Real-time Graphics

7. Post Processing

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Post processing

- Additional visual effects after scene rendering
  - Depth of Field
  - Motion Blur
  - High Dynamic Range
  - Glow / Bloom / Glare
  - SSAO, edge filter, fog, ...
- Mostly prepared and computed in screen space
- Several per-pixel information are needed
  - Color buffers
  - Depth buffer
  - Normal buffer
  - Motion vectors
- Deferred rendering

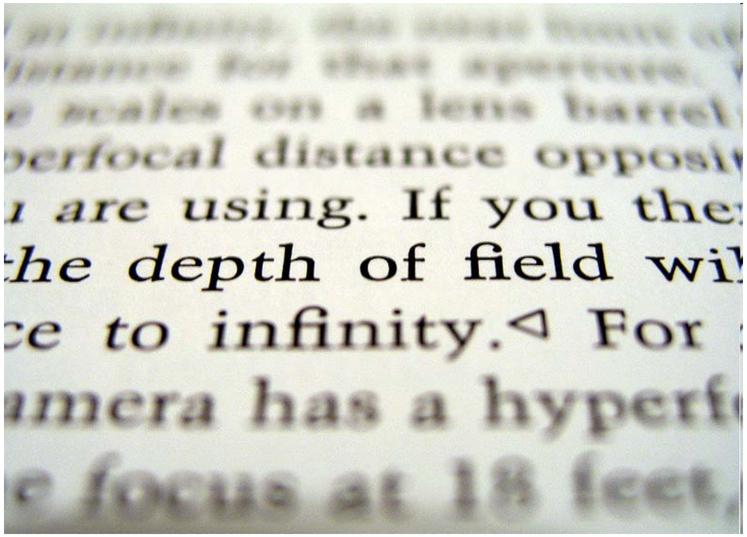
DS	Depth (24bit integer)		Stencil
RT0	Lighting accumulation RGB		Glow
RT1	View space normals XY (RG FP16)		
RT2	Motion vectors XY	Roughness, spec. intensity	
RT3	Albedo RGB		Sun shadow

Post processing

Blizzard

Depth of Field

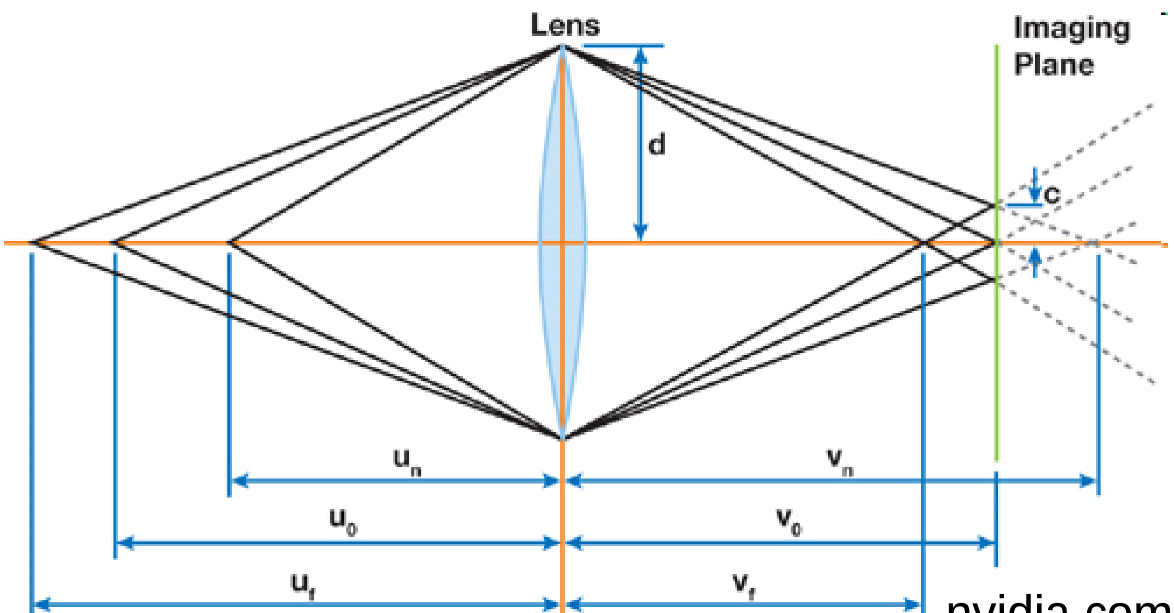
- Distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image
- Emphasizing the object vs. sharp picture



wikipedia.org

Depth of Field

- u_0 is in focus
- u_f,u_n map to a circle of confusion(CoC) with radius *c*
- Depth of field = *c* is sufficiently small



nvidia.com

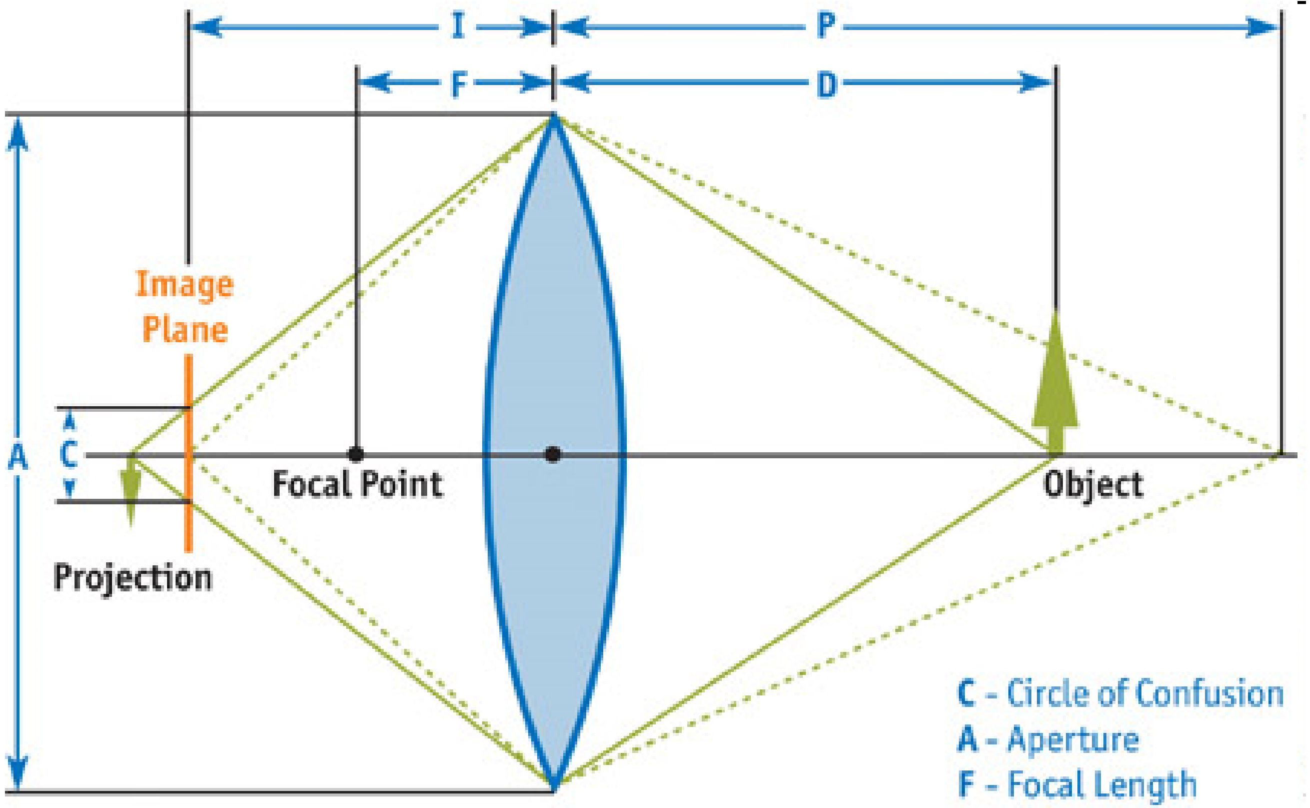
$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\frac{v_n - v_o}{v_n} = \frac{c}{d} = \frac{v_o - v_f}{v_f}$$

Circle of confusion for point *p*

$$c = d \times \left| \frac{v_p - v_o}{v_p} \right|$$

Depth of Field

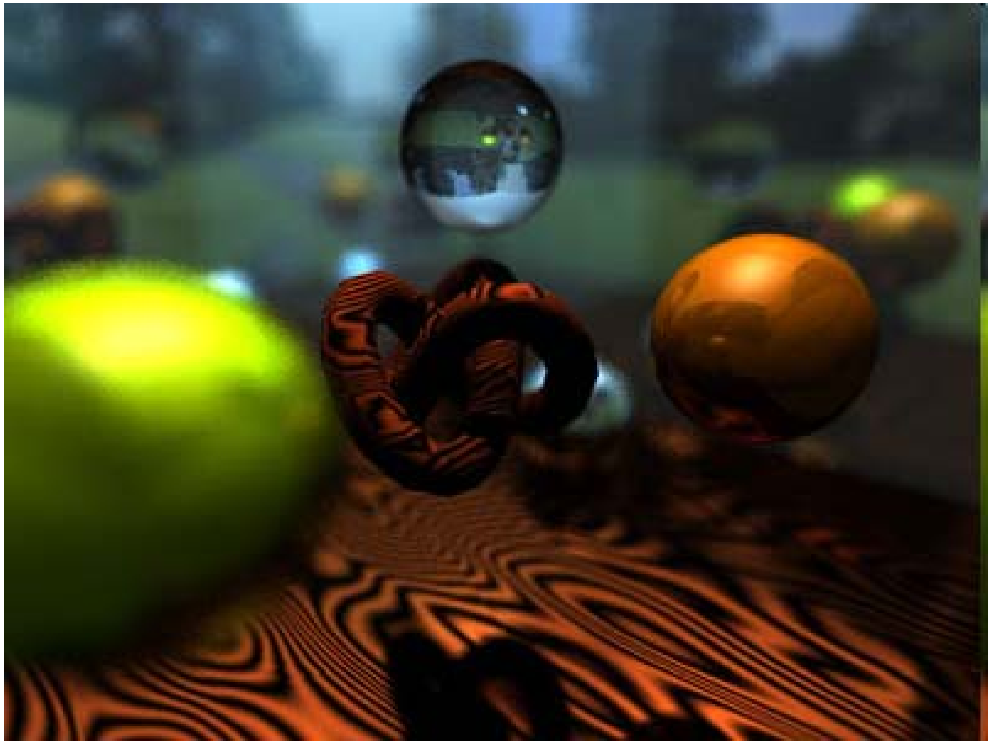


$$\frac{1}{P} + \frac{1}{I} = \frac{1}{F} \qquad C = \left| A \frac{F(P - D)}{D(P - F)} \right|$$

nvidia.com

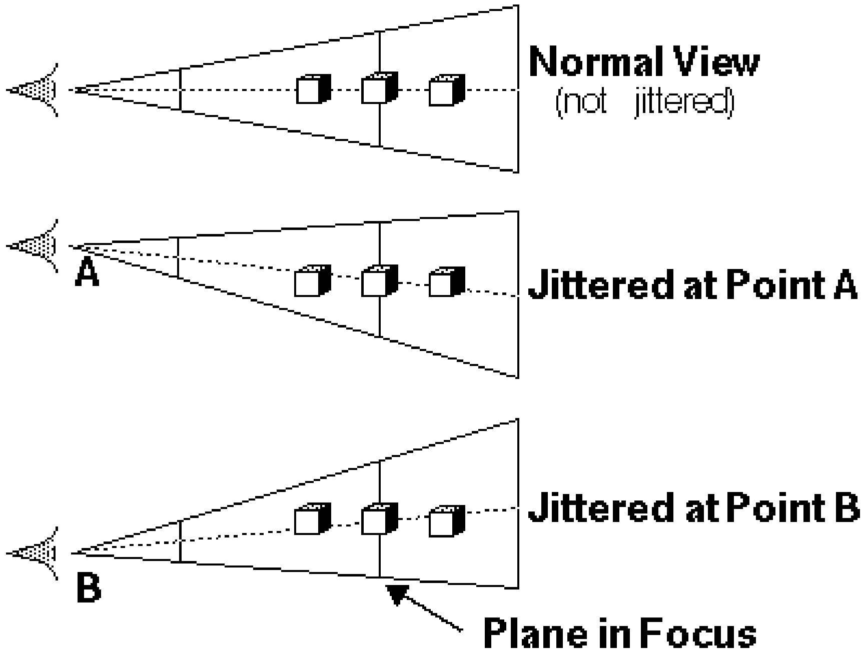
DoF – Ray tracing

- Cast rays across the lens
- Few samples → noise, artifacts
- Most accurate
- Slow



DoF – Accumulation Buffer

- Render scene multiple times from different locations
- Blend together using accumulation buffer
- Few samples
- Artifacts

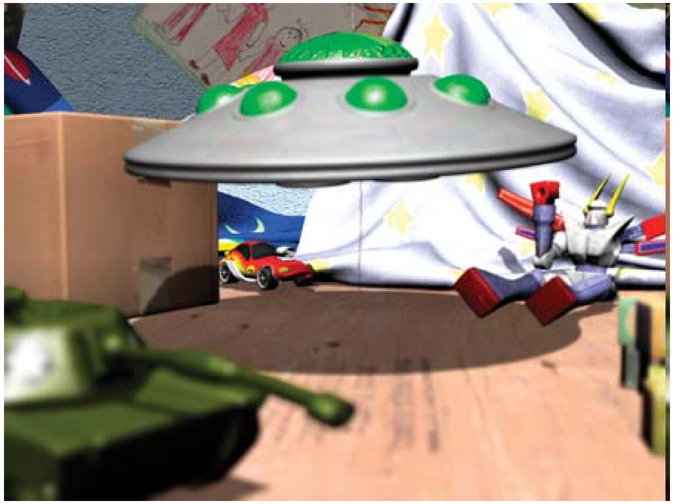


Layered DoF

- Objects sorted in layers
  - No overlapping in depth
  - Each layer blurred based on depth
  - Composition
- Problems
  - Large depth ranges
  - Overlapped objects
  - Blur factor

Forward-mapped Z-buffer

- Rendering sprites to approximate depth of field
  - Render scene to color and depth buffer
  - Use depth buffer to compute CoC for each pixel
  - Blend each pixel into framebuffer as circle with diameter equal to CoC and alpha inversely proportional to the circles' areas
  - Circles are blended only to pixels with higher depth
  - Renormalize pixels with alpha <> 1

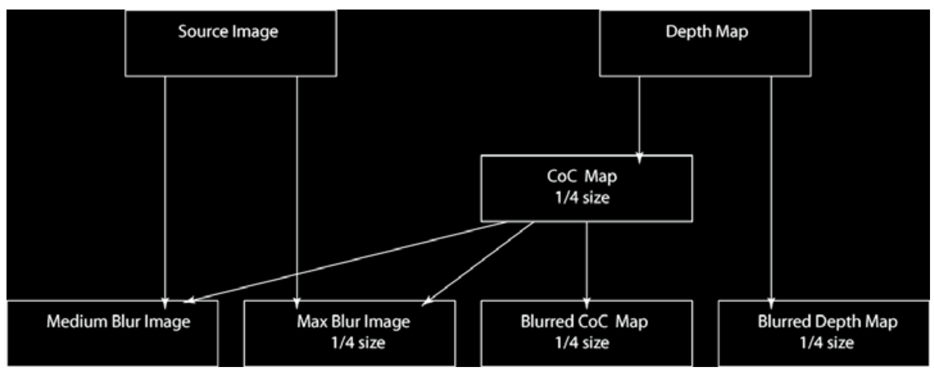


Reverse-mapped Z-buffer

- Color buffer is blurred by varying amounts per pixel
  - Render scene to color and depth buffer
  - For each pixel, determine level of blurriness = difference between pixel depth and focus plane
  - Use several blurred and downsampled color buffers and combine them based on level of blurriness
  - Use blurred depth maps, CoC maps
  - Usage of mip-maps, render-to texture, Gaussian blur

DoF – Current approach

- Generate three images for each level of blur
- Compute the CoC for each pixel, store it in CoC map
- Generated blurred CoC map and depth map
- Sample the source depth map and the blurred depth map and use depth ordering test to determine if the blurred or non-blurred CoC should be used
- Calculate contribution from each of the four blur sources based on the CoC factor and sum the contributions



CoC

$$saturate\left(\frac{DofAmount \times max(0, Depth - FocalDepth - NoBlurRange)}{MaxBlurRange - NoBlurRange}\right)$$

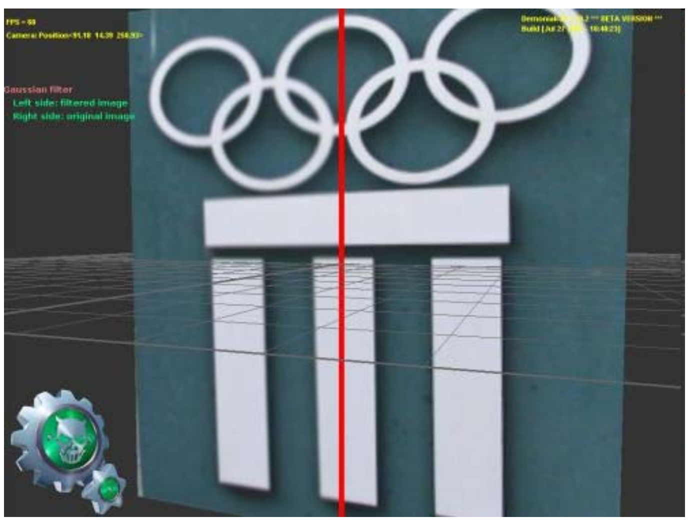
Blizzard

Gaussian blur - GLSL

- 2D Gaussian 3x3 filter
- Use separable approach ☺

```
varying vec2 vTexCoord;

// use shaders for rendering screen aligned quad
void main(void)
{
  gl_TexCoord[0] = gl_MultiTexCoord0;
  gl_Position = ftransform();
}
```



```
#define KERNEL_SIZE 9
// Gaussian kernel
// 1 2 1
// 2 4 2
// 1 2 1
const float kernel[KERNEL_SIZE] = { 1.0/16.0, 2.0/16.0, 1.0/16.0, 2.0/16.0, 4.0/16.0,
        2.0/16.0, 1.0/16.0, 2.0/16.0, 1.0/16.0 };

uniform sampler2D colorMap; // mapped color texture
uniform float width;  // width of mapped color texture
uniform float height; // height of mapped color texture

const float step_w = 1.0/width;
const float step_h = 1.0/height;
const vec2 offset[KERNEL_SIZE] = { vec2(-step_w, -step_h), vec2(0.0, -step_h),
        vec2(step_w, -step_h), vec2(-step_w, 0.0), vec2(0.0, 0.0), vec2(step_w, 0.0),
        vec2(-step_w, step_h), vec2(0.0, step_h), vec2(step_w, step_h) };

void main(void)
{
  int i = 0;
  vec4 sum = vec4(0.0);

  for( i=0; i<KERNEL_SIZE; i++ )  {
     vec4 tmp = texture2D(colorMap, gl_TexCoord[0].st + offset[i]);
     sum += tmp * kernel[i];
  }

  gl_FragColor = sum;
}
```

Gaussian blur - GLSL

- Separable approach - faster

```
float weights[9] = {0.0677841f, 0.0954044f, 0.121786f, 0.140999f, 0.148054f, 0.140999f, 0.121786f, 0.0954044f, 0.0677841f};
```

```
uniform float OffsetsH[9];
uniform float Weights[9];
uniform sampler2D Tex0;

void main (void)
{
  int i;
  vec4 color = vec4(0.0, 0.0, 0.0, 1.0);
  for(i=0; i<9; i++)
    color += (texture2D(Tex0, gl_TexCoord[0].st + vec2(Offsets[i], 0.0)) *Weights[i]);
  gl_FragColor = color;
}
```

Fragment shader for horizontal direction

```
for(int i=0; i<9; i++)
{
  OffsetsH[i] = (i - 4.0f) / float(Tex0Width/2.0f);
  OffsetsV[i] = (i - 4.0f) / float(Tex0Height/2.0f);
}
```

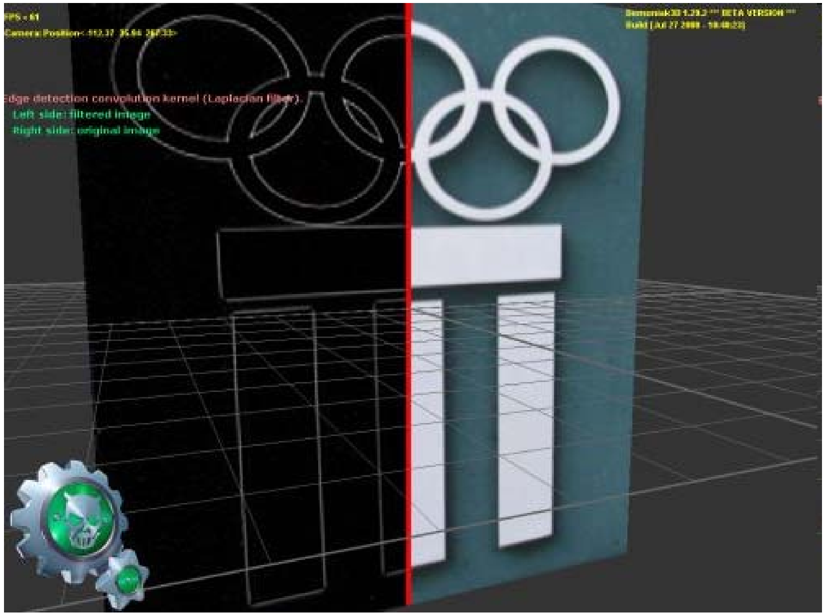
```
uniform float OffsetsV[9];
uniform float Weights[9];
uniform sampler2D Tex0;

void main (void)
{
  int i;
  vec4 color = vec4(0.0, 0.0, 0.0, 1.0);
  for(i=0; i<9; i++)
    color += (texture2D(Tex0, gl_TexCoord[0].st + vec2(0.0, Offsets[i])) *Weights[i]);
  gl_FragColor = color;
}
```

Fragment shader for vertical direction

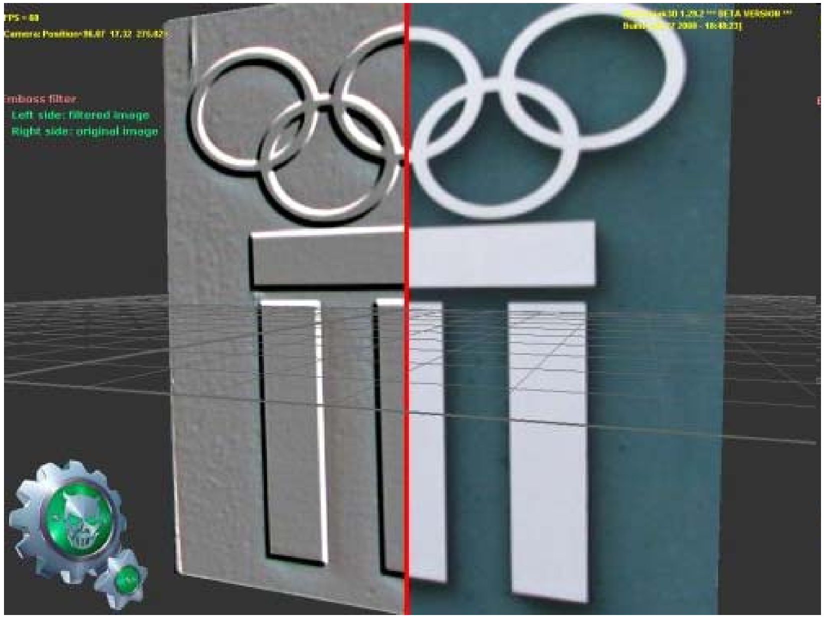
Other filters

http://www.ozone3d.net/tutorials/image_filtering.php



Laplacian Filter

$$\begin{matrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{matrix}$$



Emboss Filter

$$\begin{matrix} 2 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{matrix}$$

DoF – GLSL

Demo from http://encelo.netsons.org/programming/opengl

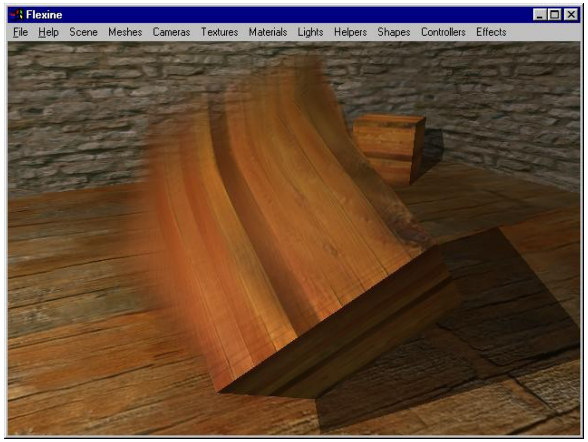
Motion blur

- Movement of an object - dynamics
- Blur - object / background
- Basic approach - precomputed
  - extended geometry (important parts)
  - various textures (wheels, road)

Accumulation buffer

- Average a series of images → accumulation buffer
- For each frame
  - Render frame
  - Store frame
  - Add frame to accumulation buffer
  - Subtract some older frame from accumulation buffer (from n back steps)
- Memory needed for previous frames
- Several previous frames can be generated in current frame – high frame rate necessary

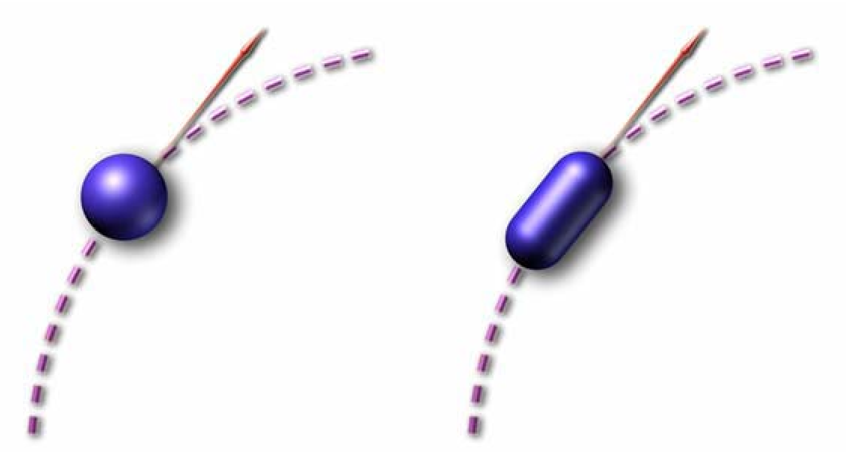
```
float q = .60;
glAccum(GL_MULT, q);
glAccum(GL_ACCUM, 1-q);
glAccum(GL_RETURN, 1.0);
```



Geometry distortion

- Drawing distorted object along path of movement, using different blending for various parts of distorted objects
- Vertex shader:
  - Distort each vertex in the velocity direction
  - Size of distortion is based on normal and velocity dot product
  - Add alpha based on size of distortion and velocity
  - Use velocity relative to camera
- Fragment shader
  - Use shading based on size of distortion

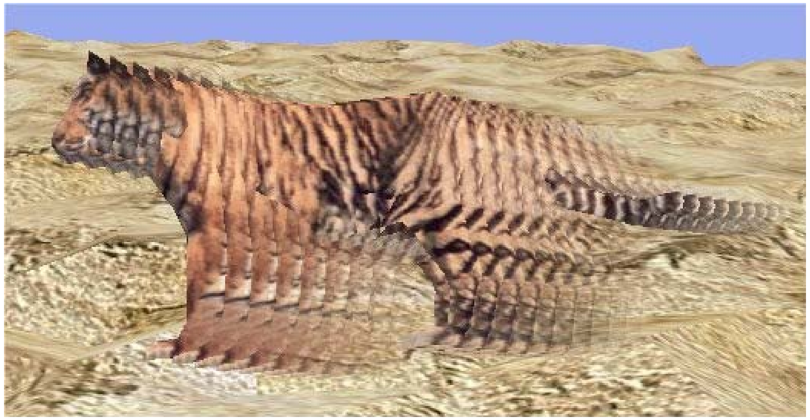
Geometry distortion

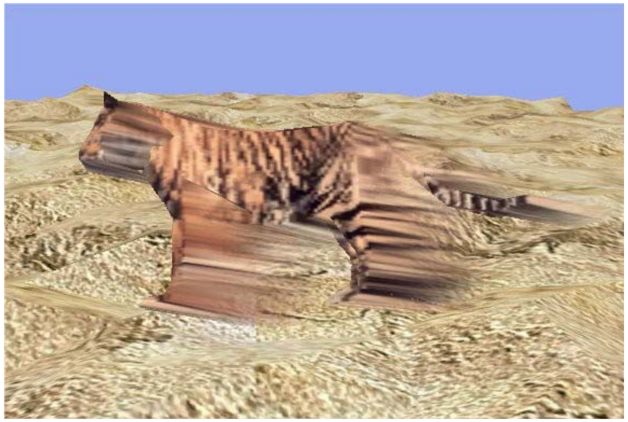


http://developer.amd.com/media/gpu_assets/ShaderX2_MotionBlurUsingGeometryAndShadingDistortion.pdf

Geometry distortion 2

- Another approach - compute velocity vector (motion vector) in vertex shader based on previous and current vertex position
- Problems: transparency (back to front), non-convex objects, fast rotation, object moves away from camera, ...





Screen space

- Generate per-pixel scene velocity maps
- For movement of camera, can be extended to movement of objects
- Computation in fragment shader
  - Velocity (motion) vector is in screen space
  - We need previous position of fragment in screen space – it is calculated using previous frame matrix
  - Depth buffer value + current frame screen-space coordinates + inverse model-view-projection matrix = fragment object coordinates + prev. frame model-view-projection matrix = prev. frame screen-space coordinates

Screen space

- Post-processing effect
- Generating blur based on screen-space velocity
  - Sampling color buffer in velocity direction
  - Convolution
- No blur for some objects - masking
- Dynamic objects
  - Masking parts of scene where is dynamic object
  - Storing screen-space velocities of object

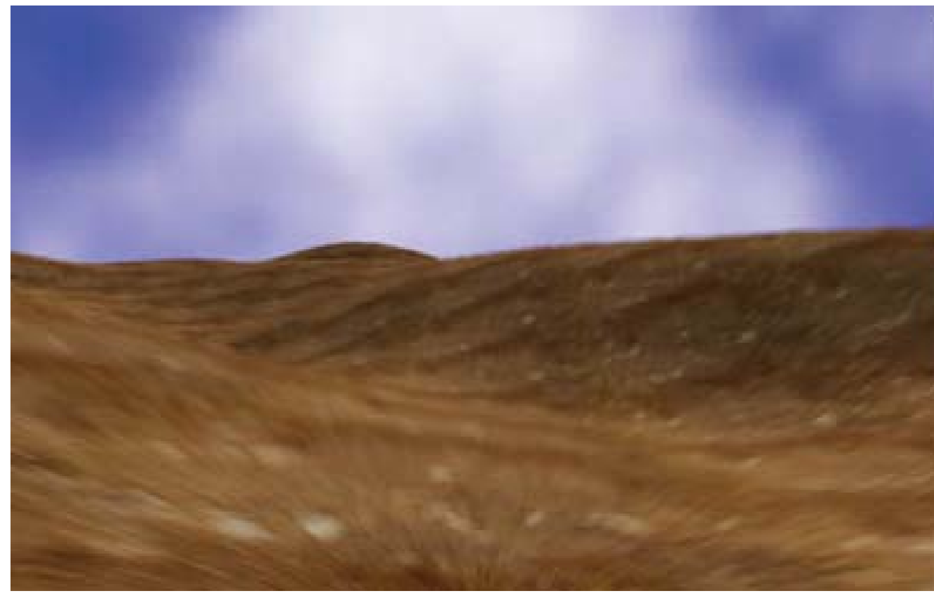
Motion blur – GLSL

Rendering full screen quad

```
uniform sampler2D colorMap; // mapped color texture
uniform sampler2D depthMap; // mapped color texture
uniform mat4 previousModelViewProjectionMatrix;
uniform int numSamples;

void main(void)
{
  // Get the depth buffer value at this pixel.
  float zOverW = shadow2D(depthTexture, vec3(gl_TexCoord[0])).r;
  // current screen-space position at this pixel in the range -1 to 1.
  vec4 currentPos = vec4(gl_TexCoord[0].s * 2 - 1, (1 - gl_TexCoord[0].t) * 2 - 1,  zOverW, 1);
  // Transform by the model-view-projection inverse.
  vec4 D = gl_ModelViewProjectionMatrixInverse * currentPos;
  // Divide by w to get the object space position.
  vec4 worldPos = D / D.w;
  // Use the world position, and transform by the previous model-view-projection matrix.
  vec4 previousPos = previousModelViewProjectionMatrix * worldPos;
  // Convert to nonhomogeneous points [-1,1] by dividing by w.
  previousPos /= previousPos.w;
  // Use this frame's position and last frame's to compute the pixel velocity.
  vec2 velocity = (currentPos - previousPos)/2.f;
  // Get the initial color at this pixel.
  vec4 color = texture2D(colorMap, gl_TexCoord[0].st);
  vec2 texCoord = gl_TexCoord[0].st + velocity;
  for (int i = 1; i < numSamples; ++i, texCoord += velocity)
  {
    // Sample the color buffer along the velocity vector and it to color sum
    color += texture2D(colorMap, texCoord);
  }
  // Average all of the samples to get the final blur color.
  gl_FragColor = color / numSamples;
}
```

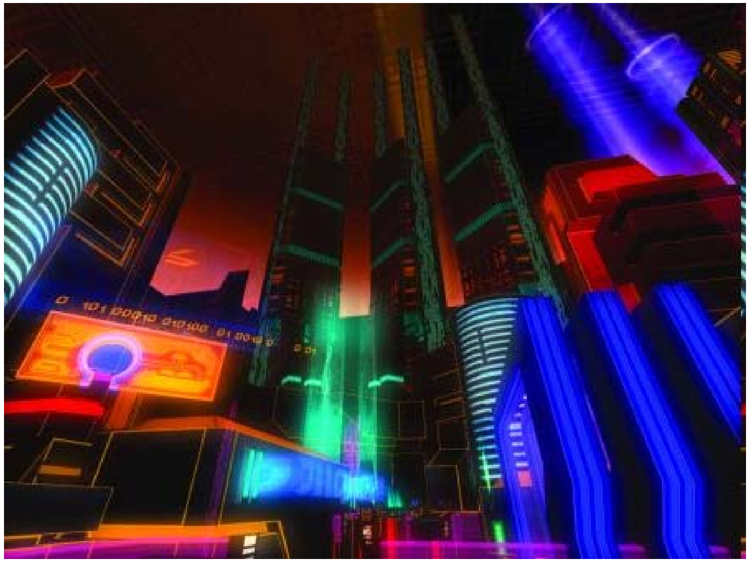
Motion blur



http://http.developer.nvidia.com/GPUGems3/gpugems3_ch27.html

Glow

- Glow / Bloom / Glare add visual cues about brightness and atmosphere in scene
- Reproducing the visual effects of intense light, very bright sources

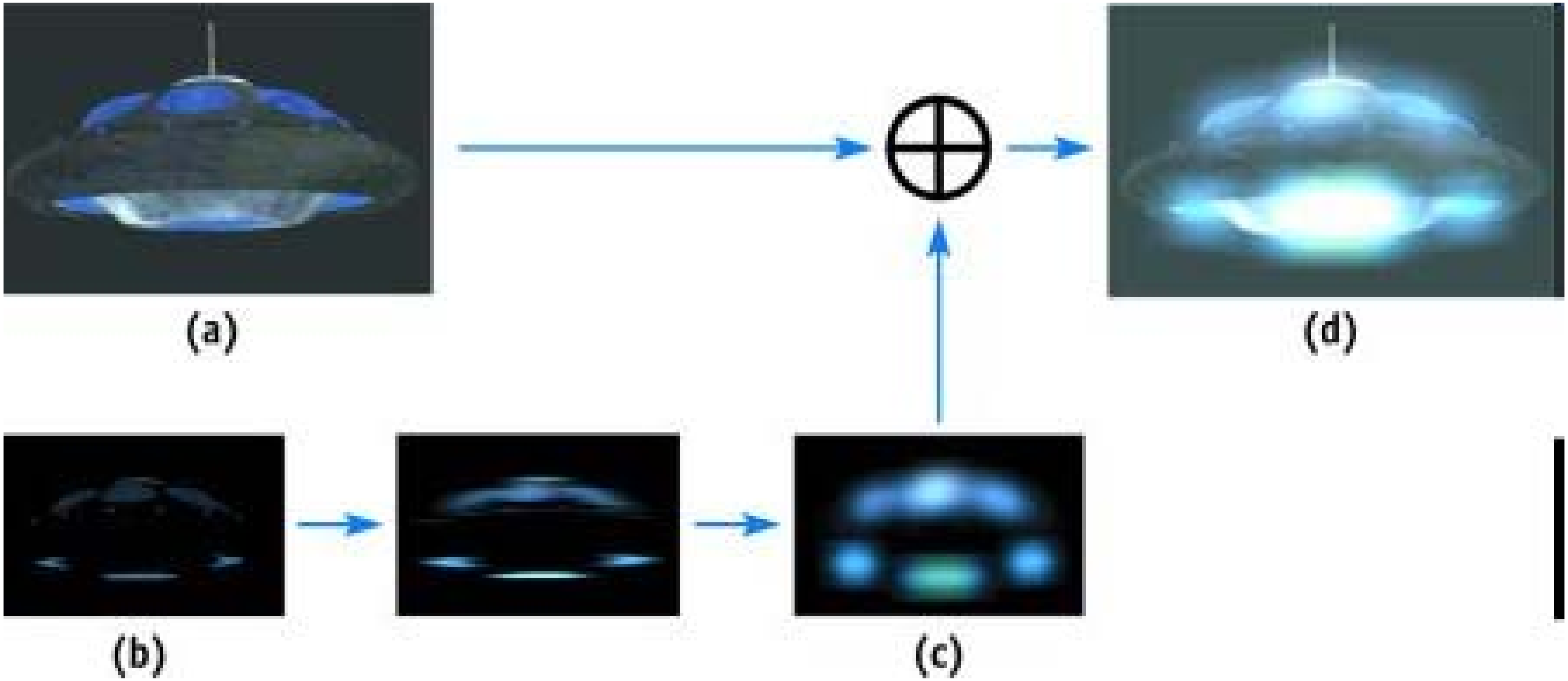


Tron 2.0

Glow

- Simple – use billboards and blending to put bright mask over bright sources
- Use two pass rendering to combine normal scene with glowing parts of screen
  - Render scene to texture, save glow parameter in alpha or downsampled texture
  - Threshold small values of glow
  - Use filter to blur glow values
  - Use additive blending to combine glow values with scene texture pixels

Glow



http://www.gamasutra.com/view/feature/2107/realtime_glow.php

High Dynamic Range

- RGB images – small range of tonal values, can't reproduce high luminance range between lightest and darkest areas, 8 bits per channel – 256:1
- Real-world luminance dynamic range - 100000:1
- HDR rendering – luminance and radiance per pixel exceeds range [0.0, 1.0] - Computation in floating point format

Lum = 0.3*R + 0.59*G + 0.11*B

Far Cry

HDR sources

- CG rendering
- Photography – different exposure times
  - Different details visible at low and high exposure

Dean S. Pemberton

HDR sources

Dean S. Pemberton

HDR requirements

- All lightning, post-processing, texturing, ... calculations must be in floating points
- Floating-point arithmetic in shaders
- Channels of used textures must exceed [0,1] – floating point textures
  - Texture internal format GL_RGBA16F, GL_RGBA32F
- Rendering to texture = floating point render targets with blending
  - Texture color attachments to FBO with internal format GL_RGBA16F, GL_RGBA32F

HDR Maps

- Radiance
  - Greg Ward, 1985
  - RGBE file format, 32bpp, shared exponent
  - http://www.graphics.cornell.edu/~bjw/rgbe.html
- OpenEXR
  - Industrial Light & Magic, 2003
  - Open standard, robust
  - http://www.openexr.com/

Tone mapping

- Mapping HDR source to LDR destination (image, display, ...), mapping [0,inf) to [0,1)
- Global
  - For every mapped pixel takes into account the intensity of whole image
- Local
  - For every mapped pixel takes into account surrounding pixel intensities

Tone mapping

- Simple $$Lum_{mapped}(F) = \frac{Lum(F)}{Lum(F)+1}$$
- Using average luminance of whole image
  - Given as parameter
  - Convert RGB frame to luminance and downscale texture using bilinear filtering to 1x1 – average luminance

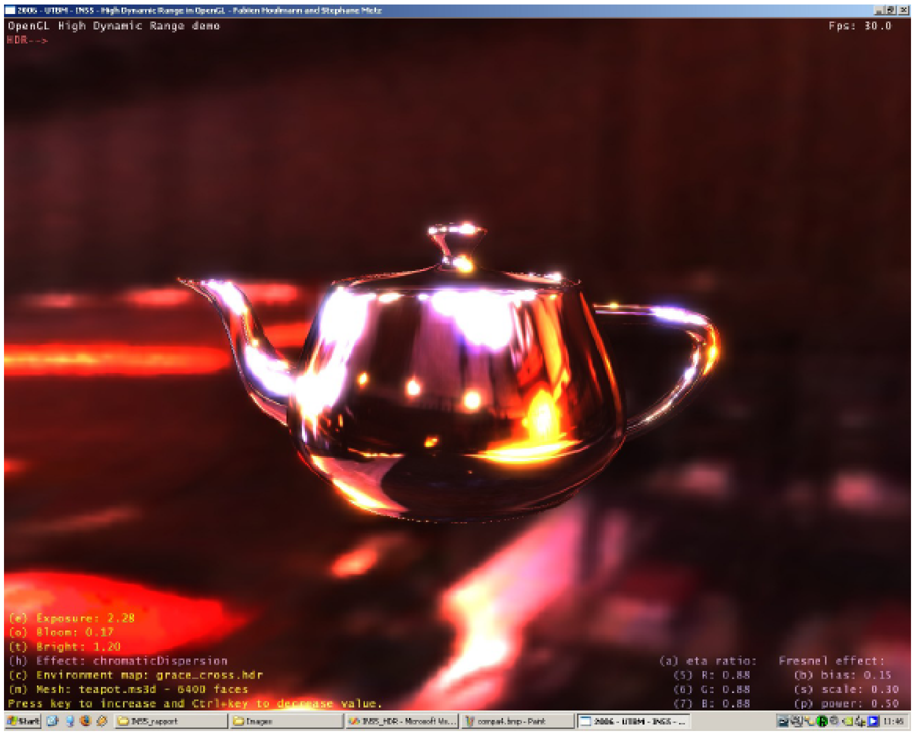
$$Lum_{mapped}(F) = \alpha * \frac{Lum(F)}{Lum_{average}}$$

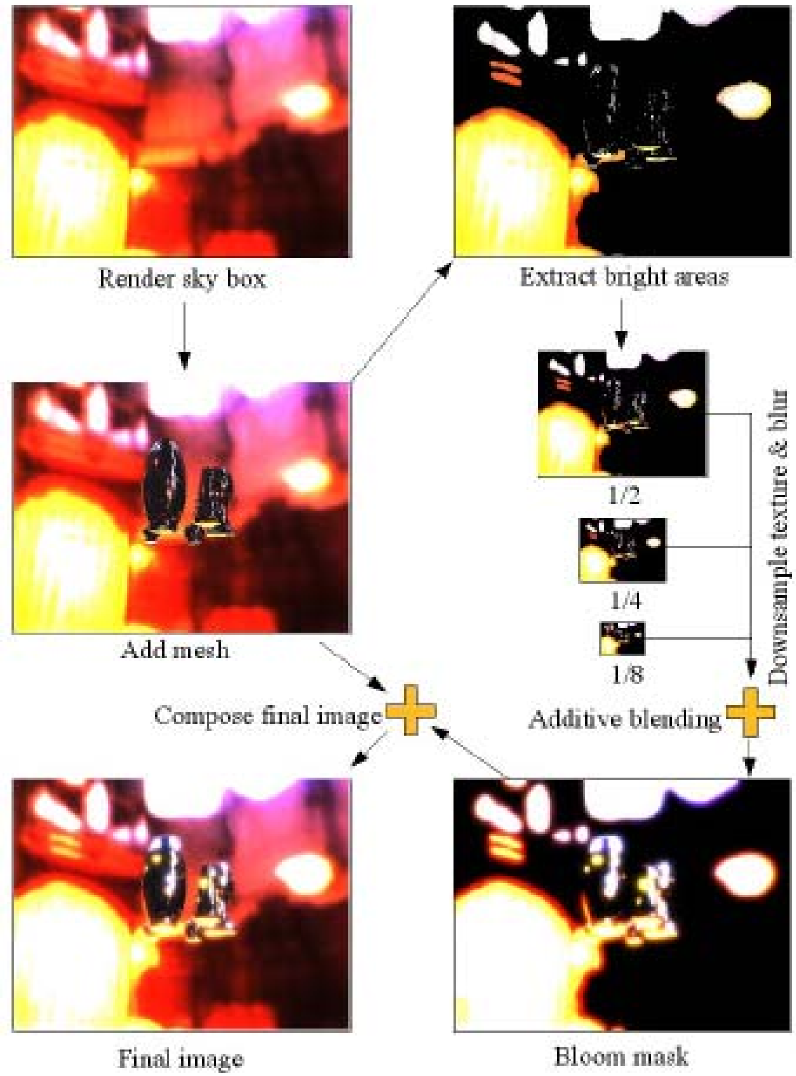
$$Lum_{mapped}(F) - final\ (LDR)\ luminance\ of\ fragment\ F$$
$$Lum_{average} - average\ luminance\ of\ the\ whole\ frame$$
$$Lum(F) - Source\ (HDR)\ luminance\ of\ fragment\ F$$

- Using maximal luminance and exposure

$$Lum_{mapped}(F) = Lum(F) * \text{exposure} * \frac{1 + \frac{\text{exposure}}{Lum_{\max}}}{1 + \text{exposure}}$$

HDR + bloom


OpenGL High Dynamic Range demo
Fps: 30.0
HDR-->
(e) Exposure: 2.28
(o) Bloom: 0.17
(t) Bright: 1.20
(h) Effect: chromaticDispersion
(c) Environment map: grace_cross.hdr
(m) Mesh: teapot.ms3d - 6400 faces
Press key to increase and Ctrl+key to decrease value.
(a) eta ratio:
(5) R: 0.88
(6) G: 0.88
(7) B: 0.88
Fresnel effect:
(b) bias: 0.15
(s) scale: 0.30
(p) power: 0.50


Render sky box
Extract bright areas
Add mesh
1/2
1/4
1/8
Downsample texture & blur
Compose final image
Additive blending
Final image
Bloom mask

HDR – OpenGL

Configuring FBO for rendering to floating point texture

```
GLint frameBuffer, depthBuffer, frame;
glGenFramebuffersEXT(1, &frameBuffer);
glBindFramebufferEXT(GL_FRAMEBUFFER_EXT, frameBuffer);
glGenRenderbuffersEXT(1, &depthBuffer);
glBindRenderbufferEXT(GL_RENDERBUFFER_EXT, depthBuffer);
glRenderbufferStorageEXT(GL_RENDERBUFFER_EXT, GL_DEPTH_COMPONENT, windowWidth, windowHeight);
glGenTextures(1, &frame);
glBindTexture(GL_TEXTURE_2D, frame);
glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB16F_ARB,  windowWidth, windowHeight, 0, GL_RGB, GL_FLOAT, NULL);
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_EDGE);
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_CLAMP_TO_EDGE);
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);
glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);
glFramebufferTexture2DEXT(GL_FRAMEBUFFER_EXT, GL_COLOR_ATTACHMENT0_EXT, GL_TEXTURE_2D, frame, 0);
```

Creating floating point texture

```
glGenTextures(1, &texture);
glBindTexture(GL_TEXTURE_2D, texture);
float* data = LoadData("texture.hdr");
glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB16F_ARB,  textureWidth, textureHeight, 0, GL_RGB, GL_FLOAT, data);
GLint format;
glGetTexLevelParameteriv(GL_TEXTURE_2D, 0, GL_TEXTURE_INTERNAL_FORMAT, &format);
```

HDR – GLSL

```
// TONE MAPPING FRAGMENT SHADER
// render texture and bloom map
uniform sampler2D tex, bloom;
// Control exposure with this value
uniform float exposure;
// How much bloom to add
uniform float bloomFactor;
// Max luminance
uniform float brightMax;

void main()
{
  vec2 st = gl_TexCoord[0].st;
  vec4 color = texture2D(tex, st);
  vec4 colorBloom = texture2D(bloom, st);
  // Add bloom to the image
  color += colorBloom * bloomFactor;
  // Perform tone-mapping
  float YD = exposure * (exposure/brightMax + 1.0);
  YD = YD / (exposure + 1.0);
  color *= YD;
  gl_FragColor = color;
}
```

```
// ANOTHER TONE MAPPING FRAGMENT SHADER
varying vec3 texCoordinate;
uniform sampler2D frame;
uniform float exposure;

void main()
{
  vec4 colorTemp = texture2D(frame, texCoordinate.xy);
  vec4 color = exposure*colorTemp;
  float temp  = (pow(exposure, 0.7))/(pow(exposure, 0.7)+pow(20.0, 0.7));
  gl_FragColor = color * temp;
}
```

```
// ILLUMINATION FRAGMENT SHADER USING HDR CUBE TEXTURES
uniform samplerCube hdrTexDiffuseSampler;
uniform samplerCube hdrTexReflectionSampler;
// interpolated normal vector from vertex shader
varying vec3 N;
// interpolated reflect vector from vertex shader
varying vec3 R;

void main (void)
{
  // mix material color, diffuse cube map and reflection cube map
  vec4 matColor = vec4(0.7, 0.7, 0.7, 1.0);
  vec4 diffuse = mix(matColor, textureCube(hdrTexDiffuseSampler, N), 0.9);
  vec4 reflected = textureCube(hdrTexReflectionSampler, R);
  vec4 color = mix(diffuse, reflected, 0.4);
  color.a = 1.0;
  gl_FragColor = color;
}
```

Sources

- http://developer.amd.com/media/gpu_assets/ShaderX2_Real-TimeDepthOfFieldSimulation.pdf
- http://http.developer.nvidia.com/GPUGems3/gpugems3_ch28.html
- http://http.developer.nvidia.com/GPUGems/gpugems_ch23.html
- http://encelo.netsons.org/programming/opengl
- http://http.developer.nvidia.com/GPUGems3/gpugems3_ch27.html
- http://www.gamasutra.com/view/feature/2107/realtime_glow.php
- http://www.gamerendering.com/2008/10/11/gaussian-blur-filter-shader/
- http://code.google.com/p/transporter-game/downloads/detail?name=HDRRenderingInOpenGL.pdf
- http://http.download.nvidia.com/developer/presentations/2004/6800_Leagues/6800_Leagues_HDR.pdf
- http://www.spieleprogrammierung.net/

Questions?