RAY TRACING IN ONE WEEKEND: THE BOOK SERIES

Notes by Yuxing Shi

https://raytracing.github.io/

Ray Tracing in One Weekend

https://raytracing.github.io/books/RayTracingInOneWeekend.html

Output an Image

- The PPM Image Format

PPM example [edit]

This is an example of a color RGB image stored in PPM format. There is a newline character at the end of each line.

```
P3
# The P3 means colors are in ASCII, then 3 columns and 2 rows,
# then 255 for max color, then RGB triplets
3 2
255
255   0   0     0 255   0     0   0 255
255 255   0   255 255 255     0   0   0
```

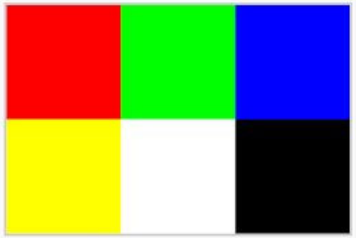


Image (magnified)

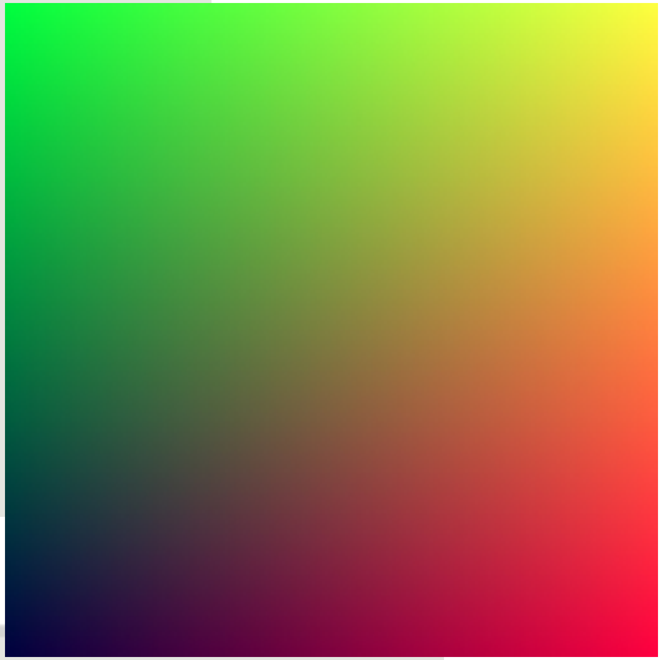
```cpp
// Render

std::cout << "P3\n" << image_width << ' ' << image_height << "\n255\n";

for (int j = image_height-1; j >= 0; --j) {
    for (int i = 0; i < image_width; ++i) {
        auto r = double(i) / (image_width-1);
        auto g = double(j) / (image_height-1);
        auto b = 0.25;

        int ir = static_cast<int>(255.999 * r);
        int ig = static_cast<int>(255.999 * g);
        int ib = static_cast<int>(255.999 * b);

        std::cout << ir << ' ' << ig << ' ' << ib << '\n';
    }
}
```



- Progress Indicator

```cpp
std::cerr << "\nDone.\n";
```

```
build/inOneWeekend > image.ppm
```

Rays, a simple camera, and bg.

4.1. The ray Class

The one thing that all ray tracers have is a ray class and a computation of what color is seen along a ray. Let's think of a ray as a function $\mathbf{P}(t) = \mathbf{A} + t\mathbf{b}$. Here $\mathbf{P}$ is a 3D position along a line in 3D. $\mathbf{A}$ is the ray origin and $\mathbf{b}$ is the ray direction. The ray parameter t is a real number (`double` in the code). Plug in a different t and $\mathbf{P}(t)$ moves the point along the ray. Add in negative t values and you can go anywhere on the 3D line. For positive t, you get only the parts in front of $\mathbf{A}$, and this is what is often called a half-line or ray.

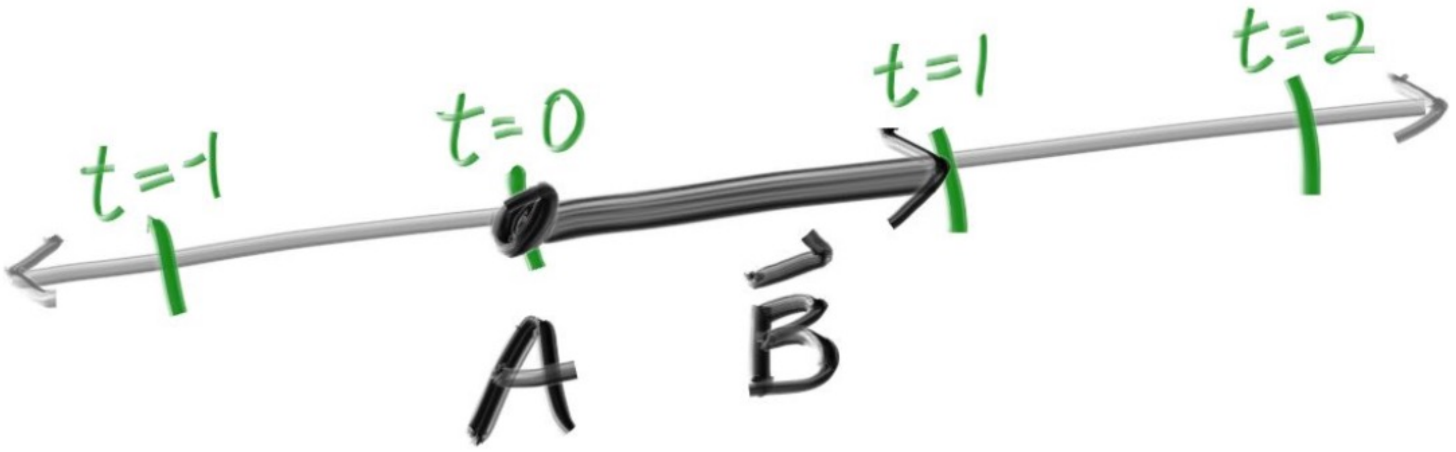


Figure 2: *Linear interpolation*

Sending Rays Into the Scene

- (1) calculate the ray from the eye to the pixel,
- (2) determine which objects the ray intersects, and
- (3) compute a color for that intersection point.

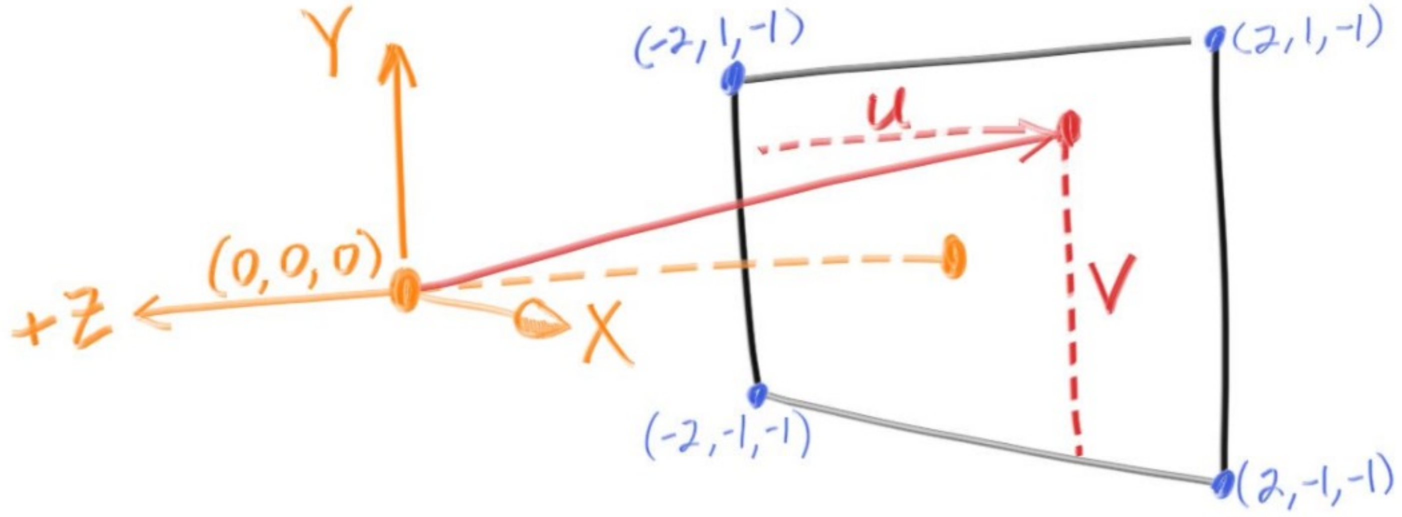


Figure 3: *Camera geometry*

Focal length = 1 unit (orange)
!= focus distance

Codes

- Viewpoint
  - through which to pass our scene rays
  - aspect ratio should be the same as our rendered image
  - Rectangle height of 2 at last slide.
  - Focal length: projection point to projection plane.

```
color ray_color(const ray& r) {
    vec3 unit_direction = unit_vector(r.direction());
    auto t = 0.5*(unit_direction.y() + 1.0);
    return (1.0-t)*color(1.0, 1.0, 1.0) + t*color(0.5, 0.7, 1.0);
}
```

- linearly blends white and blue depending on the height of the y coordinate after scaling the ray direction to unit length (-1 ~ 1)
- And then scale 0 <= t <= 1.0

Codes

- Image + Camera (+ Render)

```
// Image
const auto aspect_ratio = 16.0 / 9.0;
const int image_width = 400;
const int image_height = static_cast<int>(image_width / aspect_ratio);

// Camera

auto viewport_height = 2.0;
auto viewport_width = aspect_ratio * viewport_height;
auto focal_length = 1.0;

auto origin = point3(0, 0, 0);
auto horizontal = vec3(viewport_width, 0, 0);
auto vertical = vec3(0, viewport_height, 0);
auto lower_left_corner = origin - horizontal/2 - vertical/2 - vec3(0, 0, focal_length);
```

Codes

- (Image + Camera +) Render

```
// Render

std::cout << "P3\n" << image_width << " " << image_height << "\n255\n";

for (int j = image_height-1; j >= 0; --j) {
    std::cerr << "\rScanlines remaining: " << j << ' ' << std::flush;
    for (int i = 0; i < image_width; ++i) {
        auto u = double(i) / (image_width-1);
        auto v = double(j) / (image_height-1);
        ray r(origin, lower_left_corner + u*horizontal + v*vertical - origin);
        color pixel_color = ray_color(r);
        write_color(std::cout, pixel_color);
    }
}
```

Image 2: A blue-to-white gradient depending on ray Y coordinate

Adding a Sphere

- Sphere: $(x - Cx)^2 + (y - Cy)^2 + (z - Cz)^2 = r^2$
- Vector form: $(\mathbf{P} - \mathbf{C}) \cdot (\mathbf{P} - \mathbf{C}) = r^2$
- Ray hits sphere: $(\mathbf{P}(t) - \mathbf{C}) \cdot (\mathbf{P}(t) - \mathbf{C}) = r2$
  Where: $\mathbf{P}(t) = \mathbf{A} + t\mathbf{b}$
- **=>** $t^2 \mathbf{b} \cdot \mathbf{b} + 2t \mathbf{b} \cdot (\mathbf{A} - \mathbf{C}) + (\mathbf{A} - \mathbf{C}) \cdot (\mathbf{A} - \mathbf{C}) - r^2 = 0$

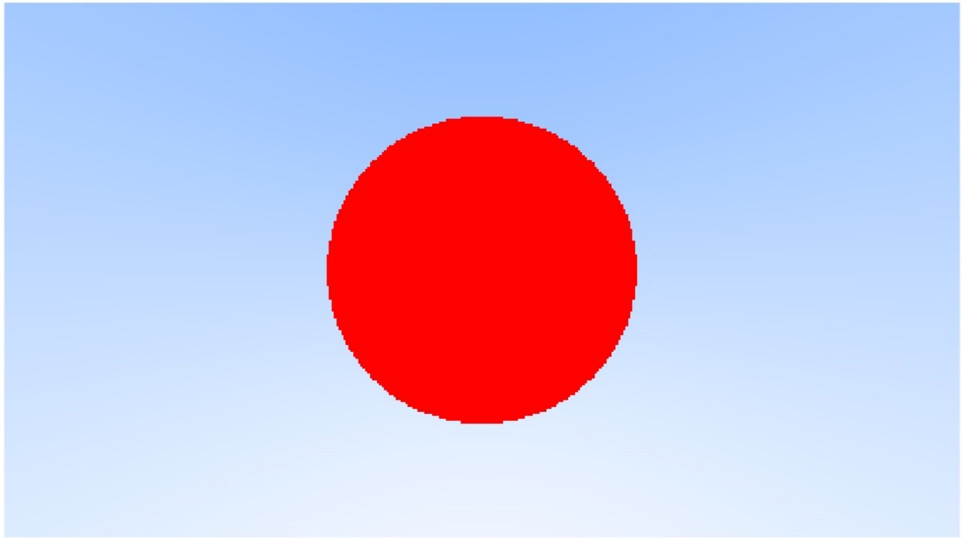


Image 3: A simple red sphere

```
bool hit_sphere(const point3& center, double radius, const ray& r) {
```

```
    return (discriminant > 0);
}
```

```
color ray_color(const ray& r) {
    if (hit_sphere(point3(0,0,-1), 0.5, r))
        return color(1, 0, 0);
    vec3 unit_direction = unit_vector(r.direction());
    auto t = 0.5*(unit_direction.y() + 1.0);
    return (1.0-t)*color(1.0, 1.0, 1.0) + t*color(0.5, 0.7, 1.0);
}
```

Surface Normals and Multiple Objects

- Surface normal: vector that is perpendicular to the surface at the point of intersection
- Code: configure hit_sphere to return smalltes t.

Image 4: A sphere colored according to its normal vectors

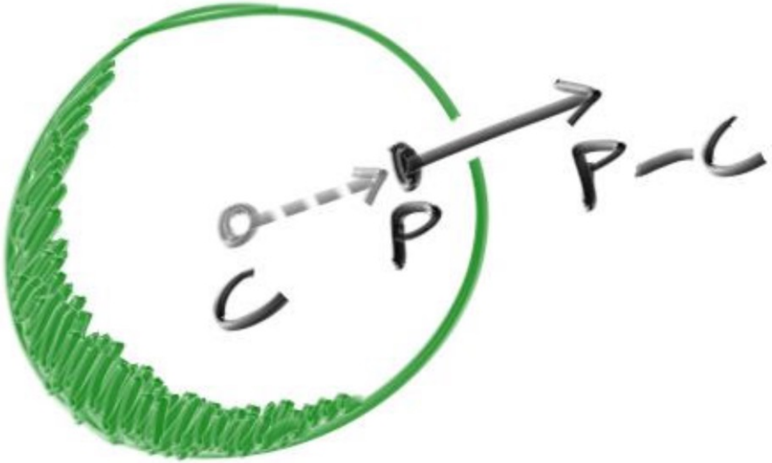


Figure 5: *Sphere surface-normal geometry*

An Abstraction for Hittable Objects

- Object, surface, hittable
- Struct hit_record: P, N, t
- Normal directions
  - Always out
  - Against ray

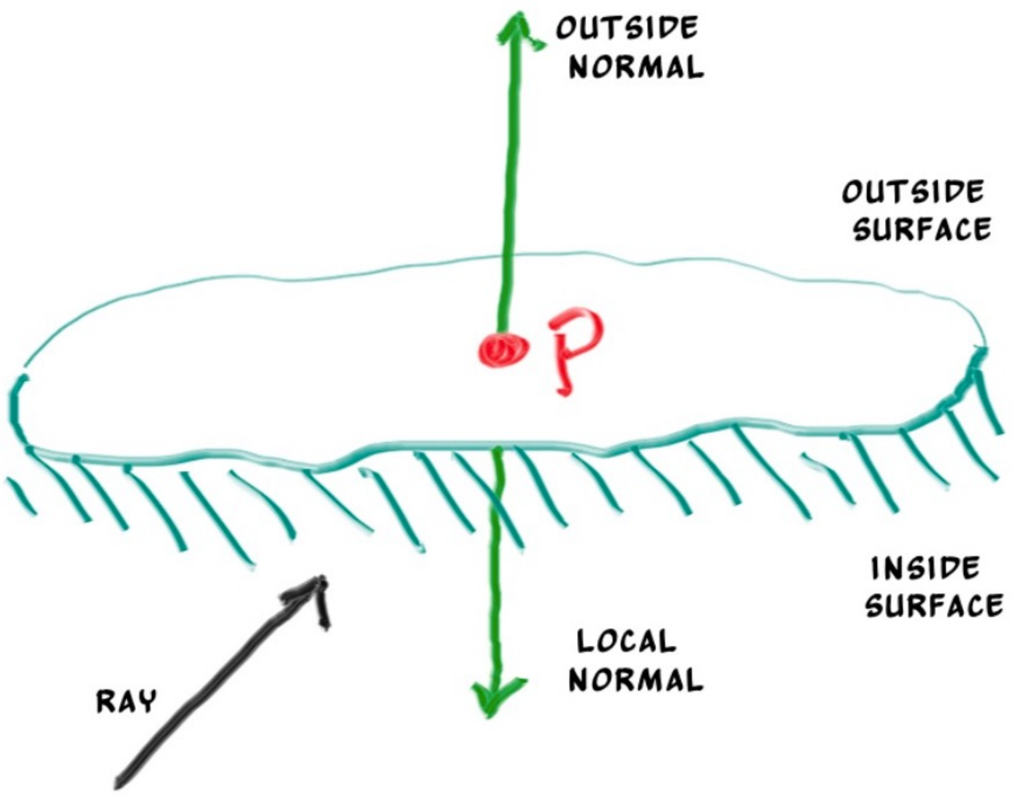


Figure 6: *Possible directions for sphere surface-normal geometry*

Add hittable_list

```
Vector3 ray_color(Ray r, hittable_list world) {
    hit_record rec;
    if (world.hit(r, 0, infinity, rec)) {
        return 0.5 * (rec.N + Vector3(1,1,1));
        std::cout<<"hit"<<std::endl;
    }
    Vector3 unit_direction = r.direction().unit();
    auto t = 0.5*(unit_direction.y() + 1.0);
    return (1.0-t)*Vector3(1.0, 1.0, 1.0) + t*Vector3(0.5, 0.7, 1.0);
}
```

```
// World
hittable_list world;
world.add(make_shared<sphere>(point3(0,0,-1), 0.5));
world.add(make_shared<sphere>(point3(0,-100.5,-1), 100));
```

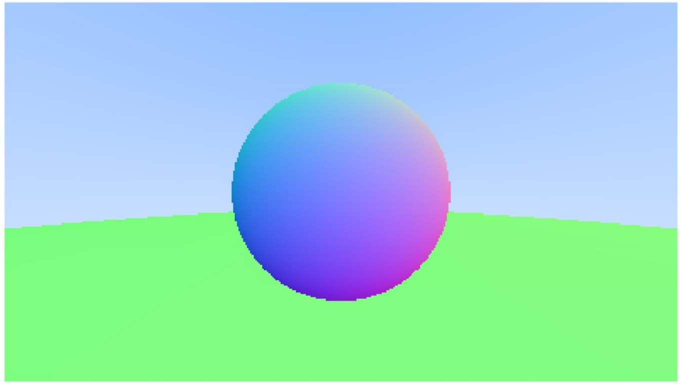


Image 5: Resulting render of normals-colored sphere with ground

Antialiasing

- Real camera: no jaggies along edges because the edge pixels are a blend of some foreground and some background.
- => averaging a bunch of samples inside each pixel
- Canonical random number 0 <= r < 1
- => use rand() in <cstdlib> returns a random integer 0, RAND_MAX

```
inline double random_double() {
    // Returns a random real in [0,1).
    return rand() / (RAND_MAX + 1.0);
}

inline double random_double(double min, double max) {
    // Returns a random real in [min,max).
    return min + (max-min)*random_double();
}
```

Add camera class

```
class camera {
private:
    Vector3 _origin;
    Vector3 _lower_left_corner;
    Vector3 _horizontal;
    Vector3 _vertical;

public:
    camera();
    Ray get_ray(double u, double v);
};
```

```
inline double clamp(double x, double min, double max) {
    if (x < min) return min;
    if (x > max) return max;
    return x;
}
```

- Write_color: add the full color each iteration, and then perform a single divide at the end (by the number of samples) when writing out the color

Add samples

```
const int image_height = static_cast<ir
const int samples_per_pixel = 100;
```

```
for (int i = 0; i < image_width; ++i) {
    color pixel_color(0, 0, 0);
    for (int s = 0; s < samples_per_pixel; ++s) {
        auto u = (i + random_double()) / (image_width-1);
        auto v = (j + random_double()) / (image_height-1);
        ray r = cam.get_ray(u, v);
        pixel_color += ray_color(r, world);
    }
    write_color(std::cout, pixel_color, samples_per_pixel);
}
```

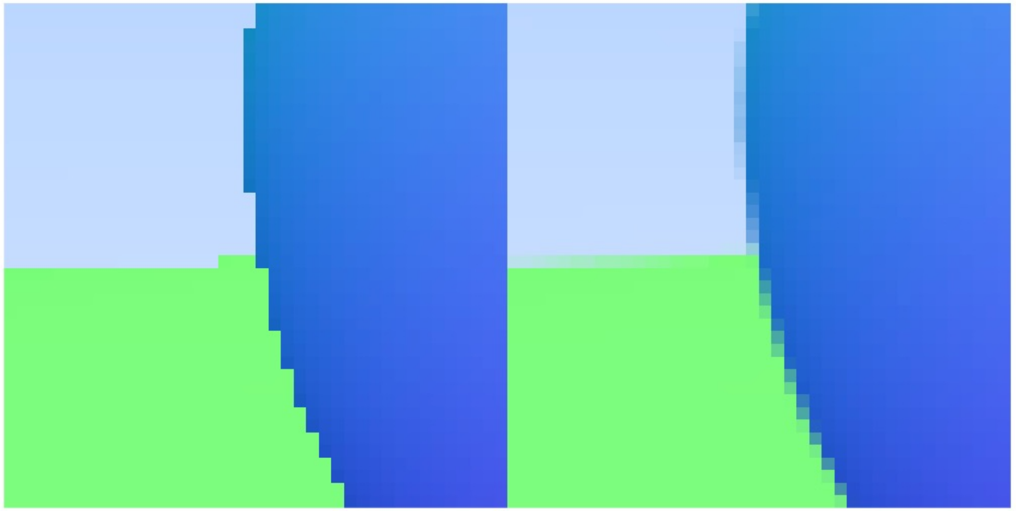


Image 6: Before and after antialiasing

Diffuse Materials

- take on the color of their surroundings, but they modulate that with their own intrinsic color
- Light that reflects off a diffuse surface has its direction randomized

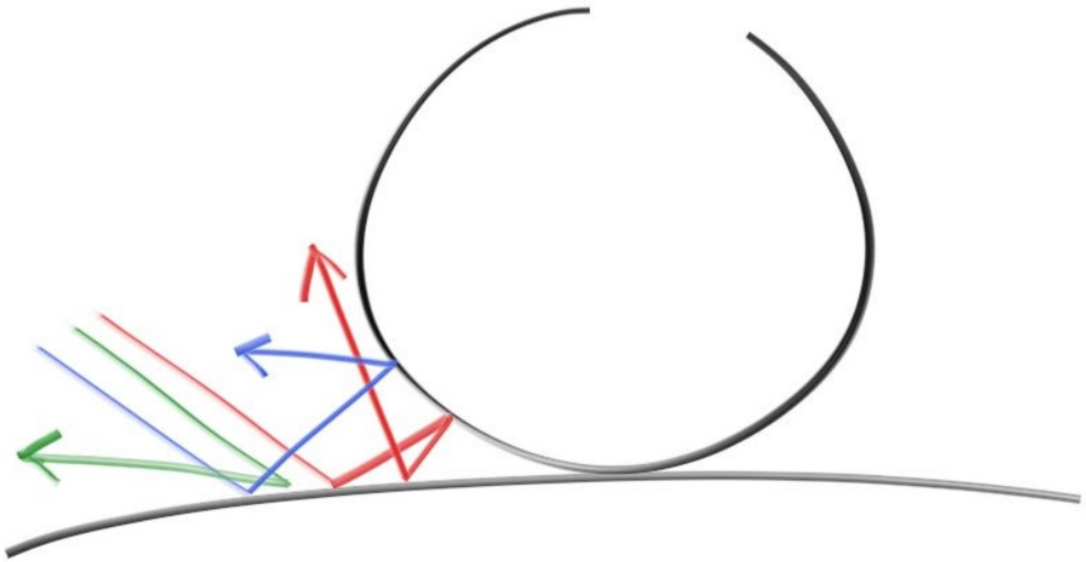


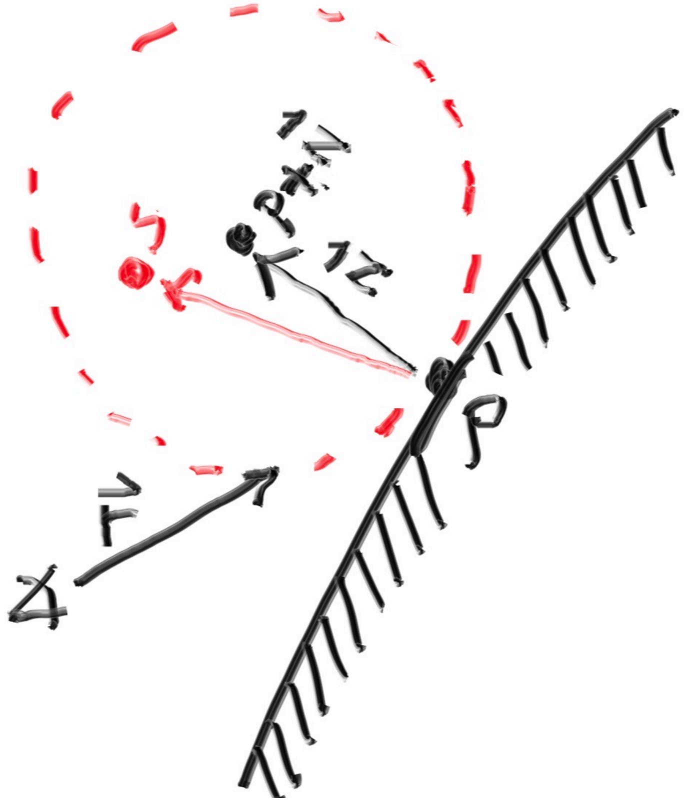
Figure 8: *Light ray bounces*

Diffuse Materials

- Also absorbed. The darker the surface, the more likely absorption is.
- algorithm randomizes direction will produce surfaces that look matte
- The sphere with a center at ($\mathbf{P}-\mathbf{n}$) is considered

inside the surface, whereas the sphere with center ($\mathbf{P}+\mathbf{n}$) is considered *outside* the surface.

- Select radius on the same side as the ray origin
- Pick random **S** inside this unit radius.



Pick random S.

- Rejection method:
- First, pick a random point in the unit cube where x, y, and z all range from −1 to +1. Reject this point and try again if the point is outside the sphere.

```
static Vector3 random();
static Vector3 random(double min, double max);

Vector3 random_in_unit_sphere();
```

Recursive ray_color

- Limit the number of child rays by depth.

```
Vector3 ray_color(Ray r, hittable_list world, int depth) {
    hit_record rec;

    if (depth <= 0) return Vector3(0, 0, 0);

    if (world.hit(r, 0, infinity, rec)) {
        Vector3 target = rec.P + rec.N + Vector3::random_in_unit_sphere();
        return 0.5 * ray_color(Ray(rec.P, target - rec.P), world, depth - 1);
    }
```

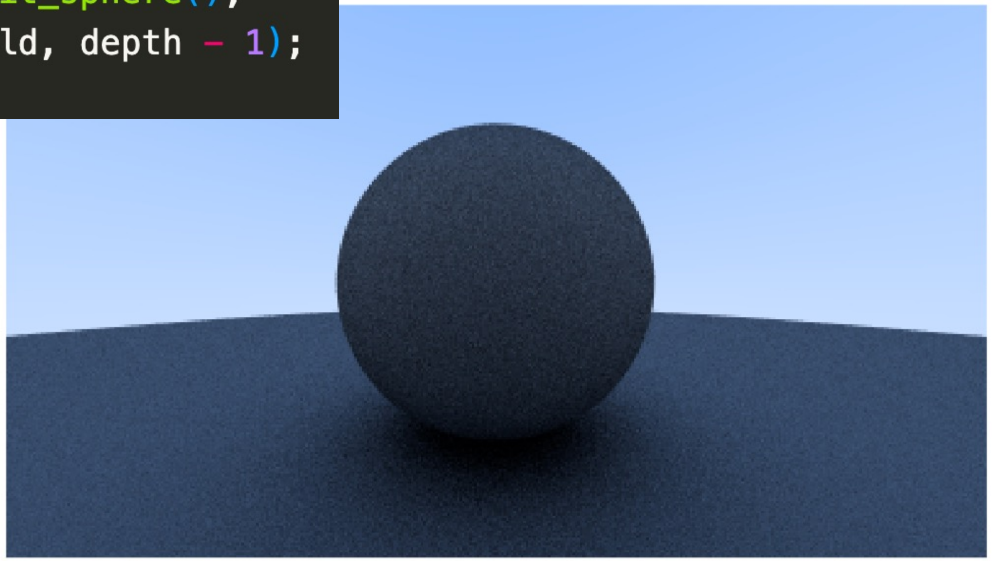


Image 7: First render of a diffuse sphere

Gamma correction for accurate color intensity

- meaning the 0 to 1 values have some transform before being stored as a byte
- use “gamma 2” which means raising the color to the power $1/gamma$, or in our simple case ½, which is just square-root:

```
void write_color(std::ostream &out, color pixel_color, int samples_per_pixel) {
    auto r = pixel_color.x();
    auto g = pixel_color.y();
    auto b = pixel_color.z();

    // Divide the color by the number of samples and gamma-correct for gamma=2.0.
    auto scale = 1.0 / samples_per_pixel;
    r = sqrt(scale * r);
    g = sqrt(scale * g);
    b = sqrt(scale * b);

    // Write the translated [0,255] value of each color component.
    out << static_cast<int>(256 * clamp(r, 0.0, 0.999)) << ' '
        << static_cast<int>(256 * clamp(g, 0.0, 0.999)) << ' '
        << static_cast<int>(256 * clamp(b, 0.0, 0.999)) << '\n';
}
```

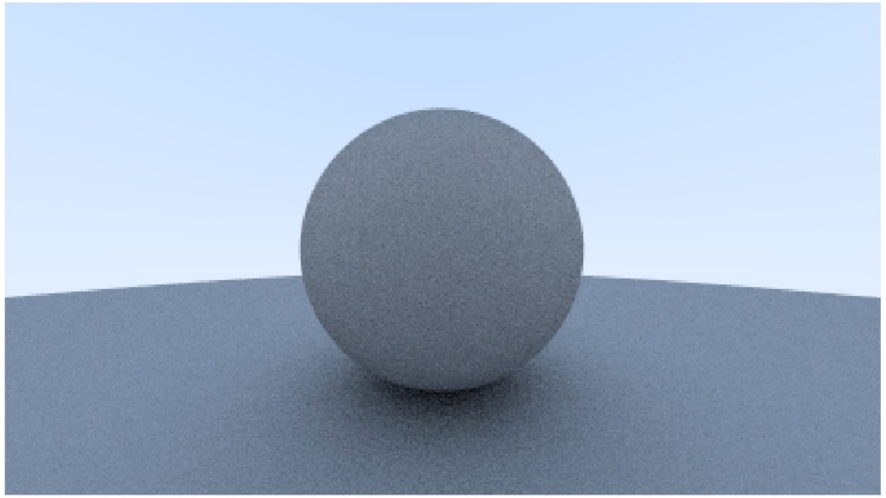


Image 8: Diffuse sphere, with gamma correction

Shadow acne problem

- Some of the reflected rays hit the object they are reflecting off of not at exactly t=0t=0, but instead at t=−0.0000001t=−0.0000001 or t=0.00000001t=0.00000001 or whatever floating point approximation the sphere intersector gives us. So we need to ignore hits very near zero:

```
if (world.hit(r, 0.001, infinity, rec)) {
```