Realtime Computer Graphics on GPUs

Realtime Raytracing

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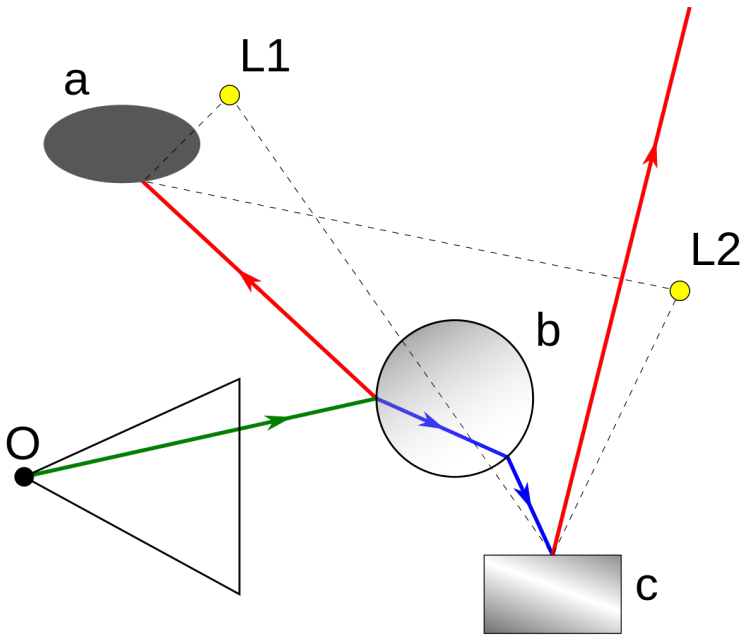
Terminology

RAYCASTING

- Arthur Appel in 1968
- Simplest ray-based method
- Shoot rays from the eye and find the closest object blocking the path of that ray

Whitted's Raytracing

- Turner Whitted in 1979
- Extending raycasting by using recursion
- New reflected/refracted rays are generated and color is recursively propagated back
- Perfect reflections/refractions
- Simple shadow computation – ray to light source



Distributed Raytracing

- Modeling soft effects:
  - Soft shadows
  - Depth of field
  - Soft reflections
- Shooting multiple rays
  - Sampling the domain (angle, lens)
  - Weighted average of the payloads
  - Suppression of alias

Path Tracing

- James Kajiya in 1986
- Systematic approach to solving global illumination problem
- Rendering equation:
  - Integral equation in which the radiance leaving a point is given as the sum of emitted plus reflected radiance under a geometric optics approximation
- Raytracing using Monte-Carlo method for the rendering equation solving
- Bidirectional path tracing – faster convergence

Comparison with Rasterization

- Advantages
  - General camera model
  - Reflection and refraction – exact computation with minimum code
  - Simple computation of hard and soft shadows
  - Usable for preprocessing and/or rendering pass in combination with rasterization (lightmaps, AO, exact reflections as postprocess, . . .)
  - Logarithmic acceleration structures
- Disadvantages
  - Expensive build of high quality acceleration structure
  - Worse support of dynamic scenes – acc. structure rebuild is not trivial
  - Suitable HW only recently
  - Computationally more expensive
  - Geometry cannot be streamed

Overview of Typical Shaders in Ray Tracing Engines

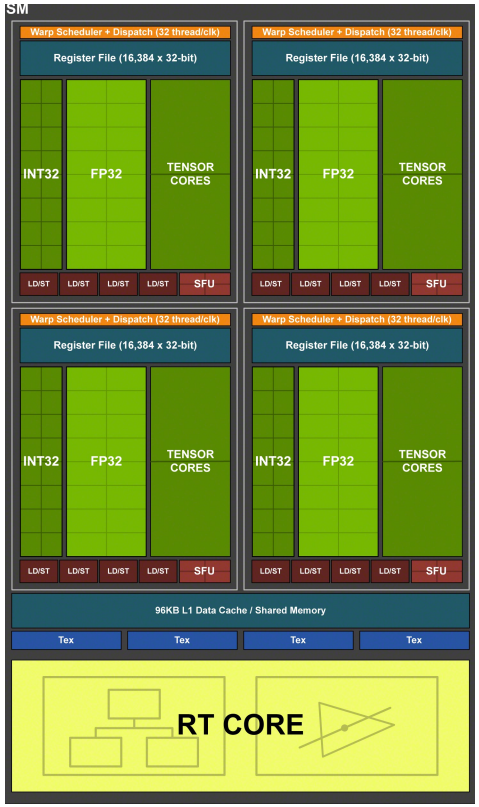
Ray tracing engines utilize various specialized shaders to achieve realistic rendering. The primary shaders used are:

- **Ray Generation Shader**
- **Intersection Shader**
- **Any-Hit Shader**
- **Closest-Hit Shader**
- **Miss Shader**
- **Callable Shader**

Nvidia RTX

New HW Architecture

- First GPUs with raytracing support (NVidia Turing)
- RT cores (ASIC –Application-specific integrated circuit)
- Usable in OptiX, MS DirectX Raytracing API, Vulcan raytracing extension



RT Cores in NVIDIA GPUs

- **RT Cores**:
  - **Bounding Volume Hierarchy (BVH) Traversal**:
    - RT Cores accelerate BVH traversal, a hierarchical structure that organizes scene geometry.
    - Efficiently skips large portions of the scene that rays do not intersect.
  - **Ray/Triangle Intersection Testing**:
    - RT Cores perform fast intersection tests between rays and triangles.
    - Reduces computational load on the main GPU cores (CUDA cores).
  - **Parallel Processing**:
    - RT Cores operate in parallel with traditional rasterization pipelines.
    - Allows simultaneous execution of rasterization and ray tracing workloads.

VULCAN EXTENSIONS

Raytracing available in Vulcan as an extension

- **VK_KHR_ray_tracing_pipeline**: Core ray tracing functionality.
- **VK_KHR_acceleration_structure**: Optimizes ray tracing performance.
- **VK_KHR_ray_query**: Allows ray queries within shaders.
- **VK_KHR_pipeline_library** and **VK_EXT_descriptor_indexing**: Manage complex configurations.

SHADERS

- New GLSL shader types:
  - Any hit
  - Intersection
  - Miss
  - Closest hit
- All shaders must be available – ray may intersect any object

Handle Ray Tracing Shaders

```
// Example of a ray generation shader
#version 460
#extension GL_EXT_ray_tracing : require

layout(set = 0, binding = 0) uniform accelerationStructureEXT topLevelAS;
layout(location = 0) rayPayloadEXT vec3 hitValue;

void main() {
    vec3 origin = vec3(0.0, 0.0, 0.0);
    vec3 direction = vec3(0.0, 0.0, -1.0);
    traceRayEXT(topLevelAS, 0, 0xFF, 0, 1, 0, origin, 0.0, direction, 10000.0, 0);
}
```

Bottom-Level Acceleration Structures (BLAS)

- **Purpose**:
  - Represent individual objects or meshes in the scene.
- **Structure**:
  - Consist of geometric primitives like triangles.
  - Optimized using a Bounding Volume Hierarchy (BVH).
- **Usage**:
  - Built once and reused for multiple frames.
  - Can be updated if the geometry changes.

Top-Level Acceleration Structures (TLAS)

- **Purpose**:
  - Represent the entire scene, including instances of BLAS.
- **Structure**:
  - Contains instances of BLAS with their transformations.
  - Organized in a BVH for efficient traversal.
- **Usage**:
  - Built from instances of BLAS.
  - Updated when the scene layout changes.

Optix

OptiX I

- OptiX is not just a raytracer
- OptiX is framework for creating application using raytracing, independent from any specific method
- Build on CUDA architecture
- Most of the components programmable
- Usable not only for CG, but also for:
  - collision detection
  - visibility determination
  - sound propagation simulation
  - volume estimation of complicated objects
  - ...

OptiX II

- Abstract model of generic raytracer
- Future-proofed – build to scale with future development of powerful GPUs
- Similar abstraction to OpenGL/DirectX/Vulcan
- Mechanism for execution of custom CUDA C code
  - Shading + recursive rays
  - Camera model, ray generator
  - Ray payload
  - Intersection with arbitrary geometry (e.g. exact sphere without tesselation)
  - ...

OptiX Versions

- **OptiX 6 and earlier**
  - High-level API: automatic memory & launch handling
  - Built-in program linking and variable scoping
- **OptiX 7+**
  - Low-level GPU programming model, RTX optimized
  - Full control: manual SBT, memory, and ray dispatch
  - Backward-incompatible with earlier versions

PROGRAMS I – SHADER STAGES

- 8 types of GPU programs supported by OptiX
- **Ray Generation** – Launch entry point, invoked per-pixel/sample
- **Exception** – Called on invalid state (e.g., stack overflow)
- **Closest Hit** – Executed on closest geometry hit (used for shading)
- **Any Hit** – Invoked on all intersections (used for early-out, transparency, shadows)
- **Intersection** – User-defined geometry intersection logic (procedural primitives)

Programs II – Shader Stages Continued

- **Miss** – Executed when ray misses the scene (e.g., skybox sampling)
- **Direct Callable** – Fast inlined function calls via SBT (e.g., shading models)
- **Continuation Callable** – May trigger new ray traces or shading logic
- PTX or CUBIN – Programs written in CUDA C++, compiled with `nvcc`
- OptiX SDK provides API and helpers for C/C++ pipeline integration

VARIABLES VS SBT

- Optix 6 and older
  - System for declaration and definition of variables, so they are correctly passed into and between different programs
  - Program reference via specific set of rules
    - Internal semantics maybe specified
    - Variable color can be connected to *Material*
    - Specific geometry instances can redefine the variable
- Optix 7 and newer
  - Ray payload only 32bit integers (can be a pointer)
  - Shaders/programs and data store in *Shader Binding Table*

Acceleration Structures

- OptiX uses RTX hardware to accelerate BVH traversal
- Two-level hierarchy:
  - **GAS** – Geometry Acceleration Structure (individual meshes / primitives)
  - **IAS** – Instance Acceleration Structure (transforms & references to GAS)
- Built using optixAccelBuild() on the GPU
- Traversal happens via optixTrace() at runtime

EXECUTION

- All informations and data passed to context instance
- Specify dimensions and execution parameters
- Ray generator is executed, once for each element(pixel)
- Results stored into output buffer

Examples

EXAMPLE 1 - NORMAL SHADER

- Most used program – **closest hit**

Normal shader

```
extern "C" __global__ void __closesthit__normal_shader() {
    float3 shading_normal = make_float3(
 __uint_as_float(optixGetAttribute_0()),
 __uint_as_float(optixGetAttribute_1()),
 __uint_as_float(optixGetAttribute_2())
    );

    float3 world_normal = normalize(
        optixTransformNormalFromObjectToWorldSpace(shading_normal));
    float3 color = 0.5f * world_normal + 0.5f;

    setPayload(color);
}
```

EXAMPLE 1 - VARIABLES

- The shading normal is passed via attributes from the intersection program

Intersection Attribute Passing

```
// In __intersection__ program
float3 shading_normal = calculate_normal();
optixReportIntersection(t_hit, 0,
    __float_as_uint(shading_normal.x),
    __float_as_uint(shading_normal.y),
    __float_as_uint(shading_normal.z));
```

- Result is written via payload or a user-defined payload struct

```
// Launch parameters or inline payload (example: RGB packed)
static __forceinline__ void setPayload(float3 color) {
    optixSetPayload_0(__float_as_uint(color.x));
    optixSetPayload_1(__float_as_uint(color.y));
    optixSetPayload_2(__float_as_uint(color.z));
}
```

Example 1 - Miss Program

- No intersection — handled by the **miss** program
- Returns background color from launch parameters

Miss program

```
extern "C" __global__ void __miss__radiance() {
    float3 bg_color = params.bg_color;
    optixSetPayload_0(__float_as_uint(bg_color.x));
    optixSetPayload_1(__float_as_uint(bg_color.y));
    optixSetPayload_2(__float_as_uint(bg_color.z));
}
```

EXAMPLE 1 - RAY GENERATION PROGRAM

```
extern "C" __global__ void __raygen__pinhole_camera() {
    const uint3 idx = optixGetLaunchIndex();
    const uint3 dim = optixGetLaunchDimensions();

    float2 d = (make_float2(idx.x, idx.y) / make_float2(dim.x, dim.y)) *
    float3 origin = params.eye;
    float3 direction = normalize(d.x * params.U + d.y * params.V + param

    uint32_t p0, p1, p2;
    optixTrace(
     // ...
    );

    float3 color = make_float3(__uint_as_float(p0),
                               __uint_as_float(p1),
                               __uint_as_float(p2));
    params.output_buffer[idx.y * dim.x + idx.x] = make_color(color);
}
```

EXAMPLE 1 - TRACE CALL

- Most important function: `optixTrace` (replaces `rtTrace`)
  - `params.handle` — root of scene hierarchy (OptixTraversableHandle)
  - Origin and direction — define the current ray
  - Payloads passed via registers
- The call invokes a miss or hit program and returns control
- Stack depth is managed explicitly via launch parameters like `maxTraceDepth`

EXAMPLE 1

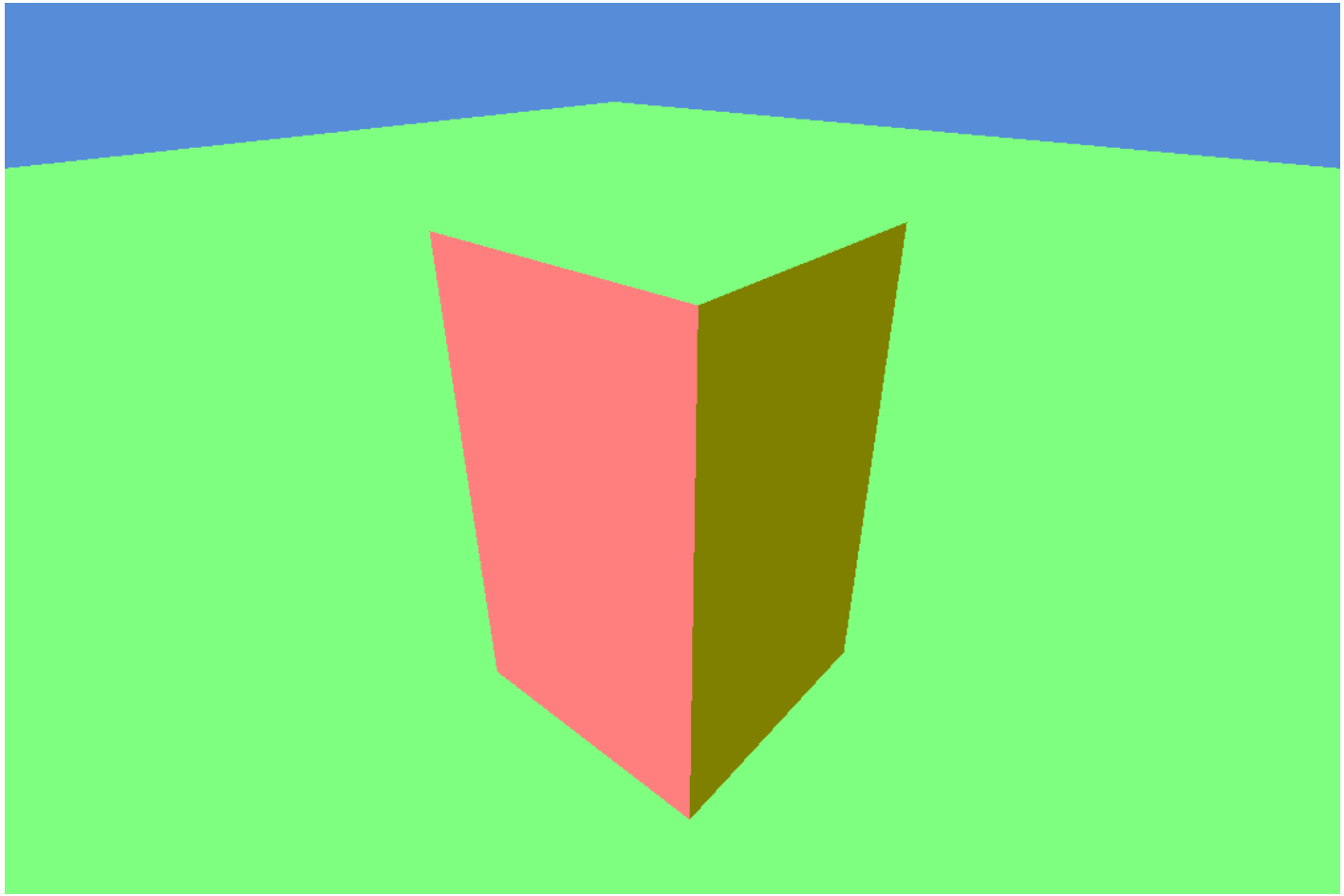


Figure: Normal shader example

EXAMPLE 2 - DIFFUSE SHADER

- Only *closest hit* program is modified
- Geometric and shading normals can differ (e.g., for bump mapping)
- Both normals are passed via attributes from the intersection program

Diffuse shader — part 1

```
extern "C" __global__ void __closesthit__diffuse() {
    float3 shading_normal = make_float3(
        __uint_as_float(optixGetAttribute_0()),
        __uint_as_float(optixGetAttribute_1()),
        __uint_as_float(optixGetAttribute_2()));
    float3 geometric_normal = make_float3(
        __uint_as_float(optixGetAttribute_3()),
        __uint_as_float(optixGetAttribute_4()),
        __uint_as_float(optixGetAttribute_5()));
    float3 world_geo_normal =
        normalize(optixTransformNormalFromObjectToWorldSpace(geometric_n
    float3 world_shade_normal =
        normalize(optixTransformNormalFromObjectToWorldSpace(shading_nor
```

EXAMPLE 2 - DIFFUSE SHADER (CONTINUED)

Diffuse shader — part 2

```
    float3 ffnormal = faceforward(world_shade_normal,
                                  -optixGetWorldRayDirection(),
                                  world_geo_normal);

    float3 hit_point = optixGetWorldRayOrigin() +
                       optixGetRayTmax() * optixGetWorldRayDirection();
    float3 color = params.Ka * params.ambient;

    for (int i = 0; i < params.num_lights; ++i) {
        BasicLight light = params.lights[i];
        float3 L = normalize(light.pos - hit_point);
        float nDl = dot(ffnormal, L);
        if (nDl > 0.f)
            color += params.Kd * nDl * light.color;
    }

    optixSetPayload_0(__float_as_uint(color.x));
    optixSetPayload_1(__float_as_uint(color.y));
    optixSetPayload_2(__float_as_uint(color.z));
}
```

EXAMPLE 2 - LIGHT SETUP

- Light info stored in a 1D array in launch parameters
- User-defined structure, allocated and uploaded by the host
- Diffuse reflectance (`Kd`) is part of the SBT or launch params

Light definition and access

```
struct BasicLight {
    float3 pos;
    float3 color;
    int    casts_shadow;
};

// In launch parameters
struct LaunchParams {
    ...
    BasicLight* lights;
    int         num_lights;
    float3      Ka, Kd, ambient;
    ...
};
extern "C" __constant__ LaunchParams params;
```

EXAMPLE 2

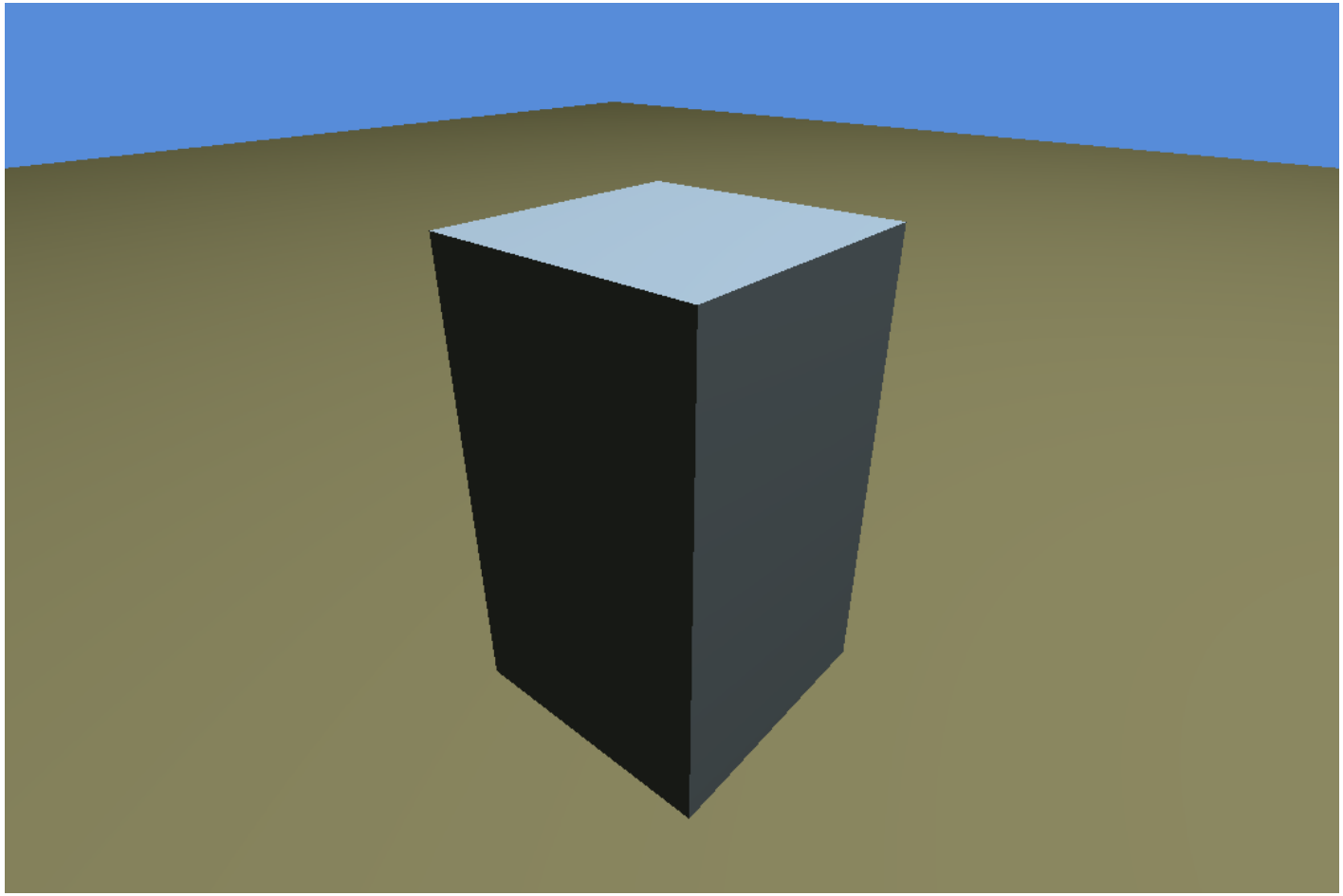


Figure: Diffuse shader

EXAMPLE 3 - PHONG LIGHT MODEL

- Adds specular highlights using Blinn-Phong model
- Uses a halfway vector between light and view direction

Phong shader

```
for (int i = 0; i < params.num_lights; ++i) {
    BasicLight light = params.lights[i];
    float3 L = normalize(light.pos - hit_point);
    float nDl = dot(ffnormal, L);

    if (nDl > 0.f) {
        float3 H = normalize(L - optixGetWorldRayDirection());
        float nDh = dot(ffnormal, H);

        float3 Lc = light.color;
        color += params.Kd * nDl * Lc;

        if (nDh > 0.f)
            color += params.Ks * pow(nDh, params.phong_exp) * Lc;
    }
}
```

EXAMPLE 3

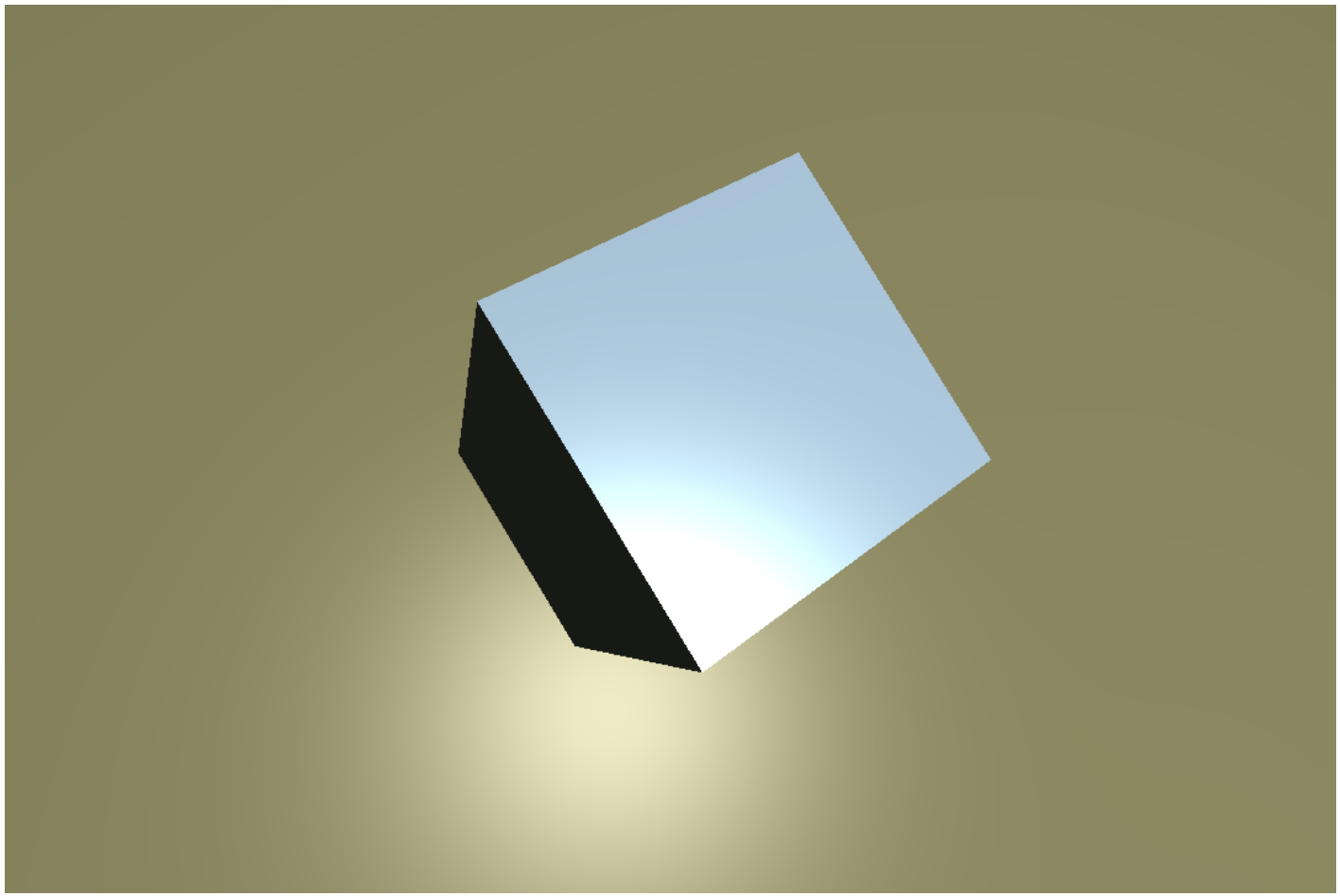


Figure: Phong shader

EXAMPLE 4 - SHADOWS

- Exact shadows for point light sources
- Shadow ray checks if geometry blocks light

Shadow ray dispatch

```
if (nDl > 0.f) {
    float3 L = normalize(light.pos - hit_point);
    float Ldist = length(light.pos - hit_point);
    uint32_t shadow = __float_as_uint(1.0f);  // visible by default
    optixTrace(
        params.handle,
        hit_point,
        L,
        1e-3f, Ldist - 1e-3f,  // avoid self-intersection
        0.0f,
        OptixVisibilityMask(255),
        OPTIX_RAY_FLAG_TERMINATE_ON_FIRST_HIT,
        SHADOW_RAY_TYPE, RAY_TYPE_COUNT, SHADOW_RAY_TYPE,
        shadow
    );
    float light_attenuation = __uint_as_float(shadow);
```

EXAMPLE 4 - SHADOWS CONTINUED

Shadowed lighting

```
    if (light_attenuation > 0.0f) {
        float3 Lc = light.color * light_attenuation;
        color += params.Kd * nDl * Lc;

        float3 H = normalize(L - optixGetWorldRayDirection());
        float nDh = dot(ffnormal, H);
        if (nDh > 0.f)
            color += params.Ks * pow(nDh, params.phong_exp) * Lc;
    }
}
```

EXAMPLE 4 - ANY-HIT SHADOW

- Shadow rays only need to know if something is hit
- **anyhit** terminates immediately upon any hit

Shadow any-hit program

```
extern "C" __global__ void __anyhit__shadow() {
    optixSetPayload_0(__float_as_uint(0.0f)); // shadowed
    optixTerminateRay();
}
```

EXAMPLE 4

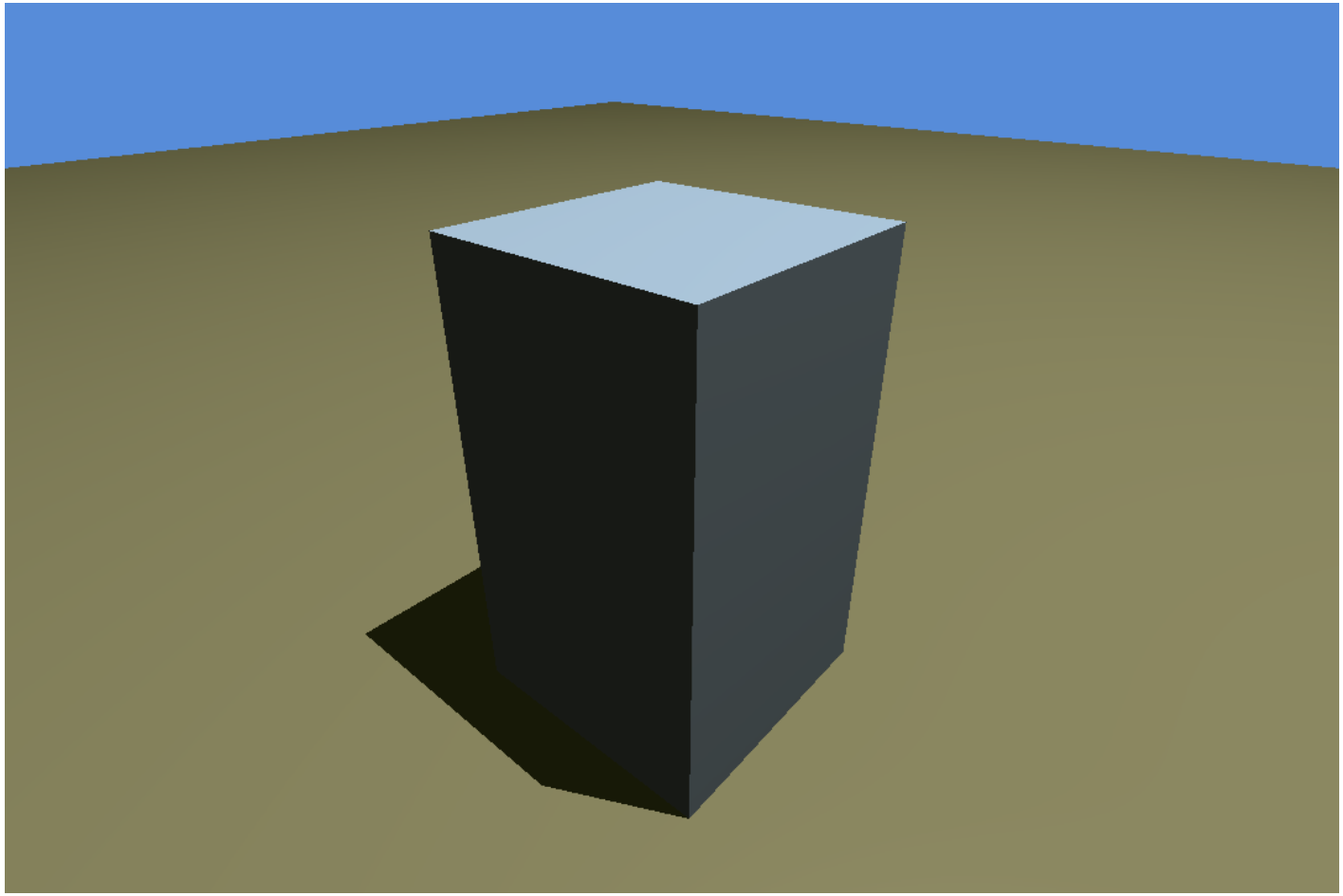


Figure: Exact shadow for point light

EXAMPLE 5 - REFLECTIONS

- Mirror reflection uses a secondary ray
- Color of reflected ray is combined with surface shading

Mirror reflection

```
float3 R = reflect(optixGetWorldRayDirection(), ffnormal);
uint32_t p0, p1, p2, depth = optixGetPayload_3() + 1;

optixTrace(
    params.handle,
    hit_point,
    R,
    1e-3f, 1e16f,
    0.0f,
    OptixVisibilityMask(255),
    OPTIX_RAY_FLAG_NONE,
    RADIANCE_RAY_TYPE, RAY_TYPE_COUNT, RADIANCE_RAY_TYPE,
    p0, p1, p2, depth
);

float3 reflected = make_float3(__uint_as_float(p0),
                               __uint_as_float(p1),
                                 uint as float(p2));
```

EXAMPLE 5 - REFLECTIONS WITH RECURSION LIMIT

- Use a per-ray depth counter
- Prevent stack overflows by bounding recursion

With recursion depth check

```
if (optixGetPayload_3() < params.max_depth) {
    float3 R = reflect(optixGetWorldRayDirection(), ffnormal);
    uint32_t p0, p1, p2;
    uint32_t next_depth = optixGetPayload_3() + 1;

    optixTrace(
        params.handle, hit_point, R,
        1e-3f, 1e16f,
        0.0f, OptixVisibilityMask(255), OPTIX_RAY_FLAG_NONE,
        RADIANCE_RAY_TYPE, RAY_TYPE_COUNT, RADIANCE_RAY_TYPE,
        p0, p1, p2, next_depth
    );
    float3 refl = make_float3(__uint_as_float(p0),
                              __uint_as_float(p1),
                              __uint_as_float(p2));
    color += params.reflectivity * refl;
}
```

EXAMPLE 5

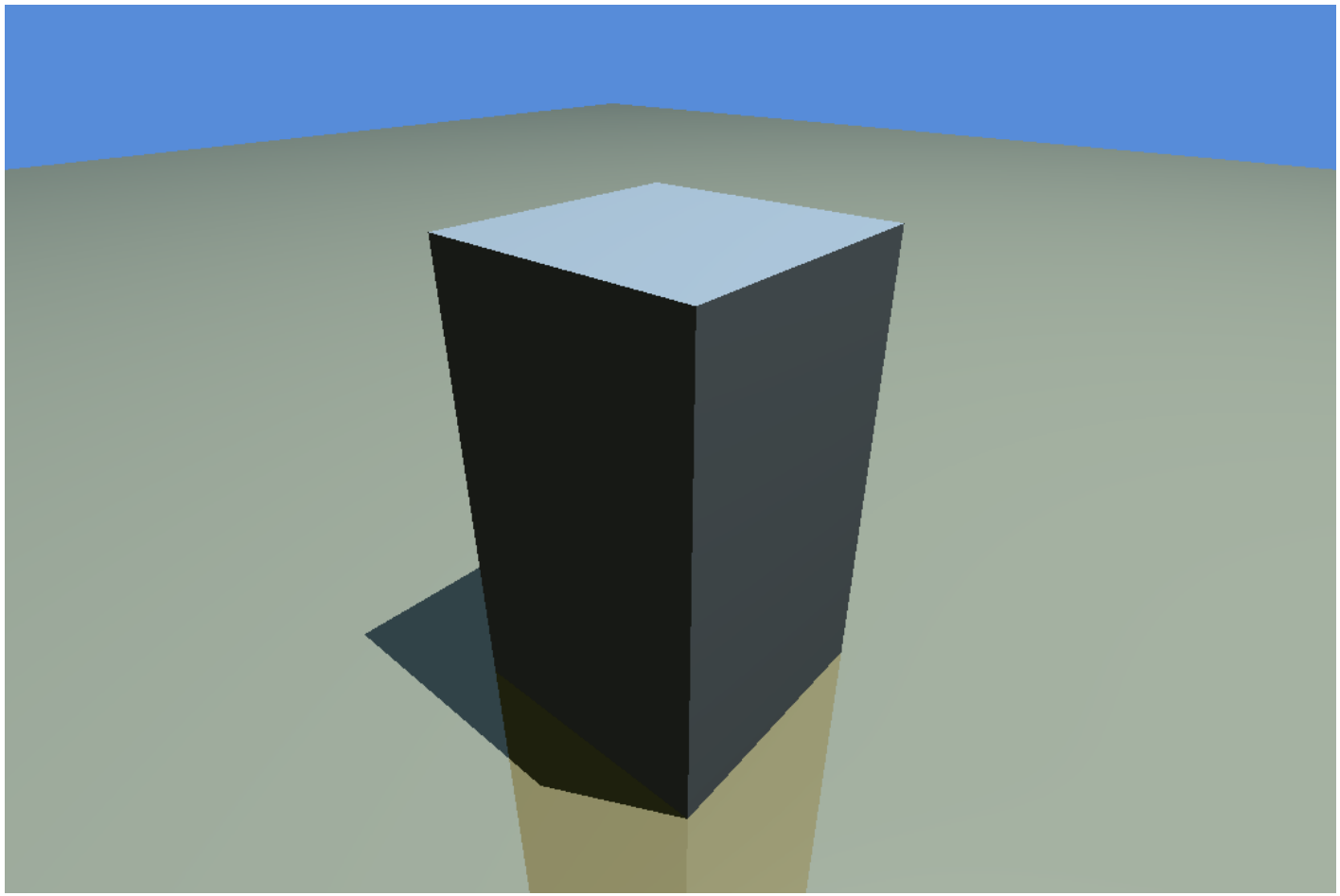


Figure: Mirror reflections

EXAMPLE 6 - ENVIRONMENT MAPPING

- Background color fetched from a 2D texture (e.g., lat-long environment map)
- Accessed in the **miss** program

Miss program with texture

```
extern "C" __global__ void __miss__envmap() {
    float3 dir = optixGetWorldRayDirection();
    float theta = atan2f(dir.x, dir.z);
    float phi   = M_PIf * 0.5f - acosf(dir.y);
    float u = (theta + M_PIf) * (0.5f * M_1_PIf);
    float v = 0.5f * (1.0f + sinf(phi));

    float4 tex = tex2D<float4>(params.envmap, u, v);
    float3 color = make_float3(tex);

    optixSetPayload_0(__float_as_uint(color.x));
    optixSetPayload_1(__float_as_uint(color.y));
    optixSetPayload_2(__float_as_uint(color.z));
}
```

EXAMPLE 6

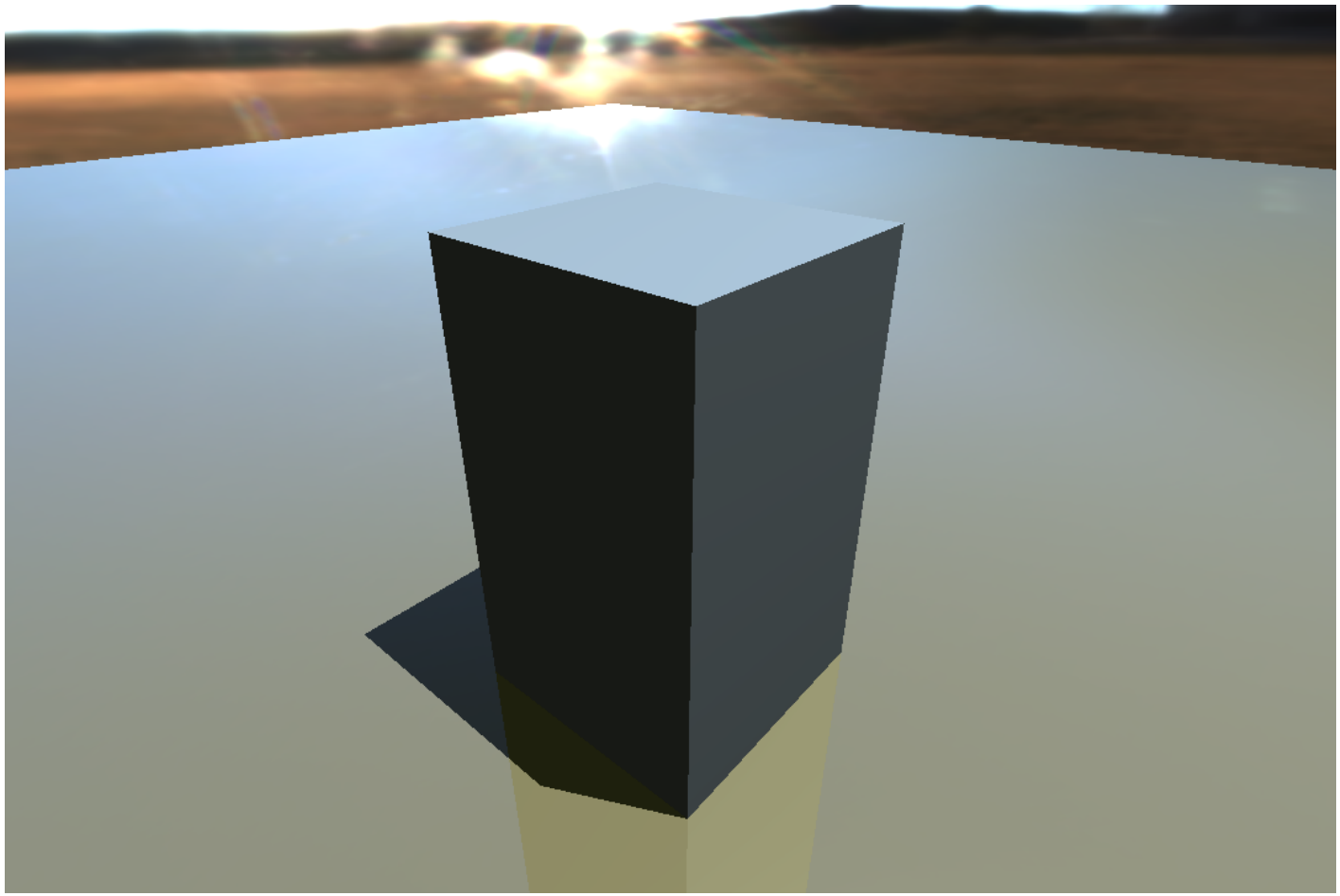


Figure: Environment mapping

EXAMPLE 7 - PROCEDURAL GEOMETRY

- Procedural primitives: e.g. convex hulls from plane equations
- Intersection program computes hit analytically

Convex hull intersection

```
extern "C" __global__ void __intersection__convex() {
    const float3 ray_origin = optixGetObjectRayOrigin();
    const float3 ray_dir = optixGetObjectRayDirection();

    int n = params.num_planes;
    float t0 = -FLT_MAX;
    float t1 =  FLT_MAX;
    float3 t0_normal = make_float3(0);
    float3 t1_normal = make_float3(0);

    for (int i = 0; i < n && t0 < t1; ++i) {
        float4 plane = params.planes[i];
        float3 n = make_float3(plane);
        float d = plane.w;
```

EXAMPLE 7 - CONVEX HULL CONTINUED

Convex hull intersection – continued

```
        float denom = dot(n, ray_dir);
        float t = -(d + dot(n, ray_origin)) / denom;
        if (denom < 0.f) {
            if (t > t0) { t0 = t; t0_normal = n; }
        } else {
            if (t < t1) { t1 = t; t1_normal = n; }
        }
    }
    if (t0 > t1) return;
    float3 normal;
    float t_hit;
    if (optixReportIntersection(t0, 0)) {
        normal = t0_normal;
        t_hit = t0;
    } else if (optixReportIntersection(t1, 0)) {
        normal = t1_normal;
        t_hit = t1;
    }
    optixSetAttribute_0(__float_as_uint(normal.x));
    optixSetAttribute_1(__float_as_uint(normal.y));
    optixSetAttribute_2(__float_as_uint(normal.z));
```

EXAMPLE 7 - AABB

- Procedural primitives require user-defined bounding boxes
- AABB data is passed from host as parameters

AABB bounds program

```
extern "C" __global__ void __bounds__convex(int primIdx, float result[6]
    result[0] = params.convex_min.x;
    result[1] = params.convex_min.y;
    result[2] = params.convex_min.z;
    result[3] = params.convex_max.x;
    result[4] = params.convex_max.y;
    result[5] = params.convex_max.z;
}
```

EXAMPLE 7

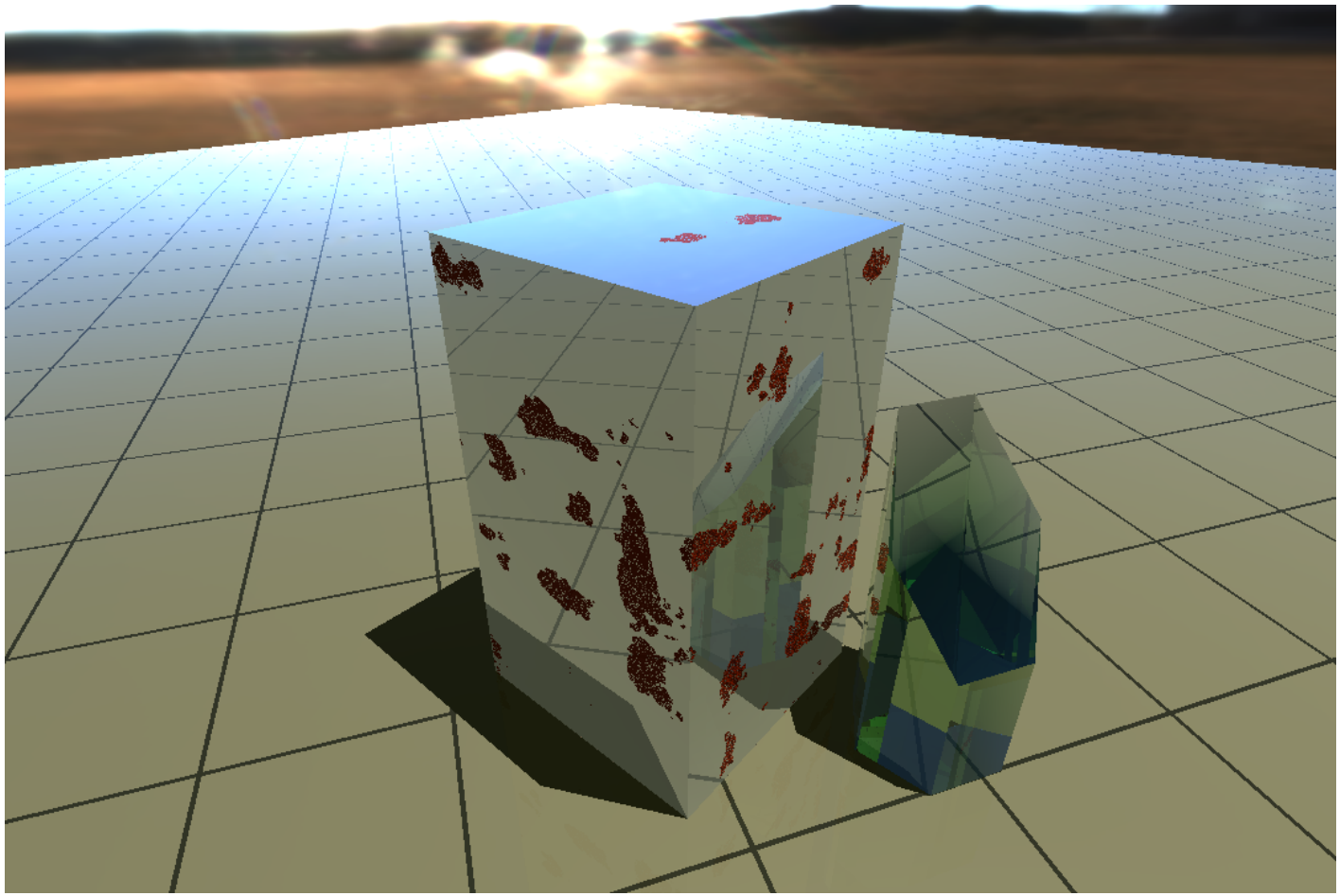


Figure: Glass convex hull

Denoising

NVIDIA DENOISING

- AI-powered denoiser trained on real path-traced images
- Removes Monte Carlo noise from ray-traced images
- Useful for real-time and interactive rendering

Benefits:

- High-quality output with fewer rays
- Works in real-time on RTX hardware
- Optional temporal support for stable animations

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Denoiser Inputs

- Denoiser can use up to 3 buffers:

Color Noisy path traced image
Albedo Diffuse color w/o lighting
Normal World-space surface normals

More inputs → better denoising quality!

Denoiser Inputs

- Denoiser can use up to 3 buffers:

Color	Noisy path traced image	
Albedo	Diffuse color w/o lighting	More inputs $\rightarrow$ better
Normal	World-space surface normals	

denoising quality!

OptiX Denoising Flow

```
// 1. Create denoiser
optixDenoiserCreate(context, OPTIX_DENOISER_MODEL_KIND_LDR, &denoiser);

// 2. Setup memory
optixDenoiserComputeMemoryResources(denoiser, ...);
cudaMalloc(&scratch, scratchSize);

// 3. Configure
optixDenoiserSetup(denoiser, stream, width, height, state, ...);

// 4. Fill guide and layer structures
OptixDenoiserGuideLayer guide = {...};
OptixDenoiserLayer layer = {
    .input = noisy_image,
    .output = denoised_image,
    ...
};

// 5. Run denoising
optixDenoiserInvoke(denoiser, stream, &params, state, ...);
```

Performance Tips

- Use normals & albedo for best quality
- Use shared scratch/state across frames (reuse!)
- Denoising latency: 1–5 ms at 1080p (RTX 30/40 series)
- Works on OptiX render outputs or CUDA buffers