基于光线追踪(Ray-Tracing)原理的物理渲染器实现

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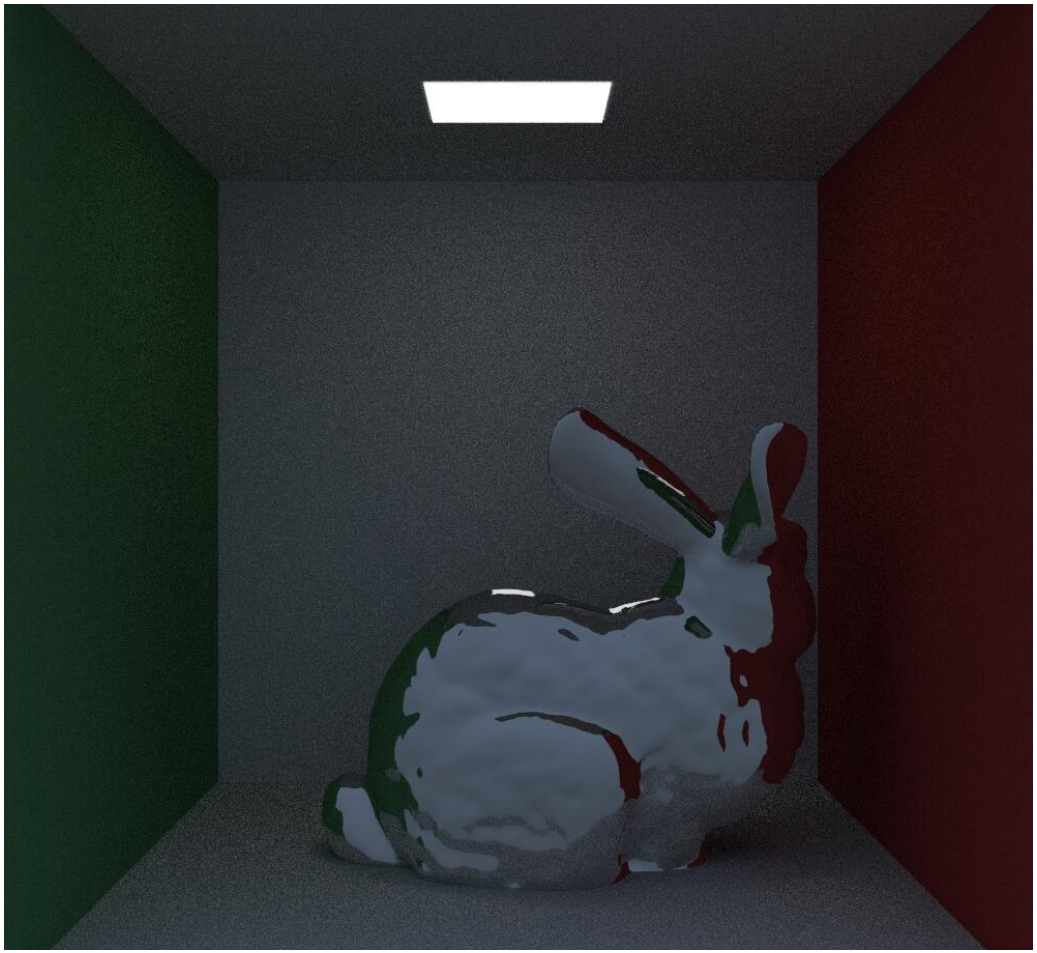
需求分析

- 渲染(Render)指将三维场景中的模型，按照设定好的环境、灯光、材质及渲染参数，二维投影成数字图像的过程。
- 光线追踪技术(Ray-Tracing)是由几何光学衍生而来。它通过追踪光线与物体表面发生的交互作用，得到光线经过路径的模型。
- 本项目旨在通过已学的线代和微积分知识，实现一个简易的光追渲染器

Samples 1

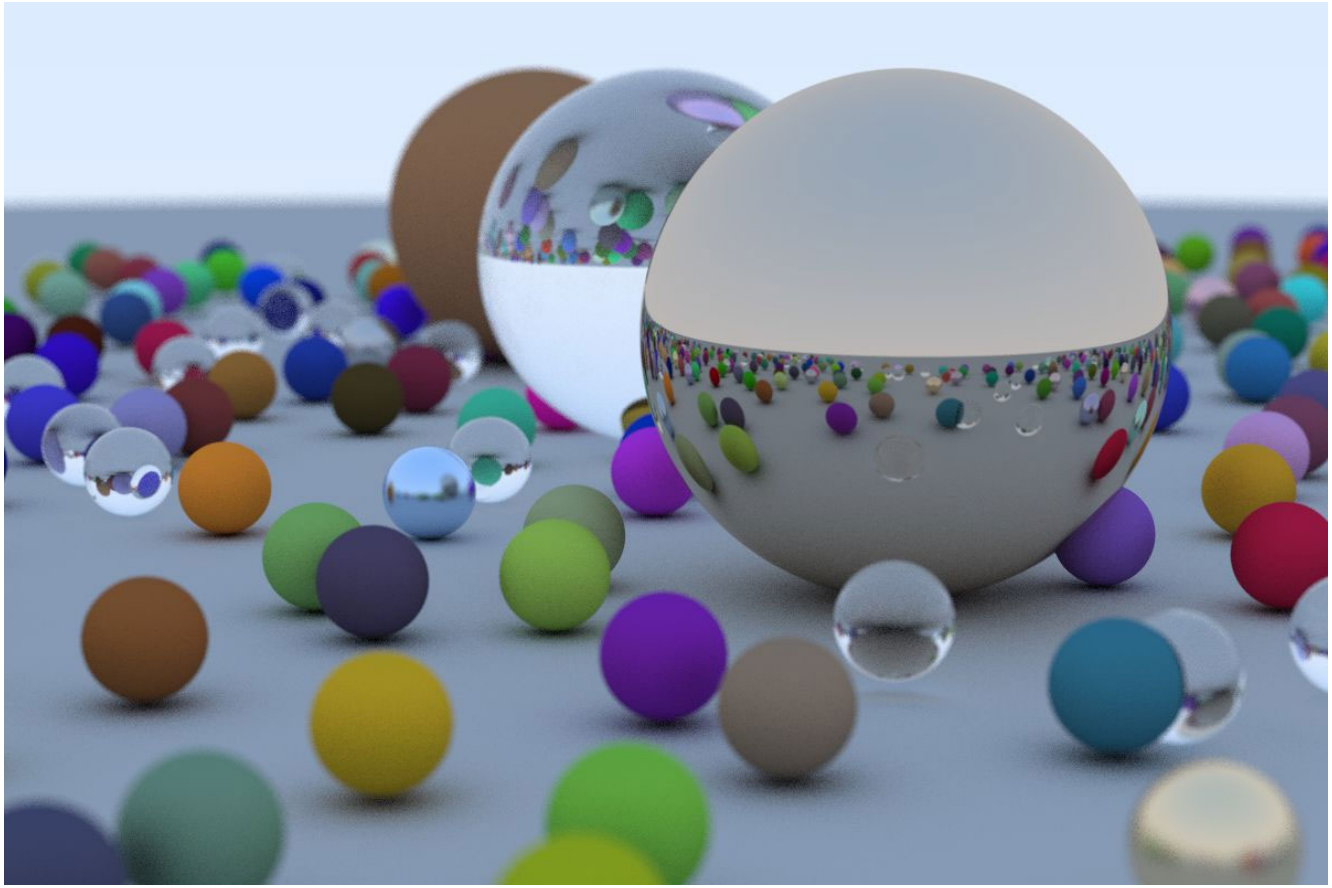
The Cornell Box (data from graphics.cornell.edu)
The Stanford Bunny (Source: Stanford University Computer Graphics Laboratory)



(600x600 500 samples per pixel)

Samples 2

spheres (data from random generator)

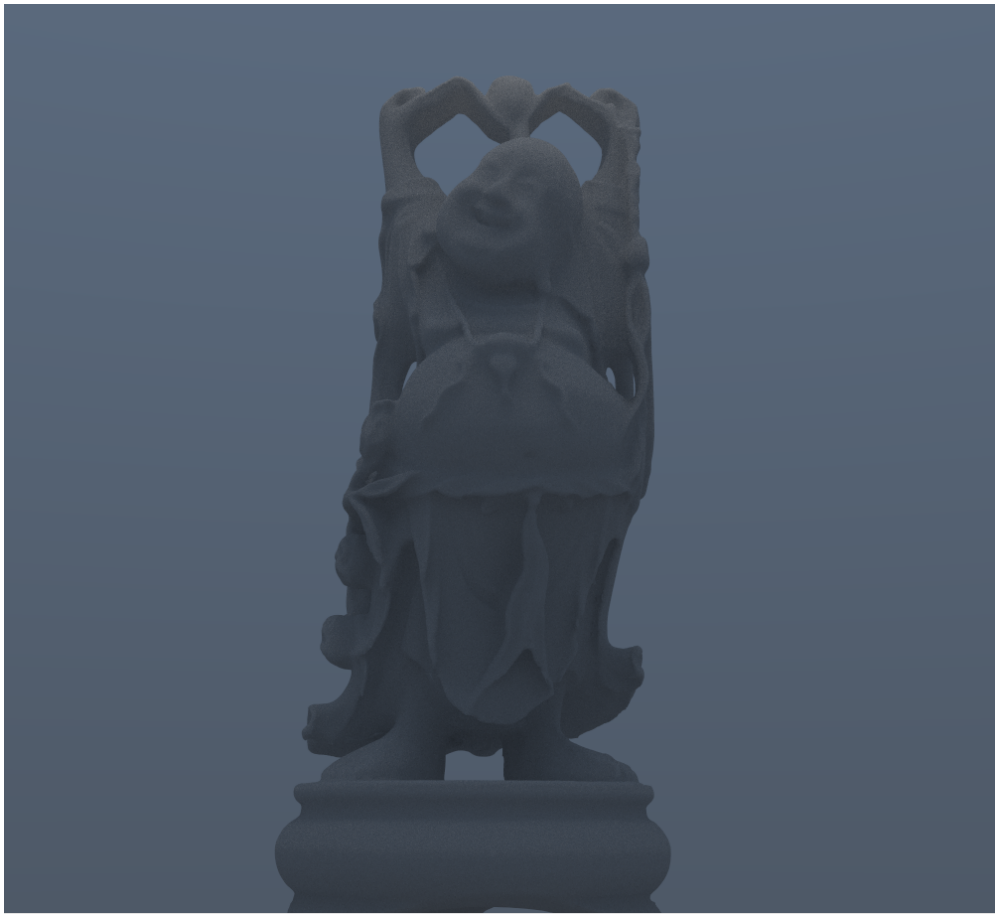


(1200x900 500 samples per pixel)

Samples 3

Happy Buddha (Source: Stanford University Computer Graphics Laboratory)

Lambertian material

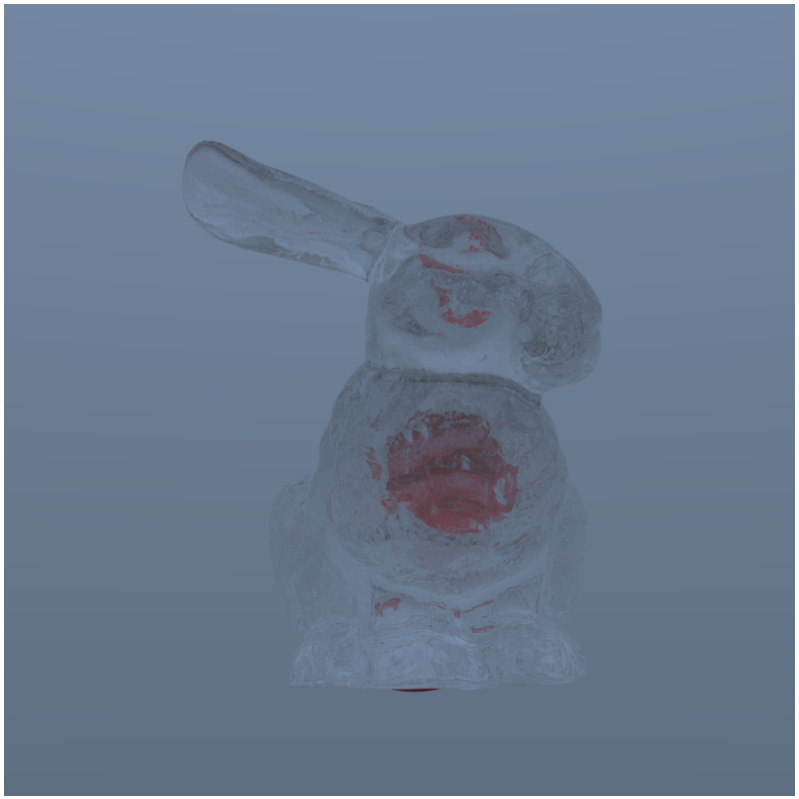


(900x900 1000 samples per pixel)

Samples 4

The Stanford Bunny (Source: Stanford University Computer Graphics Laboratory)

Dielectric material



(900x900 300 samples per pixel)

模块 1： 底层线性代数数学库

主要功能

提供常用线性代数中
数学量(点，向量，法线，矩阵）的结构体和
运算方法（线性运算，数乘，内外积，
矩阵的转置，求逆，乘法等）的函数

- ./math/vector3.h
- ./math/matrix3x3.h
- ./math/transform.h
- ./math/quaternion.h

/math/vector3.h

- 实现了Normal3, Point3, Vector3类
- 为了方便调用，运算符重载了线性运算

```
BaseVector3 operator + (const BaseVector3 &v) const;
friend BaseVector3 operator * (const float &s, const BaseVec
&v);
...
```

- 实现了点积，叉积，求长度，求距离，标准化等方法

```
float dot(const BaseVector3 &v) const;
float length() const;
float distance(const BaseVector3 &p) const;
BaseVector3& normalize();
...
```

/math/vector3.h

- SIMD(Single Instruction Multiple Data)
- 单指令多数据流，能够复制多个操作数，
  并把它们打包在大型寄存器的一组指令集。
- 向量每个分量在线性运算时候都是独立的，
  可以依靠SIMD并行运算
- 本项目通过intrin.h，实现了X86平台下的SIMD优化
- ...

```
__m128 vs = _mm_load_ss(&s);
vs = _mm_pshufd_ps(vs, 0x80);
m_val128 = _mm_mul_ps(m_val128, vs);
...
```

/math/matrix3x3.h

- 实现了Matrix3x3类
- 用三个vector3表示一个3x3的矩阵
- 实现了矩阵的常用运算

```
Matrix3x3 transpose() const;
Matrix3x3 absolute() const;
Matrix3x3 adjoin() const;
Matrix3x3 inverse() const;
...
```

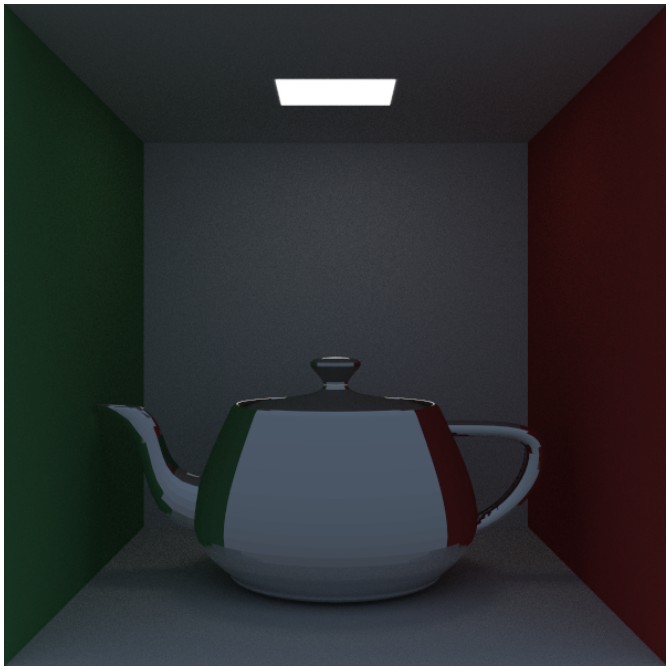
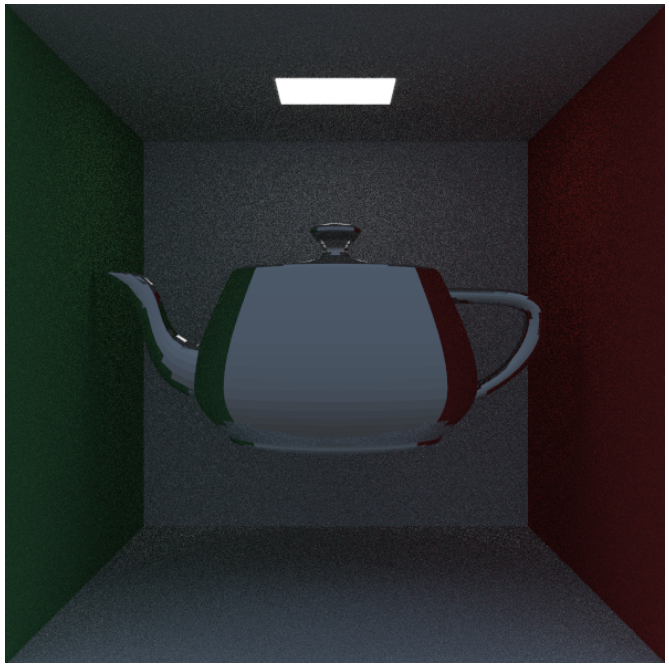
/math/transform.h

- 实现了Transform类
- 封装了一个Matrix3x3和Vector3及其逆过程，表达了空间中的一个变换

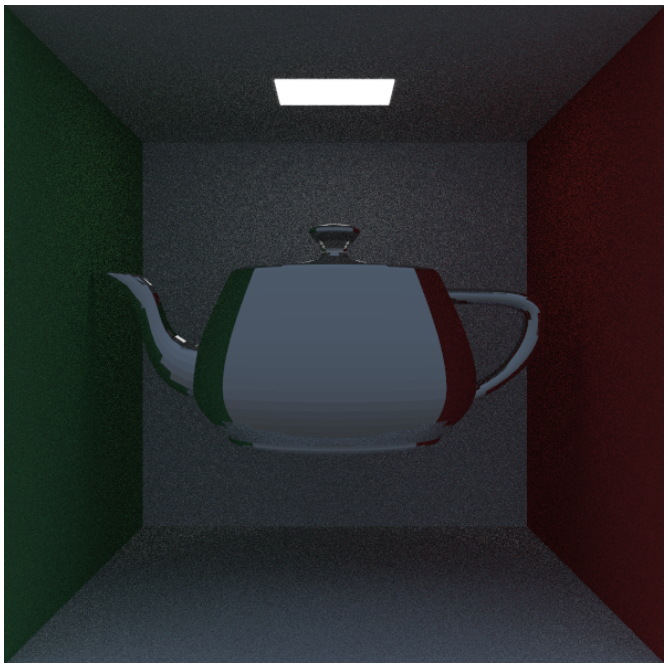
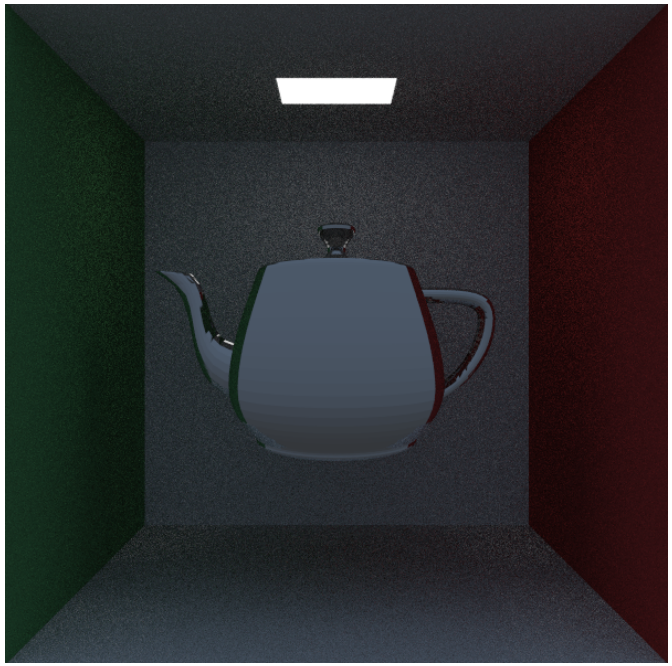
[Transform class members:]

```
Matrix3x3 m_mat, m_inv;
Vector3 m_trans;
```

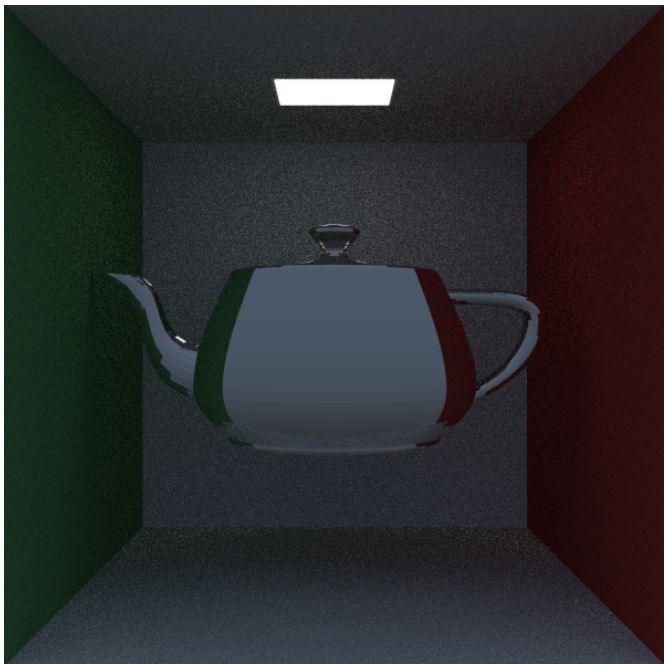
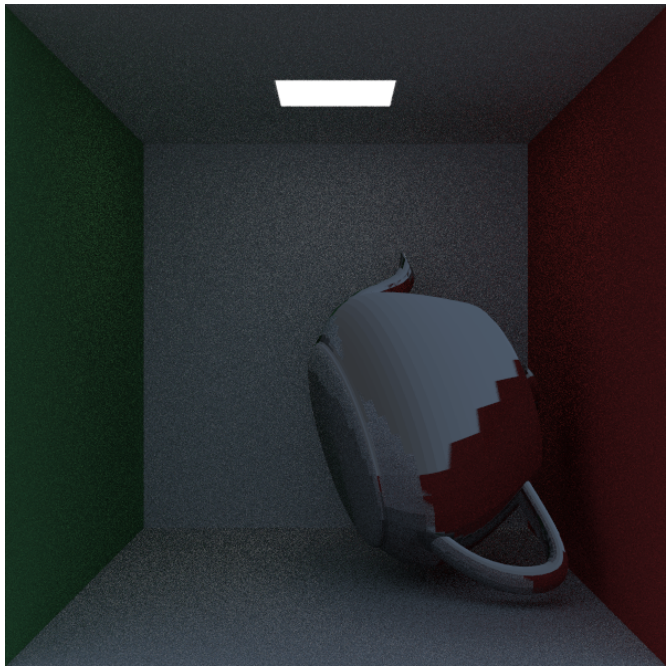
位移 (Translate)

- m_trans = (x, y, z)
-  To 

缩放 (Scale)

- $m\_mat = \begin{bmatrix} x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & z \end{bmatrix}, m\_mat^{-1} = \begin{bmatrix} \frac{1}{x} & 0 & 0 \\ 0 & \frac{1}{y} & 0 \\ 0 & 0 & \frac{1}{z} \end{bmatrix}$
-  To 

旋转 (Rotation)

- 设旋转轴为A，旋转角为θ，$c = \cos\theta, s = \sin\theta$
- $$m\_mat = \begin{bmatrix} c + (1-c)A_x^2 & (1-c)A_xA_y - sA_z & (1-c)A_xA_z + sA_y \\ (1-c)A_xA_y & c + (1-c)A_y^2 & (1-c)A_xA_y - sA_z \\ (1-c)AxAz - sA_y & (1-c)A_yA_z + sA_x & c + (1-c)A_z^2 \end{bmatrix}, m\_mat^{-1} = m\_mat^T$$
-  To 

模块 2: 光追渲染器组件实现

主要功能

定义场景中的物体，材质，纹理相机等参数，
并实现光线传播（漫反射，镜面反射，折射，相交）的相应计算

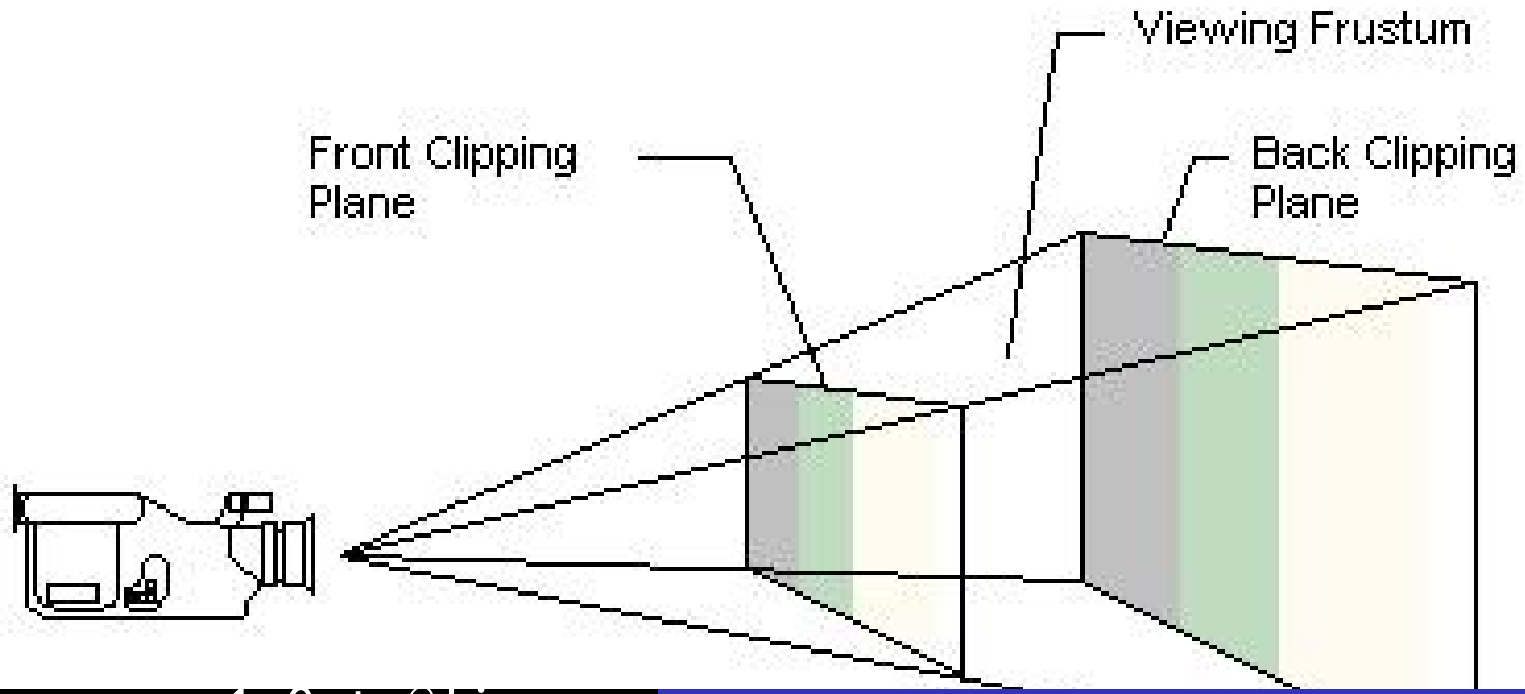
- ./core/camera.h
- ./core/integrator.h
- ./core/material.h
- ./core/primitive.h,cpp
- ./core/texture.h
- ./shapes/rectangle.h,cpp
- ./shapes/sphere.h,cpp
- ./shapes/triangle.h,cpp
- ./accelerators/BVH.h,cpp

/core/camera.h

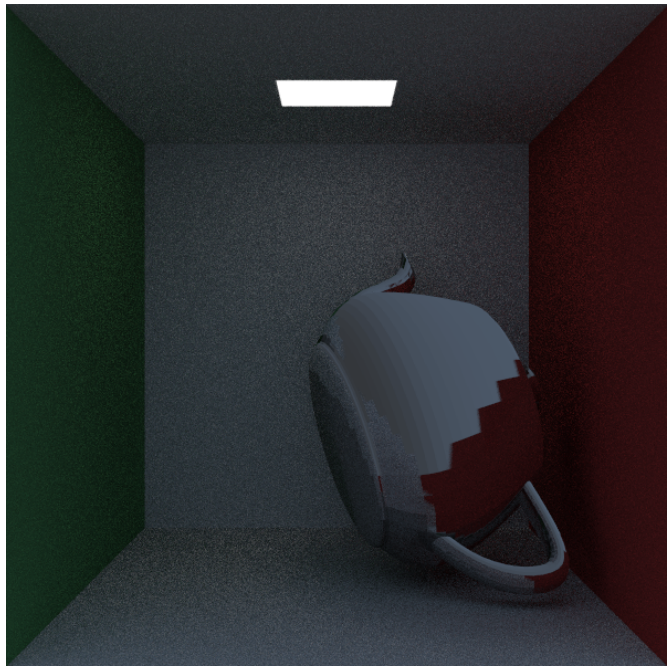
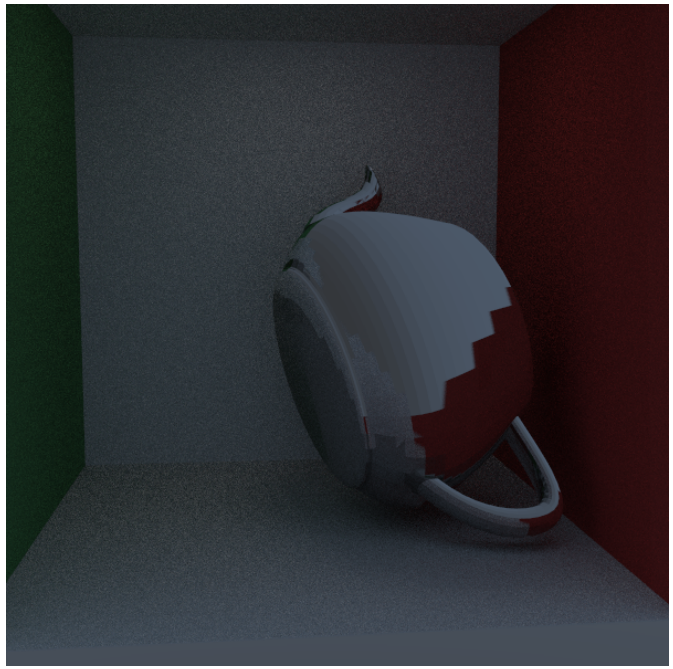
- 实现了Camera, ProjectiveCamera类
- Camera必须实现的方法

```
virtual Ray getRay(const float &s, const float &t)
const;
```

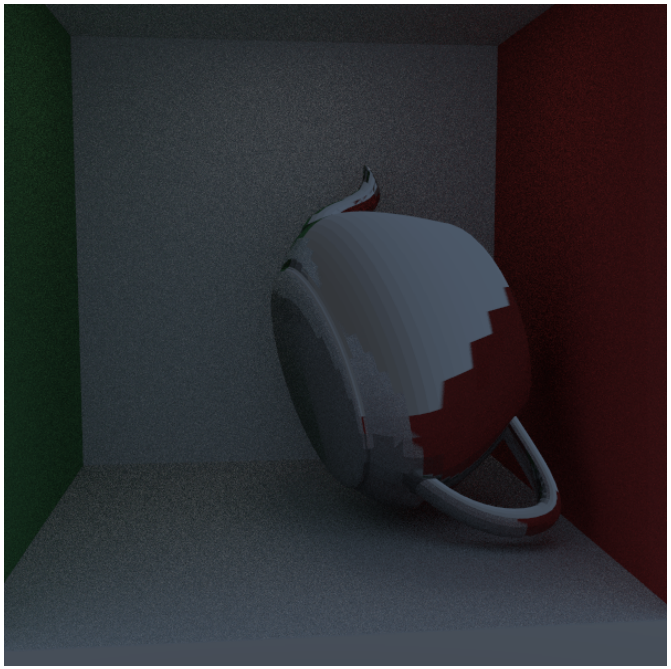
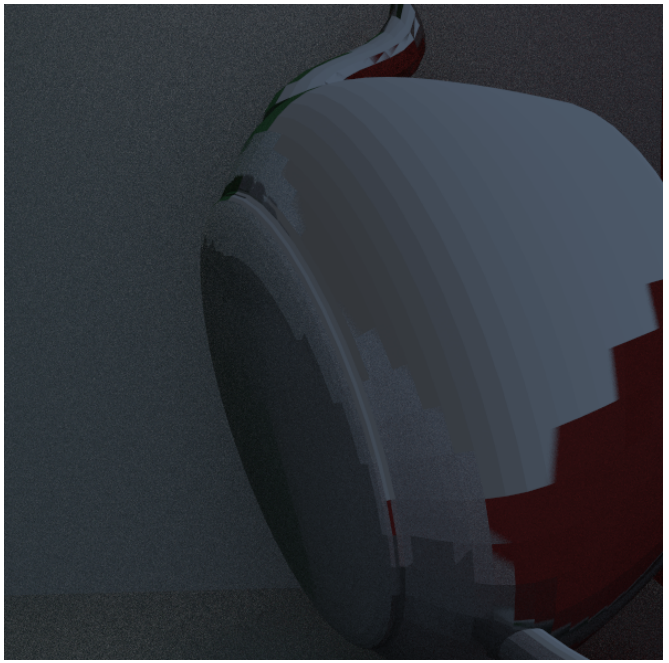
- 投影相机(ProjectiveCamera类)



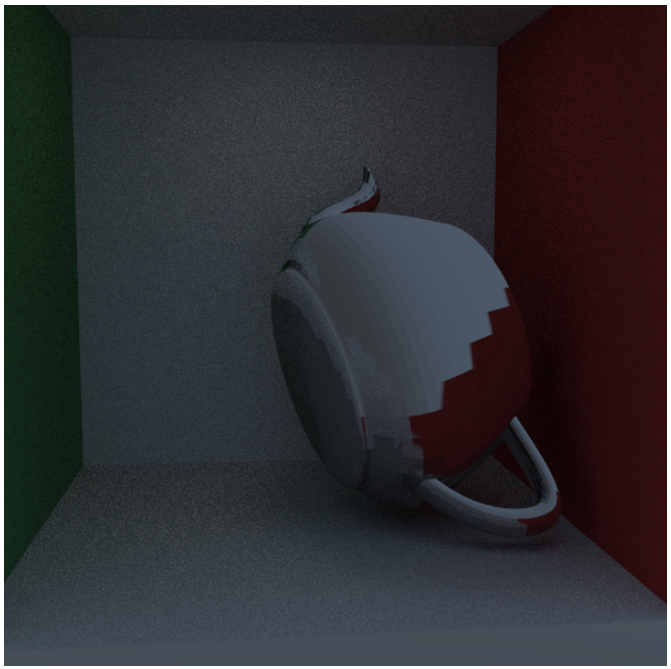
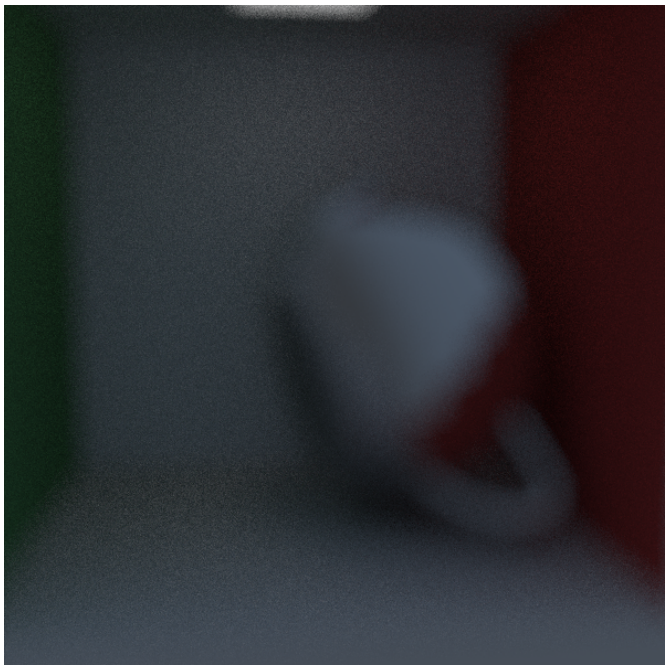
/core/camera.h

- const Point3 lookform,
  const Point3 lookat,
  const Vector3 vup
  确定了摄像机的位置和角度
-  To 

/core/camera.h

- float vfov
  确定视角的大小
-  To 

/core/camera.h

- float aperture
  确定光圈（小孔成像中小孔）的半径
-  To 

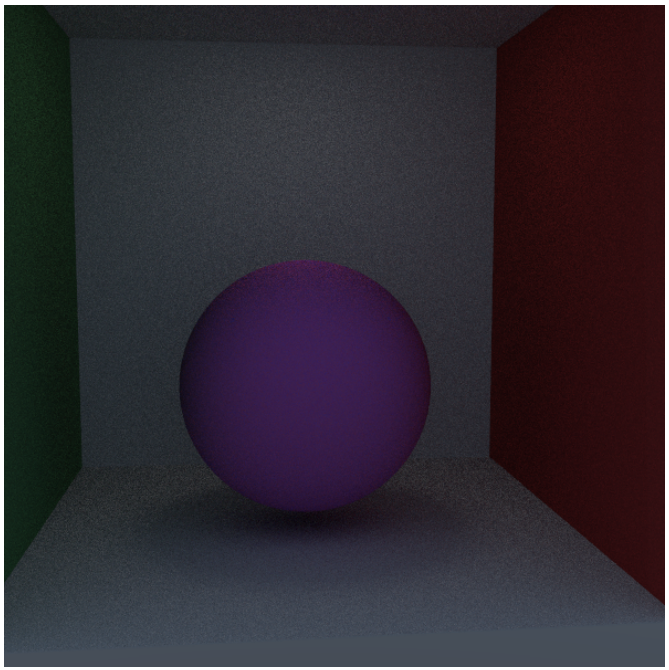
/core/texture.h

- 实现了Texture, ConstantTexture, CrossTexture, NoiseTexture类
- Texture必须实现的方法

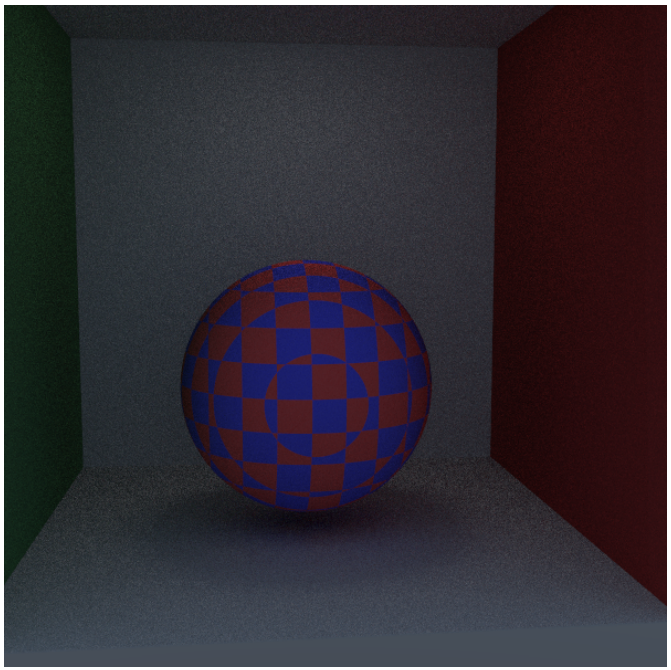
  virtual Spectrum value(float u, float v, const Point3 &p) const;

  对通过光线与平面交点及(u,v)坐标对纹理采样颜色

/core/texture.h

- ConstantTexture，返回一个常量颜色的纹理
- 

/core/texture.h

- CrossTexture，返回一个交错的棋盘纹理
- 

/core/texture.h

- NoiseTexture，返回一个柏林噪音(Perlin Noise)实现的随机纹理

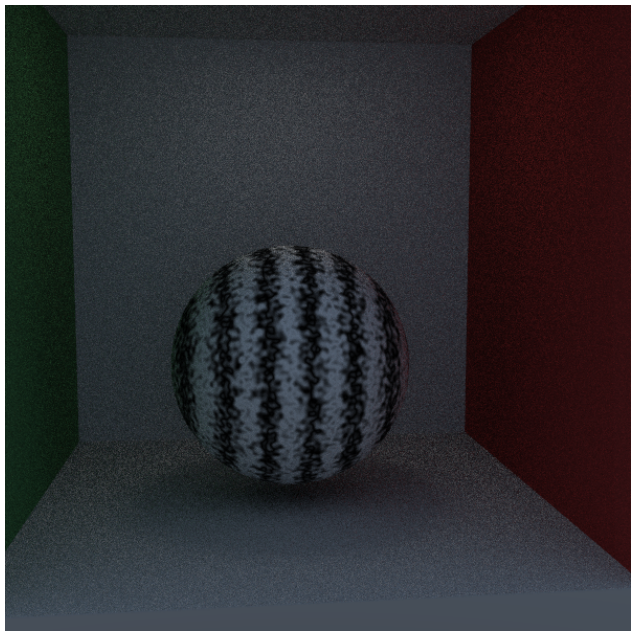


Figure: scale = 0.5

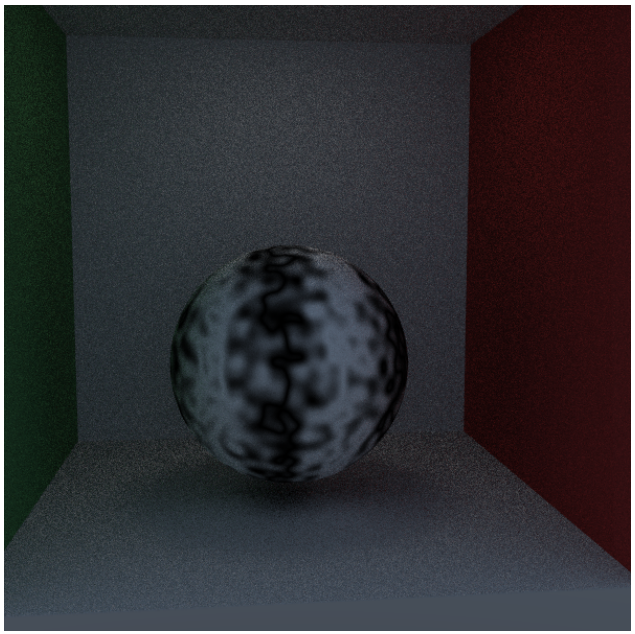


Figure: scale = 0.05

/core/material.h

- 实现了Material, MentalMaterial, LambertianMaterial, DielectricMaterial类
- Material必须实现的方法

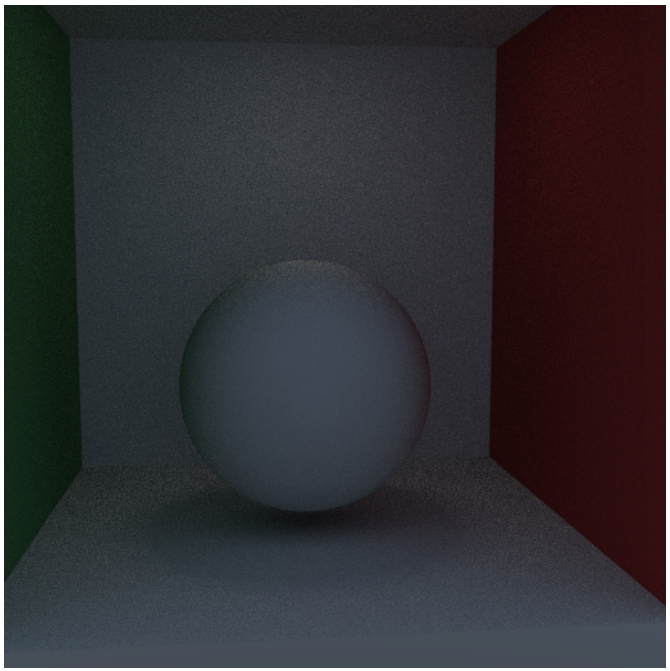
  virtual bool scatter
  (const Ray &r_in, const SurfaceInteraction &si, Spectrum &attenuation, Ray &scattered) const;

  根据入射光线和表面的信息，返回出射光线和衰减率
- virtual Spectrum emitted
  (float u, float v, const Vector3 &p) const;
  返回物体的自发光

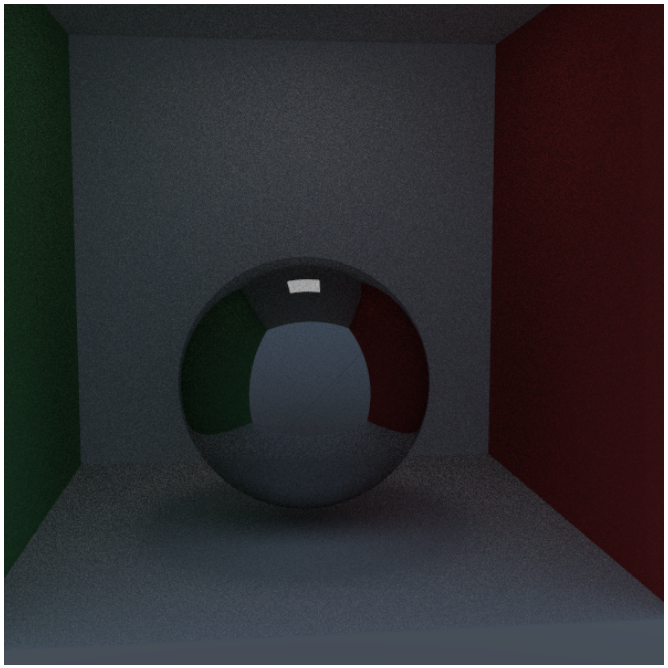
/core/material.h

- LambertianMaterial, 漫反射材质
- 光线射入物体后向各方向随机漫反射

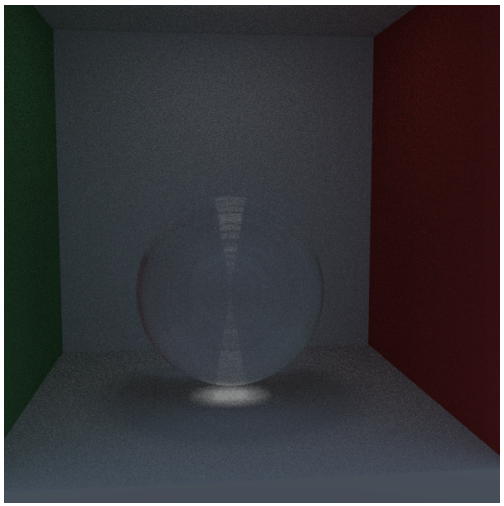
```
Vector3 target = si.p + si.n + rng.randomInUnitSphere();
scattered = Ray(si.p, target - si.p, r_in.m_time);
```

- 

/core/material.h

- MentalMaterial，金属材质
- 入射角和反射角相同，即按法线反转
- $\mathrm{out} = \mathrm{in} - (\mathrm{in}, \mathrm{n}) \cdot 2 \cdot \mathrm{n}$
- fuzz参数描述镜面的粗糙程度
- 

/core/material.h

- DielectricMaterial，电介质材质
- 同时存在镜面反射和折射效应，能量分配通过菲涅耳公式(Fresnel Formula)计算，实际项目中采用schlick公式近似
- $\frac{\sin\theta 1}{\sin\theta 2} = r$
- m_refractive_idx参数描述介质材料的折射率
- 

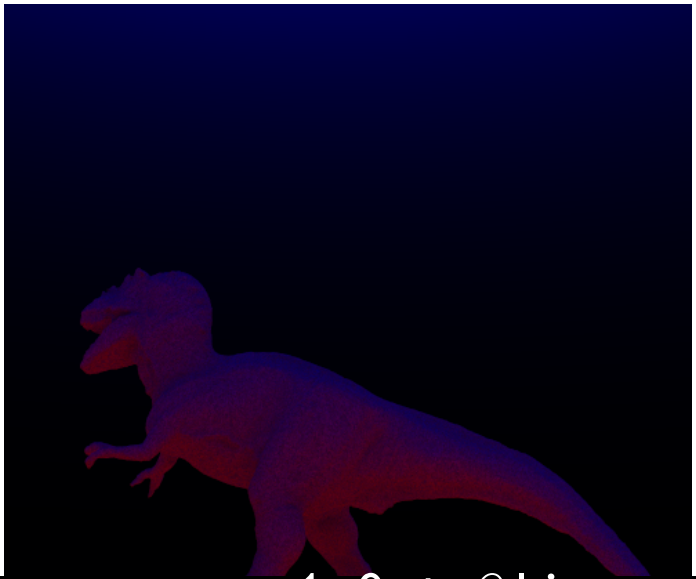
/core/shape.h

- 实现了Shape基类
- Shape必须实现的方法
- `virtual BBox objectBound() const = 0;`
  返回形状在物体参考系中的包围盒
- `virtual BBox worldBound() const = 0;`
  返回形状在世界参考系中的包围盒
- `virtual bool canIntersect() const;`
  判断当前图元是否能相交
- `virtual void refine(std::vector<SharedPtr<Shape>>&refined) const;`
  细分无法相交的图元
- `virtual bool intersect(const Ray &ray, float *hit_t, Surface *dg) const;`
  对相应光线执行相交计算

/core/shape.h

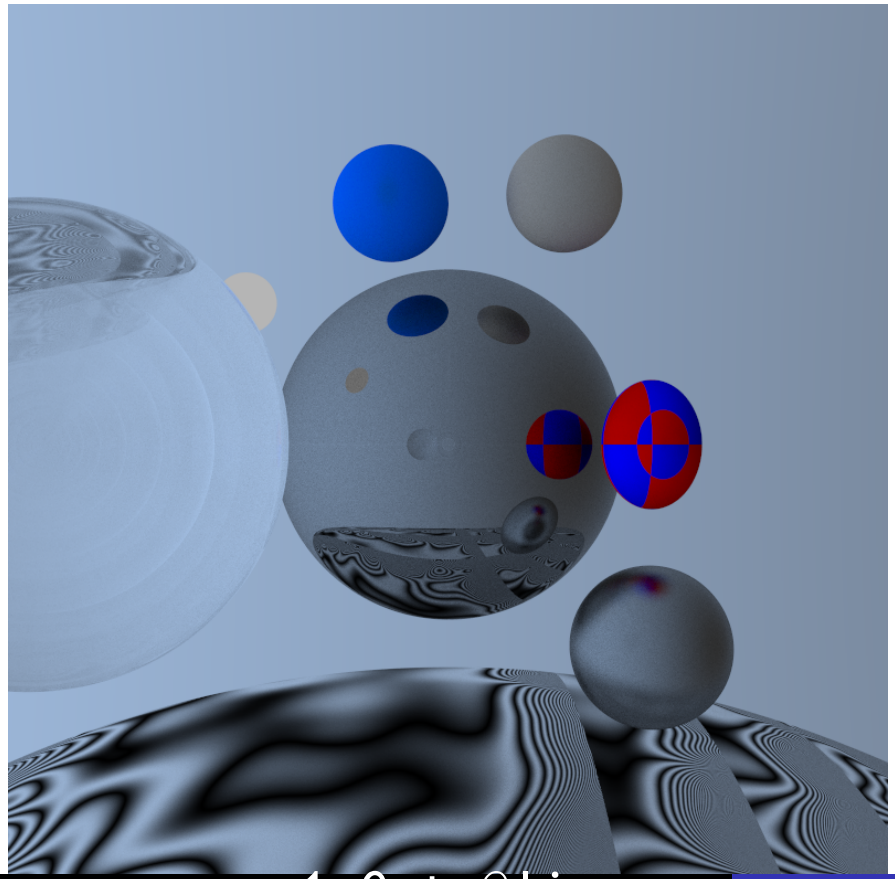
- ./shapes/triangle.h
- ./shapes/triangle.cpp
-

  为保证内存的连续性，三角形的顶点，索引等数据统一储存在TriangleMesh类中，具体计算由细分后的Triangle类实现
- 相交方法实现以Fast, Minimum Storage Ray-Triangle Intersection为参考



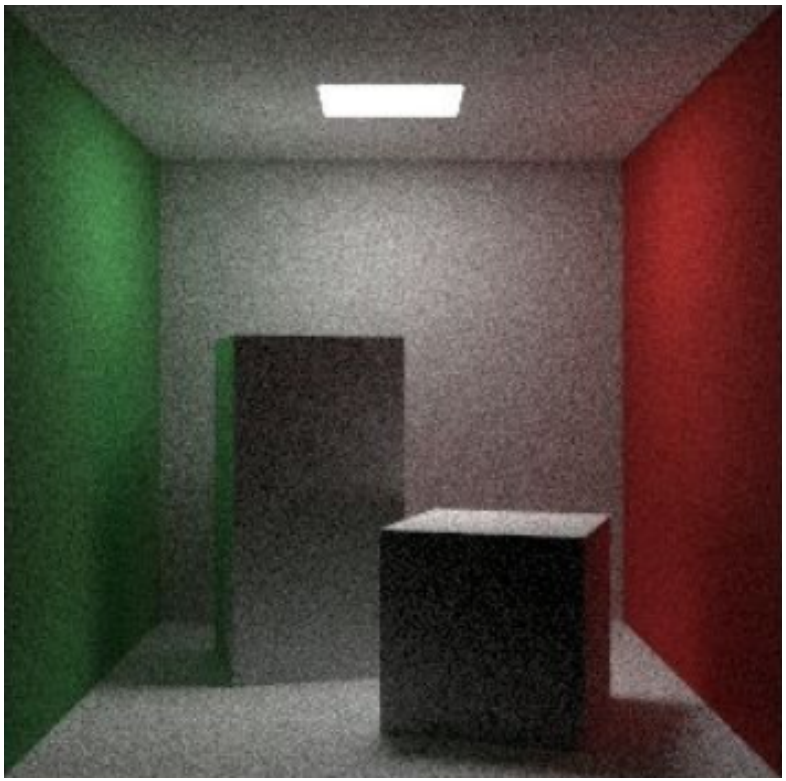
/core/shape.h

- ./shapes/sphere.h
- ./shapes/sphere.cpp
- 计算相交即解一个关于射线参数t的一元二次方程



/core/shape.h

- ./shapes/rectangle.h
- ./shapes/rectangle.cpp
- 将射线转化到物体坐标系后六个平面和坐标轴分别对齐，分别计算相交后取t的最小值的平面



-

/accelerator/BVH.h

- 如果每一束光线都对场景中的每一个物体进行相交计算，计算开销将会无法接受
- 本项目对每一个形状构建了包围盒，并使用了数据结构BVH(Bounding Volume Hierarchy)进行加速
- 本质是一类二叉搜索树，每层对三条坐标轴中的一条进行排序
- 复杂度可由O(n^2)降为O(nlogn)

/core/parser.h

- 实现了parser类，用以将描述场景的JSON文件和描述模型的OBJ文件解析入Scene结构体的内存中

/core/parser.h

- JSON(JavaScript Object Notation)
  是一种轻量级的数据交换格式。易于人阅读和编写
- JSON是一个标记符的序列。这套标记符包含六个构造字符、字符串、数字和三个字面名
- 本项目使用的描述文件是JSON的子集，
  即parser类仅按照特定语法树和关键词进行解析

/core/parser.h

- 场景文件样例(part 1.)

```
{
    "config" : {
        "screen_x" : 1000,
        "screen_y" : 1000,
        "sample_times": 500
    },
    "camera" : {
        "lookfrom" : {
            "x" : 278,
            "y" : 278,
            "z" : -760
        },
        "lookat" : {
            "x" : 278,
            "y" : 278,
            "z" : 0
        },
        "lookup" : {
            "x" : 0,
            "y" : 1,
            "z" : 0
        },
        "fov" : 40.0,
        "aspect" : 1,
        "aperture" : 0.0,
        "focus_dist" : 100000,
        "t0" : 0,
        "t1" : 0
    },
    "transforms" :
    [
```

/core/parser.h

- 场景文件样例(part 2.)

```
36          },
37          {
38              "translate" : { "x" : 555,
39              "y" : 277.5,
40              "z" : 277.5}
41          },
42          {
43              "translate" : { "x" : 277.5,
44              "y" : 277.5,
45              "z" : 555}
46          },
47          {
48              "translate" : { "x" : 277.5,
49              "y" : 555,
50              "z" : 277.5}
51          },
52          {
53              "translate" : { "x" : 277.5,
54              "y" : 0,
55              "z" : 277.5}
56          },
57          {
58              "translate" : { "x" : 278,
59              "y" : 553.5,
60              "z" : 279.5}
61          }
62      ],
63      "shapes" :
64      [
65          { "rectangle" : {
66              "transform" : 0,
```

/core/parser.h

- 场景文件样例(part 3.)

```
"materials" :
[
    {"mental" : {
        "spectrum(256)" : {"r" : 191, "g" : 173, "b" : 111},
        "fuzz" : 0.0
    }},
    {"lambertian": {
        "texture" : {
            "constant" : {
            "spectrum(1)" : {"r" : 0.73, "g" : 0.73, "b" : 0.73}
            }}
    }},
    {"lambertian": {
        "texture" : {
            "constant" : {
            "spectrum(1)" : {"r" : 0.65, "g" : 0.05, "b" : 0.05}
            }}
    }},
    {"lambertian": {
        "texture" : {
            "constant" : {
            "spectrum(1)" : {"r" : 0.12, "g" : 0.45, "b" : 0.15}
            }}
    }},
    {"diffuse" : {
        "texture" : {
            "constant" : {
            "spectrum(1)" : {"r" : 1, "g" : 1, "b" : 1}
            }}
    }}
],
```

/core/parser.h

- config对象，定义了场景输出图片的长宽和采样数
  camera对象，定义了场景中的相机信息
  transforms数组，定义了场景中所用到的转移矩阵
  shapes数组，定义了场景中的图形信息
  materials数组，定义了场景中的材质信息
  primitive数组，定义了场景中的图元信息

/core/parser.h

- `void load(const char *file);`
  从文件中导入JSON字符串（忽略无意义的空白符(ws)）
- `void run(Scene *scene);`
  开始解析入场景结构体中

/core/parser.h

- READ_BRACE_BEGIN();
  READ_BRACE_END();
  READ_COLON();
  READ_ARRAY_BEGIN();
  READ_BRACE_ELEMENT_END();
  READ_ARRAY_ELEMENT_END();
  读入构造字符构造语法树并判断合法性，
  通过assert()函数检查合法性

/core/parser.h

- ```
  std::string READ_STRING();
  bool READ_BOOL();
  int READ_INT();
  float READ_FLOAT();
  BaseVector3 READ_VECTOR();
  Spectrum READ_SPECTRUM1();
  Spectrum READ_SPECTRUM256();
  ```
  读入基本的数据类型（JSON自己基础的字符串，浮点数，整数，布尔值和扩展类型，包括向量和颜色）
  ```

/core/parser.h

- READ_SHAPES();
  READ_SHAPE();
  READ_RECTANGLE();
  READ_SPHERE();
- 进入读取shape的分支后，先用READ_SHAPES()对数组循环读取
- 在循环中用READ_SHAPE()解析其中的每个元素
- 在解析到其中的type值对后，细化为具体READ_RECTANGLE()或READ_RECTANGLE()或READ_SPHERE()的方法，进而通过读取值对读取其中的元素值
- 其余分支读取方法相同，在此不再赘述

/core/parser.h

- obj文件是3D模型文件格式。适合用于3D软件模型之间的互导
- 本项目实现了对其的读入支持

Others

- ./core/config.h 控制项目的编译选项开关
- ./core/rng.h 实现了柏林噪声(Perlin Noise)生成器，梅森旋转(Mersenne Twister)算法实现的随机数生成器
- ./core/memory.h
  实现了自动释放和拷贝内存的引用计数指针
- ./math/mathutility.h 使用SIMD重写了部分常用数学函数
- ./math/bbox.h 定义了包围盒的结构体
- ./core/primitive.h,cpp
  将shape和material封装整合为图元
- ./core/interaction.h 定义了描述相交表面细节的结构体
- ./core/scene.h 定义了描述场景内容的结构体
- ./core/ray.h 定义了射线的结构体
- ./core/integrator.h 定义了对场景采样的积分器
- ./core/spectrum.h 定义了颜色（简化后辐射度）的结构体

;)

Thank you for watching!