Welcome to 02562: Rendering - Introduction

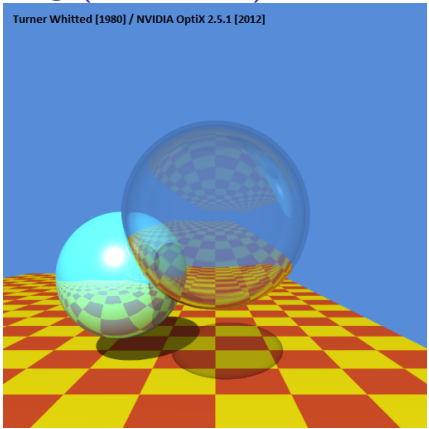
Jeppe Revall Frisvad

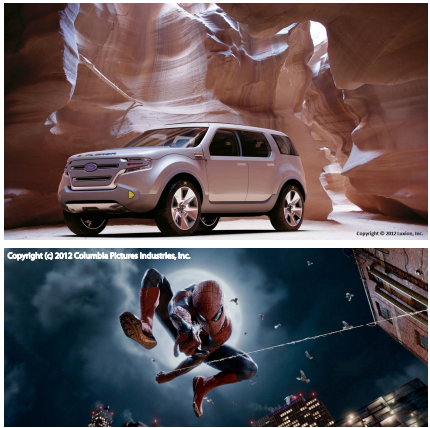
August 2023

https://www.disneyanimation.com/technology/hyperion/

0:00-5:06, 8:56-9:31

Ray tracing (weeks 1–3)

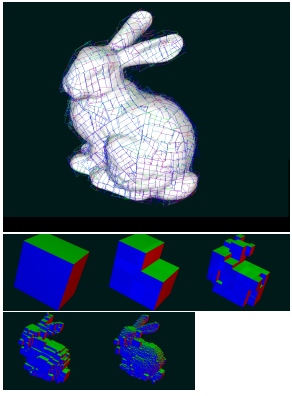




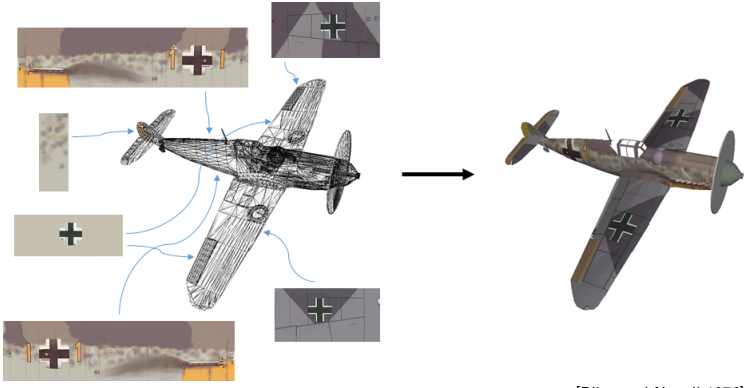
- 74 minutes in the original ray tracing paper of Turner Whitted [1980].
- More than 300 frames per second using GPU ray tracing in 2012 [Parker et al. 2010].
- That's a 6 orders of magnitude speed-up! (Beats Moore's law, but 950 fps on RTX in 2022.)
- Ray tracing is now a widely spread production-ready rendering technique.

Content (weeks 4–5)

- Triangle meshes, spatial subdivision, texturing.



[Kammaje and Mora 2007]



[Blinn and Newell 1976]

Radiometry and light transport (weeks 6–7)

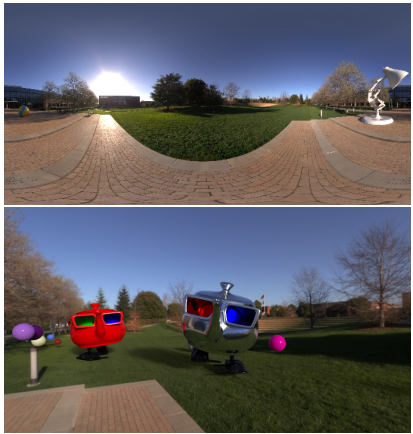
Figure 1: *Global illumination images from 'Monsters U.' These images render more than 30× faster with radiosity caching. © Disney/Pixar.*

- Diffuse reflection of indirect illumination [Cohen and Greenberg 1985; Christensen 2010; Christensen et al. 2012].
- Used in production since the mid 2000s [Christensen et al. 2018].

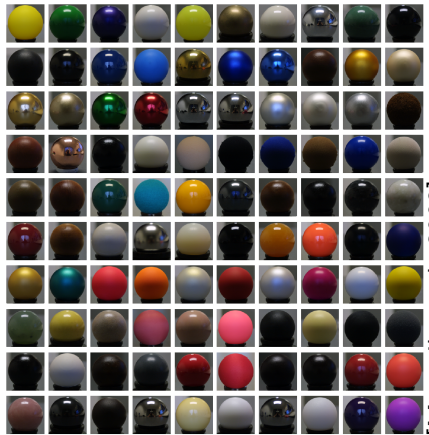
Photon mapping (week 8)

- Photon mapping enables efficient rendering of caustics and participating media (volumes) [Jensen 2001].
- Used extensively for architectural rendering as caustics are particularly important in indoor environments [video].
- Once used for production rendering of multiple scattering in participating media [Nowrouzezahrai et al. 2011]. Now called vertex merging and part of a unified framework. (beyond the scope of this course)

Connection to the real world (weeks 10-11)



Pixar RenderMan



[Matusik et al. 2003]

- Use of 360° photographed environments for natural lighting of a scene.
- Use of measured (BRDF) functions to reproduce the appearance of real materials.
- Realism is needed to render synthetic datasets for learning.

Other parts of this course (offered as projects)

- Production path tracing (denoising or material appearance modelling).
- Radiosity technique with real-time fly-through of diffuse environments.
- Rendering for computer vision (with a matrix obtained from camera calibration).
- Rendering with a textured light source (like a monitor or a projector).
- Neural radiance fields (NeRF).

Instructor and teaching style

- Course responsible: Jeppe Revall Frisvad
- TA: Bojja Venu

- Lecture (13-14)
- Exercises (14-17)

- Lab journal: Copy modified code snippets and rendered images for each part of each worksheet (or all deliverables) into a document.
- Project: Select, study and implement, describe in a report.

- Hand-in: PDF or DOCX (include all code in a ZIP file)
- Deadline: **19 December 2023 at 23:59**

References (chronologically)

- Blinn, J. F., and Newell, M. E. Texture and reflection in computer generated images. *Communications of the ACM 19*(10), pp. 542–547. October 1976.
- Whitted, T. An improved illumination model for shaded display. *Communications of the ACM 23*(6), pp. 343–349. June 1980.
- Cohen, M. F., and Greenberg, D. P. The hemi-cube: a radiosity solution for complex environments. *Computer Graphics (SIGGRAPH 1985) 19*(3), pp. 31–40. July 1985.
- Jensen, H. W. *Realistic Image Synthesis Using Photon Mapping*. A K Peters. 2001.
- Matusik, W., Pfister, H., Brand, M., and McMillan, L. Efficient isotropic BRDF measurement. In *Proceedings of EGSR 2003*, pp. 241-248. June 2003.
- Kammaje, R. P., and Mora, B. A study of restricted BSP trees for ray tracing. In *Proceedings of the IEEE Symposium on Interactive Ray Tracing (RT '07)*, pp. 55–62. October 2007.
- Parker, S. G., Bigler, J., Dietrich, A., Friedrich, H., Hoberock, J., Luebke, D., McAllister, D., McGuire, M., Morley, K., Robison, A., and Stich, M. OptiX: a general purpose ray tracing engine. *ACM Transactions on Graphics (SIGGRAPH 2010) 29*(4), Article 66. July 2010.
- Christensen, P. H. Point-based global illumination for movie production. In *Global Illumination Across Industries*. ACM SIGGRAPH Courses, Article 8. July 2010.
- Nowrouzezahrai, D., Johnson, J., Selle, A., Lacewell, D., Kaschalk, M., and Jarosz, W. A programmable system for artistic volumetric lighting. *ACM Transactions on Graphics (SIGGRAPH 2011) 30*(4), Article 29. July 2011.
- Christensen, P. H., Harker, G., Shade, J., Schubert, B., and Batali, D. Multiresolution Radiosity Caching for Efficient Preview and Final Quality Global Illumination in Movies. Pixar Technical Memo #12-06. Pixar, July 2012.
- Christensen, P., Fong, J., Shade, J., Wooten, W., Schubert, B., Kensler, A., Friedman, S., Kilpatrick, C., Ramshaw, C., Bannister, M., Rayner, B., Brouillant, J., and Liani, M. RenderMan: an advanced path-tracing architecture for movie rendering. *ACM Transactions on Graphics 37*(3), Article 30. August 2018.

02562 Rendering - Introduction

Ray Casting

Jeppe Revall Frisvad

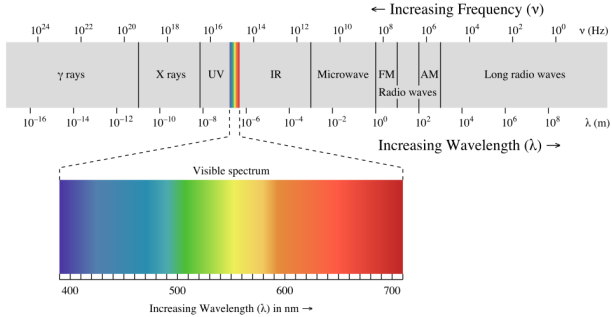
August 2023

Building blocks of realistic rendering

- Think of the experiment: "taking a picture".
- What do we need to model it?
  - Camera (light sensor).
  - Objects (scene geometry).
  - Light (light transport).
  - Luminaires (light sources).
  - Materials (light scattering).
- Mathematical models for these elements are required as a minimum in order to render an image.
- We can use very simple models:
  - Pinhole camera (perspective, lines from a point).
  - Mathematical primitives (planes, spheres, triangles).
  - Ray optics (light propagates along straight lines).
  - Practical lights (point, directional, spot).
  - Lambertian materials (constant reflectance).
- If we desire a high level of realism, more complicated models are required.

Light propagation

- Visible light is electromagnetic waves of wavelengths (λ) from 380 nm to 780 nm.



- Electromagnetic waves in transparent media propagate as *rays of light* for $\lambda \to 0$.
- Rays of light follow the path of least time (Fermat).
- How does light propagate in air? In straight lines (almost).
- The parametrisation of a straight line in 3D is therefore a good, simple model for light propagation: $\boldsymbol{r}(t) = \boldsymbol{o} + t\vec{\omega}$, $t \in [t_{\text{min}}, t_{\text{max}}]$, $t_{\text{max}} > t_{\text{min}} > 0$.

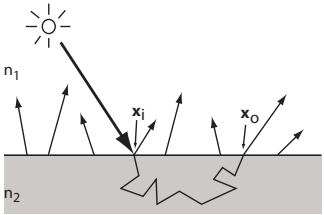
Light sources

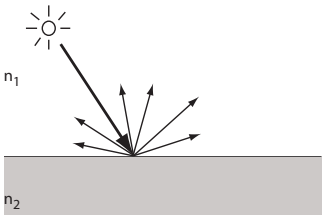
- A light source is described by a spectrum of light $L_{e,\lambda}(\boldsymbol{x}, \vec{\omega}_o)$ which is emitted from each point on the emissive object.
- A simple model is a light source that from each point emits the same amount of light in all directions and at all wavelengths, $L_{e,\lambda} = \mathrm{const}$.
- The spectrum of heat-based light sources can be estimated using Planck's law of radiation. Examples:


- The surface geometry of light sources is modelled in the same way as other geometry in the scene.

Materials (scattering and absorption of light)

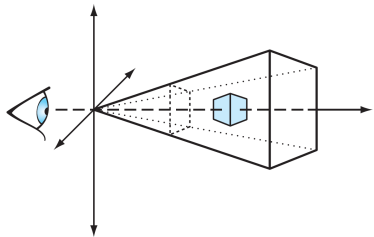
- Optical properties (index of refraction, $n(\lambda) = n'(\lambda) + i\, n''(\lambda)$).
- Reflectance distribution functions, $f(\boldsymbol{x}_i, \vec{\omega}_i; \boldsymbol{x}_o, \vec{\omega}_o)$.





Camera

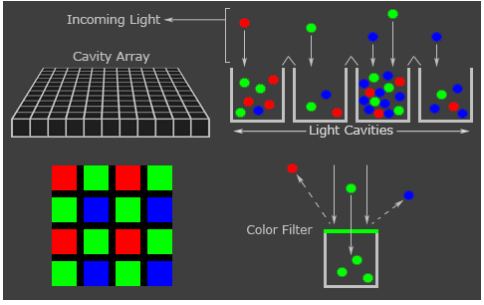
- A camera consists of a light sensitive area, a processing unit, and a storage for saving the captured images.
- The simplest model of a camera is a rectangle, which models the light sensitive area (the chip/film), placed in front of an eye point where light is gathered.



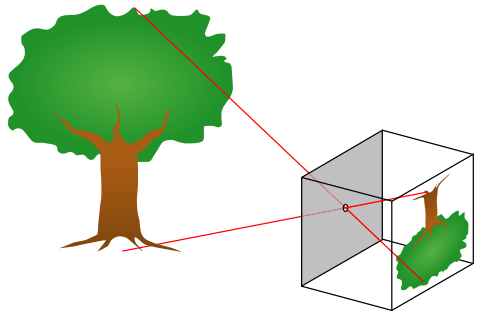
- We can use this model in two different ways:
  - Follow rays from the eye point through the rectangle and onwards (ray casting).
  - Project the geometry on the image plane and find the geometry that ends up in the rectangle (rasterization).

The light sensitive Charge-Coupled Device (CCD) chip

- A CCD chip is an array of light sensitive cavities.
- A digital camera therefore has a resolution $W \times H$ measured in number of pixels.
- A pixel corresponds to a small area on the chip.
- Several light sensitive cavities are used for one pixel because the light measurement is divided into red, green, and blue.
- Conversion from this colour pattern to an RGB image is called demosaicing.



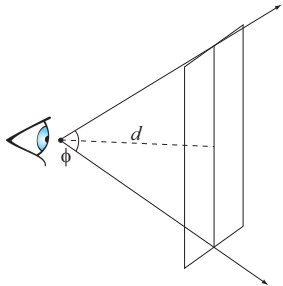
The pinhole camera model



- The lens is modelled as a point $\boldsymbol{e}$ (an infinitely small hole).
- At the distance d behind the point $\boldsymbol{e}$, we place the CCD chip.
- But is it really necessary to turn the image upside down?
  Not if we place the image plane in front of $\boldsymbol{e}$ (the eye point).

The lens as an angle and a distance

- The lens system determines how large the field of view is.
- The field of view is an angle ϕ.



$$h = 2d \tan\left(\frac{\phi}{2}\right)$$

- In the model, it is not important whether d and the size of the light sensitive area correspond to reality.
- We choose $h = 1$ and use only d or only ϕ to describe the lens system (and thereby the zoom level of the camera).
- We often use d, which is called the camera constant.

What is ray tracing?

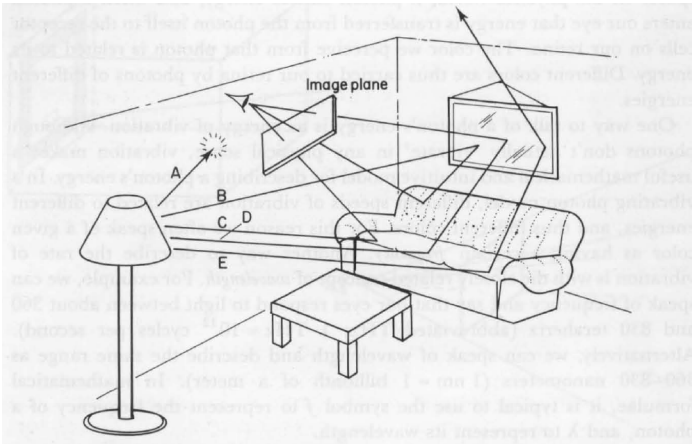


Fig. 5. Some light rays (like A and E) never reach the image plane at all. Others follow simple or complicated routes.

References

- Glassner, A. An Overview of Ray Tracing. In *An Introduction to Ray Tracing*, Chapter 1, pp. 1–17, Morgan Kaufmann, 1989.

Ray generation

Camera space coordinates: $\boldsymbol{q}_c = (x_{ip}, y_{ip}, d)$, $(x_{ip}, y_{ip}) = \left(x + \frac{1}{2}, y + \frac{1}{2}\right) \frac{1}{H} - \left(\frac{1}{2}\frac{W}{H}, \frac{1}{2}\right)$

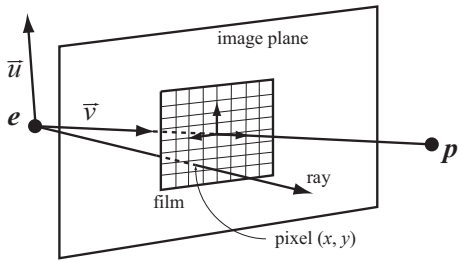
Change of basis matrix: $\begin{bmatrix} \vec{b}_1 & \vec{b}_2 & \vec{v} \end{bmatrix} = \begin{bmatrix} \frac{\vec{v}\times\vec{u}}{|\vec{v}\times\vec{u}|} & \vec{b}_1 \times \vec{v} & \frac{\boldsymbol{p}-\boldsymbol{e}}{|\boldsymbol{p}-\boldsymbol{e}|} \end{bmatrix}$

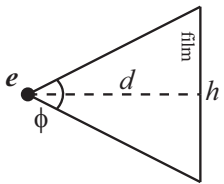
- Camera description:

Ray direction: $\vec{\omega} = \frac{\boldsymbol{q}}{|\boldsymbol{q}|}$, $\boldsymbol{q} = \begin{bmatrix} \vec{b}_1 & \vec{b}_2 & \vec{v} \end{bmatrix} \boldsymbol{q}_c = \vec{b}_1 x_{ip} + \vec{b}_2 y_{ip} + \vec{v} d$

Extrinsic parameters		Intrinsic parameters	
$\boldsymbol{e}$	Eye point	ϕ	Vertical field of view
$\boldsymbol{p}$	View point	d	Camera constant
$\vec{u}$	Up direction	W, H	Camera resolution

- Sketch of ray generation:

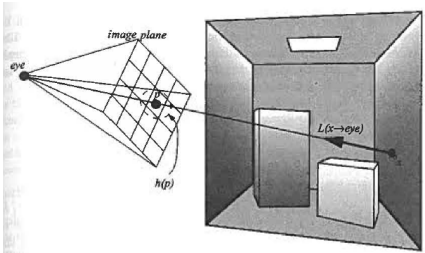


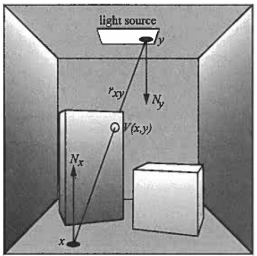


- Given pixel index (x, y), find the direction $\vec{\omega}$ of a ray through that pixel.

Rays in theory and in practice

- Parametrisation of a line: $\boldsymbol{r}(t) = \boldsymbol{o} + t\vec{\omega}$.
- Camera provides origin ($\boldsymbol{o}$) and direction ($\vec{\omega}$) of "eye rays".





- Rays in code (WGSL):

```
struct Ray {
  origin: vec3f,
  direction: vec3f,
  tmin: f32,
  tmax: f32
};
```

Hidden surface removal

- When computing ray-object intersection, we must always check that the distance to the intersection t is within the limits:

$$t_{\text{min}} \leq t \leq t_{\text{max}} \ .$$

- When searching for the closest hit, modifying t_{max} ensures that intersections further away will no longer be considered.
- When searching for any hit, terminate the search as soon as an intersection is found.

What do you need in a ray tracer?

- Render engine (for looping over all pixels).
- Camera (for ray generation).
- Objects (for ray-object intersection).
- Accelerators (for finding the closest hit point).
- Light sources (for shading and shadows).
- Materials (for assigning material properties to objects).
- Shaders (for computing the shade at the closest hit point).
- Tracer (for calling functions to shade a pixel).
- Scene (container).

Using WebGPU as the render engine

- The application runs in a web browser (https://caniuse.com/webgpu).
- The browser environment provides many render engine features for free:
  - Window management.
  - GPU rendering context.
  - User interface functionality.
  - Image file input and output.
  - Text rendering.
  - Platform independence.

- The native programming language of a browser is JavaScript.
- The browser provides developer tools
  (console for error output and debugger for stepping through code).
- An application that runs in a browser is easily published on the web.

- Handing in your lab journal is significantly simpler (no need to compose a large pdf with all the code snippets and rendering results).

Exercises

Week 1

- Implement a render engine based on WebGPU.
- Generate rays using a (modified) pinhole camera model.
- Pass data from CPU to GPU to enable interaction and load balancing.

Week 2

- Compute ray-plane, ray-triangle, and ray-sphere intersection.
- Implement conditional acceptance of intersections to find the closest hit (hidden surface removal).
- Compute shading of diffuse surfaces by point lights.
  Use Kepler's inverse square law and Lambert's cosine law.

Initializing WebGPU

- The application consists of an HTML file and a JS file.
- The webpage in the HTML file needs a HTML5 canvas element:

make a canvas

```
<!DOCTYPE html>
<html>
<head>
    <title>W1P1</title>
    <script type="text/javascript" src="w1p1.js"></script>
</head>
<body>
    <canvas id="webgpu-canvas" width="512" height="512">
        Please use a browser that supports HTML5 canvas.
    </canvas>
</body>
</html>
```

- The background JavaScript needs an asynchronous main function:

make a rendering context

```
"use strict";
window.onload = function () { main(); }
async function main()
{
  const gpu = navigator.gpu;
  const adapter = await gpu.requestAdapter();
  const device = await adapter.requestDevice();
  const canvas = document.getElementById("webgpu-canvas");
  const context = canvas.getContext("gpupresent") || canvas.getContext("webgpu");
  const canvasFormat = navigator.gpu.getPreferredCanvasFormat();
  context.configure({
    device: device,
    format: canvasFormat,
  });

  // Create a render pass in a command buffer and submit it
  ⋮
}
```

Working with WebGPU (W01P1)

- The render pass command buffer:

```
// Create a render pass in a command buffer and submit it
const encoder = device.createCommandEncoder();
const pass = encoder.beginRenderPass({
  colorAttachments: [{
      view: context.getCurrentTexture().createView(),
      loadOp: "clear",
      storeOp: "store",
  }]
});
// Insert render pass commands here
pass.end();
device.queue.submit([encoder.finish()]);
```

- Writing WGSL shaders in the HTML file:

```
<script id="wgsl" type="x-shader">
@vertex
fn main_vs(@builtin(vertex_index) VertexIndex : u32) -> @builtin(position) vec4f
{
  const pos = array<vec2f, 4>(vec2f(-0.9, 0.9), vec2f(-0.9, -0.9), vec2f(0.9, 0.9), vec2f(0.9, -0.9));
  return vec4f(pos[VertexIndex], 0.0, 1.0);
}

@fragment
fn main_fs() -> @location(0) vec4f
{
  return vec4f(0.1, 0.3, 0.6, 1.0);
}
</script>
```

Setting up a render pipeline (W01P2)

- Load the WGSL shaders from the HTML file and use them for the render pipeline:

```
const wgsl = device.createShaderModule({
  code: document.getElementById("wgsl").text
});

const pipeline = device.createRenderPipeline({
  layout: "auto",
  vertex: {
    module: wgsl,
    entryPoint: "main_vs",
  },
  fragment: {
    module: wgsl,
    entryPoint: "main_fs",
    targets: [{ format: canvasFormat }]
  },
  primitive: {
    topology: "triangle-strip",
  },
});
```

- Add the pipeline and a draw call to the render pass:

```
pass.setPipeline(pipeline);
pass.draw(4);
```

Getting image plane coordinates (W01P3)

- We need to pass information from the vertex to the fragment shader:

```
struct VSOut {
  @builtin(position) position: vec4f,
  @location(0)       coords  : vec2f,
};

@vertex
fn main_vs(@builtin(vertex_index) VertexIndex : u32) -> VSOut
{
  const pos = array<vec2f, 4>(vec2f(-1.0, 1.0), vec2f(-1.0, -1.0), vec2f(1.0, 1.0), vec2f(1.0, -1.0));
  var vsOut: VSOut;
  vsOut.position = vec4f(pos[VertexIndex], 0.0, 1.0);
  vsOut.coords = pos[VertexIndex];
  return vsOut;
}

// Define Ray struct
fn get_camera_ray(uv: vec2f) -> Ray
{
  // Implement ray generation (WGSL has vector operations like normalize and cross)
  ⋮
}

@fragment
fn main_fs(@location(0) coords: vec2f) -> @location(0) vec4f
{
  let uv = coords*0.5;
  var r = get_camera_ray(uv);
  return vec4f(r.direction*0.5 + 0.5, 1.0);
}
```

Getting user input from the CPU side

- Data that are the same for all pixels are called Uniforms.
- We can define them at the top of our WGSL code:

```
struct Uniforms {
  aspect: f32,
  cam_const: f32,
};
@group(0) @binding(0) var<uniform> uniforms : Uniforms;
```

- and use them like other structs:

```
let uv = vec2f(coords.x*uniforms.aspect*0.5, coords.y*0.5);
```

- But they require some infrastructure on the JavaScript side:

```
const uniformBuffer = device.createBuffer({
  size: 8, // number of bytes
  usage: GPUBufferUsage.UNIFORM | GPUBufferUsage.COPY_DST,
});
const bindGroup = device.createBindGroup({
  layout: pipeline.getBindGroupLayout(0),
  entries: [{
    binding: 0,
    resource: { buffer: uniformBuffer }
  }],
});
```

- and a command needs to be added to the render pass before the draw call:

```
pass.setBindGroup(0, bindGroup);
```

Making the application interactive and writing uniforms (W01P5)

- Put data in a typed array before streaming them to the GPU:

```
const aspect = canvas.width/canvas.height;
var cam_const = 1.0;
var uniforms = new Float32Array([aspect, cam_const]);
device.queue.writeBuffer(uniformBuffer, 0, uniforms);
```

- Put the render pass command buffer code in a `render` function.
- Suppose we have a mouse with a scroll wheel (if not, choose something else).
- The browser provides an interface for it.
- We can let it modify the camera constant, and pass this to the GPU as a uniform.

```
addEventListener("wheel", (event) => {
  cam_const *= 1.0 + 2.5e-4*event.deltaY;
  requestAnimationFrame(tick);
});

function tick()
{
  uniforms[1] = cam_const;
  device.queue.writeBuffer(uniformBuffer, 0, uniforms);
  render(device, context, pipeline, bindGroup);
}
tick();
```

When to do the work on the CPU

- If some computation is the same for all pixes, it is much more efficient to do it on the CPU side.
- Computing the basis vectors of the image plane is the same for all pixels.
- Consider shifting this computation to the JavaScript side and uploading the basis vectors as uniforms.
- If the image plane normal is scaled by the camera constant instead of being unit length, you can avoid having the camera constant as a uniform.
- When computing the basis vectors on the CPU side, the camera extrinsics are on the CPU side. Consider adding an interface for interactive view control.
- Note that if you use `vec3f` as a uniform, it will be considered a `vec4f` in the buffer. Pad with a zero in the JavaScript array.

- If you need a matrix-vector library for JavaScript, `MV.js` is an option. This file is available on DTU Learn.

Next steps

- Define a `HitInfo` struct for recording information when an intersection between a ray and an object is found.
- Write ray-object intersection functions (for plane, triangle, and sphere) that take a generated ray as input and outputs `HitInfo`.
- Write an overall ray-scene intersection function that defines the objects in the scene and finds the closest intersection.
- Define a `Light` struct for recording information when a light source is sampled from a point of interest in the scene.
- Implement a function for shading of diffuse objects.

- More on these topics next week, but feel free to give it a try.