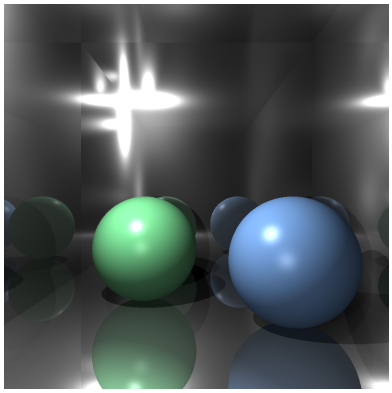
Middle East Technical University | Department of Computer Engineering

CENG 795

Advanced Ray Tracing

Fall '2025-2026
Assignment 2 - Fast and Furious
(v.1.0)

Due date: November 16, 2025, Sunday, 23:59
Blog due date: November 19, 2025, Wednesday, 23:59



1 Objectives

The focus of this assignment is to add support for acceleration structures, geometric transformations, and instancing to your ray tracers. These features will help you to create and render much more complex scenes more efficiently.

Keywords: *transformations, instancing, bounding volume hierarchy (BVH), kd-tree*

2 Specifications

1. You should name your executable as "raytracer".
2. Your executable will take a JSON scene file as argument (e.g. "scene.json"). The format of the file should be self-explanatory but some information is provided in Section 3. You should be able to run your executable via command "./raytracer scene.json".

3. You will save the resulting images in the PNG format. You can use a library of your choice for saving PNG images. A popular choice is the stb-image library[1].

4. The scene file may contain multiple camera configurations. You should render as many images as the number of cameras. The output filenames for each camera is specified in the scene file.

5. There is no time limit for rendering the input scenes. However, you should report your time measurements in your blog post. Try to write your code as optimized as possible. But if a scene takes too long to render, do not worry yet. Acceleration structures that we will learn later should help you in the second homework.

6. You should use Blinn-Phong shading model for the specular shading computations. Conductors and dielectrics should obey Fresnel reflection rules. Dielectrics are assumed to be isotropic and should obey Beer's law for light attenuation. Simple mirrors do not follow the Fresnel law.

7. You will implement two types of light sources: point and ambient. There may be multiple point light sources and a single ambient light. The values of these lights will be given as (R, G, B) color triplets that are <u>not</u> restricted to $[0, 255]$ range (however, they cannot be negative as negative light does not make sense). Any pixel color value that is calculated by shading computations and is greater than 255 must be clamped to 255 and rounded to the nearest integer before writing it to the output PNG file. This step will be replaced by the application of a tone mapping operator in our later homeworks.

8. Point lights will be defined by their intensity (power per unit solid angle). The irradiance due to such a light source falls off as inversely proportional to the squared distance from the light source. To simulate this effect, you must compute the irradiance at a distance of d from a point light as:

$$E(d) = \frac{I}{d^2},$$

   where I is the original light intensity (a triplet of RGB values given in the scene file) and $E(d)$ is the irradiance at distance d from the light source.

9. **Back-face culling** is a method used to accelerate the ray - scene intersections by not computing intersections with triangles whose normals are pointing away from the camera. Its implementation is simple and done by calculating the dot product of the ray direction with the normal vector of the triangle. If the sign of the result is positive, then that triangle is ignored. Note that shadow rays should not use back-face culling. In this homework, back-face culling implementation is optional. Experiment with enabling and disabling it in your ray tracers and report your time measurements in your blog post.

10. **Degenerate triangles** are those triangles whose at least two vertices coincide. The input files given to you should be free of such cases, but models downloaded from the Internet occasionally have this problem. You can put a check in your ray tracer either to detect or ignore such triangles (using such triangles usually produce NaN values).

[1] `https://github.com/nothings/stb`

3 Scene File

Please see HW1 for a detailed description of the scene file. In this section, only the elements introduced or updated in this homework are explained.

- **Transformations:** All transformations are defined in this element group. Each of the transformations defined below has an id for referring to them later.

Translation	Δx, Δy, and Δz values corresponding to translation amounts in each axis.
Scaling	S_x, S_y, and S_z scaling factors along each axis.
Rotation	θ, x, y, and z values that define the angle of rotation in degrees and the rotation axis. Positive angles correspond to counter-clockwise rotations.
Composite	16 values given in row-major order that defines the contents of the 4×4 composite transformation matrix.

- **Camera:** is defined as in HW1. In this homework, a camera can also have a transformation applied on it.

- **PointLight:** is defined by a position and an intensity, which are all floating point numbers. The color channel order of intensity is RGB. In this homework, point lights can also have a transformation applied on them. The only meaningful transformations for point lights are translations, rotations, and their combinations.

- **Mesh:** The mesh definition now has an extra element called **Transformations** that defines which transformations will apply to this mesh and in which order. For example, if the value of this element is **r1 t1 s2 r2**, it means first apply rotation transformation with id equal to 1, then translation with id equal to 1, then scaling with id equal to 2 and then rotation with id equal to 2. If we represent it as a matrix multiplication, the composite transformation should look like this:

  $$M = R_2 S_2 T_1 R_1, \tag{1}$$

  and the transformed coordinates of a vertex v will be equal to:

  $$v' = Mv \tag{2}$$

- **Triangle:** The same transformations element can be found under the triangle element as well.

- **Sphere:** The same transformations element can be found under the sphere element as well.

- **Plane:** The same transformations element can be found under the plane element as well.

- **MeshInstance:** This is a new object that is introduced by this homework. A mesh instance is a copy of its base mesh with a potentially different material and transformation. A mesh instance can be instanced from another mesh instance as well and because of that ids of meshes and mesh instances must not be the same. A mesh instance does not have a **Faces** element as it uses the same faces with its base mesh. An example usage of this element is given below:

```
"MeshInstance": {
  "_id": "2",
  "_baseMeshId": "1",
  "_resetTransform": "true",
  "Material": "3",
  "Transformations": "r1 t3"
}
```

This defines a mesh instance whose base mesh (or mesh instance) is the object with id equal to 1. This instance is using material 3, which may be different from the base object's material. The **resetTransform** attribute, whose default value is **false**, indicates whether the defined transformation should apply on top of the transformations that are already defined for the base object. If its value is **true**, the defined transformation is the only one that should apply on the initial geometry. Otherwise, the new transformation should be applied on top of what is already defined for the base mesh. This can be represented as follows:

$$M_{instance} = \begin{cases} T_3 R_1 & \text{if resetTransform is true} \\ T_3 R_1 M_{base} & \text{if resetTransform is false (default)} \end{cases}, \tag{3}$$

where M_{base} is the composite transformation of the base object.

4 Hints & Tips

In addition to those for HW1, the following tips may be useful for this homework.

1. There are no special elements that are defined for acceleration structures. You are expected to implement a structure of your choice, with BVH being the recommended one.

2. Planes do not play well with acceleration structures due to their unlimited extent. Therefore, you may find it simpler to keep planes outside of your acceleration structures.

3. For camera transformations, just apply the transformation matrix to the position and the coordinate system vectors of the camera.

4. To correctly implement instancing, consider storing the bounding boxes of the transformed objects in the world space. As such you can detect if a ray may intersect the object. If this is the case, you can then inverse-transform the ray and test it with the object in its local coordinate system (without any transformations applied to the object itself).

5. To find the world space bounding box of an object, you can first transform the local bounding box using the transformation matrix defined for the object. You can then recompute the bounding box from the coordinates of the transformed bounding box.

6. As our goal is to speed up our ray tracers, adding multi-threading support could be quite beneficial at this point. There are different ways of implementing this. You can divide the image region into sub-regions whose count is equal to the number of threads. Each thread renders its own region. However, if some threads finish their jobs earlier than others, this

may be sub-optimal. Alternatively, you can divide the image into a larger number of regions and assign threads to each region. Whenever a thread finishes processing its own region, it can get assigned to a new one. This would be somewhat more complex to implement but would result in a more efficient ray tracer.

5 Bonus

I will be more than happy to give bonus points to students who make important contributions such as new scenes, importers/exporters between our JSON format and other standard file formats. Note that a Blender exporter[2], which exports Blender data to our previously used XML format is available. After producing the XML file, you can run the bash script here[3] to produce the final JSON file. You can use these scripts for designing a scene in Blender and exporting it to our file format.

6 Regulations

1. **Programming Language:** C/C++ is the recommended language. However, other languages can be used if so desired. In the past, some some students used Rust or even Haskell for implementing their ray tracers.

2. **Additional Libraries:** If you are planning to use any library other than *(i)* the standard library of the language, *(ii)* pthread, *(iii)* the JSON parser[4], *(iv)* the image IO libraries[5], and *(v)* PLY parsing libraries[6] please first ask about it on ODTUClass and get a confirmation. Common sense rules apply: if a library implements a ray tracing concept that you should be implementing yourself, do not use it!

3. **Submission:** Submission will be done via ODTUClass. To submit, create a "**tar.gz**" file named "raytracer.tar.gz" that contains all your source code files and a Makefile. The executable should be named as "raytracer" and should be able to be run using the following commands (scene.json will be provided by us during grading):

   tar -xf raytracer.tar.gz
   make
   ./raytracer scene.json

   Any error in these steps will cause point penalty during grading.

4. **Late Submission:** You can submit your codes up to 3 days late. Each late day will cause a 10 point penalty. The blog deadline is 3 days later than the regular deadline and no further late submission is allowed for the blog posts.

[2] `https://user.ceng.metu.edu.tr/~akyuz/courses/795/ceng795exporter.py`
[3] `https://user.ceng.metu.edu.tr/~akyuz/courses/795/xml2json.sh`
[4] `https://github.com/nlohmann/json`
[5] `https://github.com/nothings/stb`
[6] `http://paulbourke.net/dataformats/ply/`

5. **Cheating: We have zero tolerance policy for cheating**. People involved in cheating will be punished according to the university regulations and will get 0 from the homework. You can discuss algorithmic choices, but sharing code between groups or using third party code is strictly forbidden. By the nature of this class, many past students make their ray tracers publicly available. You must refrain from using them at all costs.

   Using Large Language Models (LLMs) and other AI tools: We note that AI can be a useful learning resource but if it is used for generating code that you are supposed to write, it can have a detrimental effect on your learning. Therefore, using code from other resources, whether it is generated by humans or AI, is considered cheating.

6. **Forum:** Check the ODTUClass forum regularly for updates/discussions.

7. **Evaluation:** The primary basis of evaluation is your blog posts. Therefore try to write interesting and informative blog posts about your ray tracing journey. You can check out various past blogs for inspiration. However, also expect your codes to be compiled and tested on several input scenes for verification purposes. Therefore images that you share in your blog posts must directly correspond to your own ray tracer outputs.