Optimized pixel-projected reflections for planar reflectors

a.k.a. Pixel-projected reflections

Adam Cichocki

@multisampler

SIGGRAPH2017
ADVANCES IN REAL-TIME RENDERING

private research

Screen space reflections: Overview

- Widely adopted technique
- Algorithm based on ray-marching
- Reflection generated from:
    - color buffer
    - depth buffer
- Result usually contains multiple areas with missing data
- Often performed at half resolution for efficiency [Wronski14]
  (bandwidth heavy ray-marching)
- [McGuire14]

Pixel-projected reflections: Overview

- Constrained form of SSR
- Offers high performance and quality
- Can be selectively used where applicable [Stachowiak15]
  - through compute shader indirect dispatch
- Algorithm based on data scattering
- Reflection generated from:
  - color buffer
  - depth buffer
  - analytical reflective areas

Pixel-projected reflections: Concept

- Reverse the reflection tracing
- Instead of performing ray-marching …

  … calculate exactly where pixels are reflected
- Approximate reflective areas of the scene

  with flat analytical shapes
- Reflective areas will be provided to shader through constants
- We’ll just use rectangles to approximate reflective areas
  - this is the most practical shape
  - other shapes also possible

Limitations

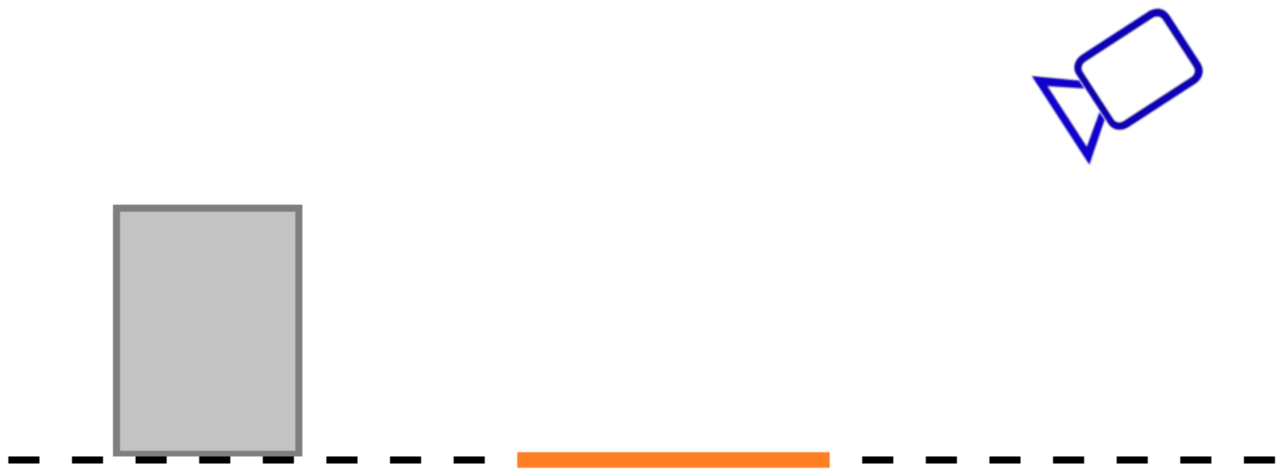
- Non-glossy reflections
- Reflections only on planar surfaces
- Normalmaps not supported
    - can be approximated, see „Bonus slides”
- Requires reflector shapes that approximate reflective areas
    - shapes are coplanar with reflective areas
    - enclose reflective areas
    - defined by artists on the scene or in prefabs

Simplified algorithm in 2D

- Just to grasp the pixel-projection concept
- We’ll switch to 3D afterward

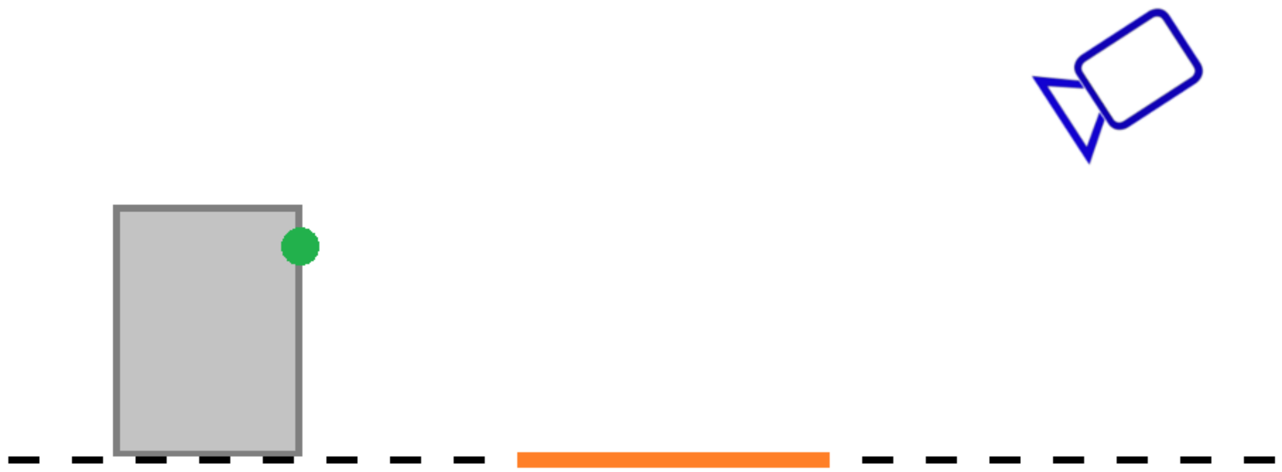
Example 2D scene

- Single object
- Puddle on the floor
- Puddle approximated with line segment



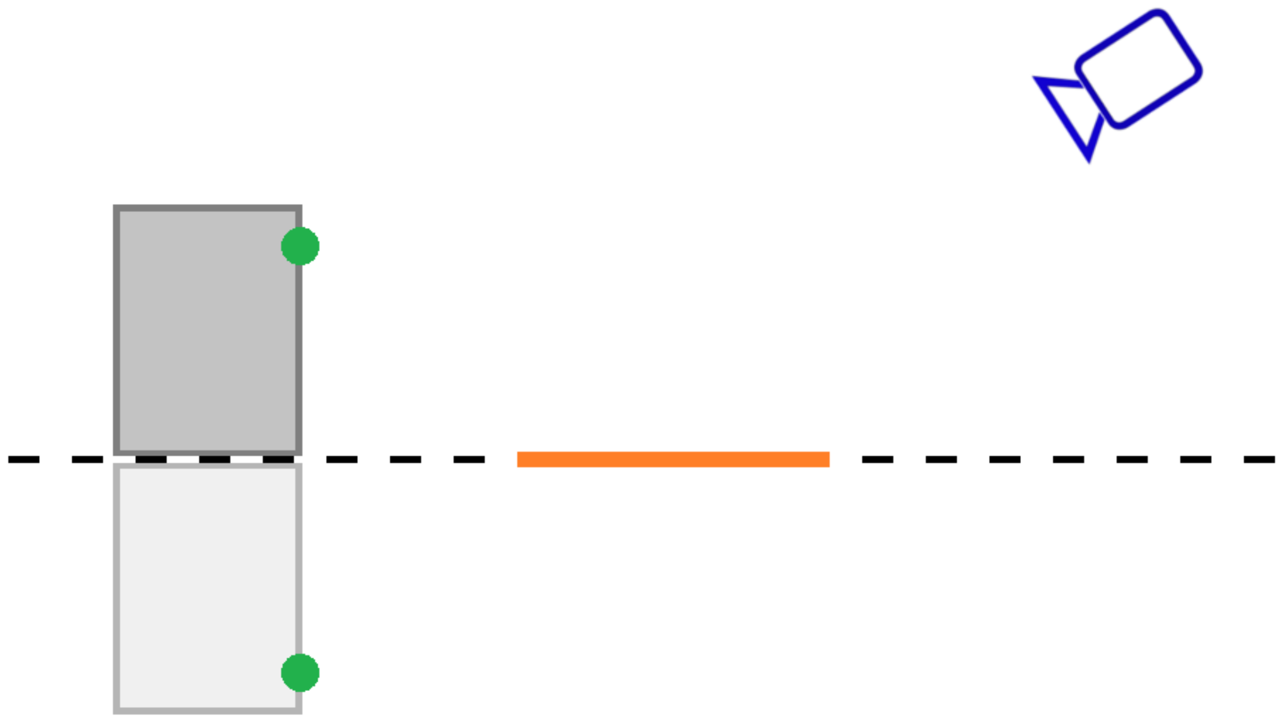
Projection pass

- First pass of the algorithm is the „projection pass”
- For every pixel calculate where it is reflected on the screen
  - single pixel in the example



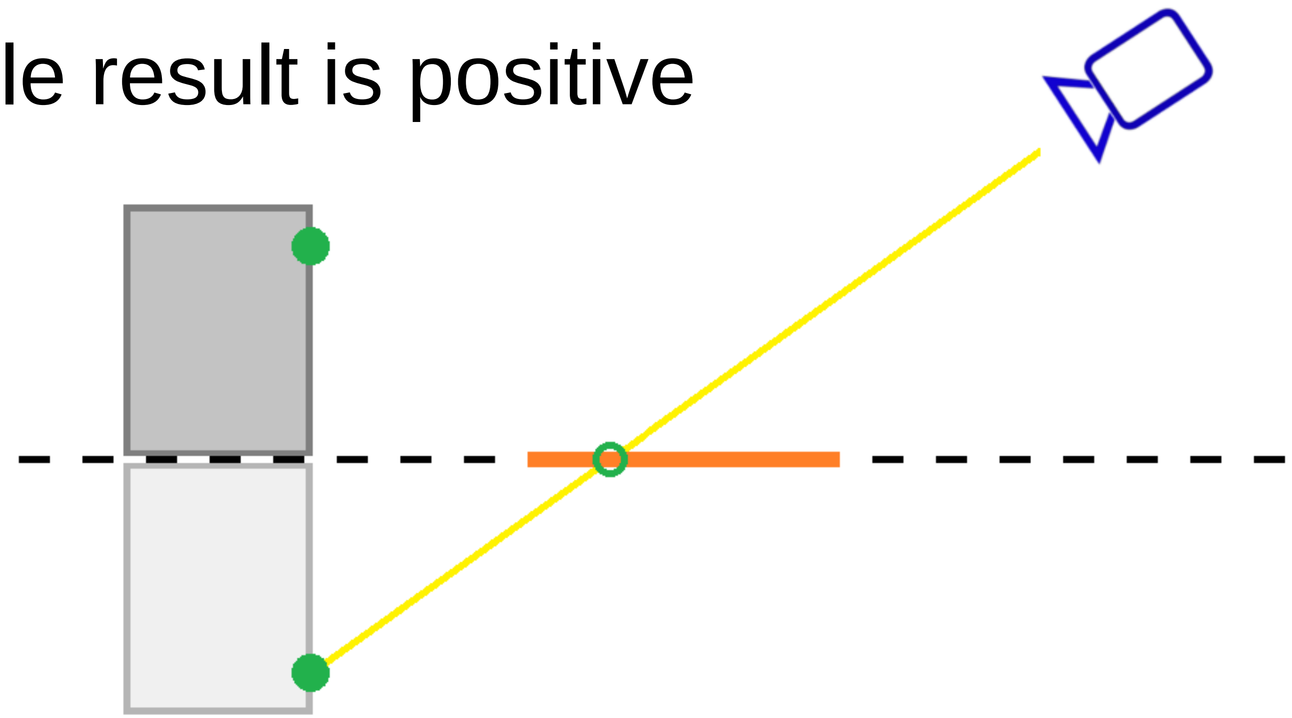
Projection pass

- Mirror pixel position against puddle's plane



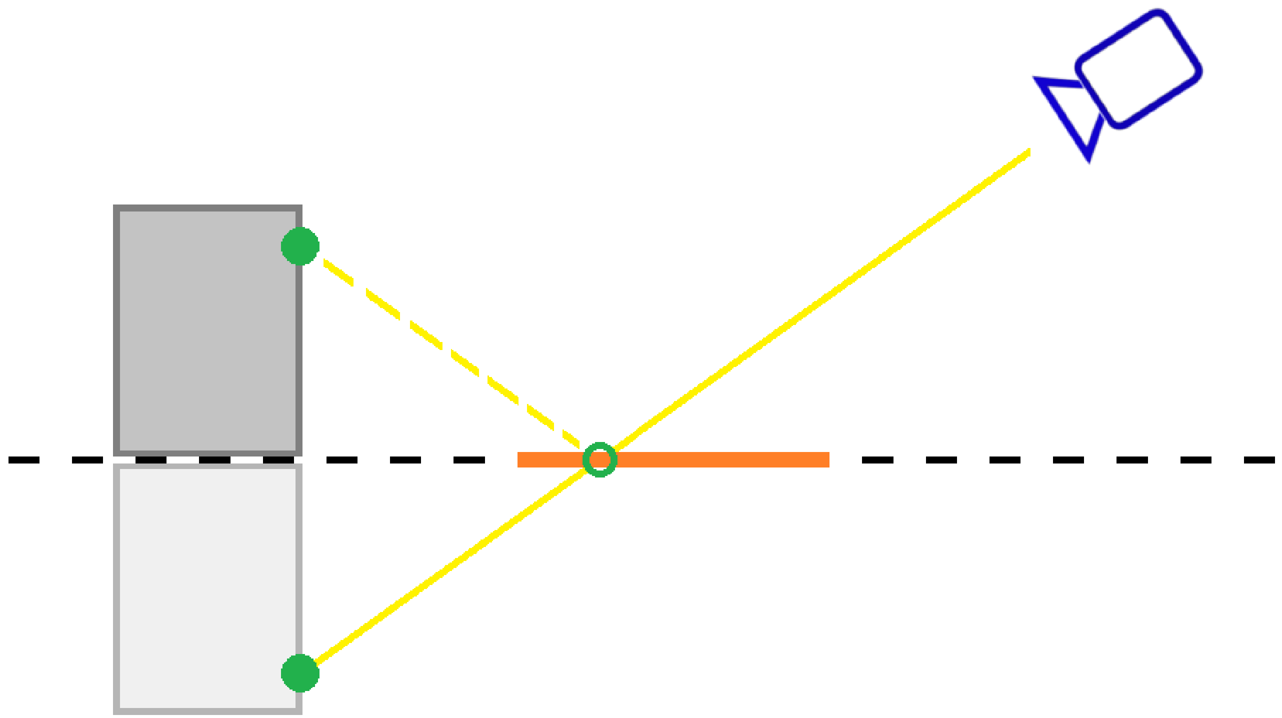
Projection pass

- Test if pixel’s reflection is visible in the puddle
  - ray-cast toward mirrored pixel position
  - test if intersection point is in puddle’s bounds
- Reject pixel if bounds test fails
- In this example result is positive



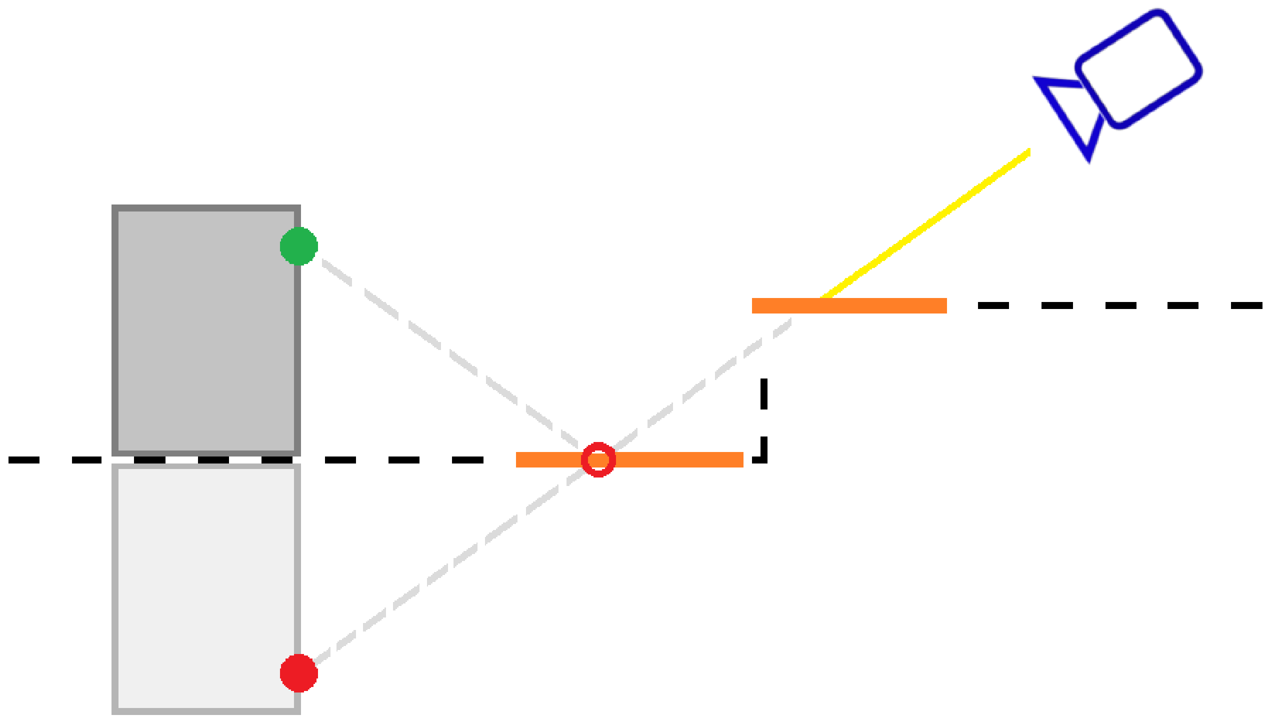
Projection pass

- We just found the reflection point
- Calculate mirrored pixel position on the screen
- Write reflected color data in that place



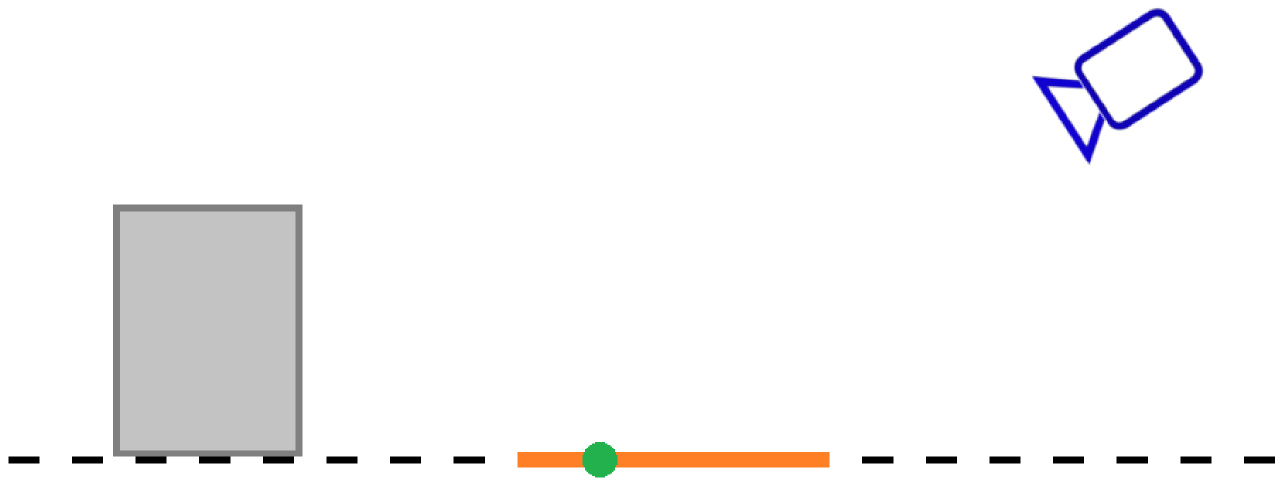
Projection pass: overlapping shapes

- What if the puddle was occluded by some other shapes?
- Test other shapes bounds during ray-cast
- Reject pixel if occluded



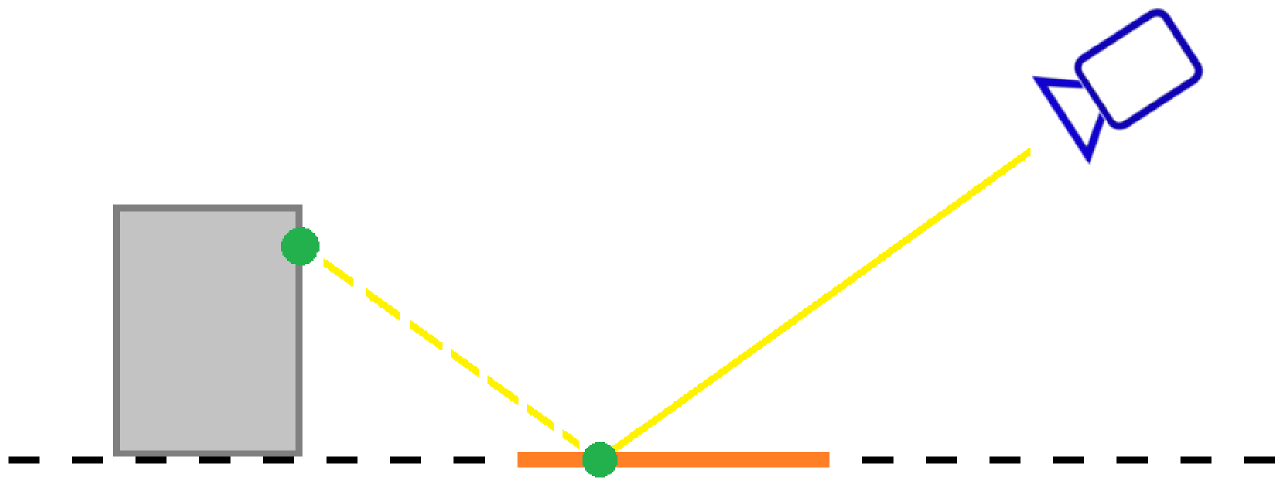
Reflection pass

- Second pass of the algorithm is the „reflection pass”
- We want to obtain reflection for given pixel
- Read data that was encoded for this pixel in „projection pass”



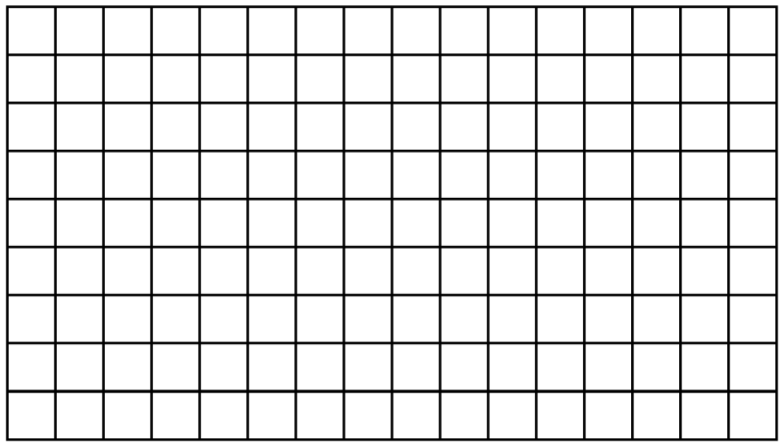
Reflection pass

- This gives us reflected color without doing any search



Intermediate buffer introduction

- Pixel-data grid
- Single value per pixel
- Filled in the „projection pass”
- Read from in the „reflection pass”



Full algorithm

- Clear the „intermediate buffer”
- Projection pass
  - use rectangles (3D) instead of line segments (2D)
  - for every pixel find rectangles that reflect it
  - project pixels on those rectangles
  - write pixel-data to „intermediate buffer”
- Reflection pass
  - read pixel-data from „intermediate buffer” (simply using ‘vpos’)
  - decode pixel-data and obtain reflected color
  - write color to reflection buffer

Rendered image

- Pillar is partially visible through the flowerpot

Intermediate buffer pixel-data

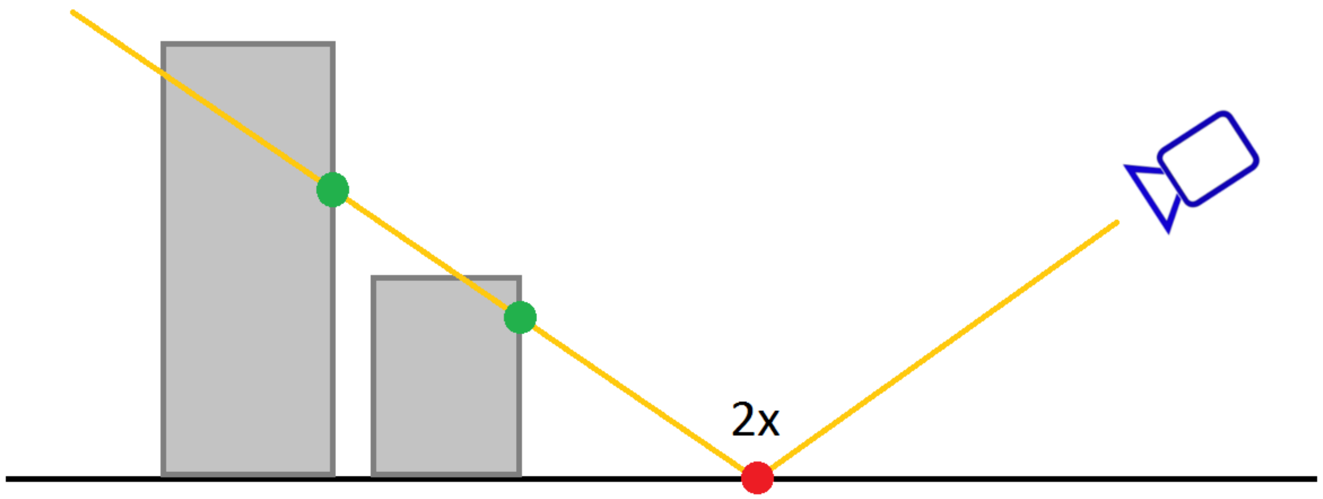
- What kind of data should we store here?
- Value ideally just a reflected pixel color, but ...

  … reflection tracing is reversed, so ...

  … multiple pixels can be written to the same place

Intermediate buffer pixel-data

- Both green pixels are projected to the same place
- We are processing pixels independently
- Write order depends on GPU scheduling
- We want the closest pixel to be reflected



Intermediate buffer pixel-data

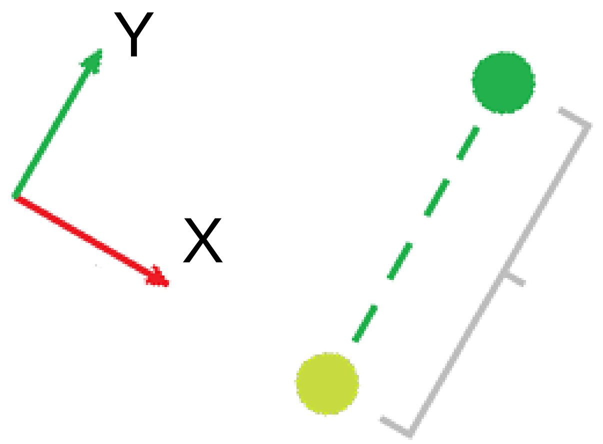
- Let's just encode screen-space offset
- For 3D scene, offset is a 2D screen-space vector
- Obtaining the offset is simple
- While writing pixel-data we already know:
  - reflected pixel coordinate (current pixel position)
  - reflecting pixel coordinate (determines where to write)
- Ensure that stored pixel-data has the smallest offset
- Write pixel-data using InterlockedMin

Intermediate buffer encoding

- We'd like to handle all possible offset orientations
- And at the same time in the „reflection pass"
  rely only on the „intermediate buffer" - to keep it simple
- Offset is 2D, so how can we encode it without precision loss …
- … while still being able to use InterlockedMin?

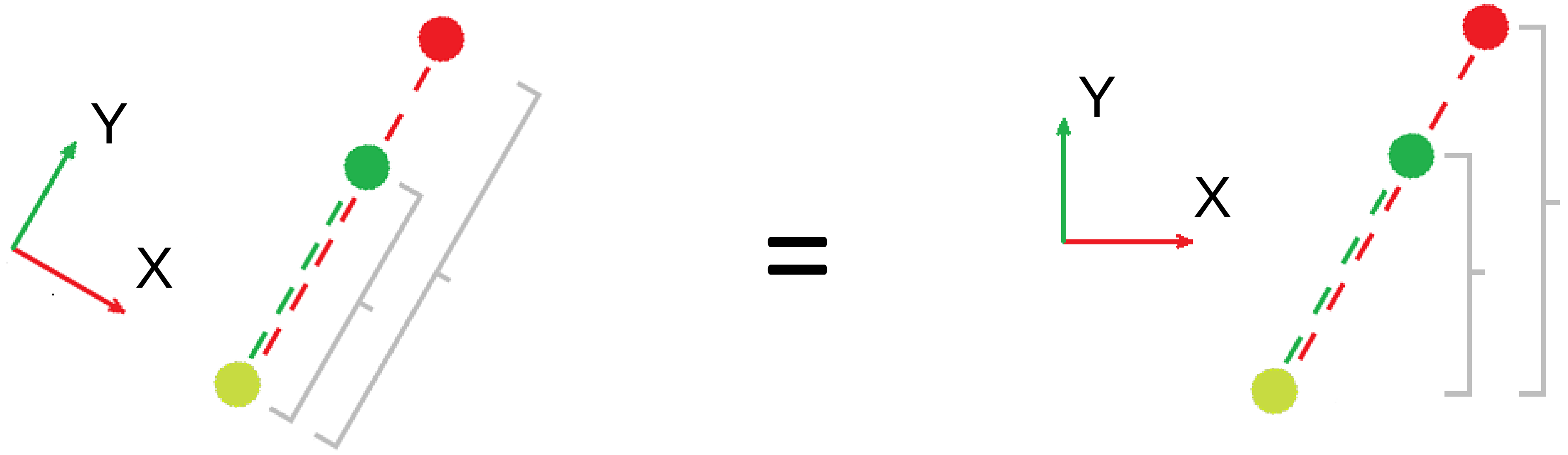
Intermediate buffer encoding

- Offset orientation defines a coordinate system
- Offset length is the ‘Y’ coordinate in this system
- ‘X’ coordinate is always zero



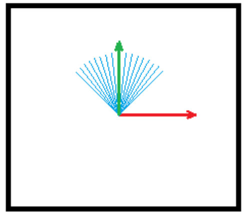
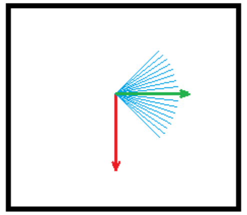
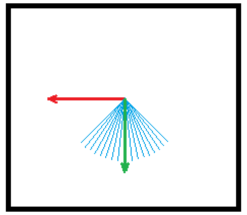
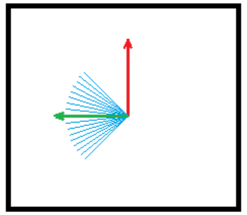
Intermediate buffer encoding

- We can also use a different coordinate system, …
- … as long as ‘Y’ coordinates are positive
- For InterlockedMin to work, encode ‘Y’ in most significant bits



Intermediate buffer encoding

- Turns out it's enough to use just four coordinate systems
- Coordinate system is chosen based on offset orientation
- In the „intermediate buffer" we need to encode:
  - 'Y' coordinate (in most significant bits)
  - 'X' coordinate
  - coordinate system index (0 .. 3)
- In the „reflection pass" we'll restore original offset based on encoded values
- „Reflection pass" based only on the „intermediate buffer"

Intermediate buffer layout

- Most → least significant bits:
  - 12 bits: 'Y’ integer (unsigned)
  - 3 bits: 'Y' fraction (signed, flipped)
  - 12 bits: 'X’ integer (signed)
  - 3 bits: 'X' fraction (signed, not flipped)
  - 2 bits: coordinate system index (0 .. 3)
- Offset fractions used for filtering – covered later

Rendered image

- Resolved writing order issue

Multiple simultaneous orientations

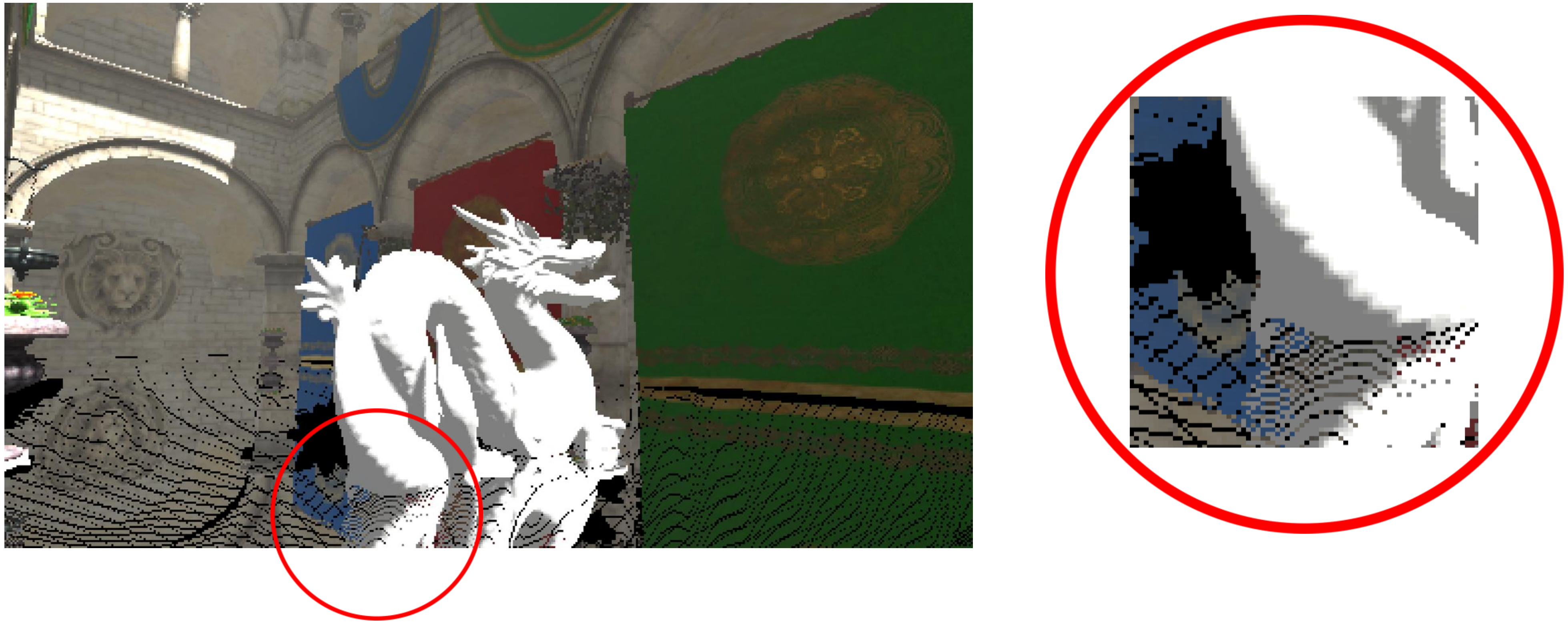
- Three different orientations encoded in the „projection pass”

Reflection pass

- We have covered the „projection pass”
- „Intermediate buffer” contains reflected pixels data
- Now it's time for „reflection pass”
    - let's read the „intermediate buffer” data
    - retrieve the offsets
    - generate reflected color
- „Reflection pass” contains four logical steps
- All steps are performed in a single shader

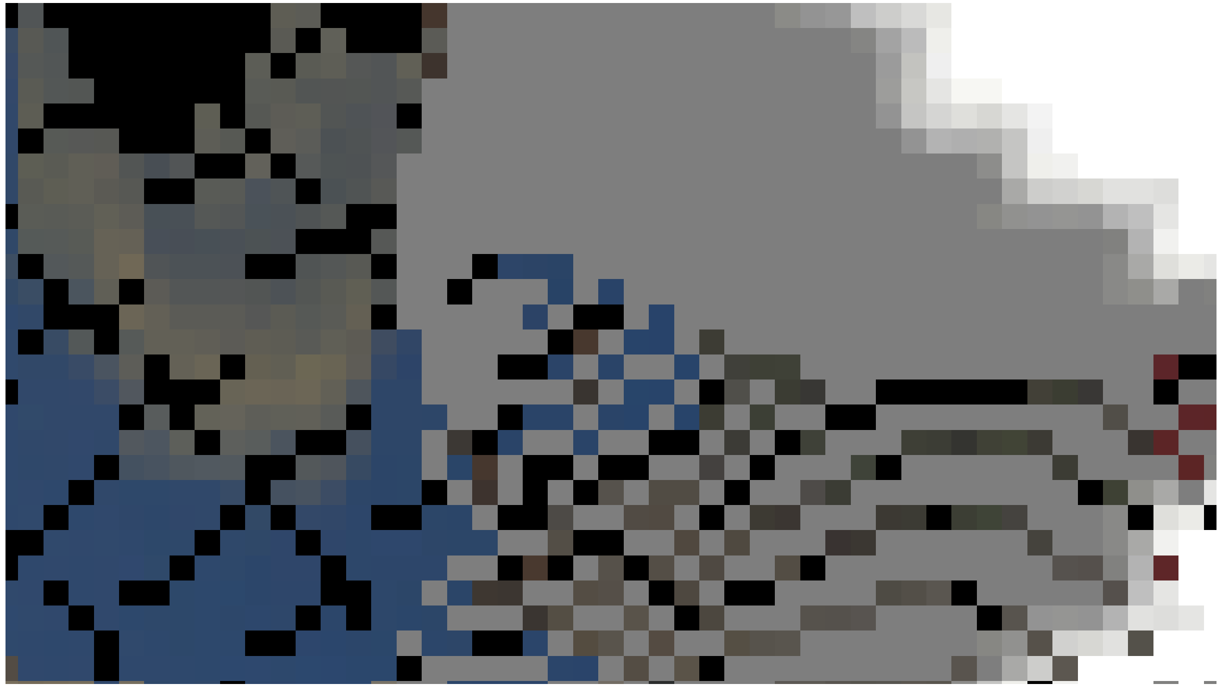
Holes

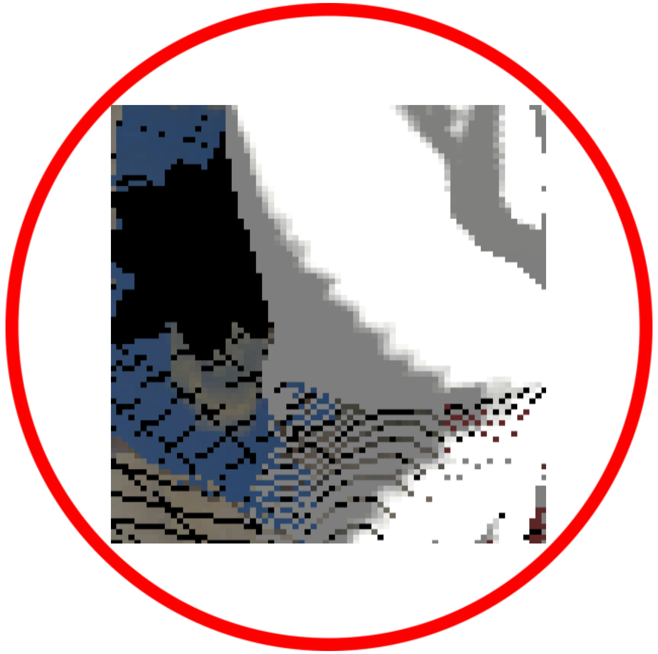
- Original image can get stretched when reflected
- This results in missing data in the „intermediate buffer”
- Fortunately holes do not form big groups



Holes

- There are two types of holes
  - holes without any data
  - holes only in the first reflection layer

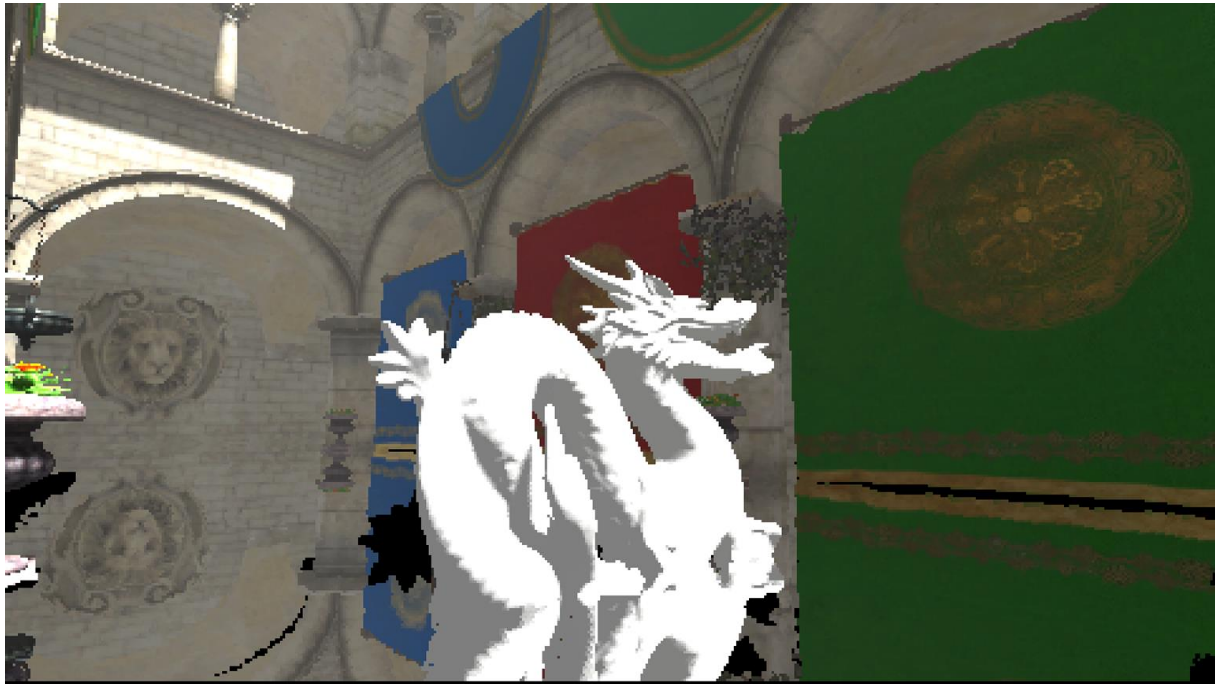


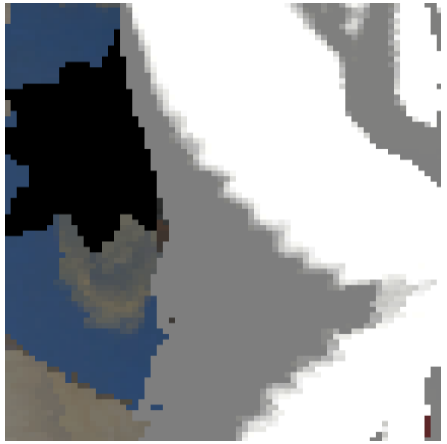


Holes patching

- Find neighboring pixel-data with smallest offset
- Calculate reflection the same way as for selected neighbor ...

  … but only if it's offset is significantly smaller than original offset



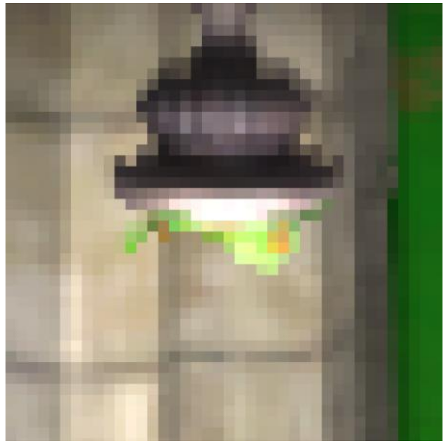


Distortion

- Reflections are slightly distorted
- Because holes are filled with neighborig pixel reflection
- Also because „intermediate buffer” is a discrete grid

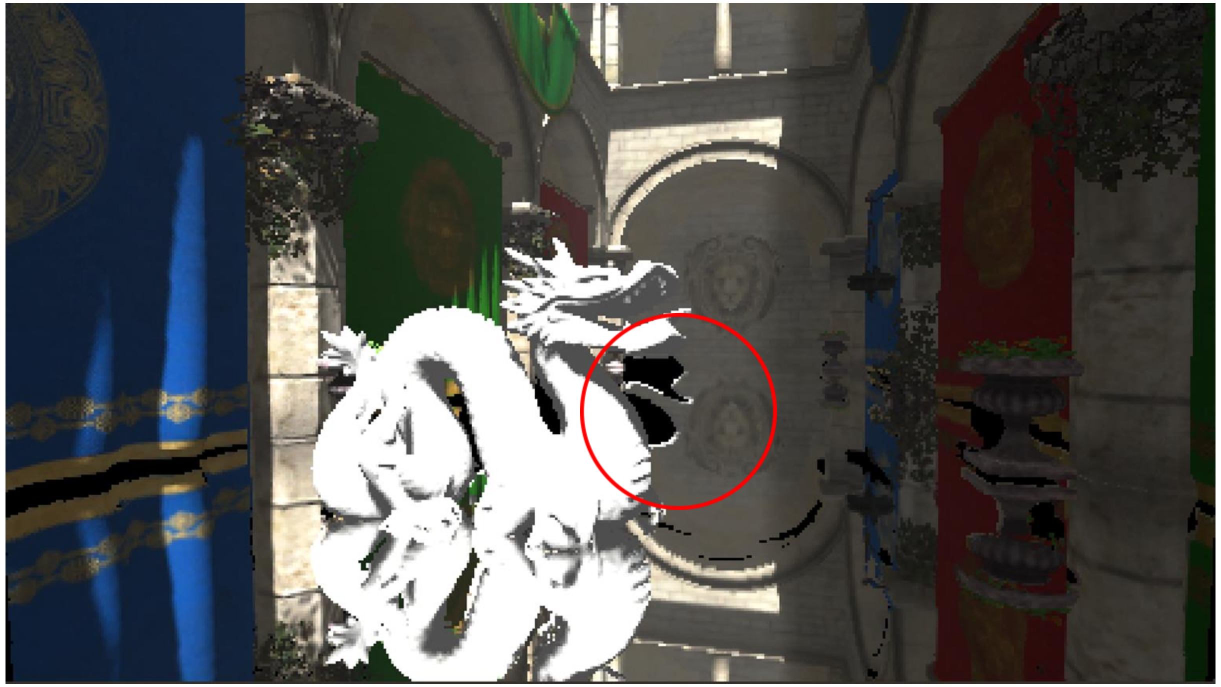
Filtering

- Filtered color sampling
- Make use of fixed point fractions encoded in the „intermediate buffer”



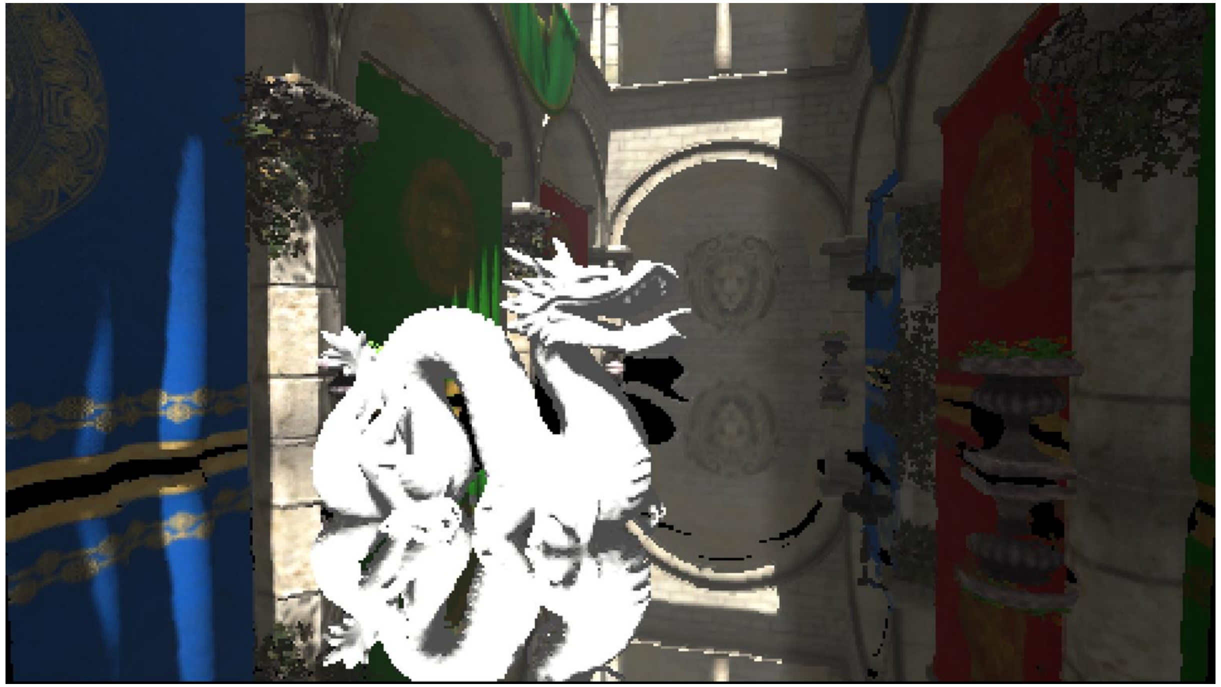
Color bleeding

- Filtered color sampling artifact
- Visible in high contrast areas
- Doesn't happen with non-filtered sampling



Color bleeding reduction

- Combine filtered and non-filtered samples
- Ensure combined result is close enough to non-filtered sample
- Hue and luminance handled separately [Karis14]

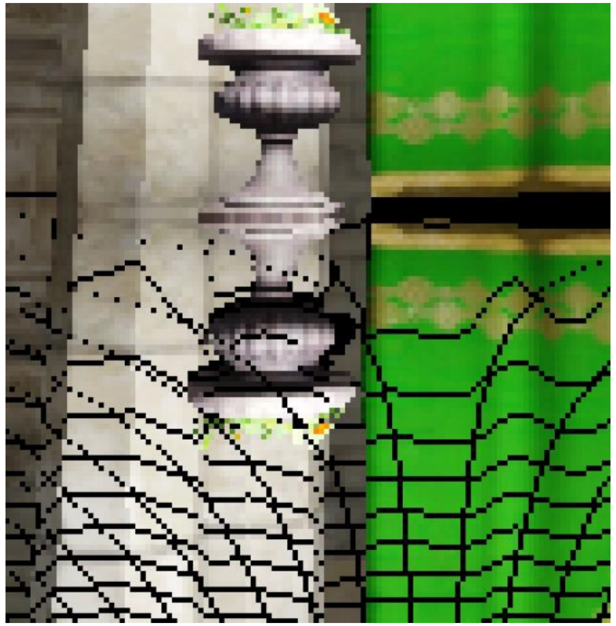


Reflection pass: step by step

- All steps are performed in a single shader execution

Reflection pass: step by step

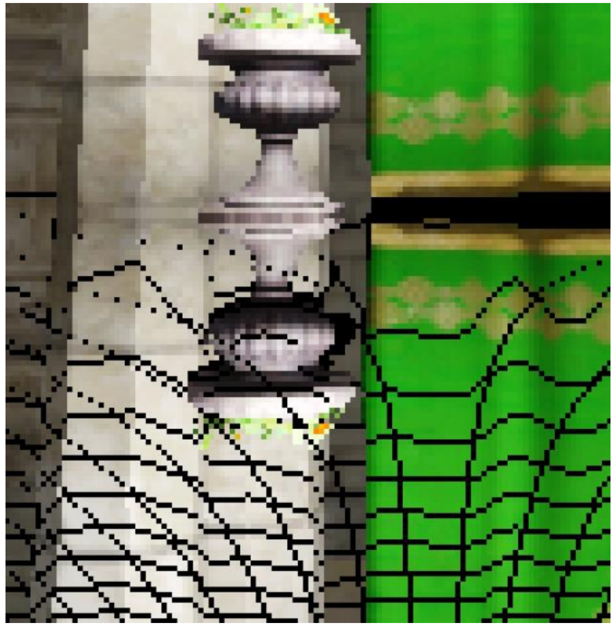
- All steps are performed in a single shader execution



Raw pixel-data

Reflection pass: step by step

- All steps are performed in a single shader execution

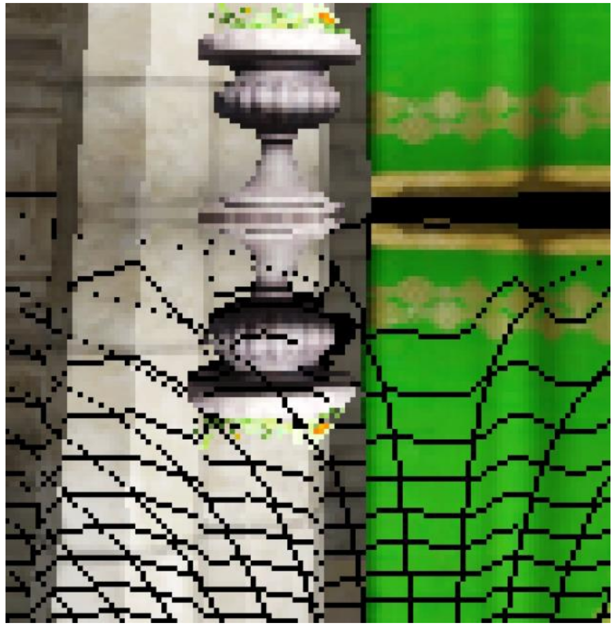


Raw pixel-data

Holes filling

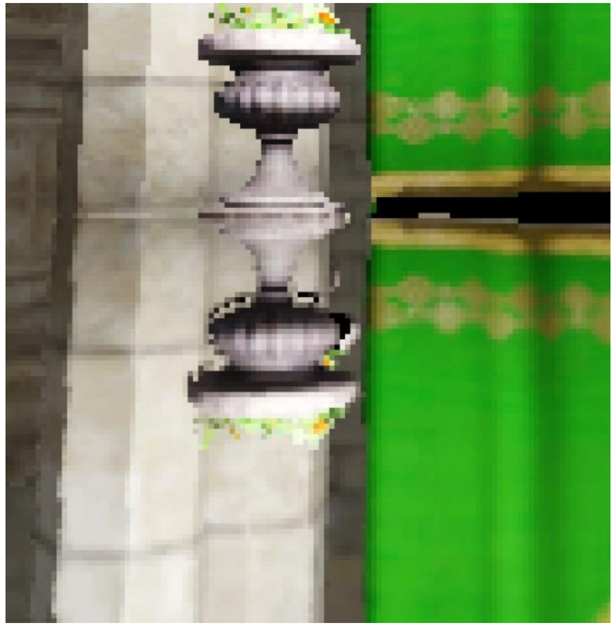
Reflection pass: step by step

- All steps are performed in a single shader execution



Raw pixel-data

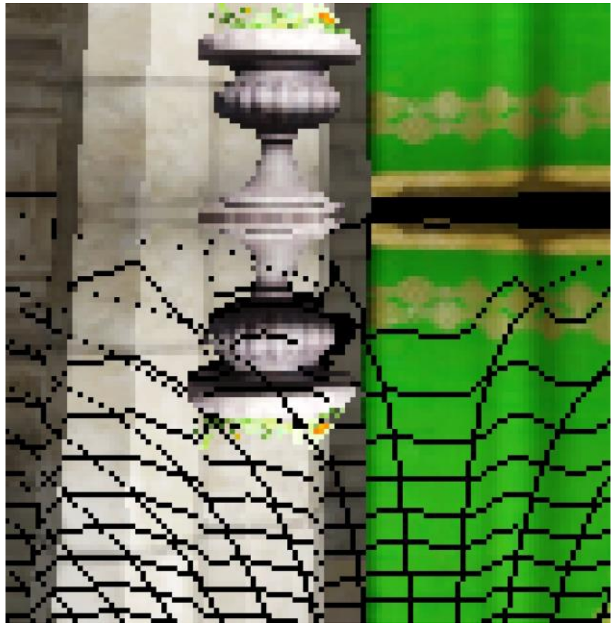
Holes filling



Filtering

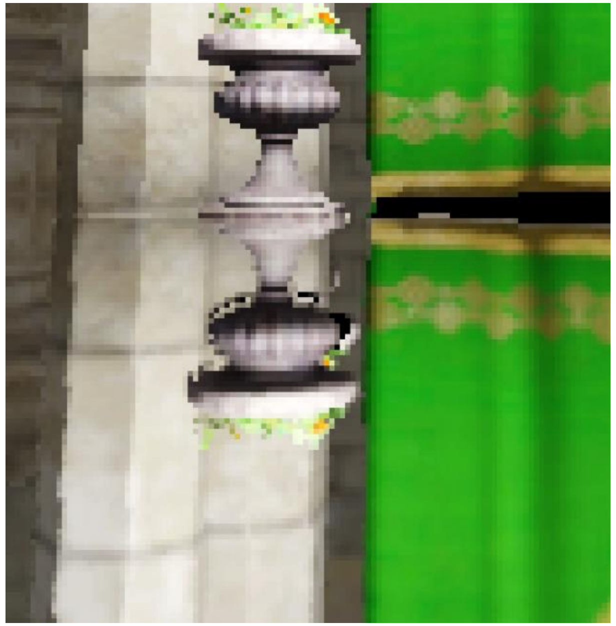
Reflection pass: step by step

- All steps are performed in a single shader execution

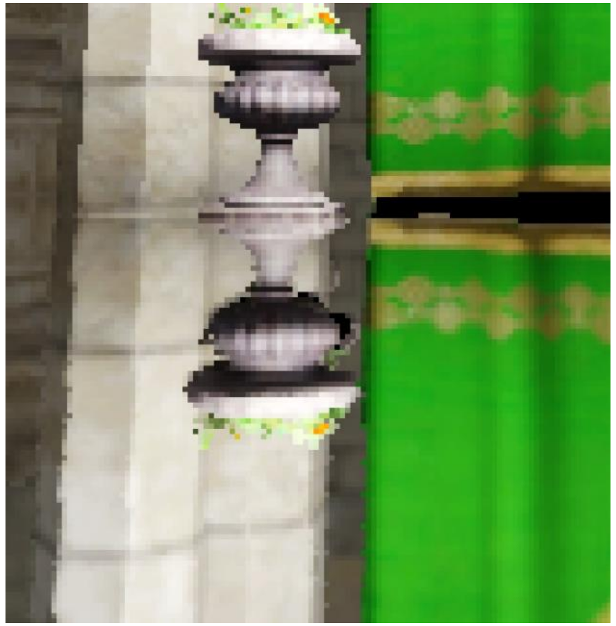


Raw pixel-data

Holes filling



Filtering



Anti-bleeding

Reflection pass: step by step

- Magnified images

Raw pixel-data

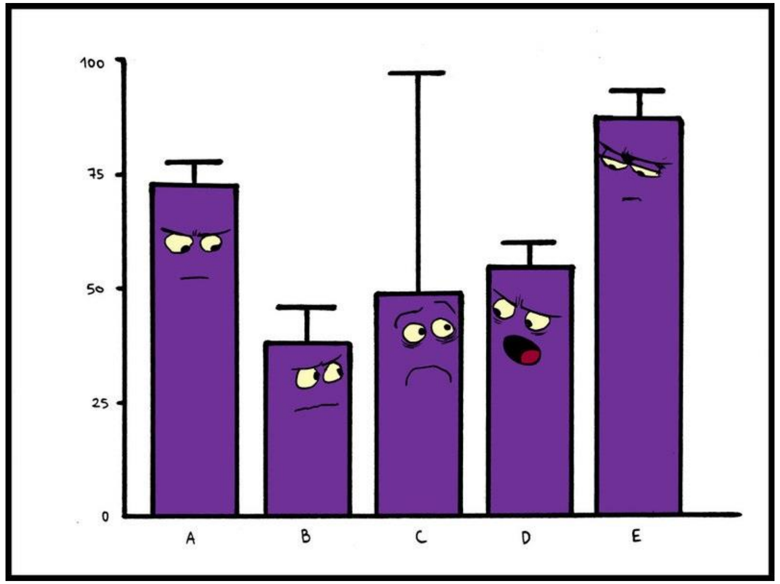
Holes filling

Filtering

Anti-bleeding

Performance and quality

- Comparison of selected techniques
- Measured on nVidia GTX 1070
- 4K resolution (3840x2160)
- Full resolution reflection



Performance and quality: Techniques

Brute force SSR [McGuire14]

- pixel granularity

Low quality SSR [McGuire14]

- skip every 64 pixels
- binary refinement

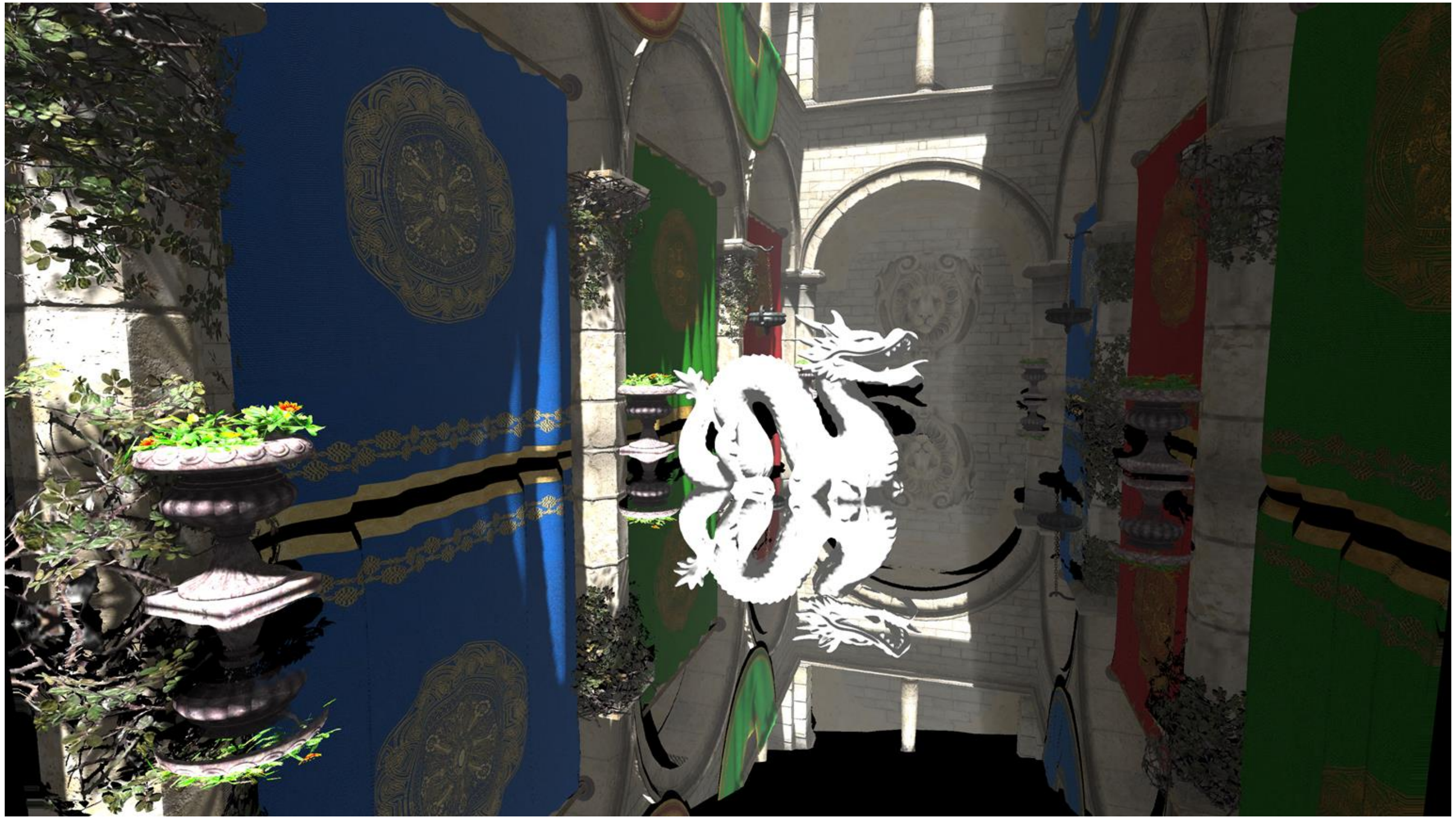
Hierarchical depth SSR [Uludag14]

- no tracing behind geometry implemented
- on the other hand that makes it cheaper

Pixel-projected reflections

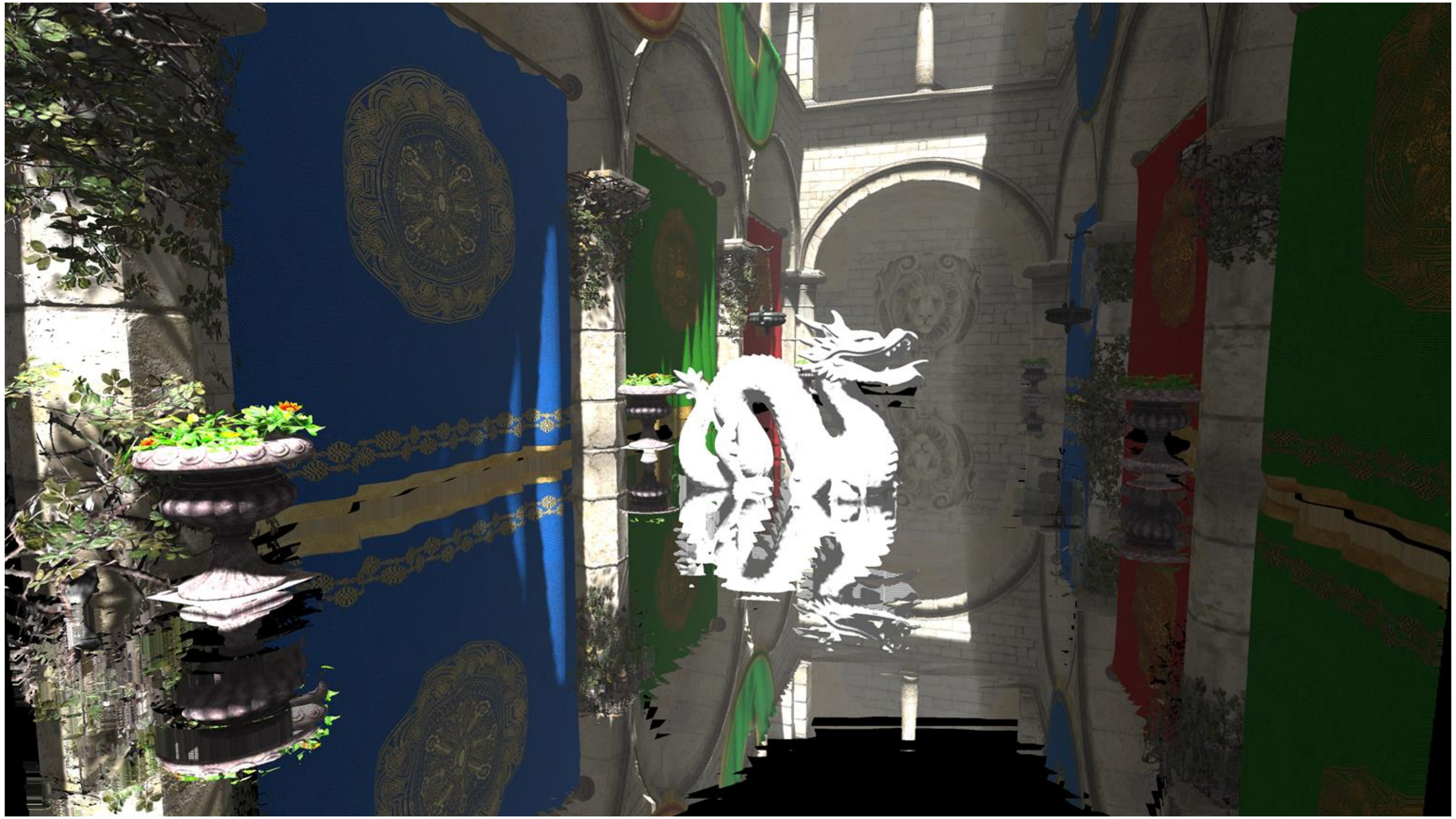
- presented technique

Performance and quality: Brute force SSR



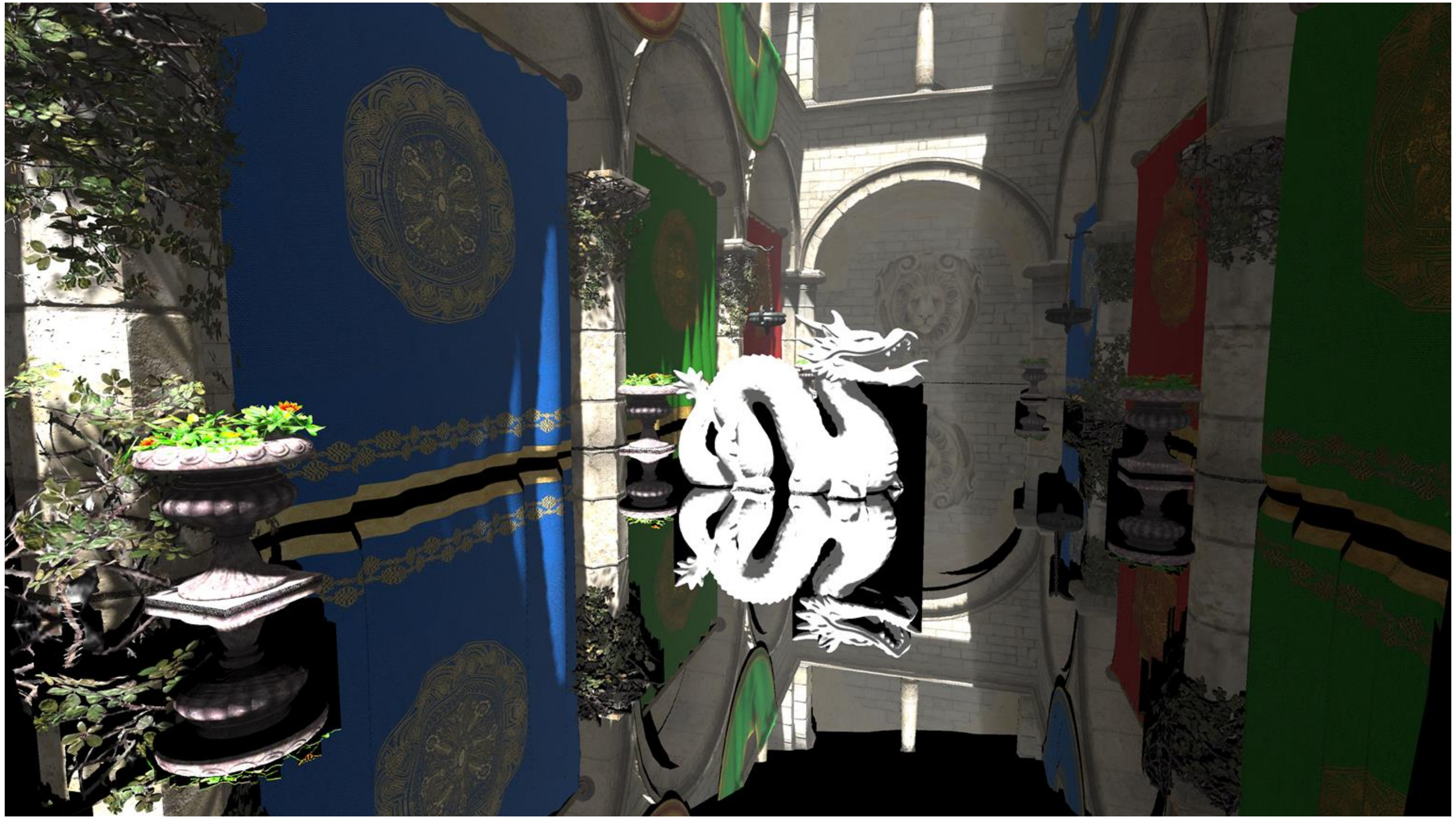
20,6 ms

Performance and quality: Low quality SSR



0.95 ms

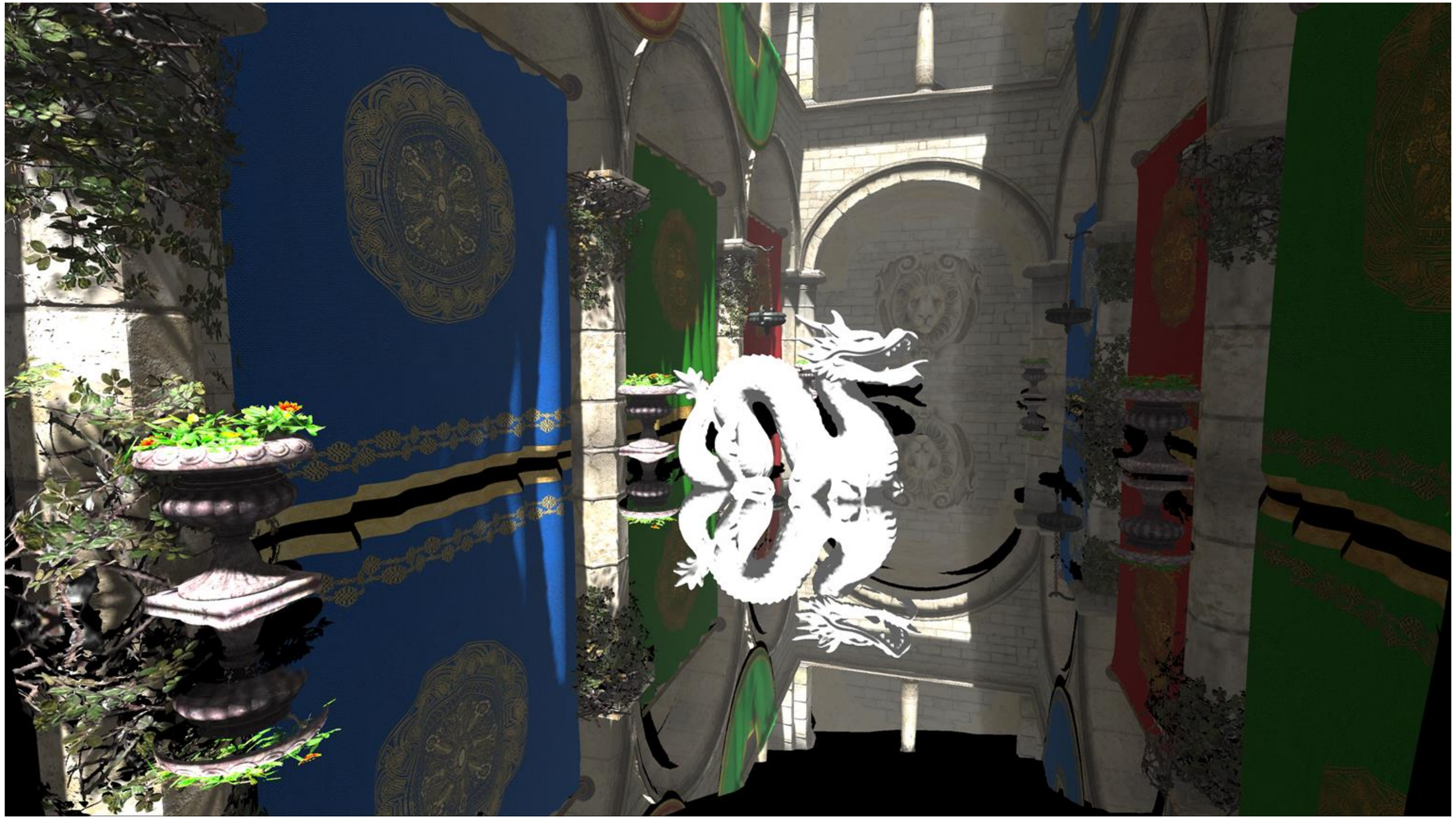
Performance and quality: Hierarchical depth SSR



3.2 ms

(+0.35ms for hiZ generation)

Performance and quality: Pixel-projected reflections



0.95 ms

Make sure to see „Bonus slides”!

Summary

- Simple technique
- Easy to integrate
- High quality / cost ratio
- More limited than SSR
- Can be selectively used where applicable

Special thanks

- Natalya Tatarchuk
- Michał Iwanicki
- Tomasz Jonarski
- Havok Germany team

Thank you!

References

- **[McGuire14] Morgan McGuire**, **Michael Mara** "Efficient GPU Screen-Space Ray Tracing“
  http://jcgt.org/published/0003/04/04
- **[Wronski14] Bart Wronski** "The future of screenspace reflections“
  https://bartwronski.com/2014/01/25/the-future-of-screenspace-reflections/
- **[Stachowiak15] Tomasz Stachowiak**, **Yasin Uludag** "Stochastic Screen-Space Reflections“
  http://advances.realtimerendering.com/s2015/
- **[Giacaone16] Michele Giacalone** "Screen Space Reflections in The Surge“
  https://www.slideshare.net/MicheleGiacalone1/screen-space-reflections-in-the-surge
- **[Valient13] Michal Valient** “Killzone Shadow Fall Demo Postmortem”
  http://www.guerrilla-games.com/presentations/Valient_Killzone_Shadow_Fall_Demo_Postmortem.html
- **[Karis14] Brian Karis** "High-quality Temporal Supersampling"
  http://advances.realtimerendering.com/s2014/
- **[Uludag14] Yasin Uludag** "Hi-Z Screen-Space Cone-Traced Reflections“
  GPU Pro 5

Content credits

- Stanford Dragon:
  - Stanford 3D Scanning Repository

- Atrium Sponza Palace:
  - Marko Dabrovic
  - Frank Meinl
  - Morgan McGuire
  - Alexandre Pestana
  - Crytek

Bonus slides

Previous work

- Just a quick memory refresher
- Screen space techniques only
- Sharp reflections only

Previous work: Basic raymarching

- Calculate reflection vector in screen space (3D)
- Sample depth buffer along this vector
- Four samples per loop iteration
- Stop if current tap behind depth buffer
- Sample color buffer with last tap coordinates
- Thickness value to raymarch behind geometry
- Very slow at pixel granularity
- [McGuire14]

Previous work: Basic optimization

- Sample every n-th pixel
- Lower depth resolution

  (we're skipping pixels anyway)
- Reversed 16bit float depth buffer
- Heavy banding
- [McGuire14]

Previous work: Binary search refinement

- Obtain reflection coordinate through raymarching
- Binary search around last step segment
- Only a few refinement taps needed
- Good if reflecting flat geometry
- Bad if reflecting depth discontinuity
- Simple and fast
- [McGuire14]

Previous work: Dithered raymarching

- Per pixel noise
- Bayer pattern works well
- Offset samples by noise * stepSize
- No banding, but reflections noisy
- Smooth with temporal filter and animated noise
- Binary search refinement to reduce bluriness
- Lowered memory coherence
- Deinterleaving possible
- [Giacaone16]

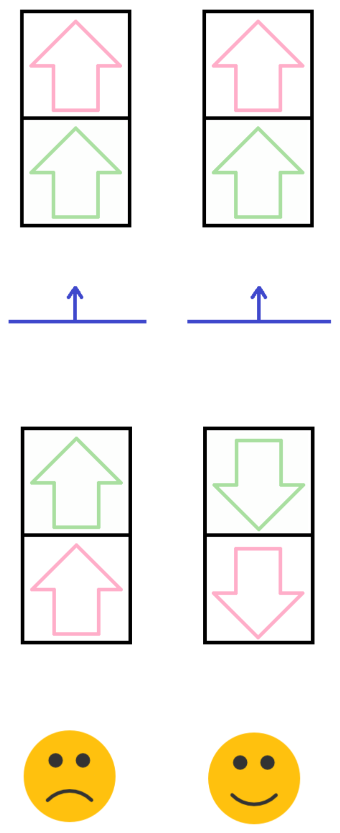
no temporal filter

Previous work: Hierarchical raymarching

- Optimized search
- Per-pixel granularity result
- Needs hierarchical depth buffer (hi-Z)
- Traverse hi-Z mipchain during raymarching
- Step size based on current mip level
- Power of two hi-Z for simpler shader
- Don't bother with full mip chain
- [Uludag14]

Offset fractions mirroring

- Filtered reflections 'shake' under motion, because pixel-data is stored in a pixel grid
- Offset fractions need to be flipped
- Flip fractions along offset direction
- XY coordinates in screen-space (2D)
- Performed in „projection pass”
- Solves the shakiness

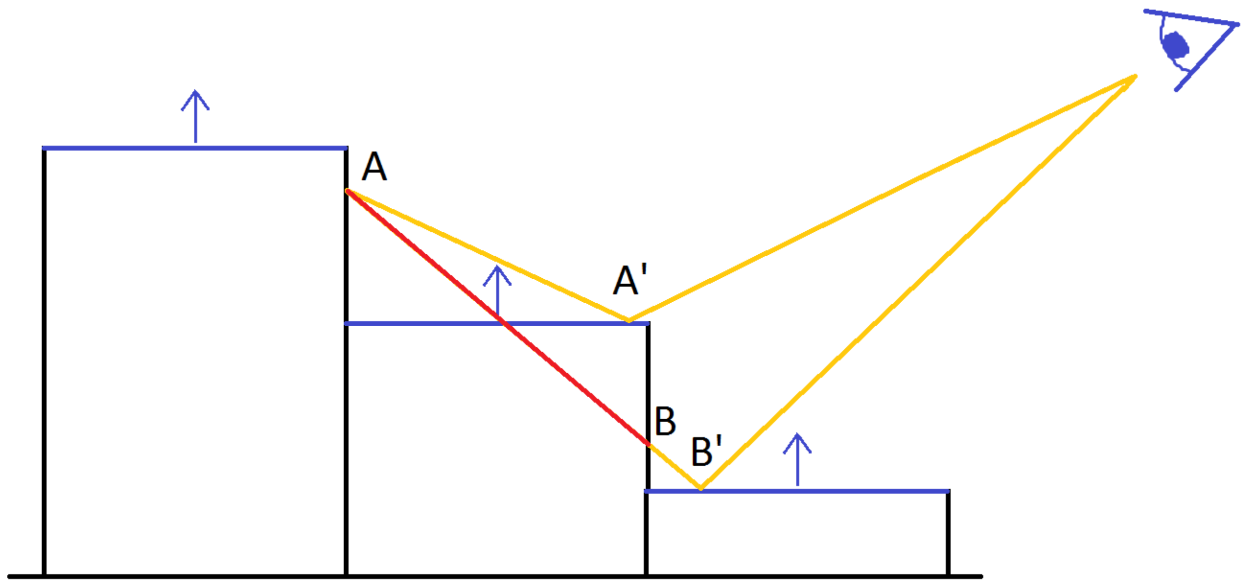


Multiple parallel shapes

- Find shapes that reflect given pixel
- Write offsets projected onto selected shape

Multiple parallel shapes

- Example: stairway with mirror steps
- All steps share the same normal
- Every pixel reflected at most once
- „Intermediate buffer” written at most once per pixel



Multiple parallel shapes

- Ignore shapes for which pixel is below shape’s plane
- Ignore shapes not reflecting the pixel (mirrored bounds test)
- Pick shape with smallest plane → pixel distance
- „Intermediate buffer” written at most once

Multiple parallel shapes

- Simple with a few shapes (just iterate over them)
- Large amounts need preselection (otherwise heavy)
- Multiple solutions:
  - preselection in „projection pass”
  - world space grid shape lists
  - froxel based shape lists
  - BVH lists
  - etc.

Multiple parallel shapes

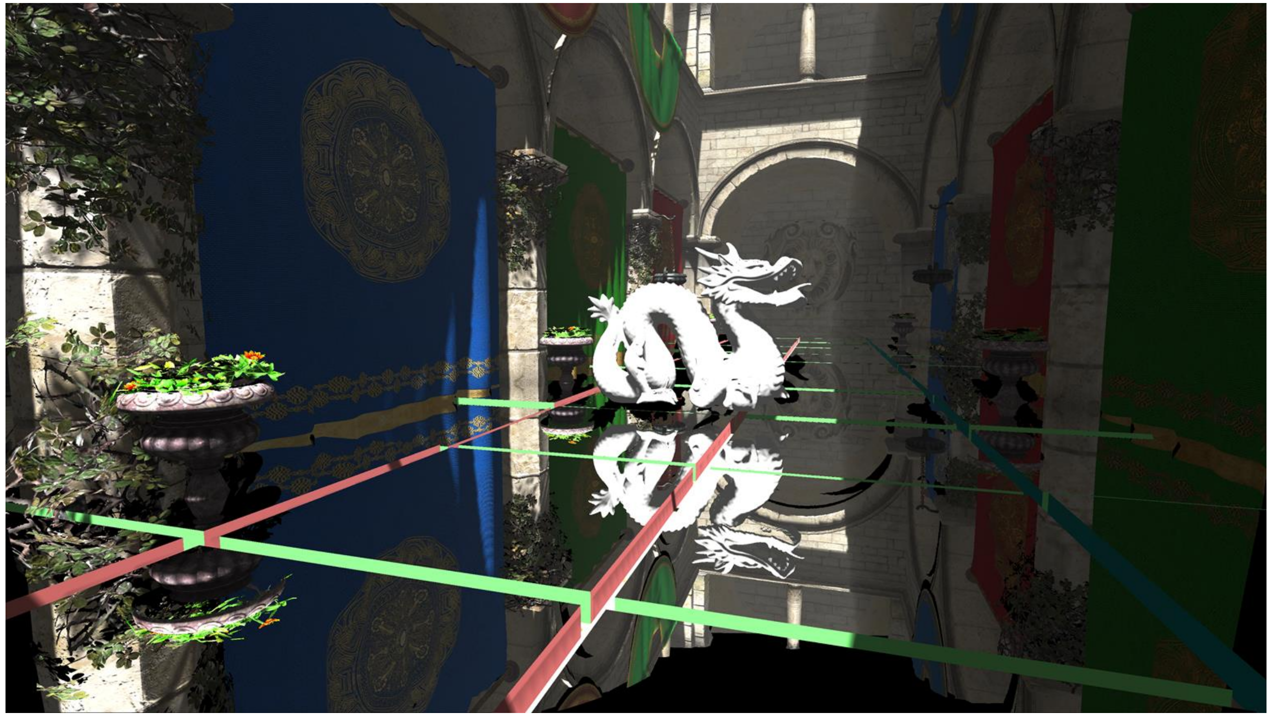
GPU based approach:

- Integrated into „projection pass”
- Build thread-group tile world space bounds
- Build per-tile shapes list in groupshared memory
  - every thread is processing one shape
  - project tile world space bounds to screen space
  - test against shape bounds
  - append to shared list (test positive)
- Pick best shape from global list
- Proceed as in single shape case

Multiple parallel shapes

GPU based approach:

- test case similar to other measurments
- 0.5 ms overhead



Transparent reflectors

- Glass panels, windows
- Barely used in games
- High cost because of raymarching
- Much cheaper with „Pixel-projected reflections”

Transparent reflectors

- Additional „intermediate buffer” (atlas)
- For every glass panel:
  - calculate screen bounds
  - allocate region in atlas
  - use atlas as „intermediate buffer”
  - write pixel-data to allocated atlas region
- Fetch atlas while rendering glass panels

Transparent reflectors

Normalmaps

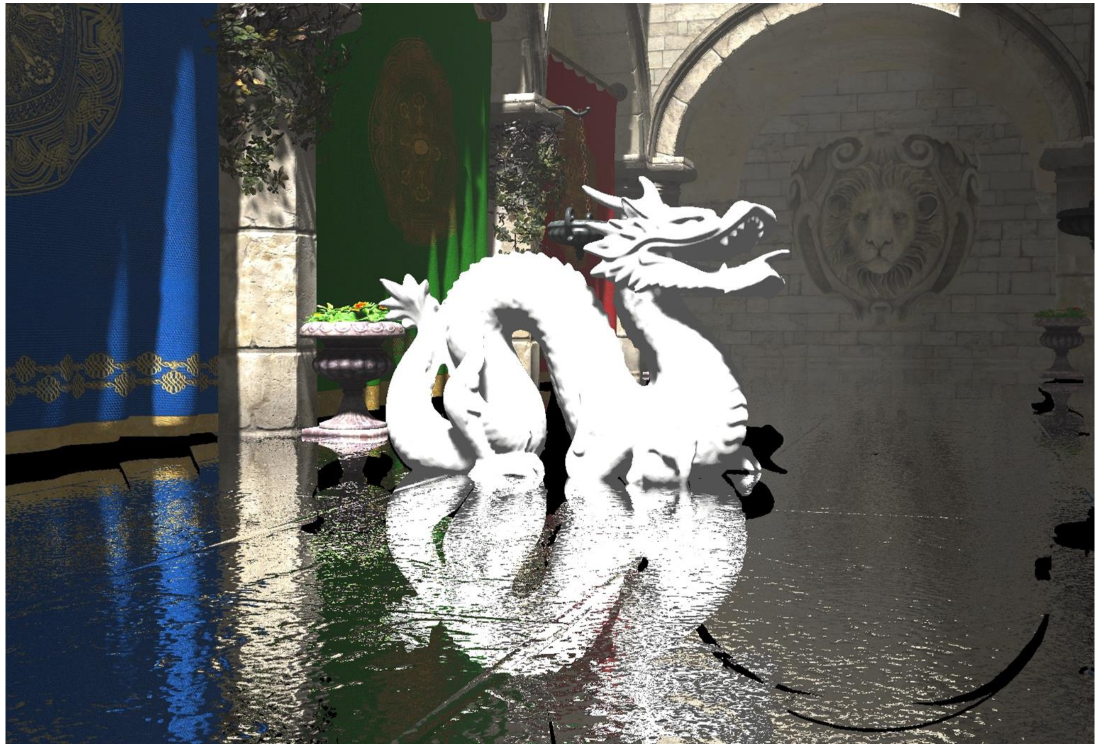
- Approximation
- Integrated into „reflection pass”
- Calculate normalmap based reflected direction
- Scale by flat reflection distance
- Add to world space position
- Project to screen-space
- Fetch color buffer

Normalmaps

- Problem: Disocclusion
- Noticeable on depth discontinuities
- Samples closer than approximated reflection

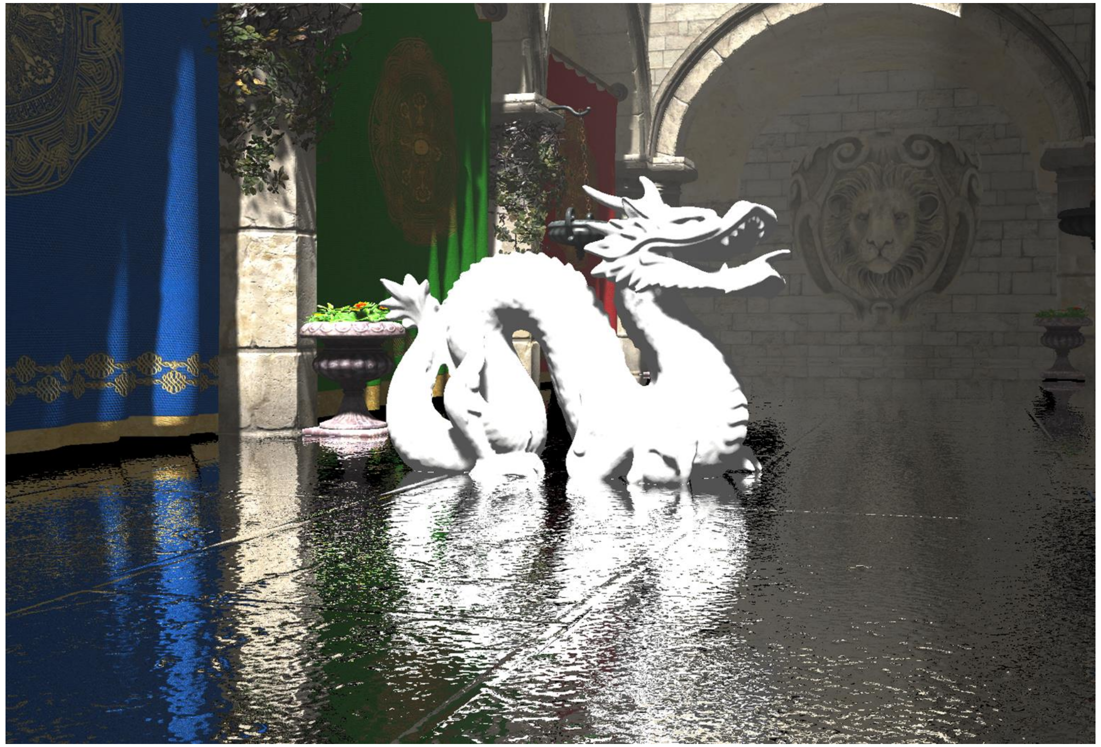
Normalmaps

- Solution: Raymarching (4 taps) toward reflecting pixel
- Accept sample if closer than depth buffer value
- Fallback to flat reflection if no sample found



Normalmaps

- Ground truth reference
- Raymarched reflection against normalmap
- Better quality on depth discontinuities



Shader code

```
// Constants for 'intermediate buffer' values encoding.
// Lowest two bits reserved for coordinate system index.
#define PPR_CLEAR_VALUE                        (0xffffffff)
#define PPR_PREDICTED_DIST_MULTIPLIER          (8)
#define PPR_PREDICTED_OFFSET_RANGE_X           (2048)
#define PPR_PREDICTED_DIST_OFFSET_X            (PPR_PREDICTED_OFFSET_RANGE_X)
#define PPR_PREDICTED_DIST_OFFSET_Y            (0)

// Calculate coordinate system index based on offset
uint PPR_GetPackingBasisIndexTwoBits( const float2 offset )
{
    if ( abs(offset.x) >= abs(offset.y) )
        return offset.x >= 0 ? 0 : 1;
    return offset.y >= 0 ? 2 : 3;
}

// Decode coordinate system based on encoded coordSystem index
float2x2 PPR_DecodePackingBasisIndexTwoBits( uint packingBasisIndex )
{
    float2 basis = 0;
    packingBasisIndex &= 3;
    basis.x += 0 == packingBasisIndex ?  1 : 0;
    basis.x += 1 == packingBasisIndex ? -1 : 0;
    basis.y += 2 == packingBasisIndex ?  1 : 0;
    basis.y += 3 == packingBasisIndex ? -1 : 0;
    return float2x2( float2( basis.y, -basis.x ), basis.xy );
}
```

Shader code

```
// Pack integer and fract offset value
uint PPR_PackValue( const float _whole, float _fract, const bool isY )
{
    uint result = 0;

    // pack whole part
    result += (uint)(_whole + (isY ? PPR_PREDICTED_DIST_OFFSET_Y : PPR_PREDICTED_DIST_OFFSET_X));
    result *= PPR_PREDICTED_DIST_MULTIPLIER;

    // pack fract part
    _fract *= PPR_PREDICTED_DIST_MULTIPLIER;
    result += (uint)min( floor( _fract + 0.5 ), PPR_PREDICTED_DIST_MULTIPLIER - 1 );

    //
    return result;
}

// Unpack integer and fract offset value
float2 PPR_UnpackValue( uint v, const bool isY )
{
    // unpack fract part
    float _fract = (v % PPR_PREDICTED_DIST_MULTIPLIER + 0.5) / float(PPR_PREDICTED_DIST_MULTIPLIER) - 0.5;
    v /= PPR_PREDICTED_DIST_MULTIPLIER;

    // unpack whole part
    float _whole = int(v) - (isY ? PPR_PREDICTED_DIST_OFFSET_Y : PPR_PREDICTED_DIST_OFFSET_X);

    //
    return float2( _whole, _fract );
}
```

Shader code

```
// Encode offset for 'intermediate buffer' storage
uint PPR_EncodeIntermediateBufferValue( const float2 offset )
{
    // build snapped basis
    const uint packingBasisIndex = PPR_GetPackingBasisIndexTwoBits( offset );
    const float2x2 packingBasisSnappedMatrix = PPR_DecodePackingBasisIndexTwoBits( packingBasisIndex );

    // decompose offset to _whole and _fract parts
    float2 _whole = floor(offset + 0.5);
    float2 _fract = offset - _whole;

    // mirror _fract part to avoid filtered result 'swimming' under motion
    const float2 dir = normalize( offset );
    _fract -= 2 * dir * dot( dir, _fract );

    // transform both parts to snapped basis
    _whole = mul( packingBasisSnappedMatrix, _whole );
    _fract = mul( packingBasisSnappedMatrix, _fract );

    // put _fract part in 0..1 range
    _fract *= 0.707;
    _fract += 0.5;

    // encode result
    uint result = 0;
    result += PPR_PackValue( _whole.y, _fract.y, true );
    result *= 2 * PPR_PREDICTED_OFFSET_RANGE_X * PPR_PREDICTED_DIST_MULTIPLIER;
    result += PPR_PackValue( _whole.x, _fract.x, false );
    result *= 4;
    result += packingBasisIndex;

    //
    return result;
}
```

Shader code

```
// Decode value read from 'intermediate buffer'
void PPR_DecodeIntermediateBufferValue( uint value, out float2 distFilteredWhole, out float2 distFilteredFract, out float2x2 packingBasis )
{
    distFilteredWhole = 0;
    distFilteredFract = 0;
    packingBasis = float4( 1, 0, 0, 1 );
    if ( value != PPR_CLEAR_VALUE )
    {
        const uint settFullValueRange = 2 * PPR_PREDICTED_OFFSET_RANGE_X * PPR_PREDICTED_DIST_MULTIPLIER;

        // decode packing basis
        packingBasis = PPR_DecodePackingBasisIndexTwoBits( value );
        value /= 4;

        // decode offsets along (y) and perpendicular (x) to snapped basis
        float2 x = PPR_UnpackValue( value & (settFullValueRange - 1), false );
        float2 y = PPR_UnpackValue( value / settFullValueRange, true );

        // output result
        distFilteredWhole = float2( x.x, y.x );
        distFilteredFract = float2( x.y, y.y );
        distFilteredFract /= 0.707;
    }
}
```

Shader code

```
// Combine filtered and non-filtered color sample to prevent color-bleeding.
// Current implementation is rather naive and may result in distortion artifacts
// (created by holes-filling) to become visible again at some extent.
// Anti-bleeding solution might use some further research to reduce artifacts.
// Note that for high resolution reflections, filtering might be skipped, making
// anti-bleeding solution unneeded.
float3 PPR_FixColorBleeding( const float3 colorFiltered, const float3 colorUnfiltered )
{
    // transform color to YCoCg, normalize chrominance
    float3 ycocgFiltered = mul( RGB_to_YCoCg(), colorFiltered );
    float3 ycocgUnfiltered = mul( RGB_to_YCoCg(), colorUnfiltered );
    ycocgFiltered.yz /= max( 0.0001, ycocgFiltered.x );
    ycocgUnfiltered.yz /= max( 0.0001, ycocgUnfiltered.x );

    // calculate pixel sampling factors for luma/chroma separately
    float lumaPixelSamplingFactor = saturate( 3.0 * abs(ycocgFiltered.x - ycocgUnfiltered.x) );
    float chromaPixelSamplingFactor = saturate( 1.4 * length(ycocgFiltered.yz - ycocgUnfiltered.yz) );

    // build result color YCoCg space
    // interpolate between filtered and nonFiltered colors (luma/chroma separately)
    float  resultY = lerp( ycocgFiltered.x, ycocgUnfiltered.x, lumaPixelSamplingFactor );
    float2 resultCoCg = lerp( ycocgFiltered.yz, ycocgUnfiltered.yz, chromaPixelSamplingFactor );
    float3 ycocgResult = float3( resultY, resultCoCg * resultY );

    // transform color back to RGB space
    return mul( YCoCg_to_RGB(), ycocgResult );
}
```

Shader code

```
// Write projection to 'intermediate buffer'.
// Pixel projected from 'originalPixelVpos' to 'mirroredWorldPos'.
// Function called in 'projectio pass' after ensuring that pixel projected into given
// place of the shape is not occluded by any other shape.
void PPR_ProjectionPassWrite( SSharedConstants globalConstants, RWStructuredBuffer<uint> uavIntermediateBuffer, const int2 originalPixelVpos, const float3 mirroredWorldPos )
{
    const float4 projPosOrig = mul( float4( mirroredWorldPos, 1 ), globalConstants.worldToScreen );
    const float4 projPos = projPosOrig / projPosOrig.w;

    if ( all( abs(projPos.xy) < 1 ) )
    {
        const float2 targetCrd = (projPos.xy * float2(0.5,-0.5) + 0.5) * globalConstants.resolution.xy;
        const float2 offset = targetCrd - (originalPixelVpos + 0.5);
        const uint writeOffset = uint(targetCrd.x) + uint(targetCrd.y) * uint(globalConstants.resolution.x);

        uint originalValue = 0;
        uint valueToWrite = PPR_EncodeIntermediateBufferValue( offset );
        InterlockedMin( uavIntermediateBuffer[ writeOffset ], valueToWrite, originalValue );
    }
}
```

Shader code

```
// 'Reflection pass' implementation.
float4 PPR_ReflectionPass(
    SSharedConstants globalConstants, const int2 vpos, StructuredBuffer<uint> srvIntermediateBuffer, Texture2D srvColor, SamplerState smpLinear,
    SamplerState smpPoint, const bool enableHolesFilling, const bool enableFiltering, const bool enableFilterBleedingReduction )
{
    int2 vposread = vpos;

    // perform holes filling.
    // If we're dealing with a hole then find a closeby pixel that will be used
    // to fill the hole. In order to do this simply manipulate variable so that
    // compute shader result would be similar to the neighbor result.
    float2 holesOffset = 0;
    if ( enableHolesFilling )
    {
        uint v0 = srvIntermediateBuffer[ vpos.x + vpos.y * int(globalConstants.resolution.x) ];
        {
            // read neighbors 'intermediate buffer' data
            const int2 holeOffset1 = int2( 1, 0 );
            const int2 holeOffset2 = int2( 0, 1 );
            const int2 holeOffset3 = int2( 1, 1 );
            const int2 holeOffset4 = int2(-1, 0 );
            const uint v1 = srvIntermediateBuffer[ (vpos.x + holeOffset1.x) + (vpos.y + holeOffset1.y) * int(globalConstants.resolution.x) ];
            const uint v2 = srvIntermediateBuffer[ (vpos.x + holeOffset2.x) + (vpos.y + holeOffset2.y) * int(globalConstants.resolution.x) ];
            const uint v3 = srvIntermediateBuffer[ (vpos.x + holeOffset3.x) + (vpos.y + holeOffset3.y) * int(globalConstants.resolution.x) ];
            const uint v4 = srvIntermediateBuffer[ (vpos.x + holeOffset4.x) + (vpos.y + holeOffset4.y) * int(globalConstants.resolution.x) ];

            // get neighbor closest reflection distance
            const uint minv = min( min( min( v0, v1 ), min( v2, v3 ) ), v4 );
```

// next slide

Shader code

```
// previous slide

            // allow hole fill if we don't have any 'intermediate buffer' data for current pixel,
            // or any neighbor has reflecion significantly closer than current pixel's reflection
            bool allowHoleFill = true;
            if ( PPR_CLEAR_VALUE != v0 )
            {
                float2 d0_filtered_whole;
                float2 d0_filtered_fract;
                float2x2 d0_packingBasis;
                float2 dmin_filtered_whole;
                float2 dmin_filtered_fract;
                float2x2 dmin_packingBasis;
                PPR_DecodeIntermediateBufferValue( v0, d0_filtered_whole, d0_filtered_fract, d0_packingBasis );
                PPR_DecodeIntermediateBufferValue( minv, dmin_filtered_whole, dmin_filtered_fract, dmin_packingBasis );

                float2 d0_offset = mul( d0_filtered_whole + d0_filtered_fract, d0_packingBasis );
                float2 dmin_offset = mul( dmin_filtered_whole + dmin_filtered_fract, dmin_packingBasis );
                float2 diff = d0_offset - dmin_offset;
                const float minDist = 6;
                allowHoleFill = dot( diff, diff ) > minDist * minDist;
            }

            // hole fill allowed, so apply selected neighbor's parameters
            if ( allowHoleFill )
            {
                if ( minv == v1 ) vposread = vpos + holeOffset1;
                if ( minv == v2 ) vposread = vpos + holeOffset2;
                if ( minv == v3 ) vposread = vpos + holeOffset3;
                if ( minv == v4 ) vposread = vpos + holeOffset4;
                holesOffset = vposread - vpos;
            }
        }
    }

// next slide
```

Shader code

```
// previous slide

    // obtain offsets for filtered and non-filtered samples
    float2 predictedDist = 0;
    float2 predictedDistUnfiltered = 0;
    {
        uint v0 = srvIntermediateBuffer[ vposread.x + vposread.y * int(globalConstants.resolution.x) ];

        // decode offsets
        float2 decodedWhole;
        float2 decodedFract;
        float2x2 decodedPackingBasis;
        {
            PPR_DecodeIntermediateBufferValue( v0, decodedWhole, decodedFract, decodedPackingBasis );
            predictedDist = mul( decodedWhole + decodedFract, decodedPackingBasis );
            // fractional part ignored for unfiltered sample, as it could end up
            // sampling neighboring pixel in case of non axis aligned offsets.
            predictedDistUnfiltered = mul( decodedWhole, decodedPackingBasis );
        }

        // include holes offset in predicted offsets
        if ( PPR_CLEAR_VALUE != v0 )
        {
            const float2 dir = normalize( predictedDist );
            predictedDistUnfiltered -= float2( holesOffset.x, holesOffset.y );
            predictedDist -= 2 * dir * dot( dir, holesOffset );
        }
    }

    // exit if reflection offset not present
    if ( all( predictedDist == 0 ) )
    {
        return 0;
    }

// next slide
```

Shader code

```
// previous slide

    // sample filtered and non-filtered color
    const float2 targetCrd = vpos + 0.5 - predictedDist;
    const float2 targetCrdUnfiltered = vpos + 0.5 - predictedDistUnfiltered;
    const float3 colorFiltered = srvColor.SampleLevel( smpLinear, targetCrd * globalConstants.resolution.zw, 0 ).xyz;
    const float3 colorUnfiltered = srvColor.SampleLevel( smpPoint, targetCrdUnfiltered * globalConstants.resolution.zw, 0 ).xyz;

    // combine filtered and non-filtered colors
    float3 colorResult;
    if ( enableFiltering )
    {
        if ( enableFilterBleedingReduction )
        {
            colorResult = PPR_FixColorBleeding( colorFiltered, colorUnfiltered );
        }
        else
        {
            colorResult = colorFiltered;
        }
    }
    else
    {
        colorResult = colorUnfiltered;
    }

    //
    return float4( colorResult, 1 );
}
```

end of file