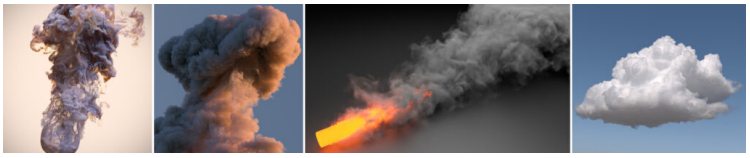
Advanced 3D Graphics for Movies and Games



Lecturer(s):
Alexander Wilkie (https://cgg.mff.cuni.cz/~wilkie/)
Code in SIS: **NPGR010**
(https://is.cuni.cz/studium/eng/predmety/index.php?do=predmet&kod=NPGR010)
Hours per week (lecture/labs), examination type: **2/2 C+Ex**
Semester(s): **Winter**

Brief Description

Advanced course in computer graphics with the emphasis on image synthesis. The course covers methods for physically-based realistic rendering used for special effects in movie production, computer animation, architectural and product visualizations etc. Specifically, we start off by briefly covering some of the math and physics behind light transport. We then give a detailed treatment of the industry-standard Monte Carlo methods for light transport simulation, such as path tracing, photon mapping etc. We also cover some of the more advanced techniques such as bidirectional path tracing.

Note: This class loosely follows up on Photorealistic Graphics (NPGR004) (https://cgg.mff.cuni.cz/~pepca/lectures/npgr004.current.en.php) and is aimed mostly at students with a deeper interest in realistic rendering methods.

Course information 2022/2023

Lectures:	Tuesdays, 9:00 – 10:30, room S4 (https://is.cuni.cz/studium/rozvrhng/roz_predmet_gl.php?tid=5&gl=22aNPGR010p1&fak=11320&skr=2022&sem=1)	Contact: Alexander Wilkie (/members/wilkie/)
Practicals:	Tuesdays, 10:40 – 12:10, room SW1 (https://is.cuni.cz/studium/rozvrhng/roz_predmet_gl.php?tid=5&gl=22aNPGR010x01&fak=11320&skr=2022&sem=1)	Contact: Tomáš Iser (/~tomas)

Lecture and practicals content and assignments for 2022/2023 will be updated throughout the semester.

Lecture content

Lecture topic	Slides & notes	Auxiliary materials

Organization, Intro	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/01b%20-%20npgr010-2020%20-%20organization.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/01b%20-%20npgr010-2020%20-%20organization.pptx) / pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/01c%20-%20npgr010-2020%20-%20introduction.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/01c%20-%20npgr010-2020%20-%20introduction.pptx)	
Radiometry	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/02%20-%20npgr010-2020%20-%20radiometry.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/02%20-%20npgr010-2020%20-%20radiometry.pptx)	Petr Olšák – dOmega (in Czech) (http://petr.olsak.net/ftp/olsak/grafika/domega.pdf) Petr Olšák – Radiometric units (in Czech) (http://petr.olsak.net/ftp/olsak/grafika/svetlo.pdf) Wikipedie – Radiometric units (http://cs.wikipedia.org/wiki/Radiometrick%C3%A9_veli%C4%8Diny)
Light reflection, BRDF	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/03%20-%20npgr010-2020%20-%20BRDF.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/03%20-%20npgr010-2020%20-%20BRDF.pptx)	Scratchpixel – Mathematics of shading (https://www.scratchapixel.com/lessons/mathematics-physics-for-computer-graphics/mathematics-of-shading) Scratchpixel – Introduction to shading (https://www.scratchapixel.com/lessons/3d-basic-rendering/introduction-to-shading) Scratchpixel – The Phong model, Reflection models and BRDF (https://www.scratchapixel.com/lessons/3d-basic-rendering/phong-shader-BRDF) Fabrizio Duroni – How to calculate reflection vector (https://www.fabrizioduroni.it/2017/08/25/how-to-calculate-reflection-vector.html)
Monte Carlo methods, Direct illumination calculation	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/04%20-%20npgr010-2020%20-%20monte%20carlo.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/04%20-%20npgr010-2020%20-%20monte%20carlo.pptx)	
Monte Carlo methods II, Image-based lighting	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/05%20-%20npgr010-2020%20-%20monte%20carlo%20II.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/05%20-%20npgr010-2020%20-%20monte%20carlo%20II.pptx)	

Combined estimators & Multiple Importance Sampling	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/06%20-%20npgr010-2020%20-%20MIS.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/06%20-%20npgr010-2020%20-%20MIS.pptx)	
Rendering equation and its solution	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/07%20-%20npgr010-2020%20-%20rendering%20equation.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/07%20-%20npgr010-2020%20-%20rendering%20equation.pptx)	
Path tracing	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/08%20-%20npgr010-2020%20-%20path%20tracing.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/08%20-%20npgr010-2020%20-%20path%20tracing.pptx)	
Quasi-Monte Carlo methods	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/09%20-%20npgr010-2020%20-%20QMC.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/09%20-%20npgr010-2020%20-%20QMC.pptx)	My favorite samples – SIGGRAPH Course 2019 (https://sites.google.com/view/myfavoritesamples) Rand() considered harmful (https://channel9.msdn.com/Events/GoingNative/2013/rand-Considered-Harmful) Constructing quasi-random blue noise sequences (http://extremelearning.com.au/a-simple-method-to-construct-isotropic-quasirandom-blue-noise-point-sequences/)(blue noise vs. low-discrepancy, extra supplementary material) Unreasonable effectiveness of quasirandom sequences (http://extremelearning.com.au/unreasonable-effectiveness-of-quasirandom-sequences/)(extra supplementary material)
Volumetric light transport and participating media rendering	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/10%20-%20npgr010-2020%20-%20volumes.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/10%20-%20npgr010-2020%20-%20volumes.pptx) Monte Carlo methods for physically based volume rendering (https://cgg.mff.cuni.cz/~jaroslav/papers/2018-mcvolrendering/index.htm)", SIGGRAPH 2018 course	Steve Marschner: "Multiple Scattering (http://www.cs.cornell.edu/Courses/cs6630/2009fa/slides/05multscat.pdf)" Note that the pseudocode in the above material is buggy: In the Kajiya-style path tracing, homogeneous volume, version 1.0, in the function directScatteredEst(x, ω) a multiplication by sigma_s/sigma_t (i.e. scattering albedo) is missing. Steve Marschner: "Volumetric path tracing (http://www.cs.cornell.edu/Courses/cs6630/2012sp/notes/09volpath.pdf)" Patrick Harrington: Henyey-Greenstein phase function – CDF inversion, Rayleigh scattering phase function (https://www.astro.umd.edu/~jph/HG_note.pdf) Walter Lewin: For the Love of Physics: Catchy demonstration of Mie and Rayleigh scattering (https://youtu.be/4a0FbQdH3dY?t=1674)

Bidirectional path tracing	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/11%20-%20npgr010-2020%20-%20BPT.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/11%20-%20npgr010-2020%20-%20BPT.pptx)	
Photon mapping	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/12%20-%20npgr010-2020%20-%20PM.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/12%20-%20npgr010-2020%20-%20PM.pptx)	
Approximate global illumination computation	Lecture: pdf (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/13%20-%20npgr010-2020%20-%20IC-PBGI.pdf) | pptx (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/13%20-%20npgr010-2020%20-%20IC-PBGI.pptx)	

Practicals schedule

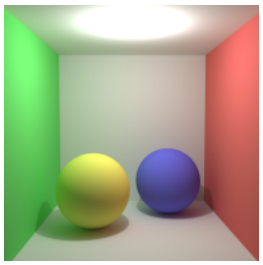
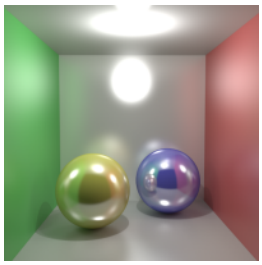
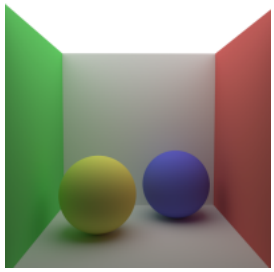
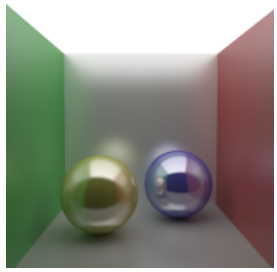
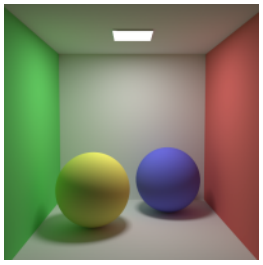
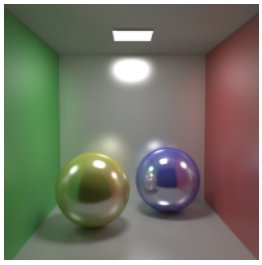
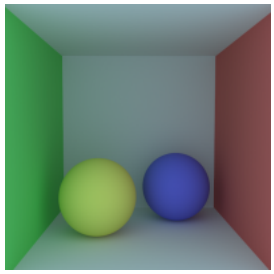
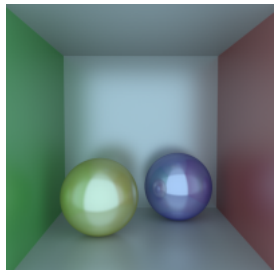
Note: This schedule may change during the semester, but it will likely stay more or less as shown here.

4.10.	Introduction, Assignment 0 (slides in .pdf) (https://drive.google.com/file/d/1x-MoYvwUqwcCZ-_h8LWjsHK06D9y6I2D/view?usp=sharing)	~~*22.11.*~~	*Cancelled*
~~*11.10.*~~	*Cancelled*	29.11.	Evaluating assignment 2, Assignment 3
18.10.	Evaluating assignment 0, Math exercises	~~*6.12.*~~	*Cancelled*
25.10.	Assignment 1, Math exercises	13.12.	Assignment 4
1.11.	Math exercises	20.12.	Evaluating assignment 3
8.11.	Evaluating assignment 1, Assignment 2	~~*27.12.*~~	*Christmas*
15.11.	*Voluntary consultation*	3.1.	Final evaluation (final deadline for all assignments)

Practicals assigments

The goal of these assignments is to write a Monte Carlo path tracer. We provide you with a small skeleton of our custom C++ framework, which can handle basic tasks such as saving an image, writing colors to pixels, generating camera rays, detecting scene intersections, a simple parallel execution, etc. It also provides abstract classes and methods that you should fill with your own code. The basic piece of C++ code that we provide can already handle rendering direct illumination from a point light source in a scene with

only diffuse surfaces. Your goal in each assignment is to expand the C++ solution with new functionality. In the end, as you complete all the assignments, you will reach a fully working Monte Carlo path tracer that computes global illumination and produces the following images on the 8 sample scenes that are part of the source code:

			
Isotropic point light Diffuse surfaces	Isotropic point light Glossy surface	Large area light Diffuse surfaces	Large area light Glossy surface
			
Small area light Diffuse surfaces	Small area light Glossy surface	Const. environment map Diffuse surfaces	Const. environment map Glossy surface

Working with the C++ solution

First, download our initial C++ project (https://cgg.mff.cuni.cz/wp-content/uploads/2022/10/npgr010_skeleton.zip). It contains a CMake file and a directory with C++ source code. The easiest way to compile the solution into an executable is to download and run CMake (https://cmake.org/) on the provided project, which should work on all standard platforms like Windows, Linux, and Mac using a C++ compiler that supports C++17 and OpenMP. Please note that I cannot assist you with compiling C++ projects on your specific computer, but the general approach using CMake is to run the following commands from the place with the C++ project:

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

to create a build directory, and initialize CMake there, and then:

```
cmake -build .
```

to compile (build) the solution into an executable.

Submitting your C++ solutions

Submitting your C++ solutions is done via ReCodEx (https://recodex.mff.cuni.cz/). You can join the NPGR010 group either by linking your account via SIS, or by following an invitation link that I sent you in an e-mail. When submitting your solution, simply upload all the .cpp and .hpp source files. Do not upload the CMake file. ReCodEx will then attempt to compile the solution. Once it succeeds, it executes your solution on the 8 demo scenes, and it compares the output images to the reference images. If the mean difference is within a given threshold, you get an OK. You can also see which exact scenes did not pass.

Please note that ReCodEx only compares the output images, but does not check if your source code really follows the instructions! For example, all assignments 1 to 3 result in the same images, meaning you could technically upload the same solution 3 times and still pass the ReCodEx checks successfully! This means that I need to check each of your solution's source codes manually to verify that you really followed the instructions. The ReCodEx verification is just intended to help you make sure your images are correct!

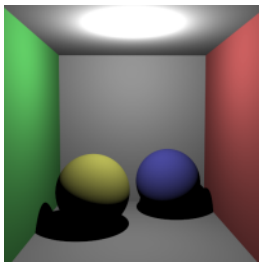
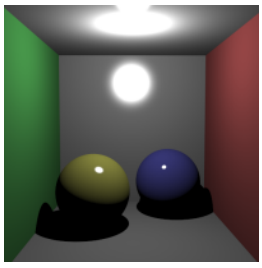
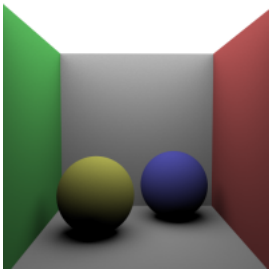
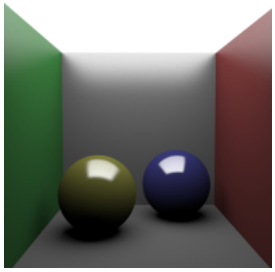
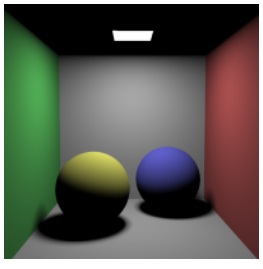
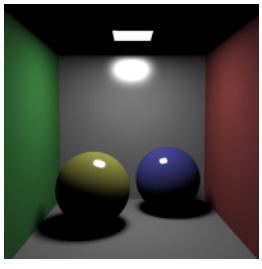
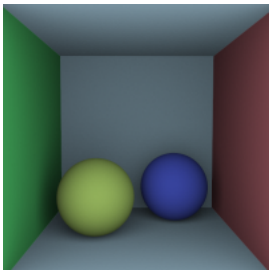
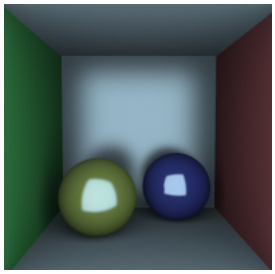
Assignment 1: Direct illumination calculation through explicit light source sampling [5 points]

The first three assignments will be about **direct illumination**, meaning only 1 bounce between camera and light (camera → surface → light). The initial version of our C++ code can only correctly render the first scene, the other ones are either incorrect or fail to run because of missing functions. In your first assignment, you should expand the initial C++ code to support direct illumination in all 8 demo scenes. This means the following:

- You need to change the material implementation in `materials.hpp` to correctly handle the glossiness in the BRDF evaluation.
- You need to change the lights implementation in `lights.hpp` to correctly handle sampling points on area and environment (background) lights.
- For the light sources, you can (but do not need to) add your custom utility functions in `utils.hpp`. Specifically, it is useful to implement functions that sample a random point on a uniform triangle (https://www.pbr-book.org/3ed-2018/Monte_Carlo_Integration/2D_Sampling_with_Multidimensional_Transformations#SamplingaTriangle) (for the area lights, which consist of 2 triangles) and on a uniform sphere (https://www.pbr-book.org/3ed-2018/Monte_Carlo_Integration/2D_Sampling_with_Multidimensional_Transformations#UniformlySamplingaHemisphere) (for the environment light; the derivation can be found here in the same section as hemisphere (https://www.pbr-book.org/3ed-2018/Monte_Carlo_Integration/2D_Sampling_with_Multidimensional_Transformations#UniformlySamplingaHemisphere)).
- You will need to edit `pathtracer.hpp` to correctly handle the situation where the ray directly hits the area light, in which case you want to evaluate its radiance directly.

A correct solution to this assignment should produce 8 images for the 8 demo scenes that are almost identical to the following reference images. Please note that since Monte Carlo is based on randomness, and the solution you will reach in this assignment is not optimal, you will almost certainly not create the exact same images because of noise. The goal is to result in images that are **unbiased**, meaning the mean difference between your images and reference images is plus minus zero. For that, it is useful to save your results in either **.hdr** or **.pfm** formats, and compare them in tev (https://github.com/Tom94/tev), which is a free HDR image viewer with various handy features.

The reference images (download a .zip with .hdr and .pfm images) (https://cgg.mff.cuni.cz/wp-content/uploads/2022/10/singlebounce.zip) for direct illumination are:

			
Isotropic point light Diffuse surfaces	Isotropic point light Glossy surfaces	Large area light Diffuse surfaces	Large area light Glossy surfaces
			
Small area light Diffuse surfaces	Small area light Glossy surfaces	Const. environment map Diffuse surfaces	Const. environment map Glossy surfaces

Assignment 2: Direct illumination estimator based on randomized direction sampling [2+2+4 = 8 points]

The second assignment is very similar to Assignment 1, but you are asked to change the mechanism in which the new ray direction is generated. In Assignment 1, when the ray intersects an object, the new reflected direction is randomly generated by explicitly asking a light source to give you a direction to itself. This is called *explicit light source sampling* and it ensures that we always make a connection to a light, unless we are in a shadow. This works, but can result in high noise in certain scenes, e.g., at the top of the walls with a large area light.

In Assignment 2, we want you to understand that explicit light source sampling is not the only solution. In fact, one can use *any random distribution* to sample the reflected directions, *as long as* you implement it correctly with the corresponding probability distribution function. We want you to try this with three different strategies:

- **Assignment 2A (Uniform hemisphere sampling) [2 points]:**
  The new reflected direction is generated by sampling a uniform hemispherical distribution (https://www.pbr-book.org/3ed-2018/Monte_Carlo_Integration/2D_Sampling_with_Multidimensional_Transformations#UniformlySamplingaHemisphere).
- **Assignment 2B (Cosine-weighted hemisphere sampling) [2 points]:**
  The new reflected direction is generated by sampling a cosine-weighted hemispherical distribution. In this case, I do **not** recommend implementing the solution in PBRT (https://www.pbr-book.org/3ed-2018/Monte_Carlo_Integration/2D_Sampling_with_Multidimensional_Transformations#Cosine-WeightedHemisphereSampling), but instead **look at Global Illumination Compendium (https://people.cs.kuleuven.be/~philip.dutre/GI/TotalCompendium.pdf)**, pages 19-20, problem (35). The best is to use the first solution, which has a PDF of $\cos\theta/\pi$. It assumes random numbers r1, r2. Notice that $\cos\theta = z$, so the PDF you can return is simply z/π.
- **Assignment 2C (BRDF importance sampling) [4 points]:**
  The new reflected direction is generated by sampling a distribution proportional to the surface's BRDF.
  To implement this, see the relevant slides 20-28 for a Phong model (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/05%20-%20npgr010-2020%20-%20monte%20carlo%20II.pdf). You can use the formulas and pseudocode from the slides, but it should also help you to realize that:
  - The *diffuse part* of the sampling is the same as the cosine-weighted hemisphere sampling in (2B) above, so you can re-use that code.
  - The *specular (glossy) part* of the sampling is similar, but proportional to the n-th power, which corresponds to the problem (36) on page 20 in the **Global Illumination Compendium (https://people.cs.kuleuven.be/~philip.dutre/GI/TotalCompendium.pdf)**.
  - Keep in mind that the random sampling has 2 branches (diffuse, specular), and its final PDF is not a constant, but instead needs to be combined and re-computed based on which direction you actually ended up choosing!

The rendered images with all of the methods above should eventually converge to the same images as in Assignment 1, but they will have different qualities:

- Assignments 2A, 2B, and 2C do **not** work for point light sources (scenes 0 and 1). They only generate a black image. Why?
- Compare the results of Assignments 1, 2A, 2B, and 2C. Which solutions result in the best images, with the least amount of noise?
  - Cosine-weighted sampling (2B) results in images with slightly less noise than uniform sampling (2A). Why?
  - BRDF importance sampling (2C) results in images with significantly less noise than (1), (2A), and (2B). It is the best solution. Why?

I recommend implementing the reflection sampling methods in `SampleReflectedDirection` in `materials.hpp`. You will also need to appropriately change the tracing code in `pathtracer.hpp`, especially, you will need to stop using `SamplePointOnLight`, and instead use `SampleReflectedDirection`. Keep in mind that in scenes 6 and 7 with the background environment light, you cannot intersect the background directly, so instead if no intersection is found, use `mScene.GetBackground()` to retrieve the background light pointer.

All solutions (2A, 2B, 2C) are submitted separately to ReCodEx, because your implementations will have slightly different C++ source codes.

Assignment 3: Multiple importance sampling [10 points]

The third assignment is a combination of Assignments 1 and 2. You are asked to combine the explicit light source sampling (Assignment 1) with the BRDF importance sampling (Assignment 2C) using multiple importance sampling with the balance heuristic (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/06%20-%20npgr010-2020%20-%20MIS.pdf).

What does this mean practically?

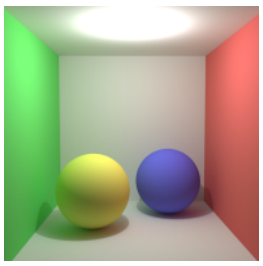
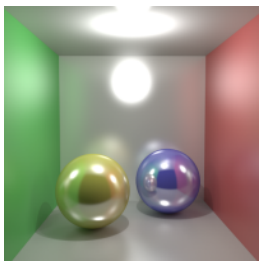
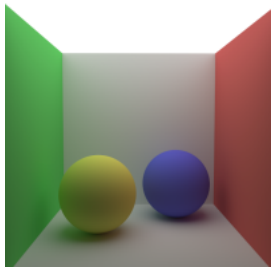
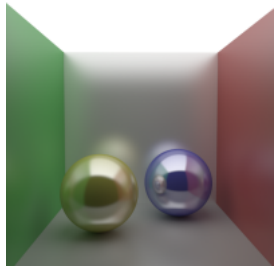
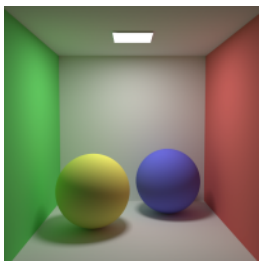
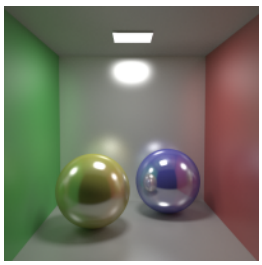
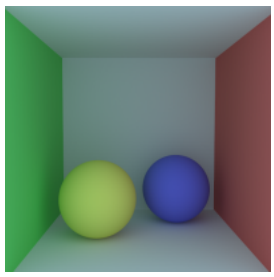
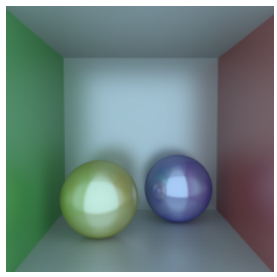
- When the camera ray hits a surface, you now need to generate two new directions: one using the explicit light source sampling (Assignment 1), and one using the BRDF importance sampling (Assignment 2C).
- Two rays (one in each of the directions) are created and each of them is separately tested whether it hit a light source, and if yes, its contribution is added to the final radiance of the pixel.
- The final PDF of the combined contribution needs to be computed using the balance heuristic formula. In this formula, you need to use the PDF of each of the two strategies, so you will need to implement the `PDF` methods in `materials.hpp` and `lights.hpp`.

Your solution should now work for all scenes 0 to 7, converging to the reference images above with a significantly lower amount of noise.

Assignment 4: Path tracing [6+8+8 = 22 points]

The fourth assignment is about extending the previous assignments into a full **path tracer (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/08%20-%20npgr010-2020%20-%20path%20tracing.pdf)** that supports indirect illumination, i.e., paths that bounce more than just once.

The reference images (download a .zip with .hdr and .pfm images) (https://cgg.mff.cuni.cz/wp-content/uploads/2022/12/pathtracing.zip) for path tracing are:

			
Isotropic point light Diffuse surfaces	Isotropic point light Glossy surface	Large area light Diffuse surfaces	Large area light Glossy surface
			
Small area light Diffuse surfaces	Small area light Glossy surface	Const. environment map Diffuse surfaces	Const. environment map Glossy surface

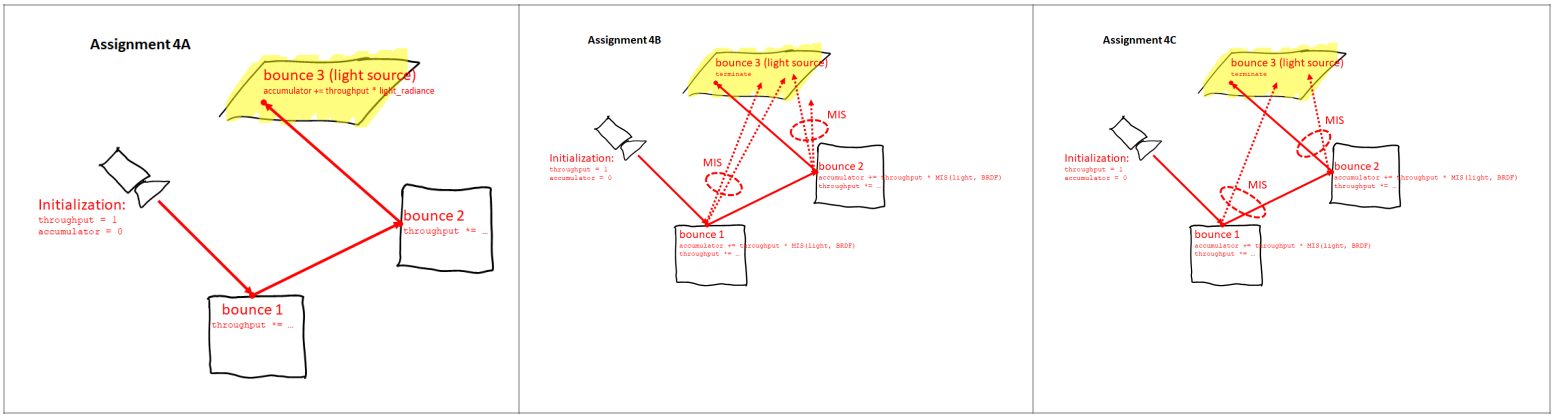
We want you to try this with three different strategies, each uploaded separately into ReCodEx:

- **Assignment 4A (Trivial path tracing) [6 points]:**
  The most trivial way of implementing path tracing is to simply wrap Assignment 2C into a `while(true)` loop, such that the code does not terminate until the first bounce, but keeps finding new intersections until a light source is hit. In practice, you need to keep a `throughput` variable that will be lowered (multiplied) with every bounce, and the final light energy needs to be

multiplied by the final throughput of the whole path. To prevent bouncing infinitely, the Russian roulette technique based on the throughput should be implemented. This is all explained in the slides (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/slides/08%20-%20npgr010-2020%20-%20path%20tracing.pdf), especially slide 12. **Note that this solution will only generate a black image for scenes 0 and 1.**

- **Assignment 4B (Multiple importance sampling, 3 rays per bounce) [8 points]:**
  A more robust path tracer uses multiple importance sampling, which essentially means merging Assignment 4A with Assignment 3. To keep things simple, implement it the following way. With each bounce, generate 2 new rays with MIS (just like in Assignment 3), and add their contribution to an `accumulator` variable multiplied by the current path `throughput`. Then generate a 3rd new ray, which will determine where the path continues towards the next bounce. **Note that if you directly hit a light source, you can only add its contribution in the very first bounce, otherwise your estimator would be incorrectly weighted.**
- **Assignment 4C (Multiple importance sampling, 2 rays per bounce) [8 points]:**
  Similar to Assignment 4B, but in this case, you will not generate a 3rd new ray to continue the path tracing, but instead you will use the 2nd ray (from the BRDF sampling) to continue the tracing. This is more efficient as only 2 rays are required per bounce.

If you have trouble understanding the difference between assignments 4A, 4B, and 4C from the explanation above, perhaps my following images will help:



Archive

Course information for the previous academic years:

- 2021/2022 (https://cgg.mff.cuni.cz/wp-content/uploads/2022/09/NPGR010_Archived20212022.pdf)
- 2020/2021 (https://cgg.mff.cuni.cz/~jirka/teaching/npgr010-2020/index.html)
- 2019/2020 (https://cgg.mff.cuni.cz/~jaroslav/teaching/2019-npgr010/index.html)

Computer Graphics Group
Charles University, KSVI, MFF

Malostranské náměstí 25
118 00 Prague 1

Czech Republic