can only be created and modified until the first `rtcCommit` call. After the `rtcCommit` call, each access to any geometry of that static scene is invalid, including enabling, disabling, modifying, and deletion of geometries. Consequently, geometries that got created inside a static scene can only get deleted by deleting the entire scene.

The modification of geometry, building of hierarchies using `rtcCommit`, and tracing of rays have always to happen separately, never at the same time.

The following flags can be used to tune the used acceleration structure. These flags are only hints and may be ignored by the implementation.

Scene Flag	Description
RTC_SCENE_COMPACT	Creates a compact data structure and avoids algorithms that consume much memory.
RTC_SCENE_COHERENT	Optimize for coherent rays (e.g. primary rays).
RTC_SCENE_INCOHERENT	Optimize for in-coherent rays (e.g. diffuse reflection rays).
RTC_SCENE_HIGH_QUALITY	Build higher quality spatial data structures.

Table 4.3 – Acceleration structure flags for `rtcNewScene`.

The following flags can be used to tune the traversal algorithm that is used by Embree. These flags are only hints and may be ignored by the implementation.

The second argument of the `rtcNewScene` function are algorithm flags, that allow to specify which ray queries are required by the application. Calling for a scene a ray query API function that is different to the ones specified at scene creation time is not allowed. Further, the application should only pass ray query

Scene Flag	Description
<code>RTC_SCENE_ROBUST</code>	Avoid optimizations that reduce arithmetic accuracy.

Table 4.4 – Traversal algorithm flags for `rtcNewScene`.

requirements that are really needed, to give Embree most freedom in choosing the best algorithm. E.g. in case Embree implements no packet traversers for some highly optimized data structure for single rays, then this data structure cannot be used if the user enables any ray packet query.

Algorithm Flag	Description
<code>RTC_INTERSECT1</code>	Enables the <code>rtcIntersect</code> and <code>rtcOccluded</code> functions (single ray interface) for this scene.
<code>RTC_INTERSECT4</code>	Enables the <code>rtcIntersect4</code> and <code>rtcOccluded4</code> functions (4-wide packet interface) for this scene.
<code>RTC_INTERSECT8</code>	Enables the <code>rtcIntersect8</code> and <code>rtcOccluded8</code> functions (8-wide packet interface) for this scene.
<code>RTC_INTERSECT16</code>	Enables the <code>rtcIntersect16</code> and <code>rtcOccluded16</code> functions (16-wide packet interface) for this scene.

Table 4.5 – Enabled algorithm flags for `rtcNewScene`.

4.2 Geometries

Geometries are always contained in the scene they are created in. Each geometry is assigned an integer ID at creation time, which is unique for that scene. The current version of the API supports triangle meshes (`rtcNewTriangleMesh`), Catmull-Clark subdivision surfaces (`rtcNewSubdivisionMesh`), hair geometries (`rtcNewHairGeometry`), single level instances of other scenes (`rtcNewInstance`), and user defined geometries (`rtcNewUserGeometry`). The API is designed in a way that easily allows adding new geometry types in later releases.

For dynamic scenes, the assigned geometry IDs fulfill the following properties. As long as no geometry got deleted, all IDs are assigned sequentially, starting from 0. If geometries got deleted, the implementation will reuse IDs later on in an implementation dependent way. Consequently sequential assignment is no longer guaranteed, but a compact range of IDs. These rules allow the application to manage a dynamic array to efficiently map from geometry IDs to its own geometry representation.

For static scenes, geometry IDs are assigned sequentially starting at 0. This allows the application to use a fixed size array to map from geometry IDs to its own geometry representation.

Alternatively the application can also use the void `rtcSetUserData` (`RTCScene scene, unsigned geomID, void* ptr`) function to set a pointer `ptr` to its own geometry representation, and later read out this pointer again using the void* `rtcGetUserData` (`RTCScene scene, unsigned geomID`) function.

4.2.1 Triangle Meshes

Triangle meshes are created using the `rtcNewTriangleMesh` function call, and potentially deleted using the `rtcDeleteGeometry` function call.

The number of triangles, the number of vertices, and optionally the number of time steps (1 for normal meshes, and 2 for linear motion blur) have to get specified at construction time of the mesh. The user can also specify additional flags

that choose the strategy to handle that mesh in dynamic scenes. The following example demonstrates how to create a triangle mesh without motion blur:

```
unsigned geomID = rtcNewTriangleMesh(scene, geomFlags, numTriangles, numVertices);
```

The following geometry flags can be specified at construction time of the triangle mesh:

Geometry Flag	Description
RTC_GEOMETRY_STATIC	The mesh is considered static and should get modified rarely by the application. This flag has to get used in static scenes.
RTC_GEOMETRY_DEFORMABLE	The mesh is considered to deform in a coherent way, e.g. a skinned character. The connectivity of the mesh has to stay constant, thus modifying the index array is not allowed. The implementation is free to choose a BVH refitting approach for handling meshes tagged with that flag.
RTC_GEOMETRY_DYNAMIC	The mesh is considered highly dynamic and changes frequently, possibly in an unstructured way. Embree will rebuild data structures from scratch for this type of mesh.

Table 4.6 – Flags for the creation of new geometries.

The triangle indices can be set by mapping and writing to the index buffer (RTC_INDEX_BUFFER) and the triangle vertices can be set by mapping and writing into the vertex buffer (RTC_VERTEX_BUFFER). The index buffer contains an array of three 32 bit indices, while the vertex buffer contains an array of three float values aligned to 16 bytes. The 4th component of the aligned vertices can be arbitrary. All buffers have to get unmapped before an `rtcCommit` call to the scene.

```
struct Vertex { float x, y, z, a; };
struct Triangle { int v0, v1, v2; };
```

```
Vertex* vertices = (Vertex*) rtcMapBuffer(scene, geomID, RTC_VERTEX_BUFFER);
// fill vertices here
rtcUnmapBuffer(scene, geomID, RTC_VERTEX_BUFFER);
```

```
Triangle* triangles = (Triangle*) rtcMapBuffer(scene, geomID, RTC_INDEX_BUFFER);
// fill triangle indices here
rtcUnmapBuffer(scene, geomID, RTC_INDEX_BUFFER);
```

Also see tutorial00 for an example of how to create triangle meshes.

4.2.2 Subdivision Surfaces

Catmull-Clark subdivision surfaces for meshes consisting of triangle and quad primitives (even mixed inside one mesh) are supported, including support for edge creases, vertex creases, holes, and non-manifold geometry.

A subdivision surface is created using the `rtcNewSubdivisionMesh` function call, and deleted again using the `rtcDeleteGeometry` function call.

```
unsigned rtcNewSubdivisionMesh(RTCScene scene,
                              RTCGeometryFlags flags,
```

```
size_t numFaces,  
size_t numEdges,  
size_t numVertices,  
size_t numEdgeCreases,  
size_t numVertexCreases,  
size_t numCorners,  
size_t numHoles,  
size_t numTimeSteps);
```

The number of faces (`numFaces`), edges/indices (`numEdges`), vertices (`numVertices`), edge creases (`numEdgeCreases`), vertex creases (`numVertexCreases`), holes (`numHoles`), and time steps (`numTimeSteps`) have to get specified at construction time.

The following buffers have to get setup by the application: the face buffer (`RTC_FACE_BUFFER`) contains the number edges/indices (3 or 4) of each of the `numFaces` faces, the index buffer (`RTC_INDEX_BUFFER`) contains multiple (3 or 4) 32 bit vertex indices for each face and `numEdges` indices in total, the vertex buffer (`RTC_VERTEX_BUFFER`) stores `numVertices` vertices as single precision x, y, z floating point coordinates aligned to 16 bytes. The value of the 4th float used for alignment can be arbitrary.

Optionally, the application can setup the hole buffer (`RTC_HOLE_BUFFER`) with `numHoles` many 32 bit indices of faces that should be considered non-existing.

Optionally, the application can fill the level buffer (`RTC_LEVEL_BUFFER`) with a tessellation level for each or the edges of each face, making a total of `numEdges` values. The tessellation level is a positive floating point value, that specifies how many quads along the edge should get generated during tessellation. The tessellation level is a lower bound, thus the implementation is free to choose a larger level. If no level buffer is specified a level of 1 is used. Note that some edge may be shared between (typically 2) faces. To guarantee a watertight tessellation, the level of these shared edges has to be exactly identical.

Optionally, the application can fill the sparse edge crease buffers to make some edges appear sharper. The edge crease index buffer (`RTC_EDGE_CREASE_INDEX_BUFFER`) contains `numEdgeCreases` many pairs of 32 bit vertex indices that specify unoriented edges. The edge crease weight buffer (`RTC_EDGE_CREASE_WEIGHT_BUFFER`) stores for each of these crease edges a positive floating point weight. The larger this weight, the sharper the edge. Specifying a weight of infinity is supported and marks an edge as infinitely sharp. Storing an edge multiple times with the same crease weight is allowed, but has lower performance. Storing an edge multiple times with different crease weights results in undefined behavior. For a stored edge (i,j), the reverse direction edges (j,i) does not have to get stored, as both are considered the same edge.

Optionally, the application can fill the sparse vertex crease buffers to make some vertices appear sharper. The vertex crease index buffer (`RTC_VERTEX_CREASE_INDEX_BUFFER`), contains `numVertexCreases` many 32 bit vertex indices to specify a set of vertices. The vertex crease weight buffer (`RTC_VERTEX_CREASE_WEIGHT_BUFFER`) specifies for each of these vertices a positive floating point weight. The larger this weight, the sharper the vertex. Specifying a weight of infinity is supported and makes the vertex infinitely sharp. Storing a vertex multiple times with the same crease weight is allowed, but has lower performance. Storing a vertex multiple times with different crease weights results in undefined behavior.

Like for triangle meshes, the user can also specify a geometry mask and additional flags that choose the strategy to handle that subdivision mesh in dynamic scenes.

Also see `tutorial08` for an example of how to create subdivision surfaces.

4.2.3 Hair Geometry

Hair geometries are supported, which consist of multiple hairs represented as cubic Bézier curves with varying radius per control point. Individual hairs are considered to be subpixel sized which allows the implementation to approximate the intersection calculation. This in particular means that zooming onto one hair might show geometric artifacts.

Hair geometries are created using the `rtcNewHairGeometry` function call, and potentially deleted using the `rtcDeleteGeometry` function call.

The number of hair curves, the number of vertices, and optionally the number of time steps (1 for normal curves, and 2 for linear motion blur) have to get specified at construction time of the hair geometry.

The curve indices can be set by mapping and writing to the index buffer (`RTC_INDEX_BUFFER`) and the control vertices can be set by mapping and writing into the vertex buffer (`RTC_VERTEX_BUFFER`). In case of linear motion blur, two vertex buffers (`RTC_VERTEX_BUFFER0` and `RTC_VERTEX_BUFFER1`) have to get filled, one for each time step.

The index buffer contains an array of 32 bit indices pointing to the ID of the first of four control vertices, while the vertex buffer stores all control points in the form of a single precision position and radius stored in `x, y, z, r` order in memory. The hair radii have to be greater or equal zero. All buffers have to get unmapped before an `rtcCommit` call to the scene.

Like for triangle meshes, the user can also specify a geometry mask and additional flags that choose the strategy to handle that mesh in dynamic scenes.

The following example demonstrates how to create some hair geometry:

```
unsigned geomID = rtcNewHairGeometry(scene, geomFlags, numCurves, numVertices);

struct Vertex { float x, y, z, r; };

Vertex* vertices = (Vertex*) rtcMapBuffer(scene, geomID, RTC_VERTEX_BUFFER);
// fill vertices here
rtcUnmapBuffer(scene, geomID, RTC_VERTEX_BUFFER);

int* curves = (int*) rtcMapBuffer(scene, geomID, RTC_INDEX_BUFFER);
// fill indices here
rtcUnmapBuffer(scene, geomID, RTC_INDEX_BUFFER);
```

Also see `tutorial07` for an example of how to create and use hair geometry.

4.2.4 User Defined Geometry

User defined geometries make it possible to extend Embree with arbitrary types of geometry. This is achieved by introducing arrays of user geometries as a special geometry type. These objects do not contain a single user geometry, but a set of such geometries, each specified by an index. The user has to provide a user data pointer, bounding function as well as user defined intersect and occluded functions to create a set of user geometries. The user geometry to process is specified by passing its user data pointer and index to each invocation of the bounding, intersect, and occluded function. The bounding function is used to query the bounds of each user geometry. When performing ray queries, Embree will invoke the user intersect (and occluded) functions to test rays for intersection (and occlusion) with the specified user defined geometry.

As Embree supports different ray packet sizes, one potentially has to provide different versions of user intersect and occluded function pointers for these packet sizes. However, the ray packet size of the called user function always

matches the packet size of the originally invoked ray query function. Consequently, an application only operating on single rays only has to provide single ray intersect and occluded function pointers.

User geometries are created using the `rtcNewUserGeometry` function call, and potentially deleted using the `rtcDeleteGeometry` function call. The following example illustrates creating an array with two user geometries:

```
struct UserObject { ... };

void userBoundsFunction(UserObject* userGeom, size_t i, RTCBounds& bounds) {
    bounds = <bounds of userGeom[i]>;
}

void userIntersectFunction(UserObject* userGeom, RTCRay& ray, size_t i) {
    if (<ray misses userGeom[i]>)
        return;
    <update ray hit information>;
}

void userOccludedFunction(UserObject* userGeom, RTCRay& ray, size_t i) {
    if (<ray misses userGeom[i]>)
        return;
    geomID = 0;
}

...

UserObject* userGeom = new UserObject[2];
userGeom[0] = ...
userGeom[1] = ...
unsigned geomID = rtcNewUserGeometry(scene, 2);
rtcSetUserData(scene, geomID, userGeom);
rtcSetBounds(scene, geomID, userBoundsFunction);
rtcSetIntersectFunction(scene, geomID, userIntersectFunction);
rtcSetOccludedFunction(scene, geomID, userOccludedFunction);
```

The user intersect function (`userIntersectFunction`) and user occluded function (`userOccludedFunction`) get as input the pointer provided through the `rtcSetUserData` function call, a ray, and the index of the geometry to process. For ray packets, the user intersect and occluded functions also get a pointer to a valid mask as input. The user provided functions should not modify any ray that is disabled by that valid mask.

The user intersect function should return without modifying the ray structure if the user geometry is missed. If the geometry is hit, it has to update the hit information of the ray (`tfar`, `u`, `v`, `Ng`, `geomID`, `primID`).

Also the user occluded function should return without modifying the ray structure if the user geometry is missed. If the geometry is hit, it should set the `geomID` member of the ray to 0.

See `tutorial02` for an example of how to use the user defined geometries.

4.2.5 Instances

Embree supports instancing of scenes inside another scene by some transformation. As the instanced scene is stored only a single time, even if instanced to multiple locations, this feature can be used to create extremely large scenes. Only single level instancing is supported by Embree natively, however, multi-level instancing can principally be implemented through user geometries.

Instances are created using the `rtcNewInstance` function call, and potentially deleted using the `rtcDeleteGeometry` function call. To instantiate a scene, one first has to generate the scene B to instantiate. Now one can add an instance of this scene inside a scene A the following way:

```
unsigned instID = rtcNewInstance(sceneA, sceneB);
rtcSetTransform(sceneA, instID, RTC_MATRIX_COLUMN_MAJOR, &column_matrix_3x4);
```

One has to call `rtcCommit` on scene B before one calls `rtcCommit` on scene A. When modifying scene B one has to call `rtcModified` for all instances of that scene. If a ray hits the instance, then the `geomID` and `primID` members of the ray are set to the geometry ID and primitive ID of the primitive hit in scene B, and the `instID` member of the ray is set to the instance ID returned from the `rtcNewInstance` function.

The `rtcSetTransform` call can be passed an affine transformation matrix with different data layouts:

Layout	Description
<code>RTC_MATRIX_ROW_MAJOR</code>	The 3×4 float matrix is laid out in row major form.
<code>RTC_MATRIX_COLUMN_MAJOR</code>	The 3×4 float matrix is laid out in column major form.
<code>RTC_MATRIX_COLUMN_MAJOR_ALIGNED16</code>	The 3×4 float matrix is laid out in column major form, with each column padded by an additional 4th component.

Table 4.7 – Matrix layouts for `rtcSetTransform`.

Passing homogeneous 4×4 matrices is possible as long as the last row is (0, 0, 0, 1). If this homogeneous matrix is laid out in row major form, use the `RTC_MATRIX_ROW_MAJOR` layout. If this homogeneous matrix is laid out in column major form, use the `RTC_MATRIX_COLUMN_MAJOR_ALIGNED16` mode. In both cases, Embree will ignore the last row of the matrix.

The transformation passed to `rtcSetTransform` transforms from the local space of the instantiated scene to world space.

See `tutorial04` for an example of how to use instances.

4.3 Ray Queries

The API supports finding the closest hit of a ray segment with the scene (`rtcIntersect` functions), and determining if any hit between a ray segment and the scene exists (`rtcOccluded` functions).

```
void rtcIntersect (          RTCScene scene, RTCRay& ray);
void rtcIntersect4 (const void* valid, RTCScene scene, RTCRay4& ray);
void rtcIntersect8 (const void* valid, RTCScene scene, RTCRay8& ray);
void rtcIntersect16(const void* valid, RTCScene scene, RTCRay16& ray);
void rtcOccluded (          RTCScene scene, RTCRay& ray);
void rtcOccluded4 (const void* valid, RTCScene scene, RTCRay4& ray);
void rtcOccluded8 (const void* valid, RTCScene scene, RTCRay8& ray);
void rtcOccluded16 (const void* valid, RTCScene scene, RTCRay16& ray);
```

The ray layout to be passed to the ray tracing core is defined in the `embree2/rtcore_ray.h` header file. It is up to the user if he wants to use the ray structures defined in that file, or resemble the exact same binary data layout with their

own vector classes. The ray layout might change with new Embree releases as new features get added, however, will stay constant as long as the major Embree release number does not change. The ray contains the following data members:

Member	In/Out	Description
<code>org</code>	in	ray origin
<code>dir</code>	in	ray direction (can be unnormalized)
<code>tnear</code>	in	start of ray segment
<code>tfar</code>	in/output	end of ray segment, set to hit distance after intersection
<code>time</code>	in	time used for motion blur
<code>mask</code>	in	ray mask to mask out geometries
<code>Ng</code>	out	unnormalized geometry normal
<code>u</code>	out	barycentric u-coordinate of hit
<code>v</code>	out	barycentric v-coordinate of hit
<code>geomID</code>	out	geometry ID of hit geometry
<code>primID</code>	out	primitive ID of hit primitive
<code>instID</code>	out	instance ID of hit instance

Table 4.8 – Data fields of a ray.

This structure is in struct of array layout (SOA) for ray packets. Note that the `tfar` member functions as an input and output.

In the ray packet mode (with packet size of N), the user has to provide a pointer to N 32 bit integers that act as a ray activity mask. If one of these integers is set to `0x00000000` the corresponding ray is considered inactive and if the integer is set to `0xFFFFFFFF`, the ray is considered active. Rays that are inactive will not update any hit information. Data alignment requirements for ray query functions operating on single rays is 16 bytes for the ray.

Data alignment requirements for query functions operating on AOS packets of 4, 8, or 16 rays, is 16, 32, and 64 bytes respectively, for the valid mask and the ray. To operate on packets of 4 rays, the CPU has to support SSE, to operate on packets of 8 rays, the CPU has to support AVX-256, and to operate on packets of 16 rays, the CPU has to support the Intel® Xeon Phi™ coprocessor instructions. Additionally, the required ISA has to be enabled in Embree at compile time to use the desired packet size.

Finding the closest hit distance is done through the `rtcIntersect` functions. These get the activity mask, the scene, and a ray as input. The user has to initialize the ray origin (`org`), ray direction (`dir`), and ray segment (`tnear`, `tfar`). The ray segment has to be in the range $[0, \infty)$, thus ranges that start behind the ray origin are not valid, but ranges can reach to infinity. The geometry ID (`geomID` member) has to get initialized to `RTC_INVALID_GEOMETRY_ID` (-1). If the scene contains instances, also the instance ID (`instID`) has to get initialized to `RTC_INVALID_GEOMETRY_ID` (-1). If the scene contains linear motion blur, also the ray time (`time`) has to get initialized to a value in the range $[0, 1]$. If ray masks are enabled at compile time, also the ray mask (`mask`) has to get initialized. After tracing the ray, the hit distance (`tfar`), geometry normal (`Ng`), local hit coordinates (`u`, `v`), geometry ID (`geomID`), and primitive ID (`primID`) are set. If the scene contains instances, also the instance ID (`instID`) is set, if an instance is hit. The geometry ID corresponds to the ID returned at creation time of the hit geometry, and the primitive ID corresponds to the n th primitive of that geometry, e.g. n th triangle. The instance ID corresponds to the ID returned at creation time of the instance.

The following code properly sets up a ray and traces it through the scene:

```

RTCRay ray;
ray.org = ray_origin;
ray.dir = ray_direction;
ray.tnear = 0.f;
ray.tfar = inf;
ray.geomID = RTC_INVALID_GEOMETRY_ID;
ray.primID = RTC_INVALID_GEOMETRY_ID;
ray.instID = RTC_INVALID_GEOMETRY_ID;
ray.mask = 0xFFFFFFFF;
ray.time = 0.f;
rtcIntersect(scene, ray);

```

Testing if any geometry intersects with the ray segment is done through the `rtcOccluded` functions. Initialization has to be done as for `rtcIntersect`. If some geometry got found along the ray segment, the geometry ID (`geomID`) will get set to 0. Other hit information of the ray is undefined after calling `rtcOccluded`.

See `tutorial00` for an example of how to trace rays.

4.4 Buffer Sharing

Embree supports sharing of buffers with the application. Each buffer that can be mapped for a specific geometry can also be shared with the application, by pass a pointer, offset, and stride of the application side buffer using the `rtcSetBuffer` API function.

```

void rtcSetBuffer(RTCScene scene, unsigned geomID, RTCBufferType type,
                 void* ptr, size_t offset, size_t stride);

```

The `rtcSetBuffer` function has to get called before any call to `rtcMapBuffer` for that buffer, otherwise the buffer will get allocated internally and the call to `rtcSetBuffer` will fail. The buffer has to remain valid as long as the geometry exists, and the user is responsible to free the buffer when the geometry gets deleted. When a buffer is shared, it is safe to modify that buffer without mapping and unmapping it. However, for dynamic scenes one still has to call `rtcModified` for modified geometries and the buffer data has to stay constant from the `rtcCommit` call to after the last ray query invocation.

The `offset` parameter specifies a byte offset to the start of the first element and the `stride` parameter specifies a byte stride between the different elements of the shared buffer. This support for offset and stride allows the application quite some freedom in the data layout of these buffers, however, some restrictions apply. Index buffers always store 32 bit indices and vertex buffers always store single precision floating point data. The start address `ptr+offset` and stride always have to be aligned to 4 bytes on Intel® Xeon® CPUs and 16 bytes on Xeon Phi accelerators, otherwise the `rtcSetBuffer` function will fail. For vertex buffers, the 4 bytes after the z-coordinate of the last vertex have to be readable memory, thus padding is required for some layouts.

The following is an example of how to create a mesh with shared index and vertex buffers:

```

unsigned geomID = rtcNewTriangleMesh(scene, geomFlags, numTriangles, numVertices);
rtcSetBuffer(scene, geomID, RTC_VERTEX_BUFFER, vertexPtr, 0, 3*sizeof(float));
rtcSetBuffer(scene, geomID, RTC_INDEX_BUFFER, indexPtr, 0, 3*sizeof(int));

```

Sharing buffers can significantly reduce the memory required by the application, thus we recommend using this feature. When enabling the `RTC_COMPACT`

scene flag, the spatial index structures of Embree might also share the vertex buffer, resulting in even higher memory savings.

The support for offset and stride is enabled by default, but can get disabled at compile time using the `RTCORE_BUFFER_STRIDE` parameter in CMake. Disabling this feature enables the default offset and stride which increases performance of spatial index structure build, thus can be useful for dynamic content.

4.5 Linear Motion Blur

Triangle meshes and hair geometries with linear motion blur support are created by setting the number of time steps to 2 at geometry construction time. Specifying a number of time steps of 0 or larger than 2 is invalid. For a triangle mesh or hair geometry with linear motion blur, the user has to set the `RTC_VERTEX_BUFFER0` and `RTC_VERTEX_BUFFER1` vertex arrays, one for each time step.

```
unsigned geomID = rtcNewTriangleMesh(scene, geomFlags, numTris, numVertices, 2);
rtcSetBuffer(scene, geomID, RTC_VERTEX_BUFFER0, vertex0Ptr, 0, sizeof(Vertex));
rtcSetBuffer(scene, geomID, RTC_VERTEX_BUFFER1, vertex1Ptr, 0, sizeof(Vertex));
rtcSetBuffer(scene, geomID, RTC_INDEX_BUFFER, indexPtr, 0, sizeof(Triangle));
```

If a scene contains geometries with linear motion blur, the user has to set the time member of the ray to a value in the range $[0, 1]$. The ray will intersect the scene with the vertices of the two time steps linearly interpolated to this specified time. Each ray can specify a different time, even inside a ray packet.

4.6 User Data Pointer

A user data pointer can be specified and queried per geometry, to efficiently map from the geometry ID returned by ray queries to the application representation for that geometry.

```
void rtcSetUserData (RTCScene scene, unsigned geomID, void* ptr);
void* rtcGetUserData (RTCScene scene, unsigned geomID);
```

The user data pointer of some user defined geometry get additionally passed to the intersect and occluded callback functions of that user geometry. Further, the user data pointer is also passed to intersection filter callback functions attached to some geometry.

The `rtcGetUserData` function is on purpose not thread safe with respect to other API calls that modify the scene. Consequently, this function can be used to efficiently query the user data pointer during rendering (also by multiple threads), but should not get called while modifying the scene with other threads.

4.7 Geometry Mask

A 32 bit geometry mask can be assigned to triangle meshes and hair geometries using the `rtcSetMask` call.

```
rtcSetMask(scene, geomID, mask);
```

Only if the bitwise and operation of this mask with the mask stored inside the ray is not 0, primitives of this geometry are hit by a ray. This feature can be used to disable selected triangle mesh or hair geometries for specifically tagged rays, e.g. to disable shadow casting for some geometry. This API feature is disabled in Embree by default at compile time, and can be enabled in CMake through the `RTCORE_ENABLE_RAY_MASK` parameter.

4.8 Filter Functions

The API supports per geometry filter callback functions that are invoked for each intersection found during the `rtcIntersect` or `rtcOccluded` calls. The former ones are called intersection filter functions, the latter ones occlusion filter functions. The filter functions can be used to implement various useful features, such as accumulating opacity for transparent shadows, counting the number of surfaces along a ray, collecting all hits along a ray, etc. Filter functions can also be used to selectively reject hits to enable backface culling for some geometries. If the backfaces should be culled in general for all geometries then it is faster to enable `RTCORE_BACKFACE_CULLING` during compilation of Embree instead of using filter functions.

The filter functions provided by the user have to have the following signature:

```
void FilterFunc (          void* userPtr, RTCRay& ray);
void FilterFunc4 (const void* valid, void* userPtr, RTCRay4& ray);
void FilterFunc8 (const void* valid, void* userPtr, RTCRay8& ray);
void FilterFunc16(const void* valid, void* userPtr, RTCRay16& ray);
```

The `valid` pointer points to a valid mask of the same format as expected as input by the ray query functions. The `userPtr` is a user pointer optionally set per geometry through the `rtcSetUserData` function. The ray passed to the filter function is the ray structure initially provided to the ray query function by the user. For that reason, it is safe to extend the ray by additional data and access this data inside the filter function (e.g. to accumulate opacity). All hit information inside the ray is valid. If the hit geometry is instanced, the `instID` member of the ray is valid and the ray origin, direction, and geometry normal visible through the ray are in object space. The filter function can reject a hit by setting the `geomID` member of the ray to `RTC_INVALID_GEOMETRY_ID`, otherwise the hit is accepted. The filter function is not allowed to modify the ray input data (`org`, `dir`, `tnear`, `tfar`), but can modify the hit data of the ray (`u`, `v`, `Ng`, `geomID`, `primID`).

The intersection filter functions for different ray types are set for some geometry of a scene using the following API functions:

```
void rtcSetIntersectionFilterFunction (RTCScene, unsigned geomID, RTCFilterFunc );
void rtcSetIntersectionFilterFunction4 (RTCScene, unsigned geomID, RTCFilterFunc4 );
void rtcSetIntersectionFilterFunction8 (RTCScene, unsigned geomID, RTCFilterFunc8 );
void rtcSetIntersectionFilterFunction16(RTCScene, unsigned geomID, RTCFilterFunc16);
```

These functions are invoked during execution of the `rtcIntersect` type queries of the matching ray type. The occlusion filter functions are set using the following API functions:

```
void rtcSetOcclusionFilterFunction (RTCScene, unsigned geomID, RTCFilterFunc );
void rtcSetOcclusionFilterFunction4 (RTCScene, unsigned geomID, RTCFilterFunc4 );
void rtcSetOcclusionFilterFunction8 (RTCScene, unsigned geomID, RTCFilterFunc8 );
void rtcSetOcclusionFilterFunction16(RTCScene, unsigned geomID, RTCFilterFunc16);
```

See `tutorial05` for an example of how to use the filter functions.

4.9 Displacement Mapping Functions

The API supports displacement mapping for subdivision meshes. A displacement function can be set for some subdivision mesh using the `rtcSetDisplacementFunction` API call.

```
void rtcSetDisplacementFunction(RTCScene, unsigned geomID, RTCDisplacementFunc, RTCBounds*);
```

A displacement function of `NULL` will delete an already set displacement function. The bounds parameter is optional. If `NULL` is passed as bounds, then the displacement shader will get evaluated during the build process to properly bound displaced geometry. If a pointer to some bounds of the displacement are passed, then the implementation can choose to use these bounds to bound displaced geometry. When bounds are specified, then these bounds have to be conservative and should be tight for best performance.

The displacement function has to have the following type:

```
typedef void (*RTCDisplacementFunc)(void* ptr, unsigned geomID, unsigned primID,
                                     const float* u, const float* v,
                                     const float* nx, const float* ny, const float* nz,
                                     float* px, float* py, float* pz,
                                     size_t N);
```

The displacement function is called with the user data pointer of the geometry (`ptr`), the geometry ID (`geomID`) and primitive ID (`primID`) of a patch to displace. For this patch, a number `N` of points to displace are specified in a struct of array layout. For each point to displace the local patch UV coordinates (`u` and `v` arrays), the normalized geometry normal (`nx`, `ny`, and `nz` arrays), as well as world space position (`px`, `py`, and `pz` arrays) are provided. The task of the displacement function is to use this information and move the world space position inside the allowed specified bounds around the point.

All passed arrays are guaranteed to be 64 bytes aligned, and properly padded to make wide vector processing inside the displacement function possible.

The displacement mapping functions might get called during the `rtcCommit` call, or lazily during the `rtcIntersect` or `rtcOccluded` calls.

Also see tutorial09 for an example of how to use the displacement mapping functions.

4.10 Sharing Threads with Embree

On some implementations, Embree supports using the application threads when building internal data structures, by using the

```
void rtcCommitThread(RTCScene, unsigned threadIndex, unsigned threadCount);
```

API call to commit the scene. This function has to get called by all threads that want to cooperate in the scene commit. Each call is provided the scene to commit, the index of the calling thread in the range `[0, threadCount-1]`, and the number of threads that will call into this commit operation for the scene. All threads will return again from this function after the scene commit is finished.

Multiple such scene commit operations can also be running at the same time, e.g. it is possible to commit many small scenes in parallel using one thread per commit operation. Subsequent commit operations for the same scene can use different number of threads in the `void rtcCommitThread()` or use the Embree internal threads using the `void rtcCommit()` call.

Note: When using Embree with the Intel® Threading Building Blocks (which is the default) sharing of threads is not possible through `rtcCommitThread`, as

TBB will always generate its own set of threads. Thus when using TBB the `rtcCommitThread()` call will still function, but always use the TBB threads for hierarchy building. We recommend to also use TBB inside your application to share threads with the Embree library. When enabling the Embree internal tasking system the `rtcCommitThread()` feature will work as expected and use the application threads for hierarchy building.

Note: On the Intel® Xeon Phi™ coprocessor the `rtcCommitThread()` feature is recommended to be used.

4.11 Join Build Operation

If `rtcCommit` is called multiple times from different TBB threads on the same scene, then all these threads will join the same scene build operation.

This feature allows a flexible way to lazily create hierarchies during rendering. A thread reaching a not yet constructed sub-scene of a two-level scene, can generate the sub-scene geometry and call `rtcCommit` on that just generated scene. During construction, further threads reaching the not-yet-built scene, can join the build operation by also invoking `rtcCommit`. A thread that calls `rtcCommit` after the build finishes, will directly return from the `rtcCommit` call (even for static scenes).

Note: This mode only works with the Intel® Threading Building Blocks enabled as tasking system in Embree and your application. Embree will tag the hierarchy build task as a high priority TBB task, which guarantees that worker threads that join the build operation, will only pick TBB build tasks and no TBB render tile tasks of your application. For this reason, never make your application's render tile task high priority in TBB.

4.12 Memory Monitor Callback

Using the memory monitor callback mechanism, the application can track the memory consumption of Embree, and optionally terminate API calls that consume too much memory.

The user provided memory monitor callback function has to have the following signature:

```
bool (*RTCMemoryMonitorFunc)(const ssize_t bytes, const bool post);
```

A single such callback function can be registered by calling

```
rtcSetMemoryMonitorFunction(RTCMemoryMonitorFunc func);
```

and deregistered again by calling it with `NULL`. Once registered Embree will invoke the callback function before or after it allocates or frees important memory blocks. The callback function might get called from multiple threads concurrently.

The application can track the current memory usage of the Embree library by atomically accumulating the provided `bytes` input parameter. This parameter will be `>0` for allocations and `<0` for deallocations. The `post` input parameter is true if the callback function was invoked after the allocation or deallocation, otherwise it is false.

Embree will continue its operation normally when returning true from the callback function. If false is returned, Embree will cancel the current operation with the `RTC_OUT_OF_MEMORY` error code. Cancelling will only happen when the callback was called for allocations (`bytes > 0`), otherwise the cancel request will be ignored. If a callback that was invoked before the allocation happens (`post == false`) cancels the operation, then the `bytes` parameter should not get

accumulated, as the allocation will never happen. If a callback that was called after the allocation happened (`post == true`) cancels the operation, then the `bytes` parameter should get accumulated, as the allocation properly happened. Issuing multiple cancel requests for the same operation is allowed.

4.13 Progress Monitor Callback

The progress monitor callback mechanism can be used to report progress of hierarchy build operations and to cancel long lasting build operations.

The user provided progress monitor callback function has to have the following signature:

```
bool (*RTCProgressMonitorFunc)(void* userPtr, const double n);
```

A single such callback function can be registered per scene by calling

```
rtcSetProgressMonitorFunction(RTCScene, RTCProgressMonitorFunc, void* userPtr);
```

and deregistered again by calling it with `NULL` for the callback function. Once registered Embree will invoke the callback function multiple times during hierarchy build operations of the scene, by providing the `userPtr` pointer that was set at registration time, and a double `n` in the range $[0, 1]$ estimating the completion amount of the operation. The callback function might get called from multiple threads concurrently.

When returning `true` from the callback function, Embree will continue the build operation normally. When returning `false` Embree will cancel the build operation with the `RTC_CANCELLED` error code. Issuing multiple cancel requests for the same build operation is allowed.

Chapter 5

Embree Tutorials

Embree comes with a set of tutorials aimed at helping users understand how Embree can be used and extended. All tutorials exist in an ISPC and C version to demonstrate the two versions of the API. Look for files named `tutorialname_device.ispc` for the ISPC implementation of the tutorial, and files named `tutorialname_device.cpp` for the single ray C++ version of the tutorial. To start the C++ version use the `tutorialname` executables, to start the ISPC version use the `tutorialname_ispc` executables.

Under Linux Embree also comes with an ISPC version of all tutorials for the Intel® Xeon Phi™ coprocessor. The executables of this version of the tutorials are named `tutorialname_xeonphi` and only work if a Xeon Phi™ coprocessor is present in the system. The Xeon Phi™ version of the tutorials get started on the host CPU, just like all other tutorials, and will connect automatically to one installed Xeon Phi™ coprocessor in the system. For the Intel® Xeon Phi™ coprocessor to find to Embree library you have to add the path to `libembree_xeonphi.so` to the `SINK_LD_LIBRARY_PATH` variable.

For all tutorials, you can select an initial camera using the `-vp` (camera position), `-vi` (camera look-at point), `-vu` (camera up vector), and `-fov` (vertical field of view) command line parameters:

```
./triangle_geometry -vp 10 10 10 -vi 0 0 0
```

You can select the initial windows size using the `-size` command line parameter, or start the tutorials in fullscreen using the `-fullscreen` parameter:

```
./triangle_geometry -size 1024 1024
./triangle_geometry -fullscreen
```

Implementation specific parameters can be passed to the ray tracing core through the `-rtcore` command line parameter, e.g.:

```
./triangle_geometry -rtcore verbose=2,threads=1,accel=bvh4.triangle1
```

The navigation in the interactive display mode follows the camera orbit model, where the camera revolves around the current center of interest. With the left mouse button you can rotate around the center of interest (the point initially set with `-vi`). Holding Control pressed while clicking the left mouse button rotates the camera around its location. You can also use the arrow keys for navigation.

You can use the following keys:

- F1 Default shading
- F2 Gray EyeLight shading
- F3 Wireframe shading

- F4 UV Coordinate visualization
- F5 Geometry normal visualization
- F6 Geometry ID visualization
- F7 Geometry ID and Primitive ID visualization
- F8 Simple shading with 16 rays per pixel for benchmarking.
- F9 Switches to render cost visualization. Pressing again reduces brightness.
- F10 Switches to render cost visualization. Pressing again increases brightness.
- f Enters or leaves full screen mode.
- c Prints camera parameters.
- ESC Exits the tutorial.
- q Exits the tutorial.

5.1 Triangle Geometry

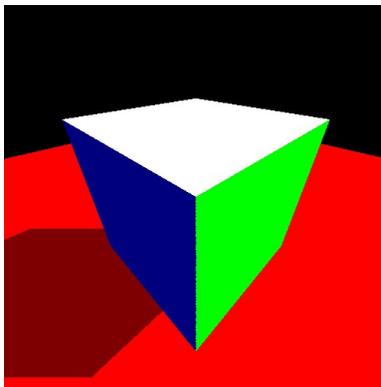


Figure 5.1

This tutorial demonstrates the creation of a static cube and ground plane using triangle meshes. It also demonstrates the use of the `rtcIntersect` and `rtcOccluded` functions to render primary visibility and hard shadows. The cube sides are colored based on the ID of the hit primitive.

5.2 Dynamic Scene

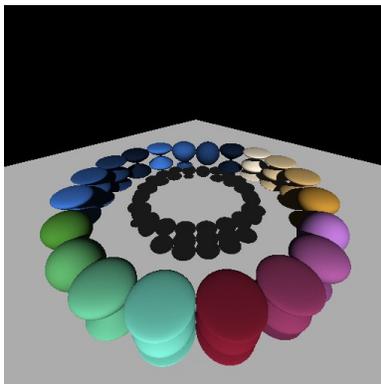


Figure 5.2

This tutorial demonstrates the creation of a dynamic scene, consisting of several deformed spheres. Half of the spheres use the `RTC_GEOMETRY_DEFORMABLE` flag, which allows Embree to use a refitting strategy for these spheres, the other half uses the `RTC_GEOMETRY_DYNAMIC` flag, causing a rebuild of their spatial data

structure each frame. The spheres are colored based on the ID of the hit sphere geometry.

5.3 User Geometry

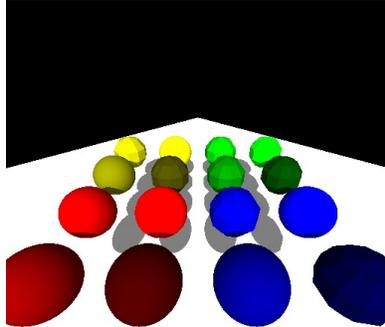


Figure 5.3

This tutorial shows the use of user defined geometry, to re-implement instancing and to add analytic spheres. A two level scene is created, with a triangle mesh as ground plane, and several user geometries, that instance other scenes with a small number of spheres of different kind. The spheres are colored using the instance ID and geometry ID of the hit sphere, to demonstrate how the same geometry, instanced in different ways can be distinguished.

5.4 Viewer



Figure 5.4

This tutorial demonstrates a simple OBJ viewer that traces primary visibility rays only. A scene consisting of multiple meshes is created, each mesh sharing the index and vertex buffer with the application. Demonstrated is also how to support additional per vertex data, such as shading normals.

You need to specify an OBJ file at the command line for this tutorial to work:

```
./tutorial03 -i model.obj
```

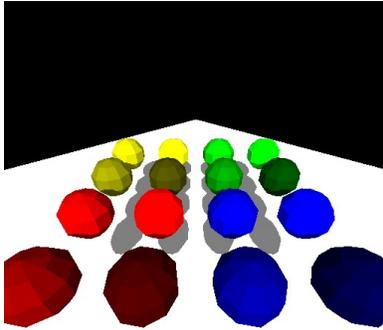


Figure 5.5

5.5 Instanced Geometry

This tutorial demonstrates the in-built instancing feature of Embree, by instancing a number of other scenes build from triangulated spheres. The spheres are again colored using the instance ID and geometry ID of the hit sphere, to demonstrate how the same geometry, instanced in different ways can be distinguished.

5.6 Intersection Filter

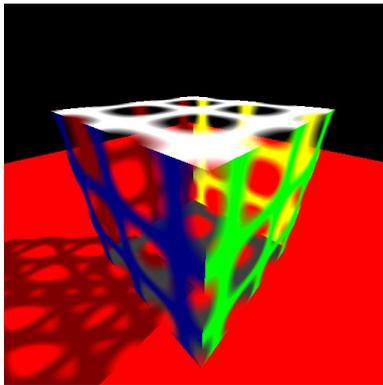


Figure 5.6

This tutorial demonstrates the use of filter callback functions to efficiently implement transparent objects. The filter function used for primary rays, lets the ray pass through the geometry if it is entirely transparent. Otherwise the shading loop handles the transparency properly, by potentially shooting secondary rays. The filter function used for shadow rays accumulates the transparency of all surfaces along the ray, and terminates traversal if an opaque occluder is hit.

5.7 Pathtracer

This tutorial is a simple path tracer, building on tutorial03.

You need to specify an OBJ file and light source at the command line for this tutorial to work:

```
./tutorial06 -i model.obj -ambientlight 1 1 1
```



Figure 5.7

5.8 Hair Geometry



Figure 5.8

This tutorial demonstrates the use of the hair geometry to render a hairball.

5.9 Subdivision Geometry

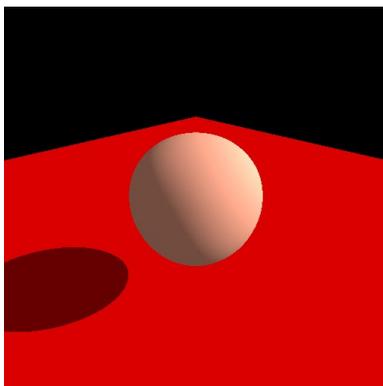


Figure 5.9

This tutorial demonstrates the use of Catmull Clark subdivision surfaces. Per default the edge tessellation level is set adaptively based on the distance to the camera origin. Embree currently supports three different modes for efficiently handling subdivision surfaces in various rendering scenarios. These three modes can be selected at the command line, e.g. `-lazy` builds internal per subdivision patch data structures on demand, `-cache` uses a small (per thread) tessellation cache for caching per patch data, and `-pregenerate` to generate and store most per patch data during the initial build process. The cache mode is most effective

for coherent rays while providing a fixed memory footprint. The `pregenerate` mode is most effective for incoherent ray distributions while requiring more memory. The `lazy` mode works similar to the `pregenerate` mode but provides a middle ground in terms of memory consumption as it only builds and stores data only when the corresponding patch is accessed during the ray traversal. The `cache` mode is currently a bit more efficient at handling dynamic scenes where only the edge tessellation levels are changing per frame.

5.10 Displacement Geometry

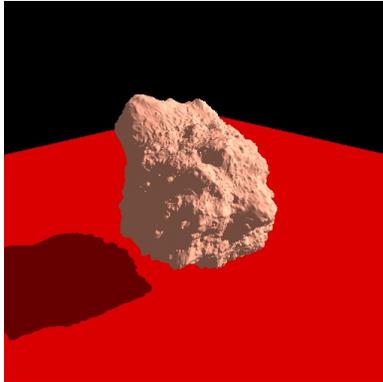


Figure 5.10

This tutorial demonstrates the use of Catmull Clark subdivision surfaces with procedural displacement mapping using a constant edge tessellation level.

5.11 BVH Builder

This tutorial demonstrates how to use the templated hierarchy builders of Embree to build a bounding volume hierarchy with a user defined memory layout using a high quality SAH builder and very fast morton builder.

5.12 Find Embree

This tutorial demonstrates how to use the `FIND_PACKAGE` CMake feature to use an installed Embree. Under Linux and MacOSX the tutorial finds the Embree installation automatically, under Windows the `embree_DIR` CMake variable has to be set to the following folder of the Embree installation: `C:\Program Files\Intel\Embree X.Y.Z\lib\cmake\embree-X.Y.Z`.

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