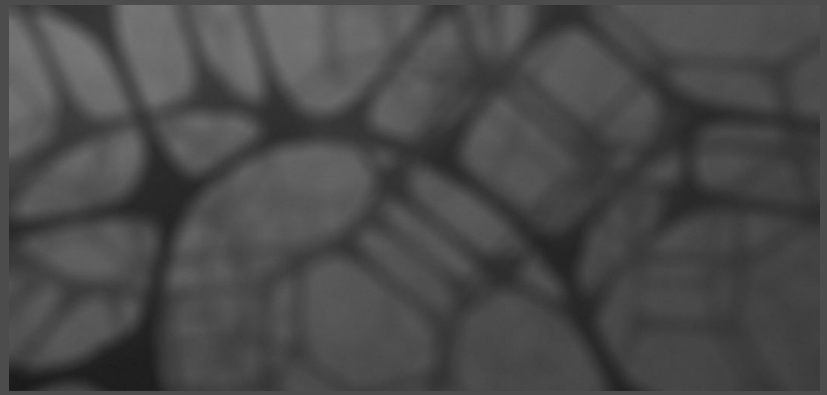
Conemarching in VR

Developing a Fractal experience at 90 FPS

Johannes Saam
Mariano Merchante

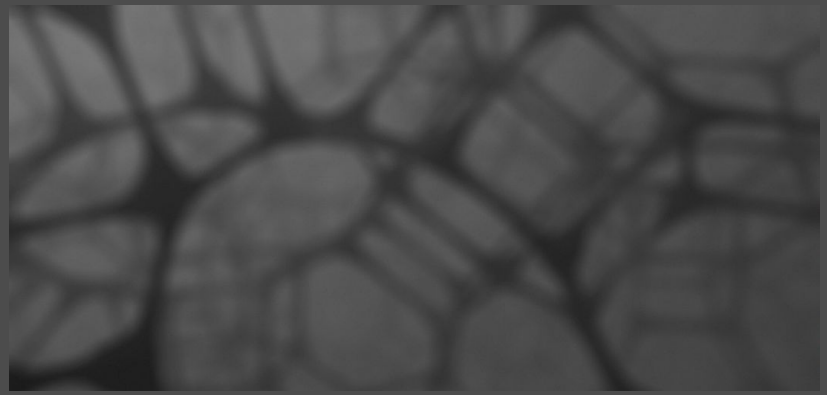
FRAMESTORE

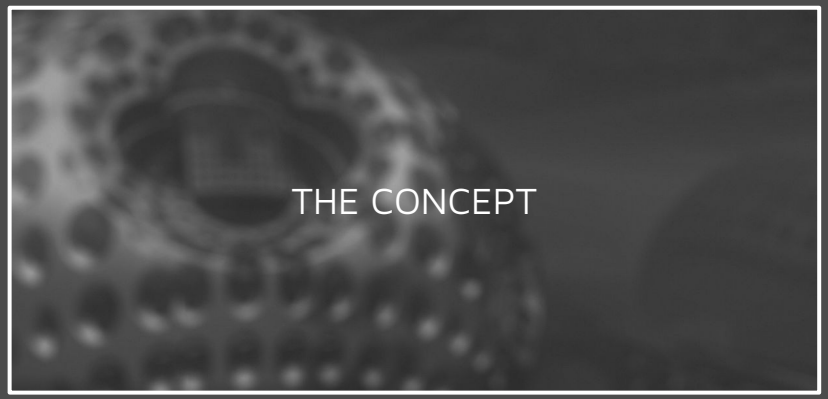
THE CONCEPT



THE CONCEPT

FRACTALS AND
COLLISIONS

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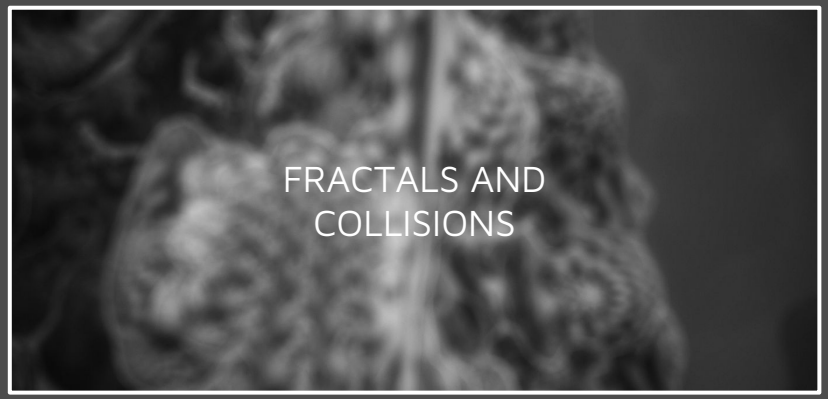
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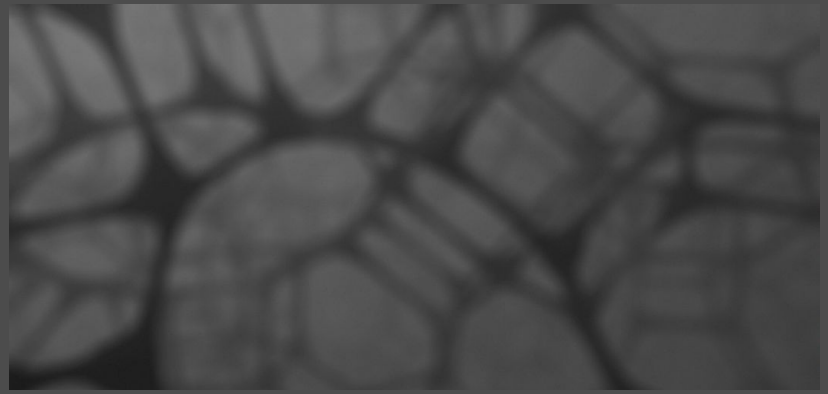
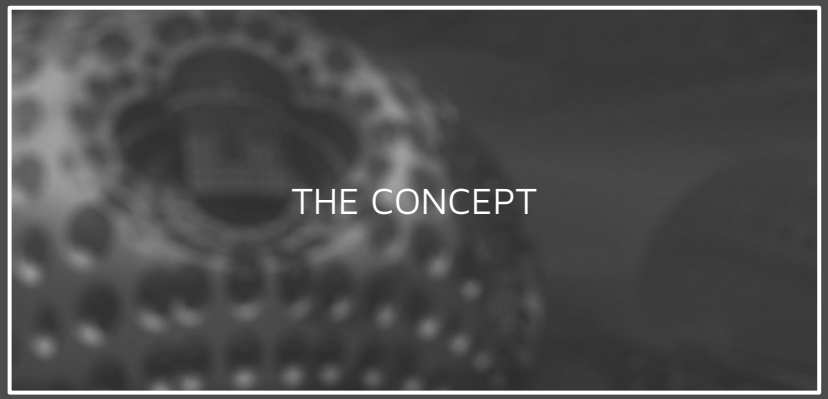
RAYMARCHING AND VR

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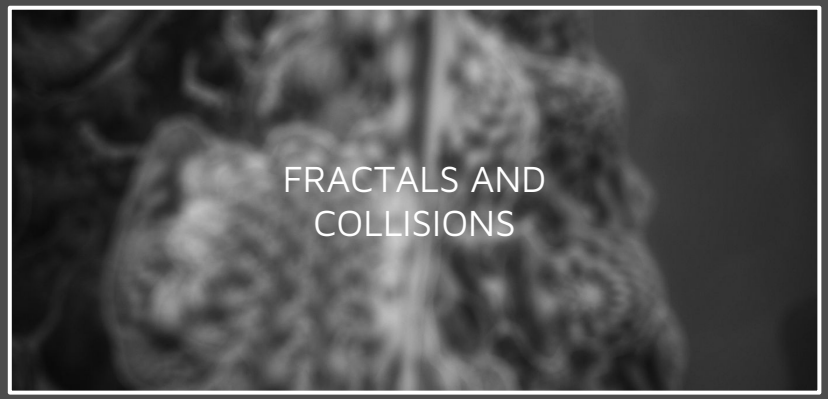
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THE SHADING CHALLENGE

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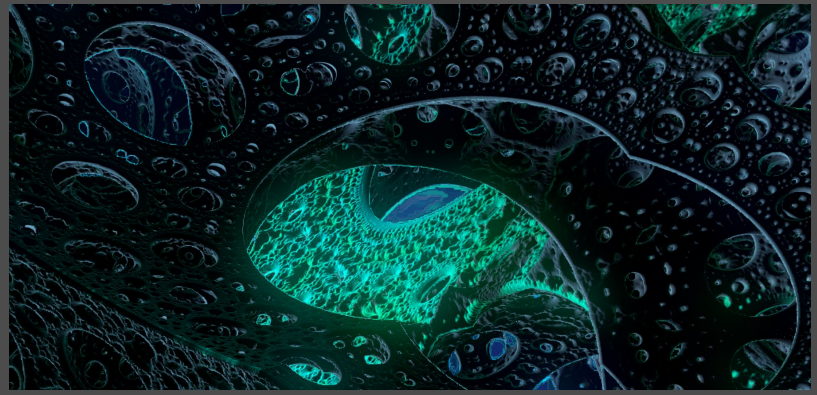

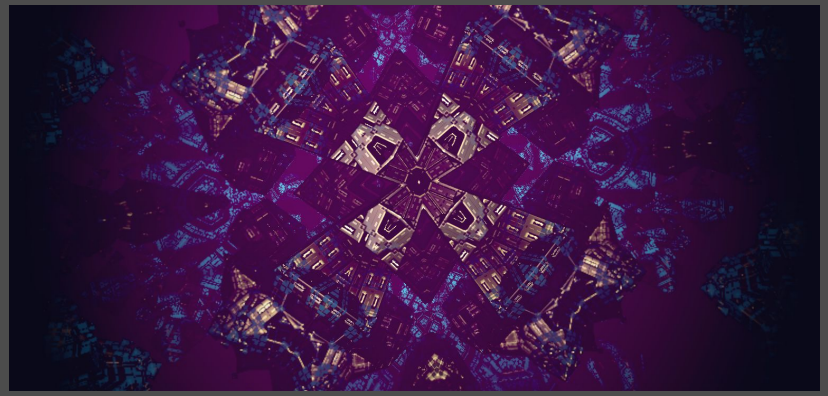

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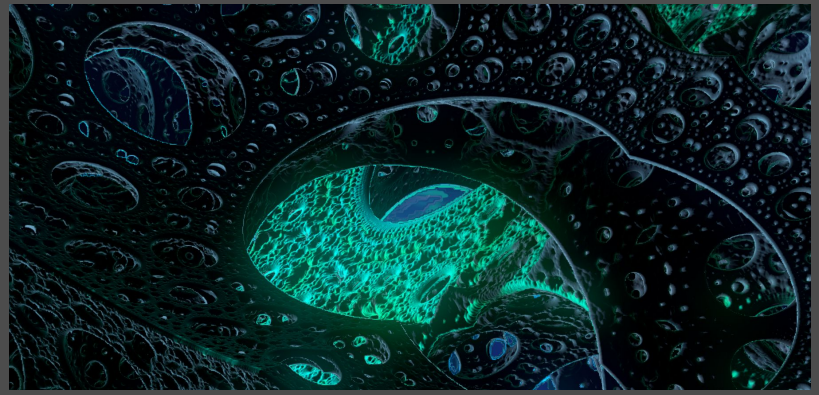

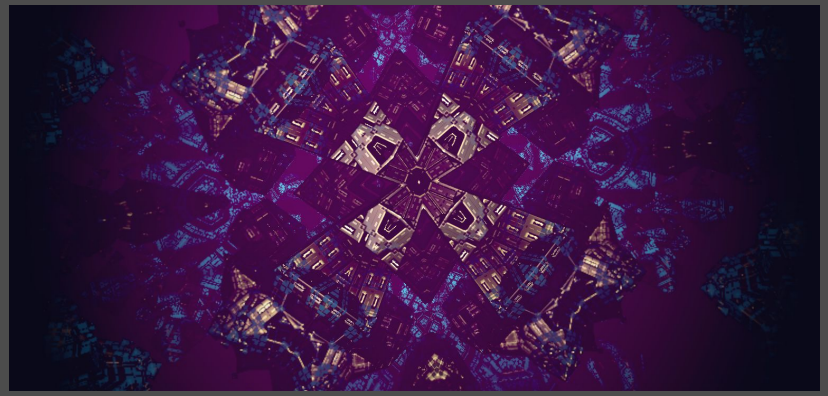

- Explore classic fractals in real-time VR
- Simple interaction model, sandbox feel
- Break a few rules!

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THE LOCOMOTION CHALLENGE

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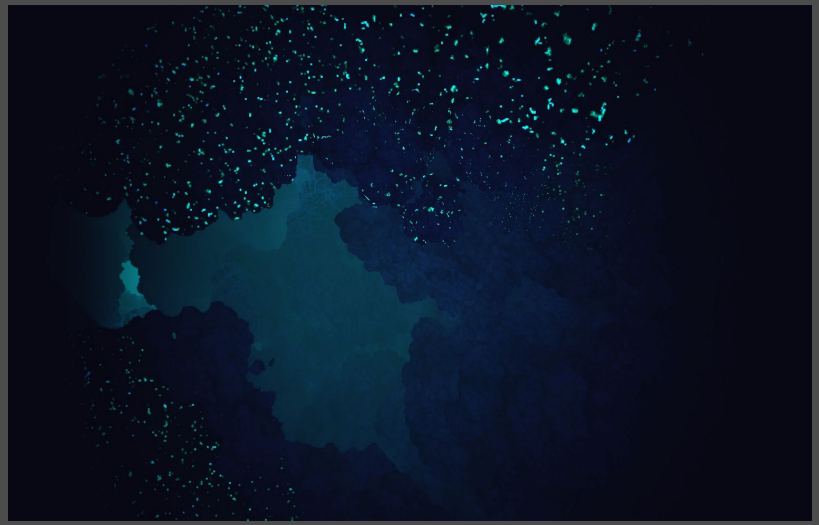

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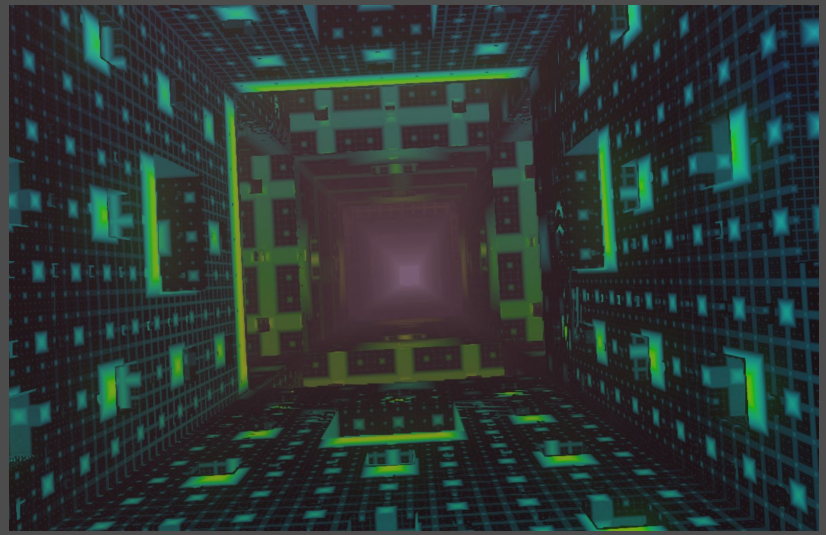

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- Make sure we smooth scale to prevent discontinuities
- Design shading such that there is enough size contrast
- Loop each fractal to emphasize the sense of infinity

- Always move in the direction of your head…

THE LOCOMOTION CHALLENGE

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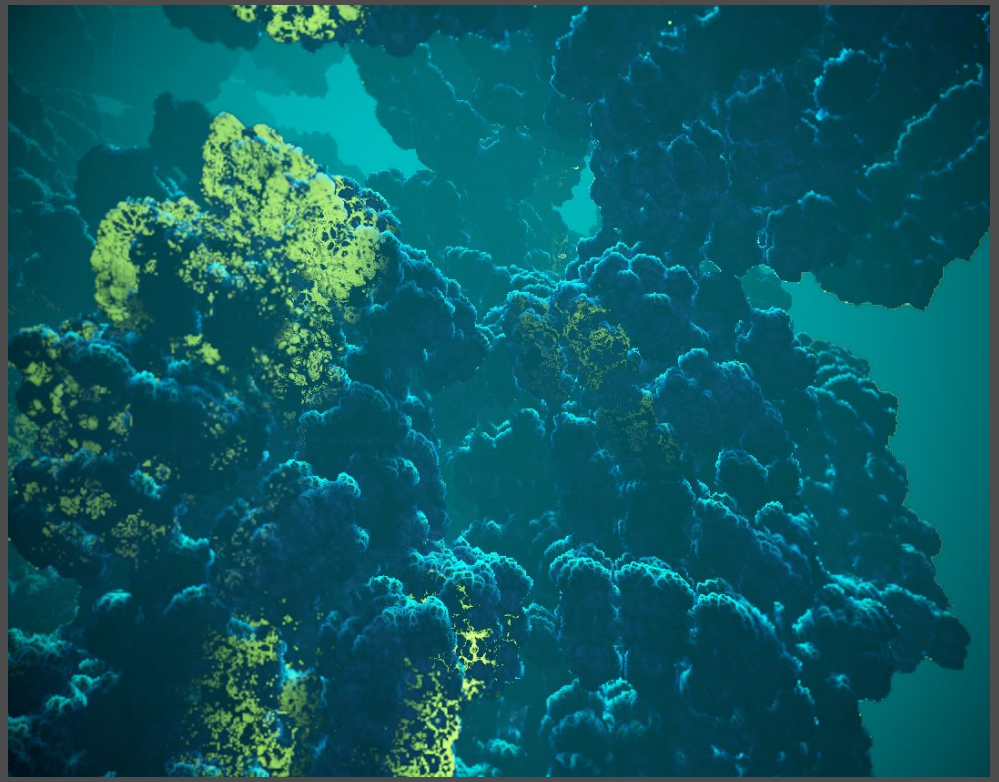
- Option to rotate 90 degrees with fade
- Vignette intensity directly proportional to velocity and angular velocity.

THE LOCOMOTION CHALLENGE

FRACTALS AND COLLISIONS



FRACTALS

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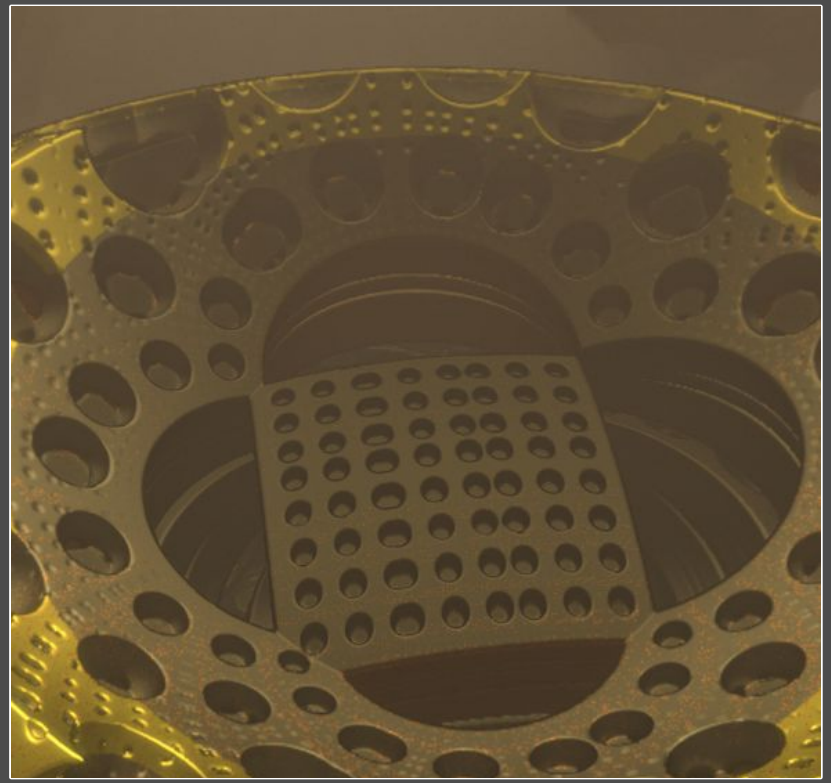
- Generally very expensive!
  - Usually have multiple iterations for a single estimation



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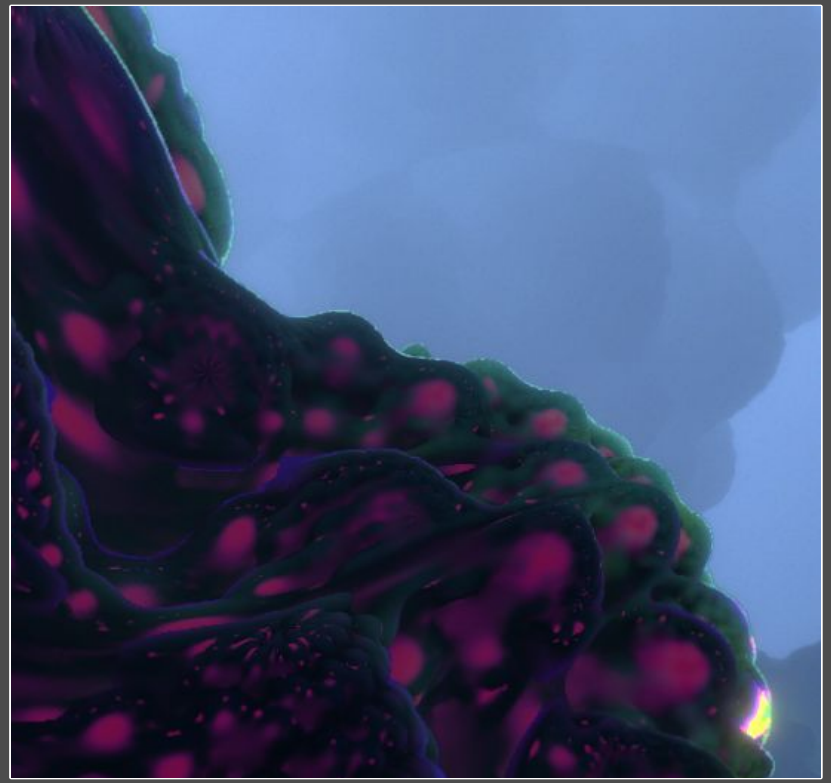

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  - Usually have multiple iterations for a single estimation
- Scale detail as player approaches fractal
  - Rendering more expensive as we get smaller!
- Hard to predict and high frequency shapes
- Scaling leads to floating point precision problems!
  - Theoretically infinite detail

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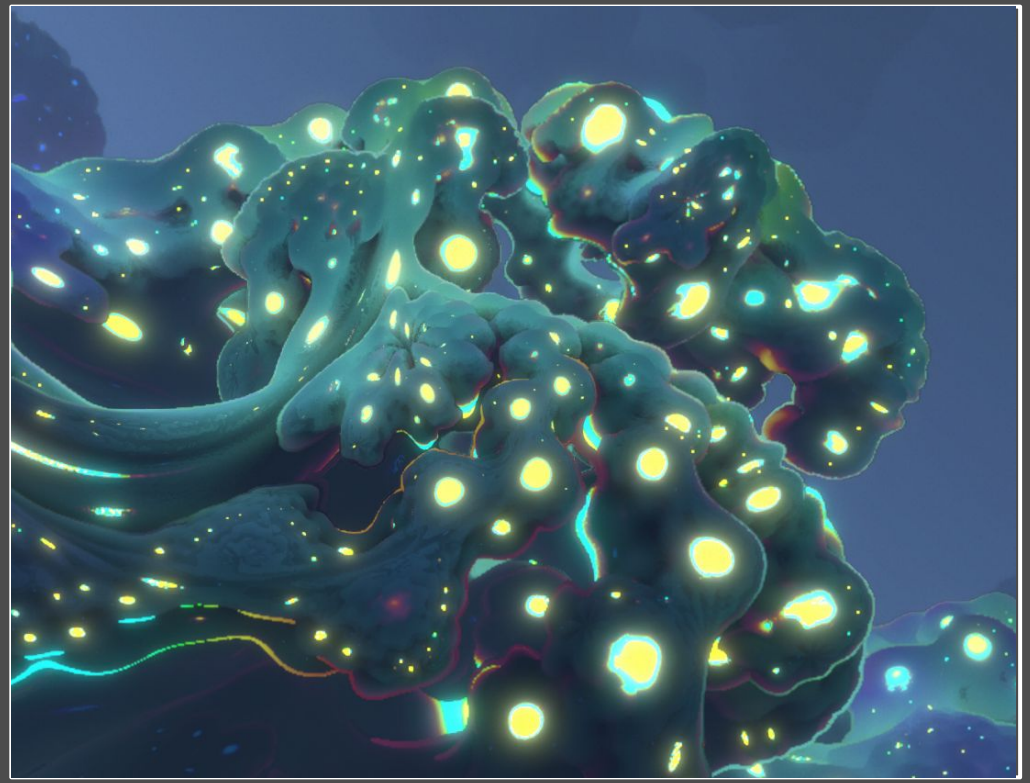
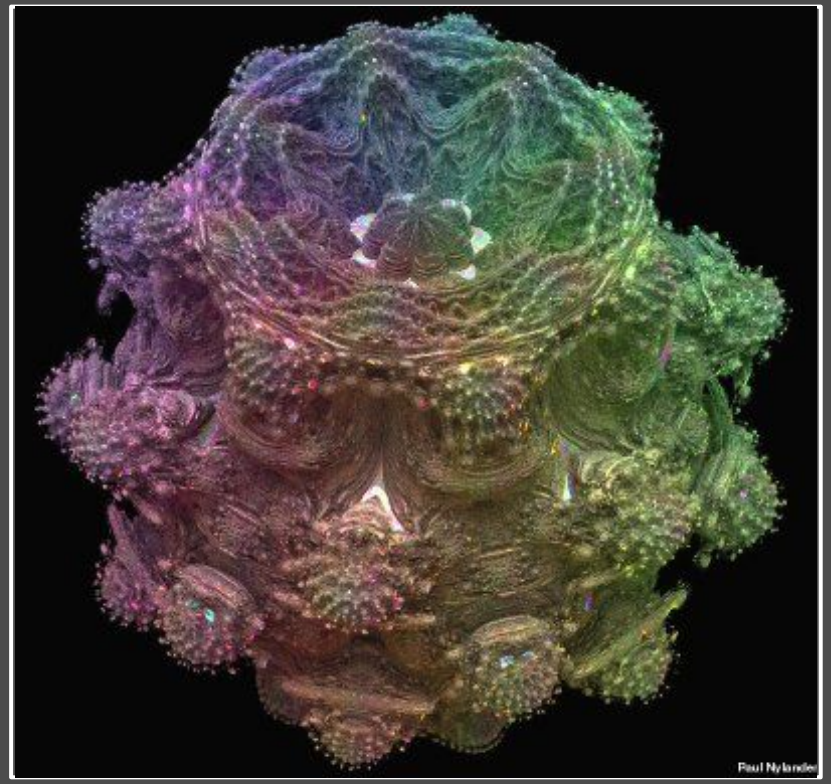
  - Why not CPU?
- Predict a bit due to latency

FIRST STEPS: MANDELBULB





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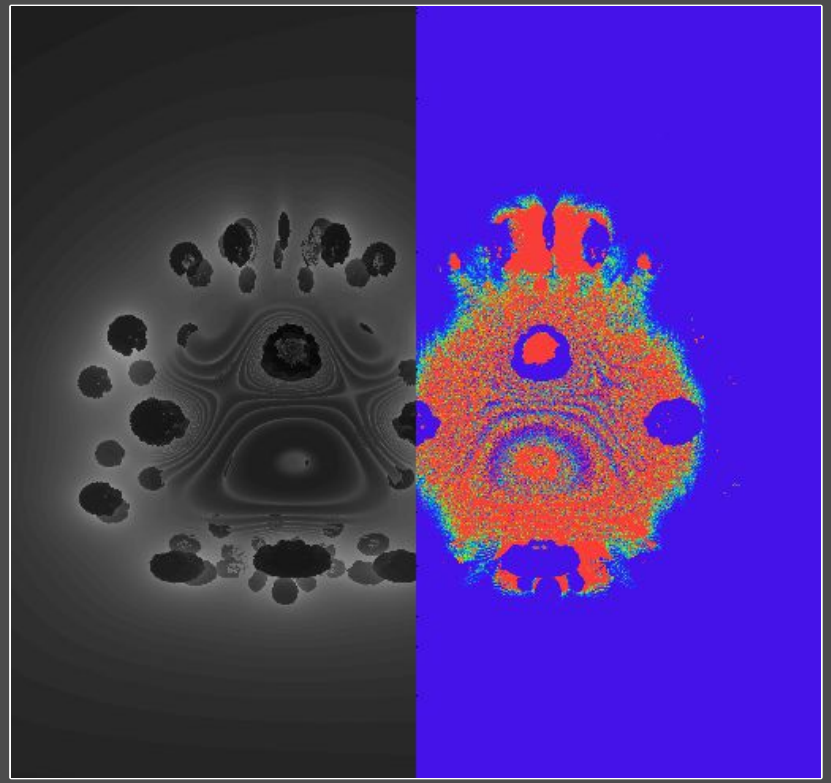
  - The fractalforums thread is amazing!



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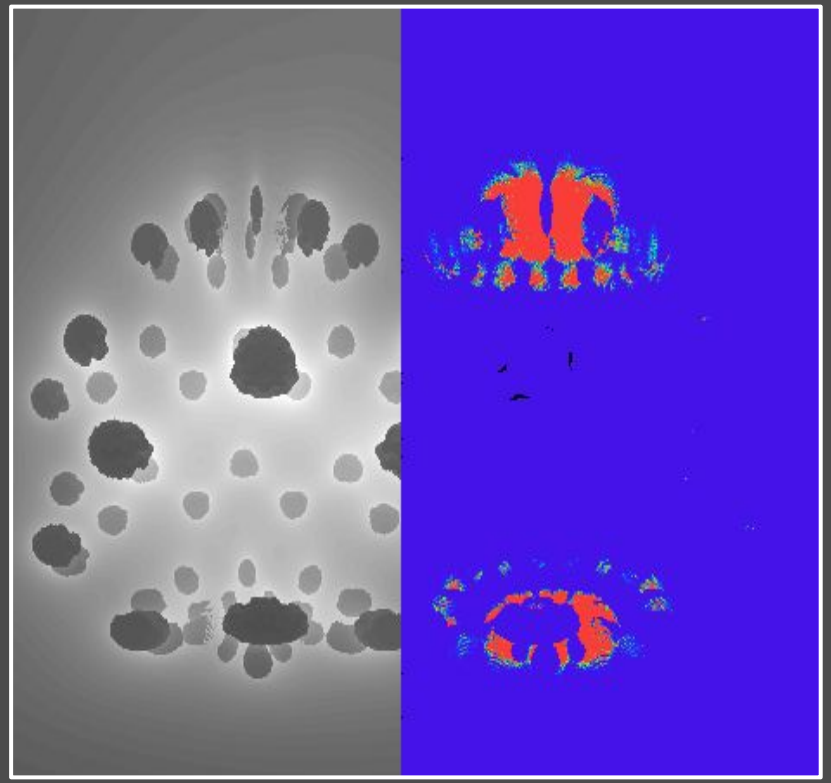
- Decided to use Íñigo Quílez's formula, but found bubbles of overestimation for Julia offsets
  - We built a tool for finding these bubbles through stochastic brute force



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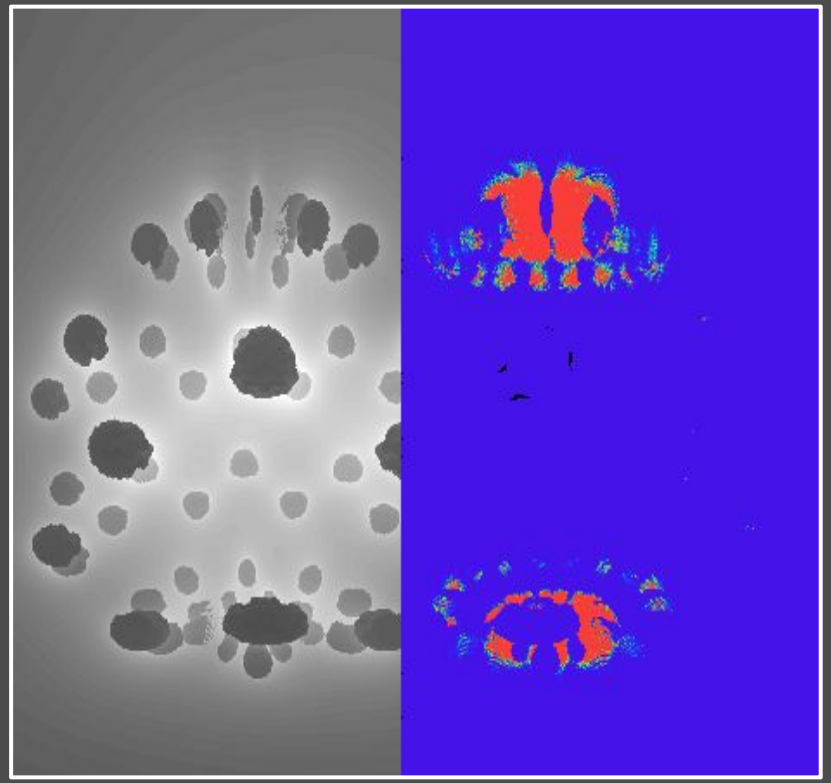

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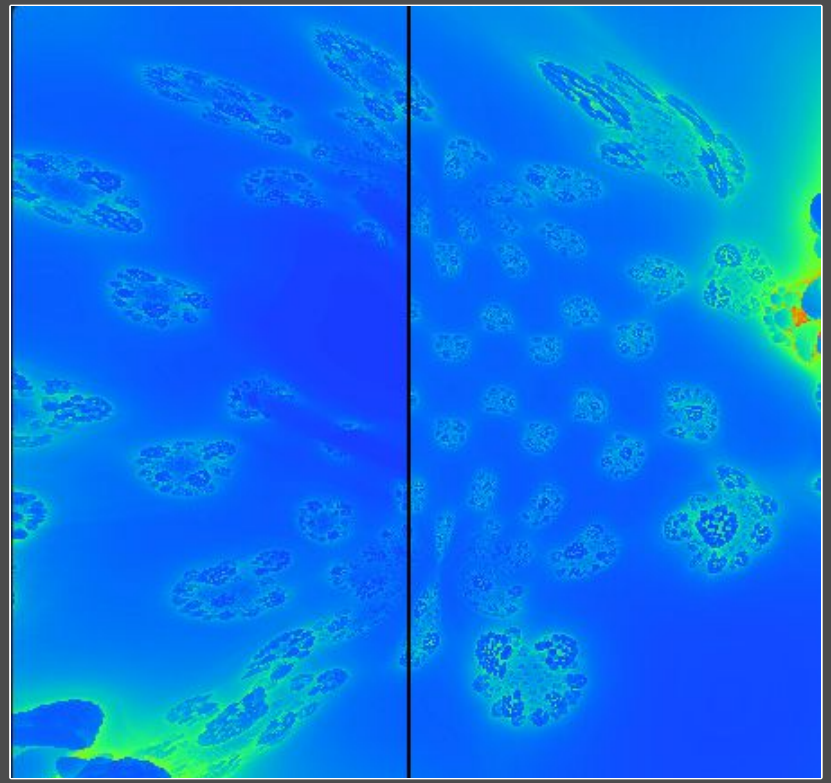
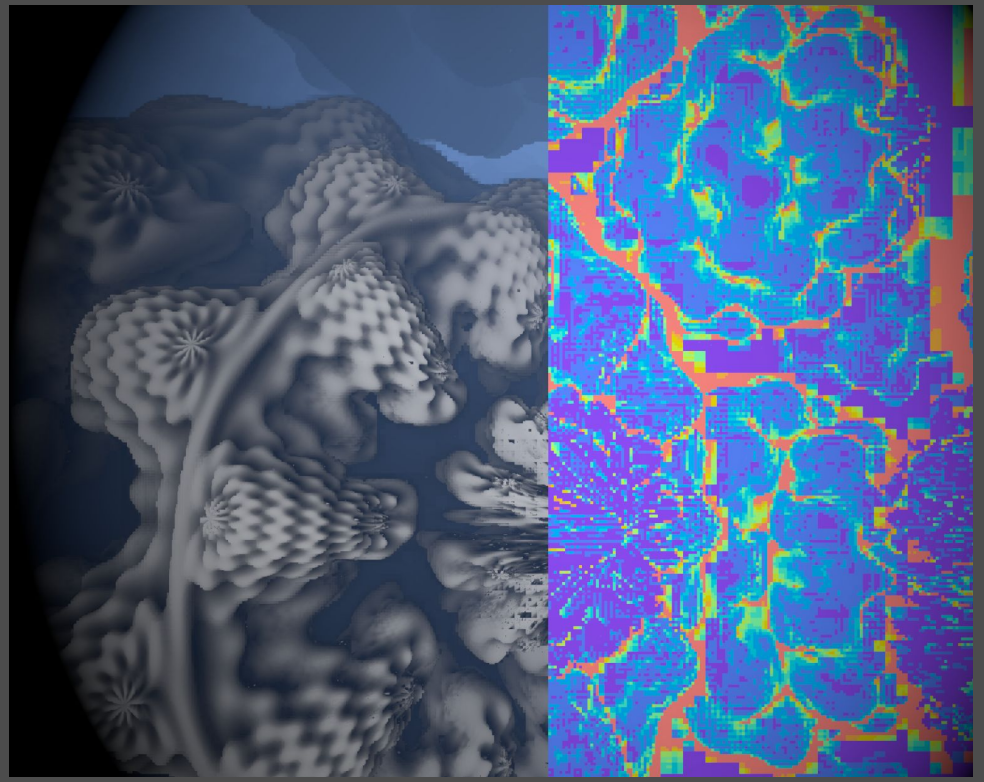
- Decided to use Íñigo Quílez's formula, but found bubbles of overestimation for Julia offsets
- Tweaked the formula to prevent these bubbles
  - Kept the maximum derivative as we iterate
- More iterations needed to render, but overall better than reducing the epsilon



```
float evaluateMandelbulb(in vec3 p, in bool conservative)
{
    vec3 w = p;
    float m = dot(w,w);

    float dz = 1.0;
    vec3 J = vec3(.2);

    for( int i=0; i < 5; i++ )
    {
        if(conservative)
            dz = max(dz * DERIVATIVE_BIAS, 8.0*pow(m ,3.5)*dz + 1.0);
        else
            dz = 8.0*pow(m ,3.5)*dz + 1.0;

        float r = length(w);
        float b = 8.0*acos( clamp(w.y/r, -1.0, 1.0));
        float a = 8.0*atan( w.x, w.z );
        w = p + J + pow(r,8.0) * vec3( sin(b)*sin(a), cos(b), sin(b)*cos(a) );

        m = dot(w,w);

        if( m > 4.0 )
            break;
    }

    return 0.25*log(m)*sqrt(m)/dz;
}
```

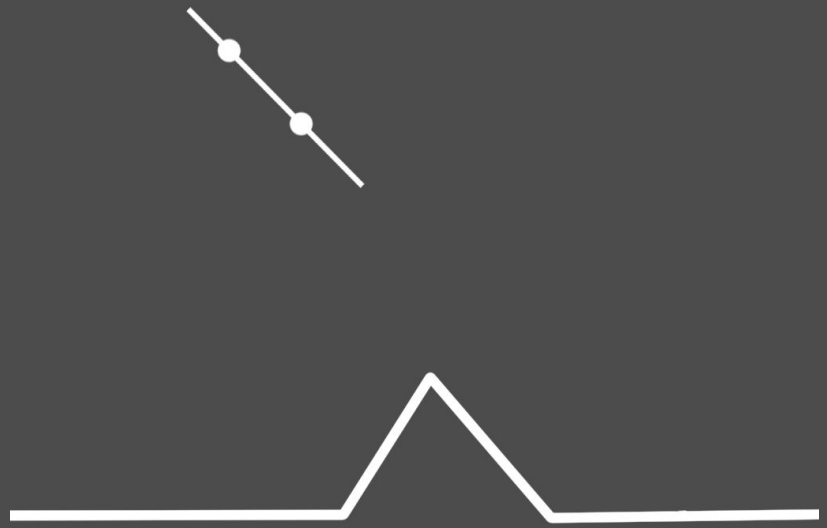
https://www.shadertoy.com/view/MdSBDR

RAYMARCHING AND VR



CLASSIC RAYMARCHING

- Define a function that gives us the distance to a surface



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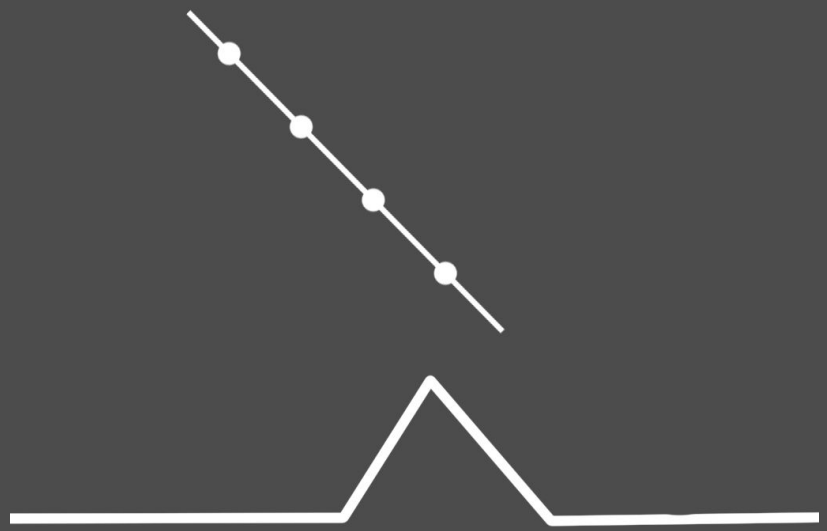
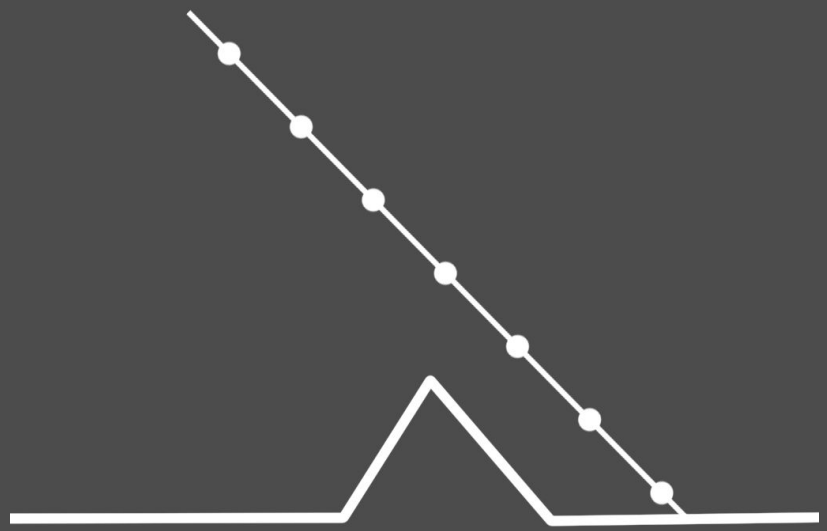
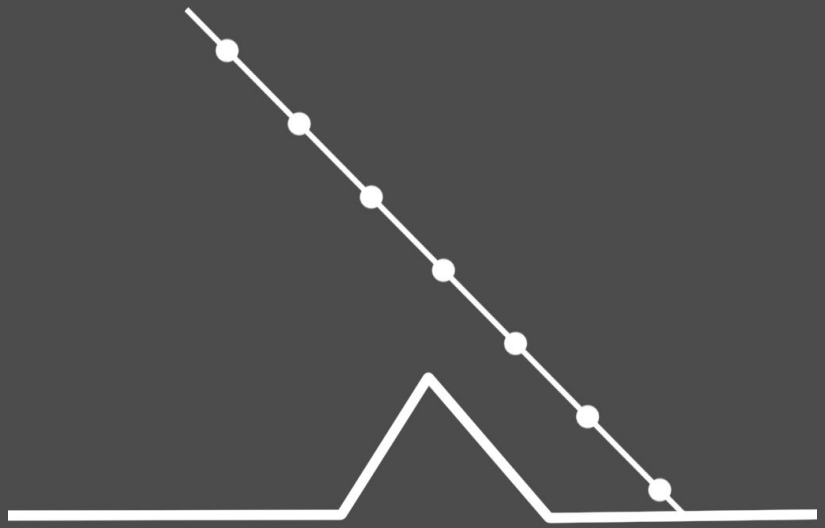


- Define a function that gives us the distance to a surface
- Iterate through a ray with a fixed step



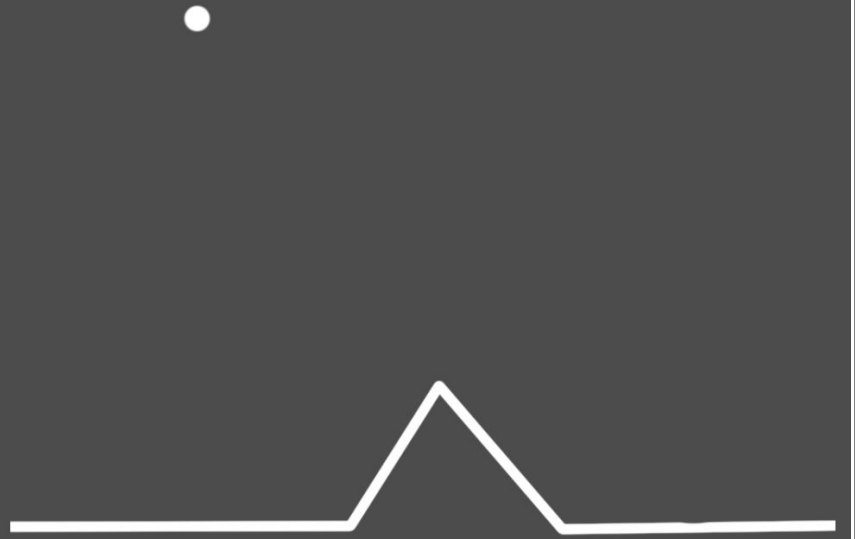
- Define a function that gives us the distance to a surface
- Iterate through a ray with a fixed step
- If the distance to the surface is less than a specified amount, we hit the surface



- Define a function that gives us the distance to a surface
- Iterate through a ray with a fixed step
- If the distance to the surface is less than a specified amount, we hit the surface
- Use finite differences for normal estimation and shading
- Shadows, AO, SSS, godrays very straightforward
- **Very** expensive!

SPHERE TRACING

- Each step jump is proportional to the distance of the surface



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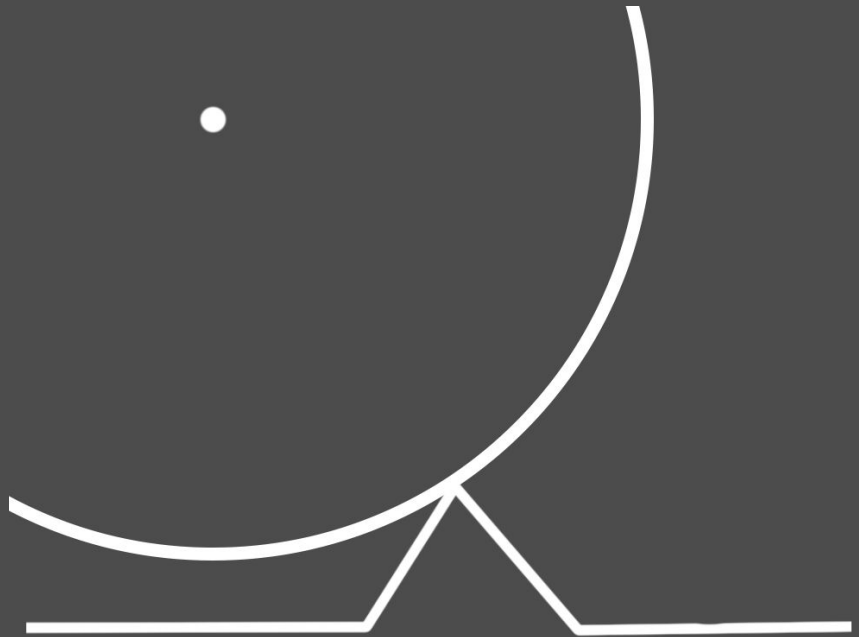

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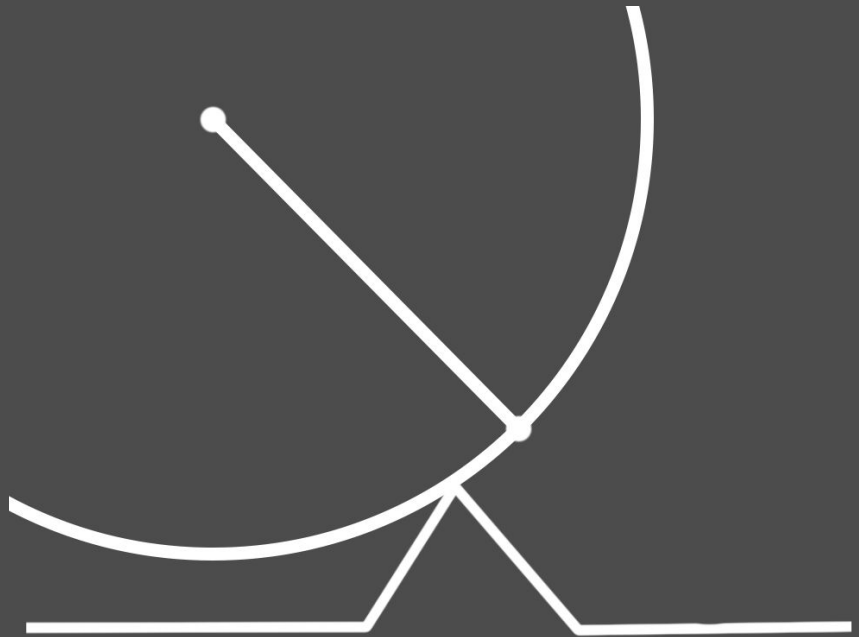

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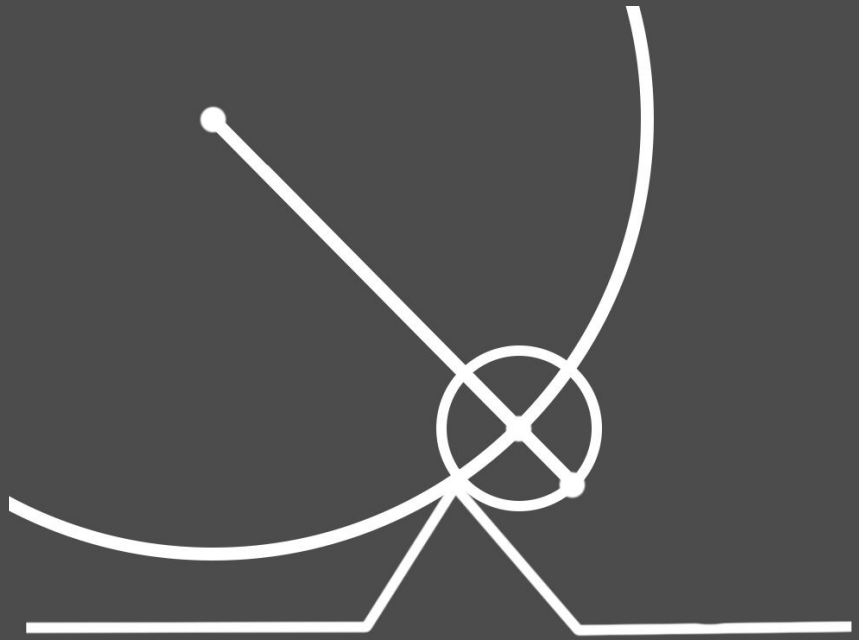

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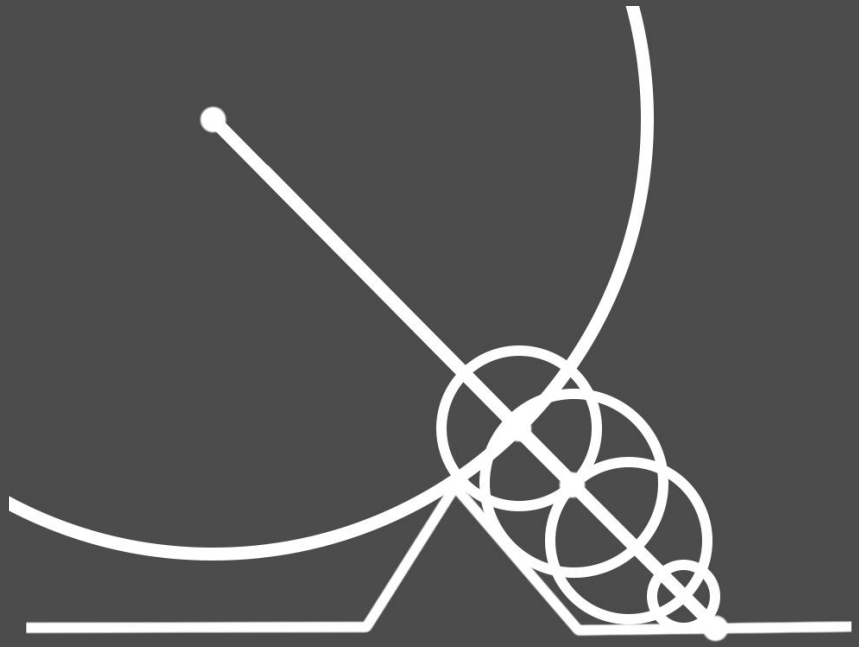

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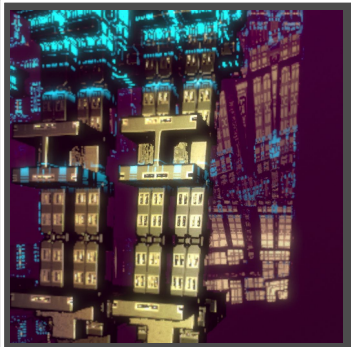
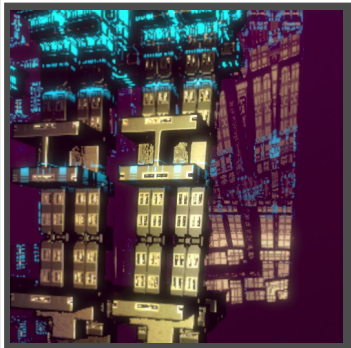
- Each step jump is proportional to the distance of the surface
- Can lead to overestimation if the function is not well defined
  - Fractals are not ideal!
  - We bias each fractal SDF empirically
- Preferred way to raymarch in modern approaches



VIRTUAL REALITY CONSTRAINTS

- Our target is 90fps, so that gives us ~10ms



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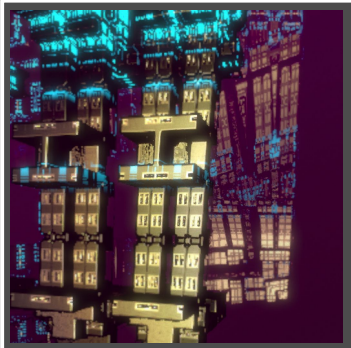

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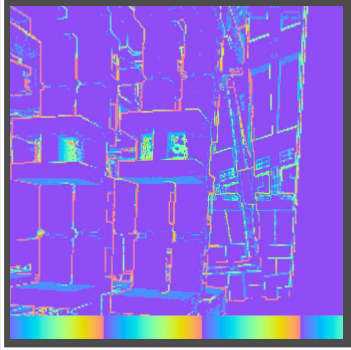

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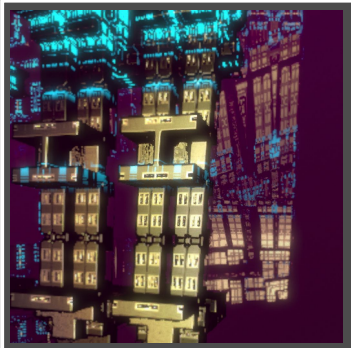

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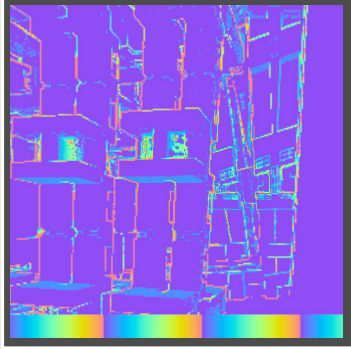

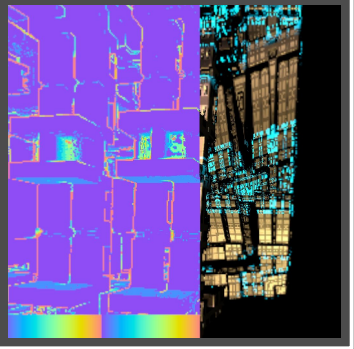

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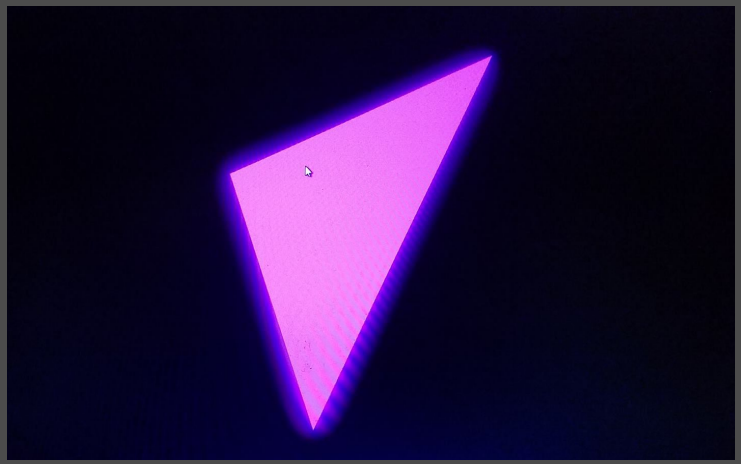

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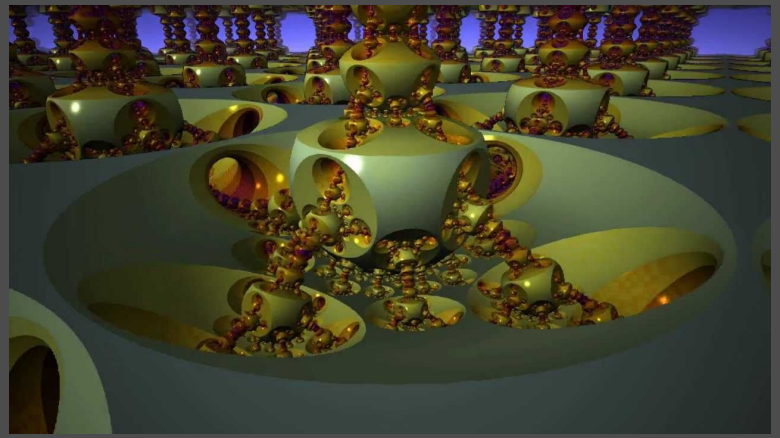
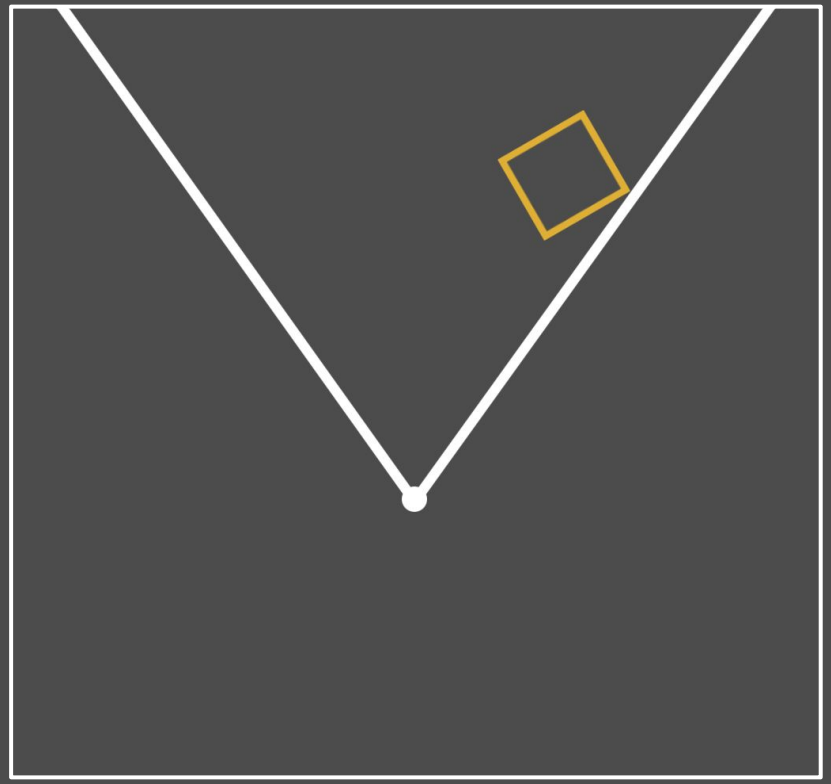
- We have to render the same thing twice! :(
- Pipeline is not designed for raymarching, we have to hack Unity a bit
  - Big triangle where everything happens

CONEMARCHING

- Originally from the demoscene
  - Fractus by Fulcrum, Revision 2012





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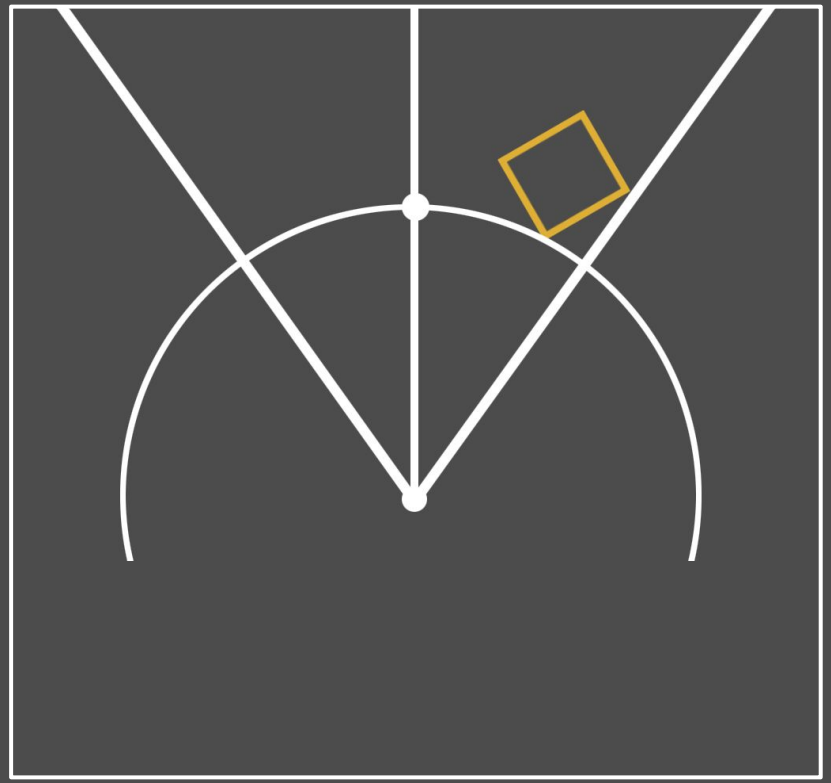

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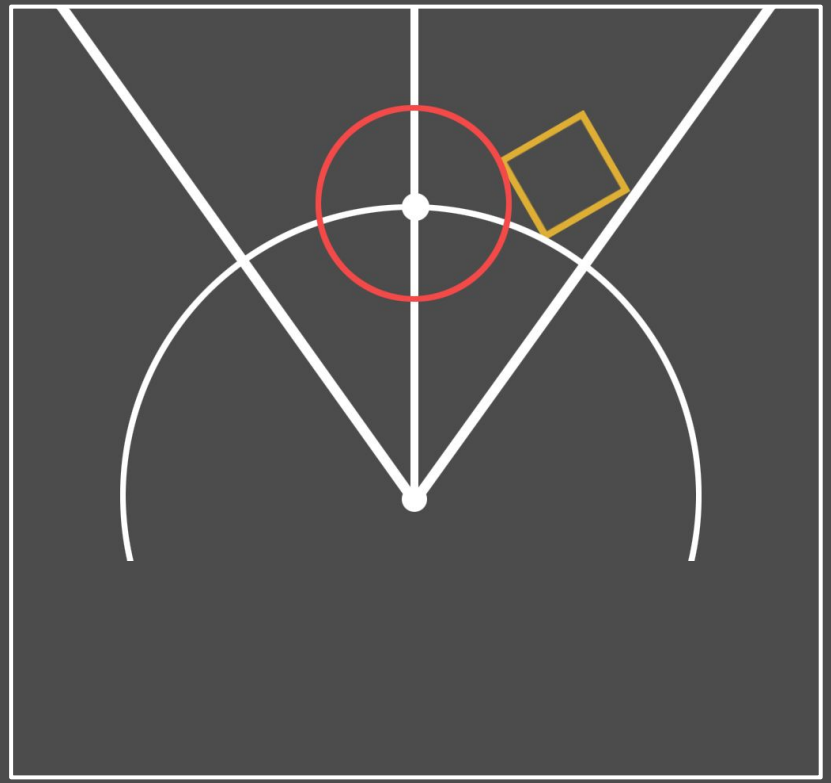
- On each pass, sphere trace until we can't guarantee there isn't an intersection



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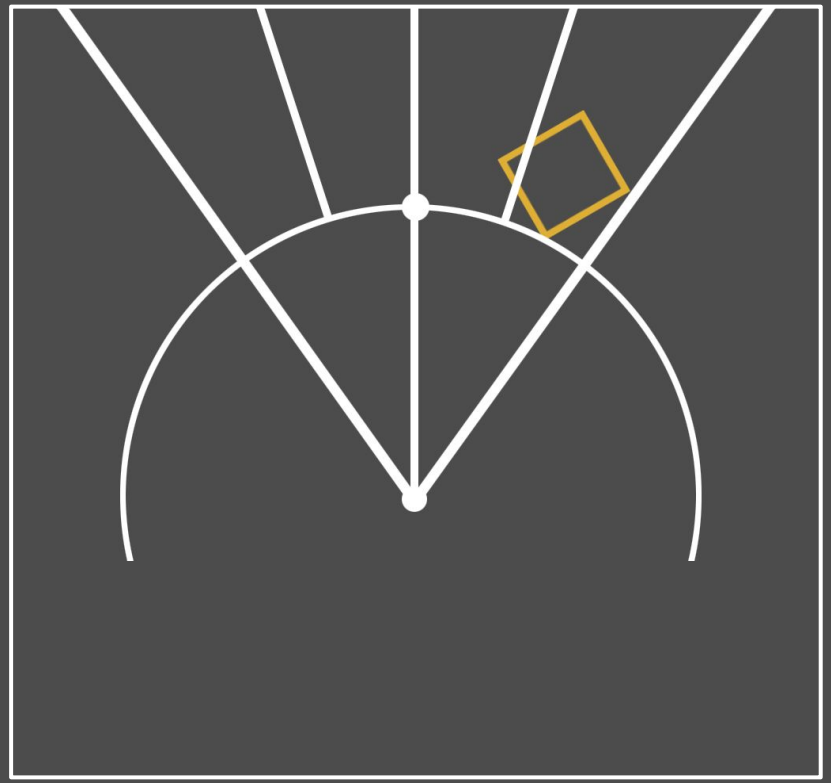

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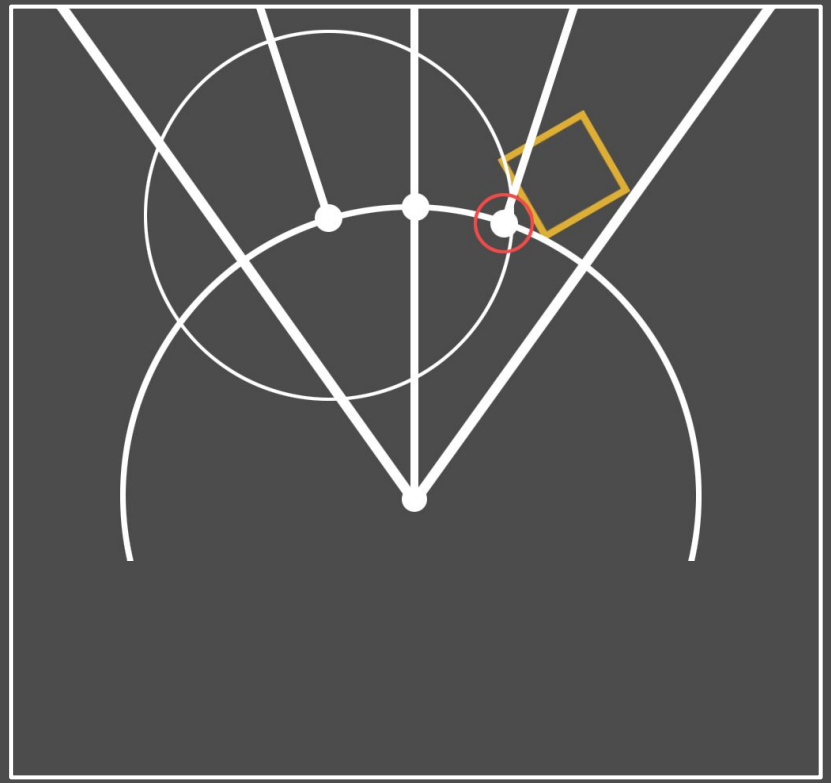

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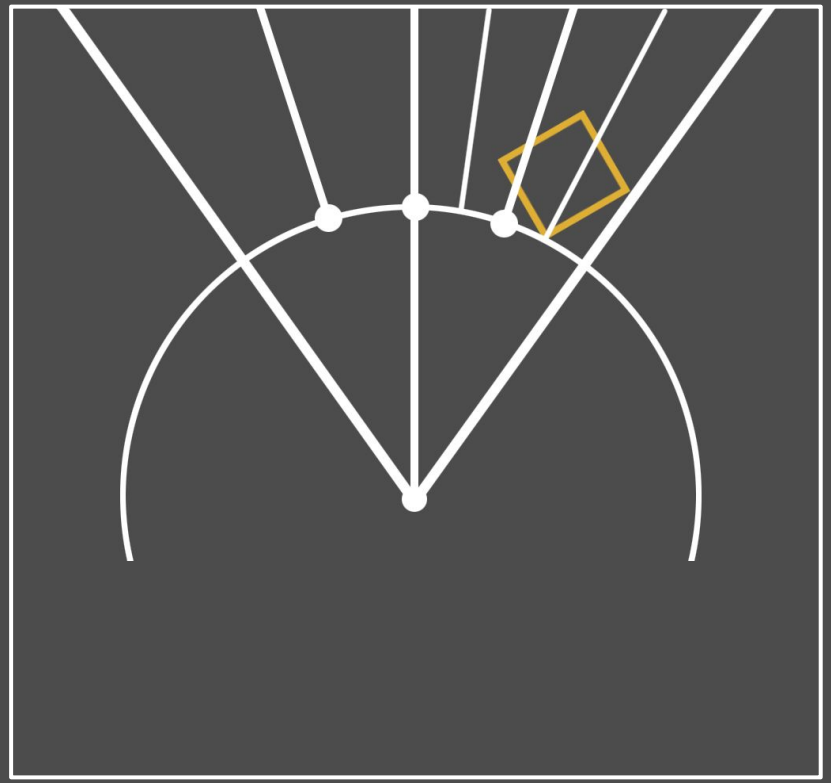

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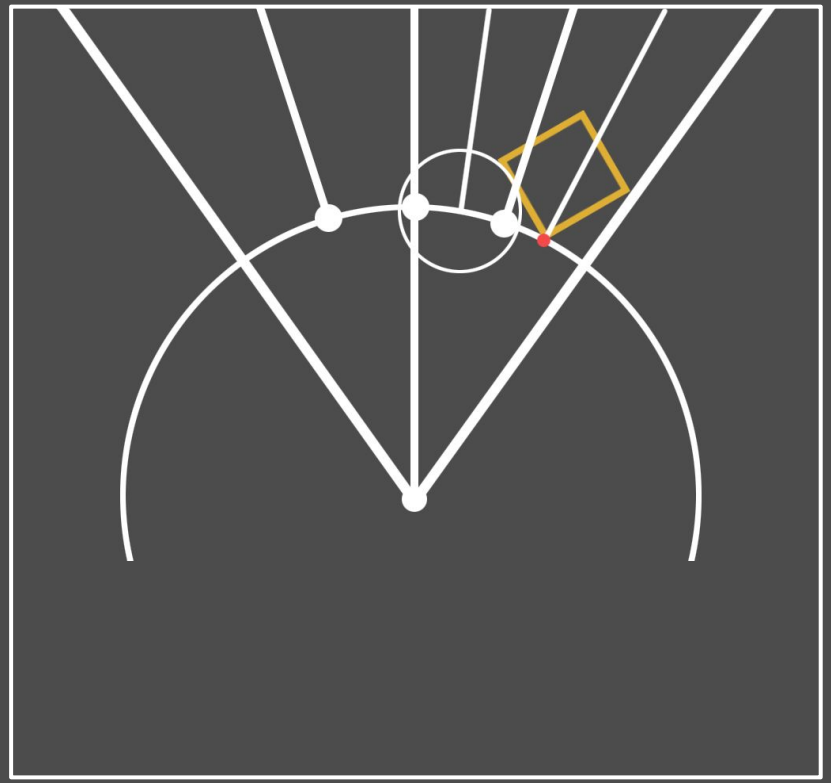

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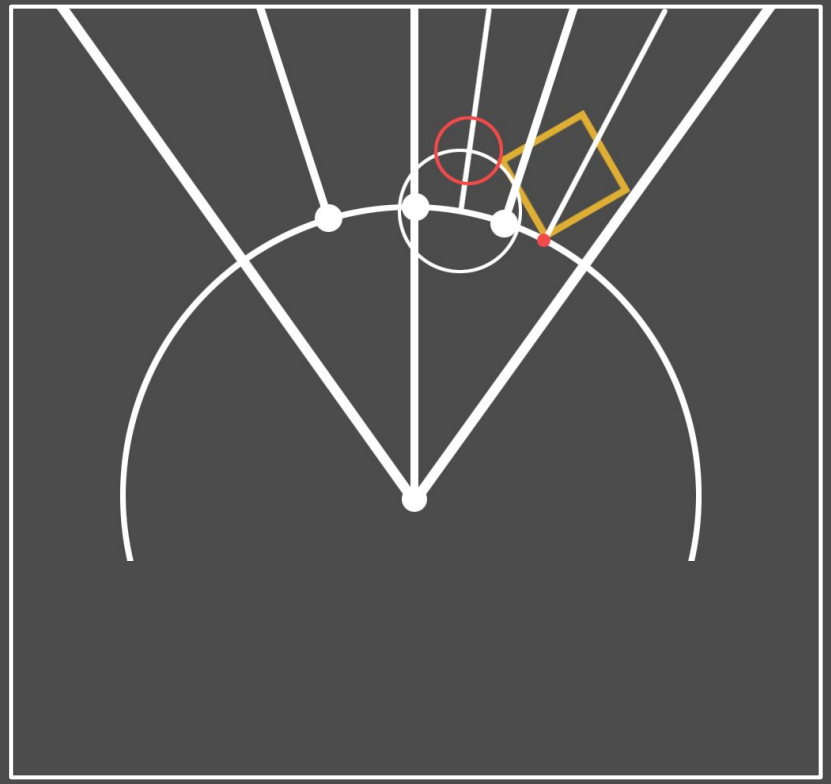

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CONEMARCHING

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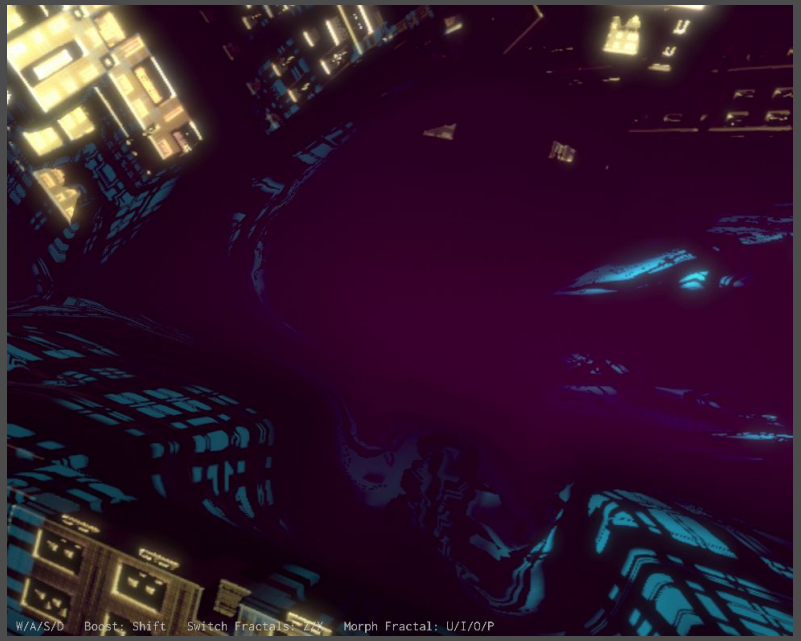
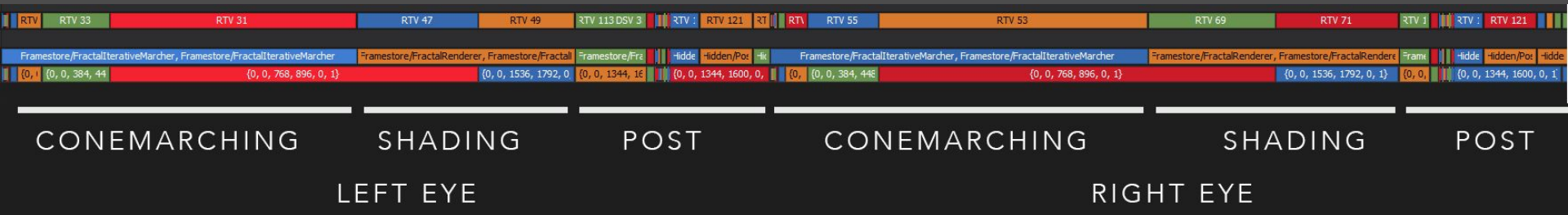
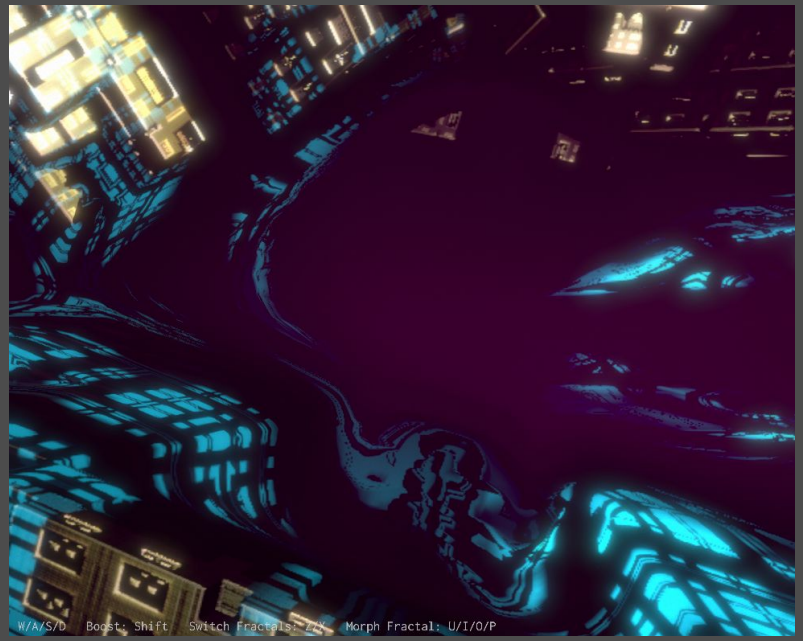
- Double the resolution and reuse the distance
  - Some bias is *usually* needed
- Optimizing the number of iterations and passes is not trivial. Some emergent behaviour can appear!



- 55-150 steps per pass
- 8 steps at highres





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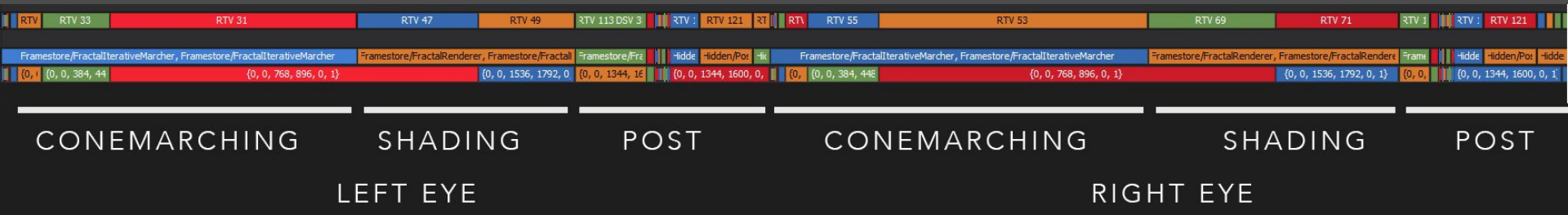

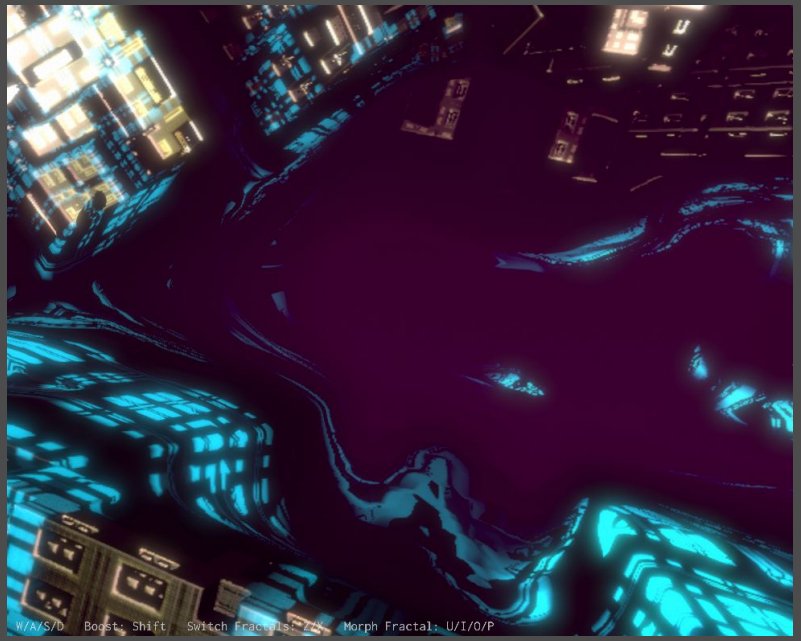

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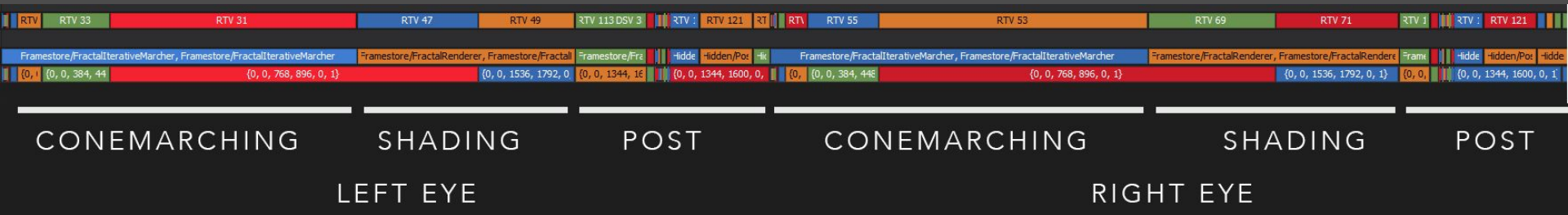

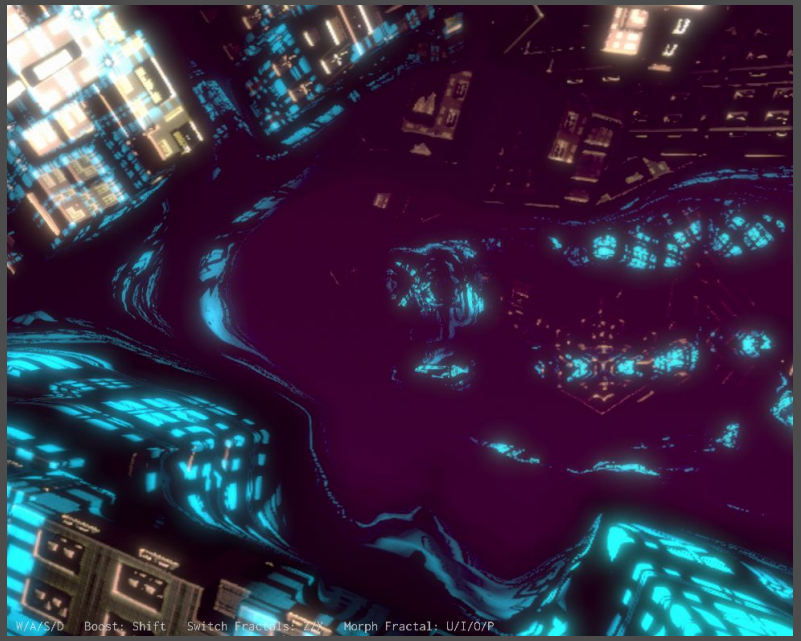

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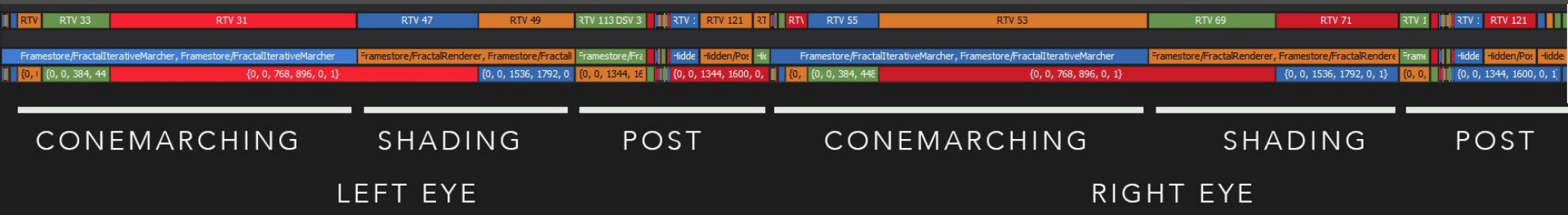

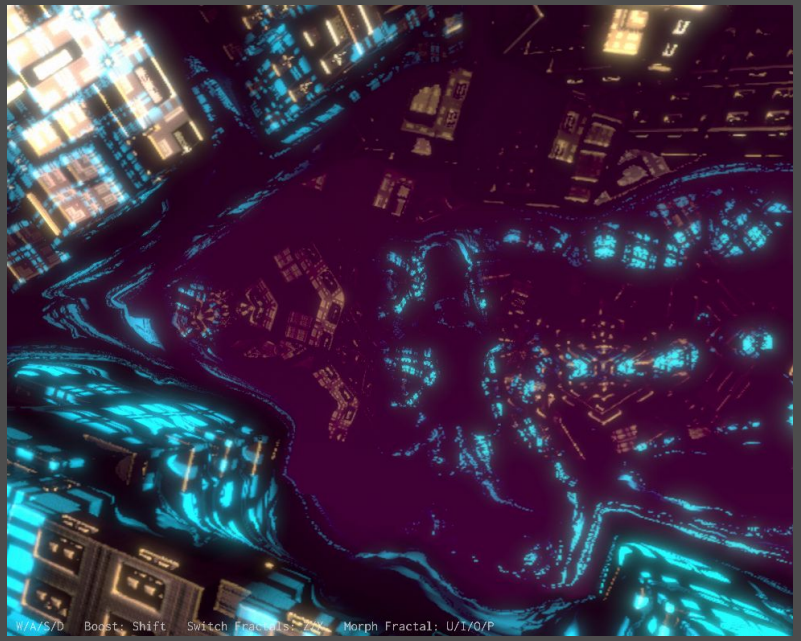

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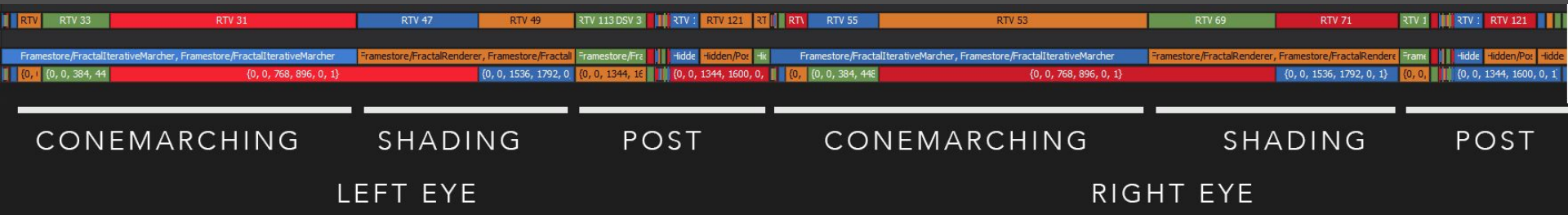

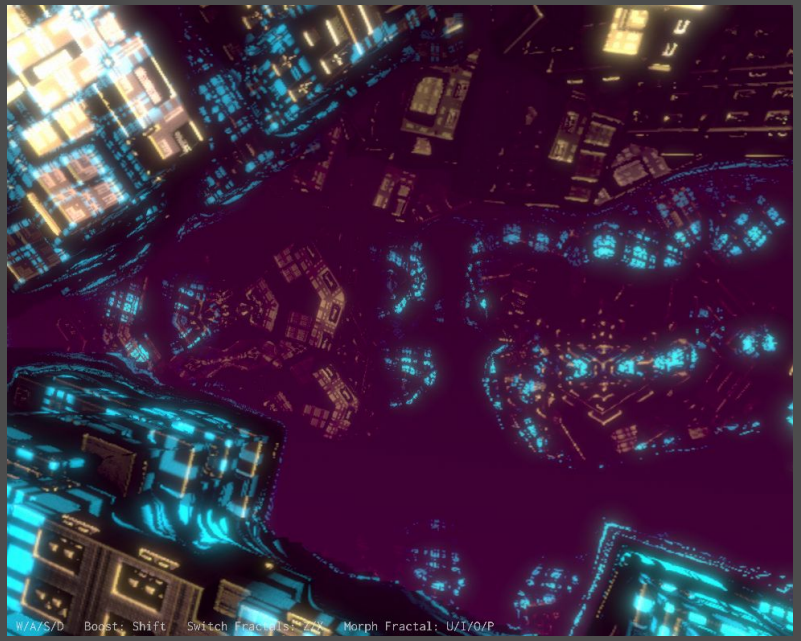

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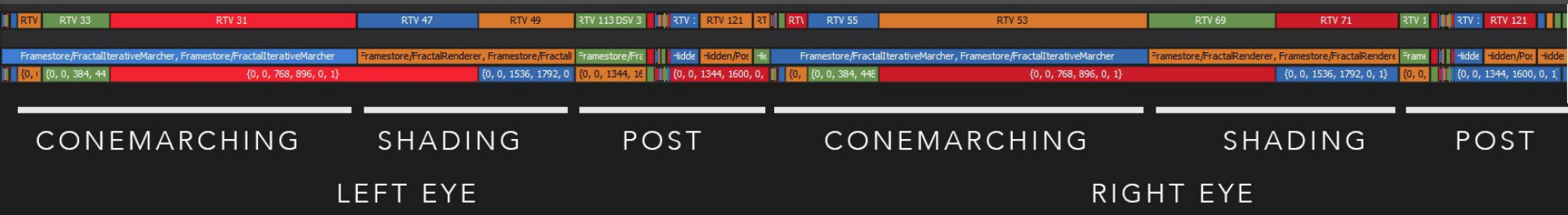

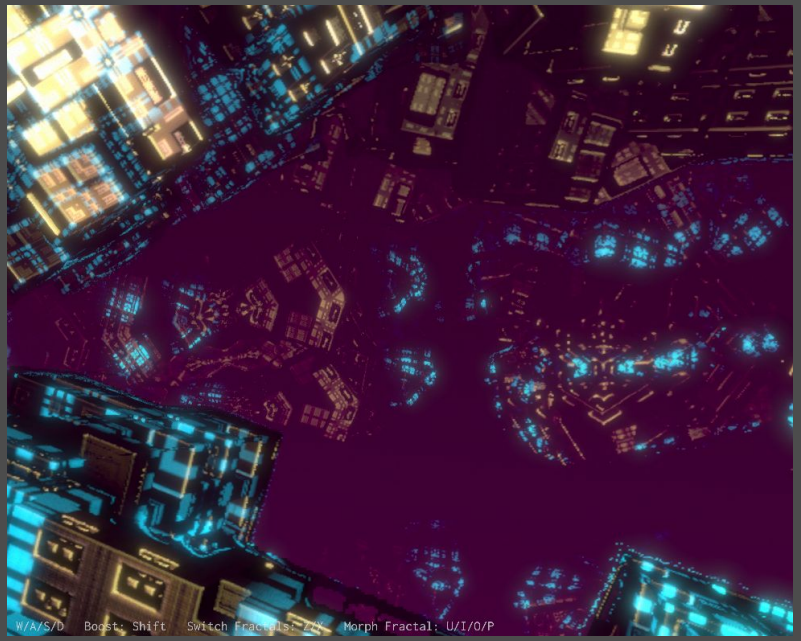

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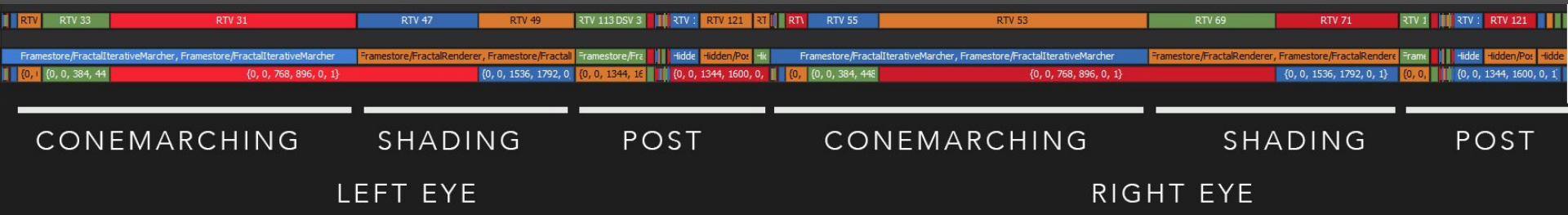

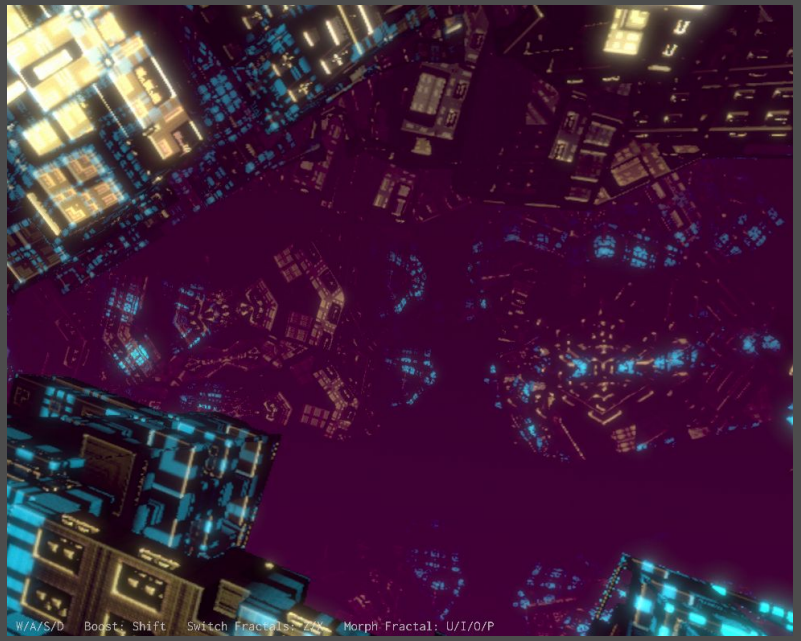

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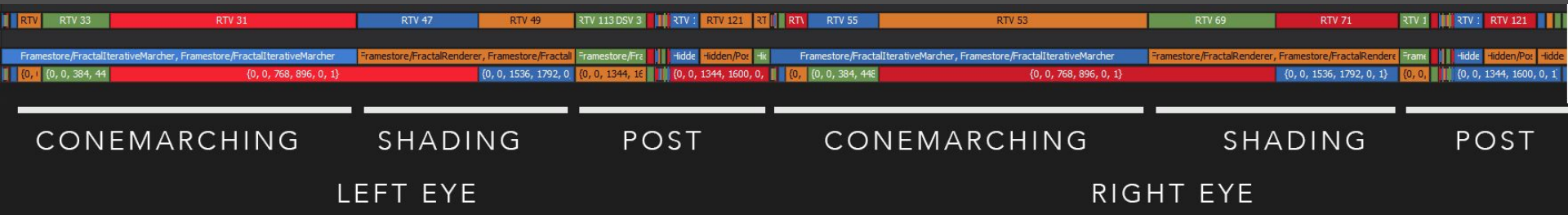

BUT…

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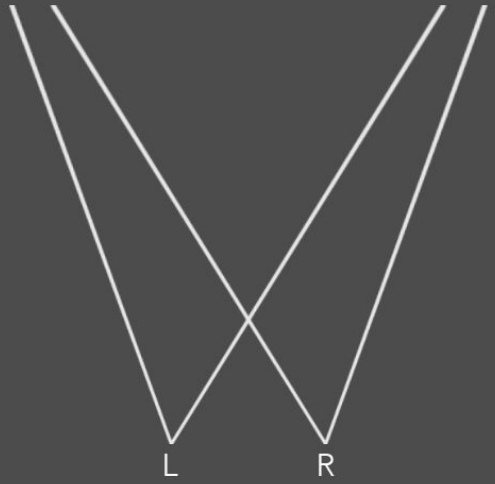
REPROJECTION

- We’re still rendering everything twice!
- Two problems: depth estimation and shading
  - Maybe we can we reproject depth? Yes!



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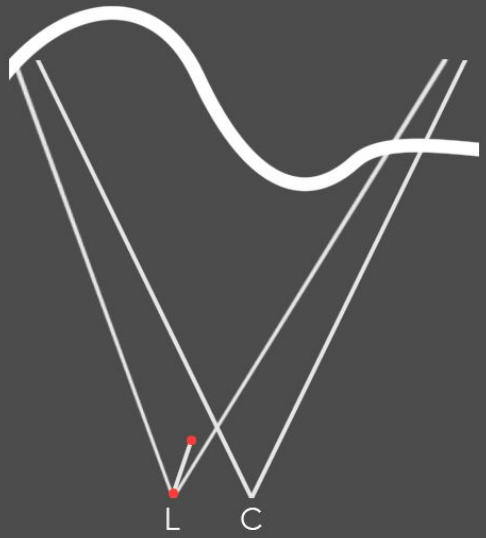

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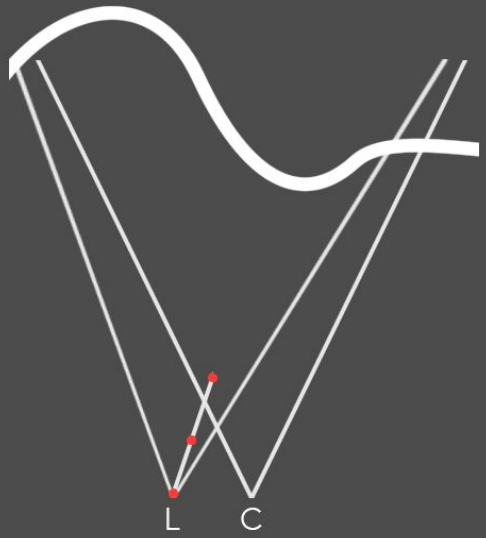

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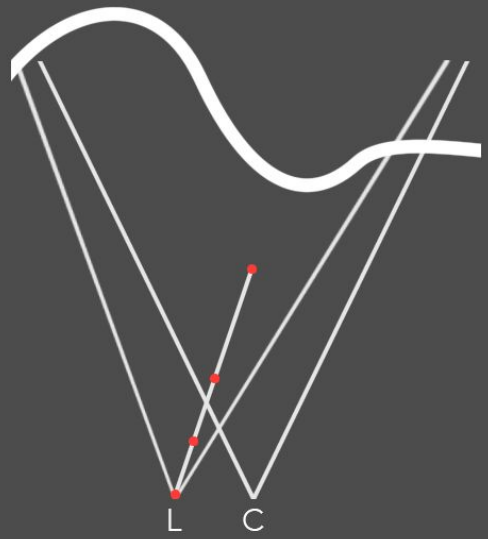

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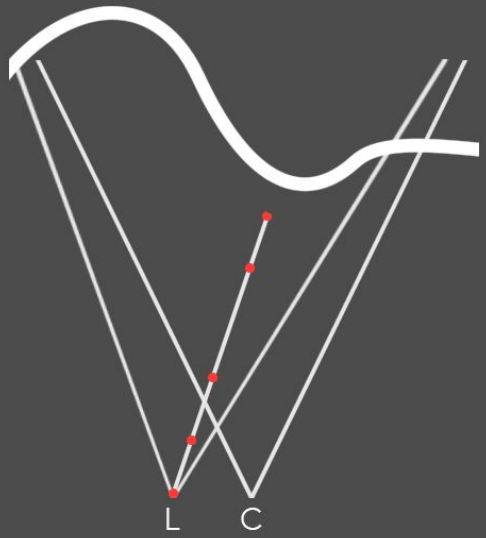

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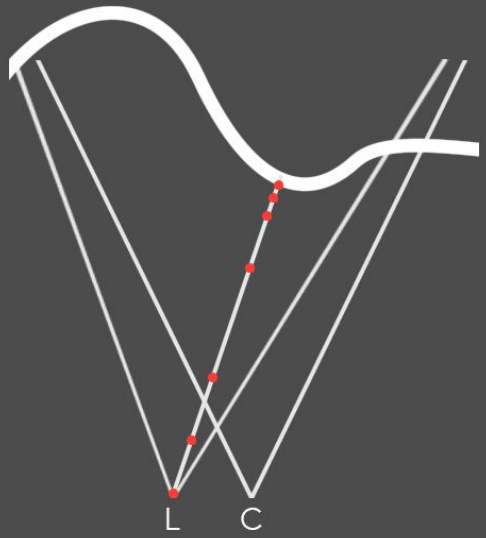

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```
// Iterate at different levels
t = GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_6, 2, .2);
t = GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_5, 4, .15);
t = GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_3, 8, .075);
t = GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_2, 4, .075);
t = GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_1, 4, .075);
t = GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_0, 16, 0.025);
```

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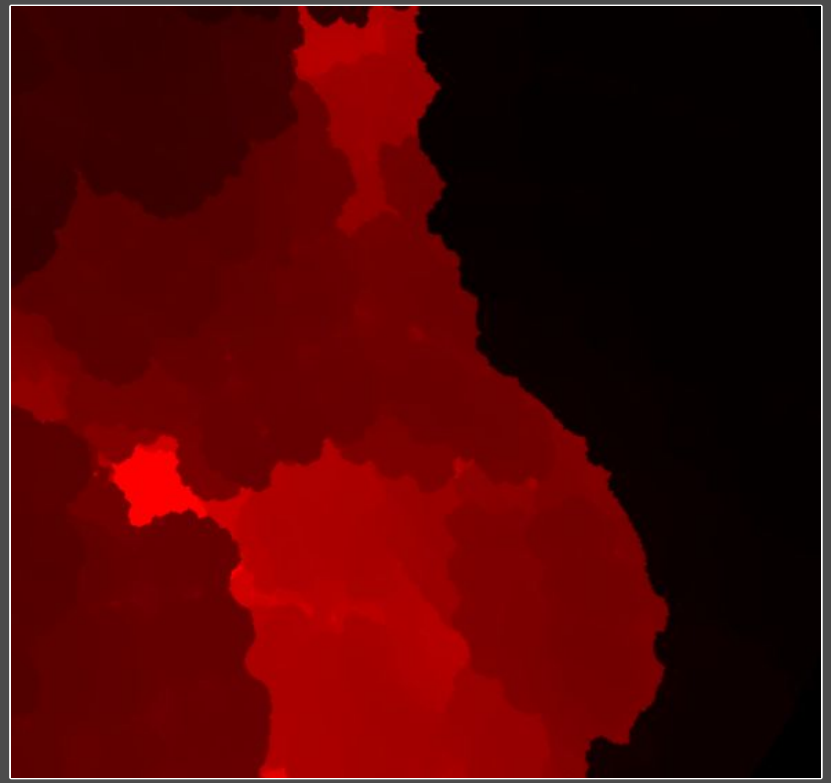
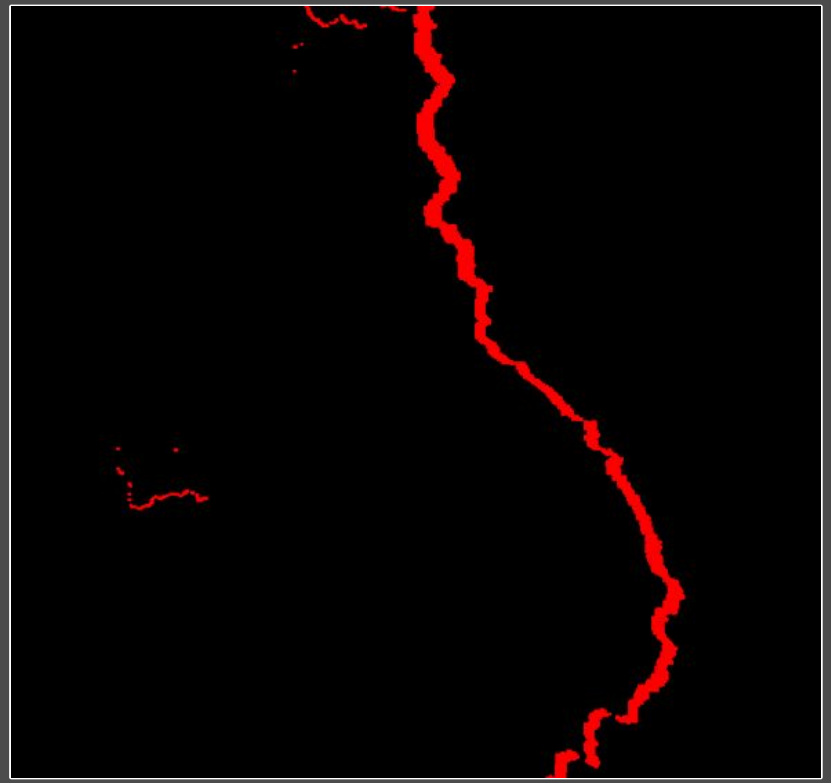
- Screen space ray marching with horizontal offset
- To get a better converging distance, we use the conemarching passes at lower res



- Original paper deals with rasterization and couldn’t fix the discontinuities
  - **Fast Gather-based Construction of Stereoscopic Images Using Reprojection [van de Hoef, Zalmstra]**



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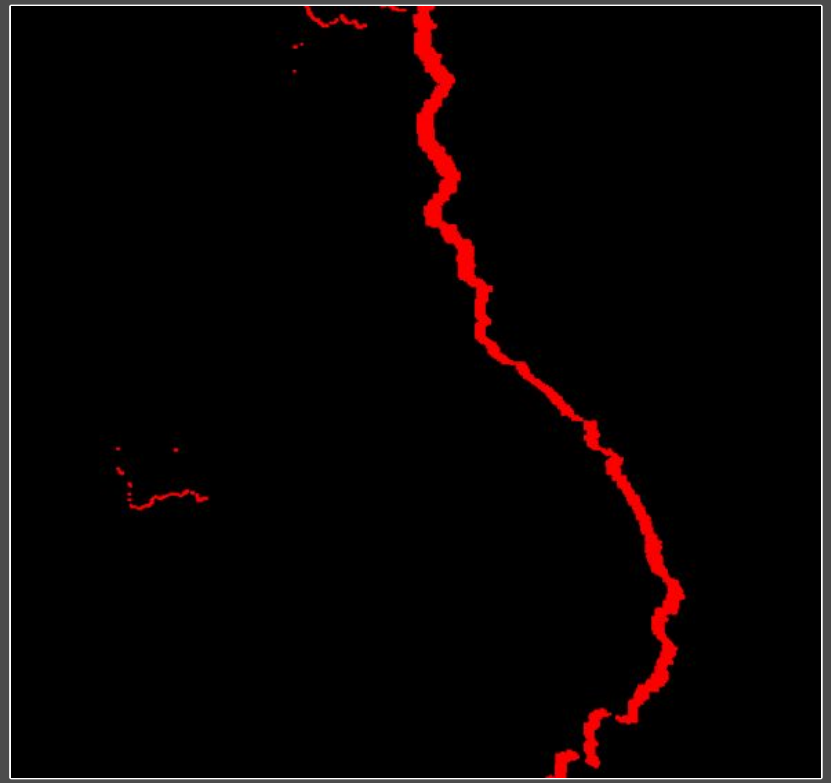
  - Just keep marching where there is a lot of stereo disparity



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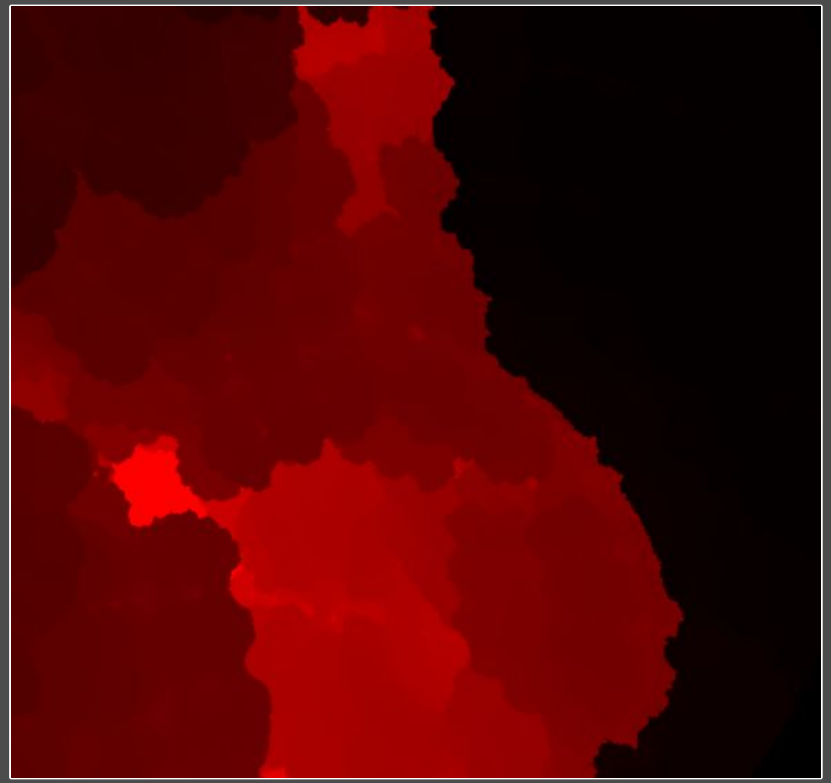
  - Also, shift samples horizontally



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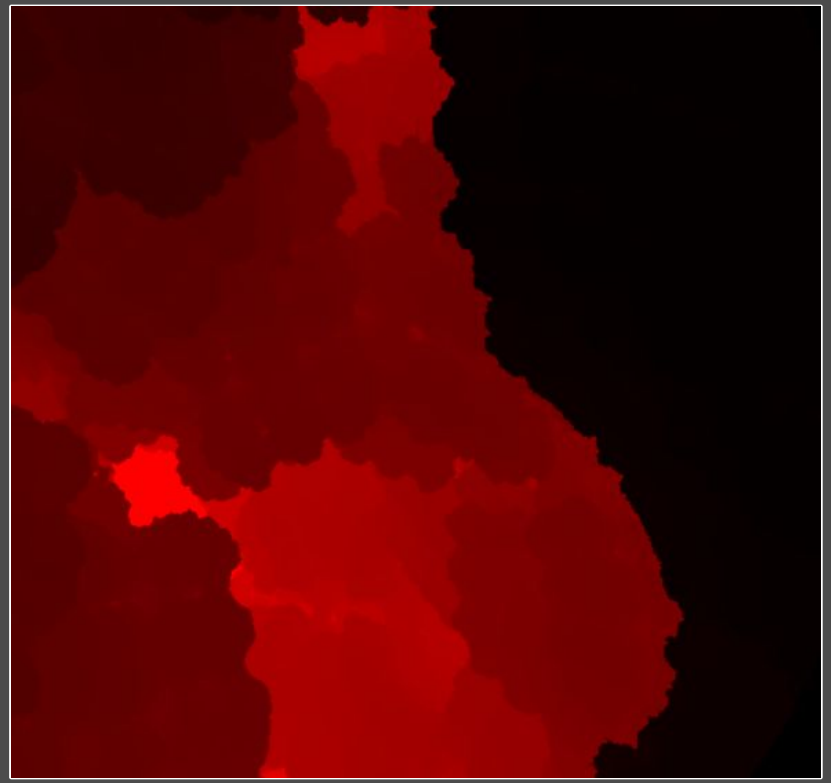
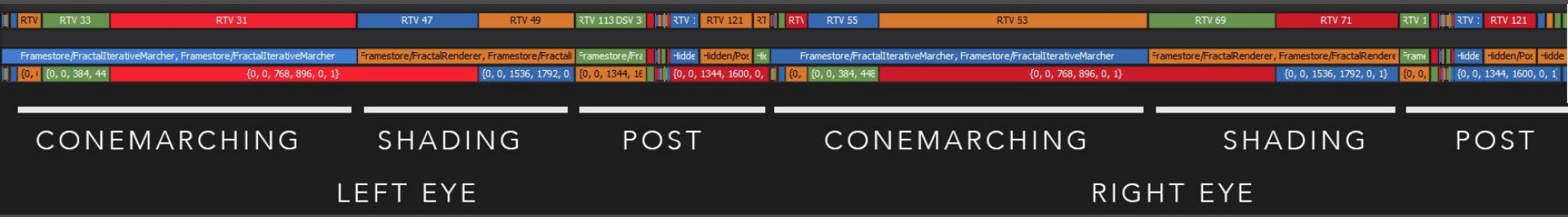


- Original paper deals with rasterization and couldn’t fix the discontinuities
- We can!
  - Just keep marching where there is a lot of stereo disparity
  - Also, shift samples horizontally
- Small artifacts, but can be masked
- Decreases quality with stereo separation
  - Fortunately, we already scale the fractal all the time, so that you’re always one unit away from the closest intersection

- With the conemarcher, we had to estimate depth twice



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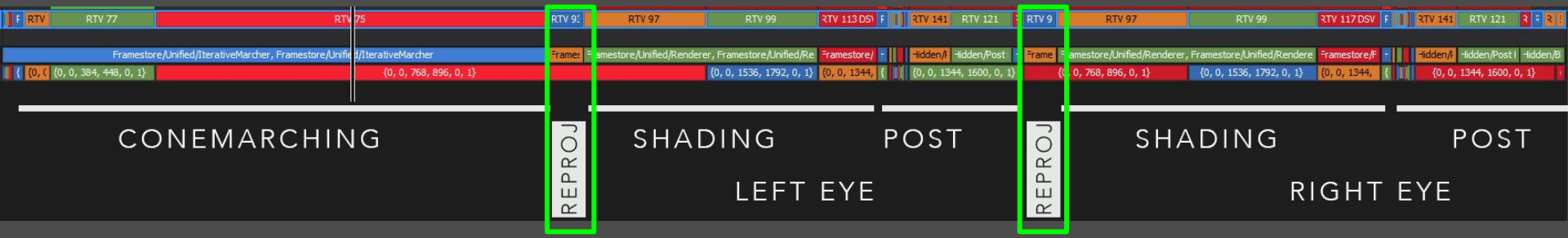

- With the conemarcher, we had to estimate depth twice
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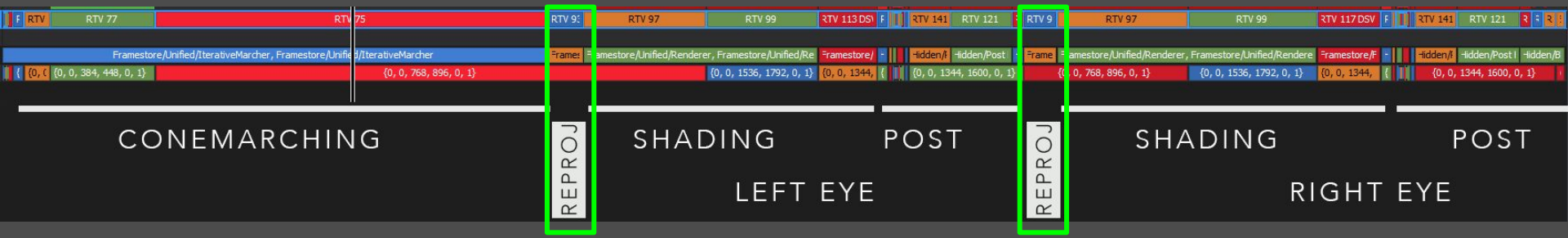
- Reprojection pass is usually fast
  - Performance improves proportionally to the conemarching pass
- Shading pass requires some tweaking, because some of the reprojection estimates are not perfect



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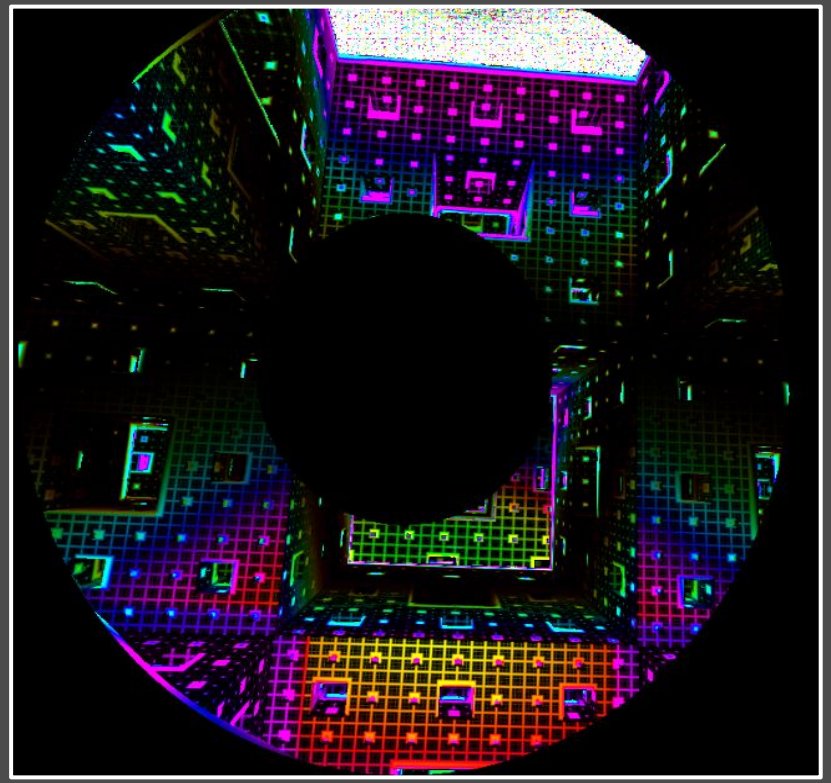

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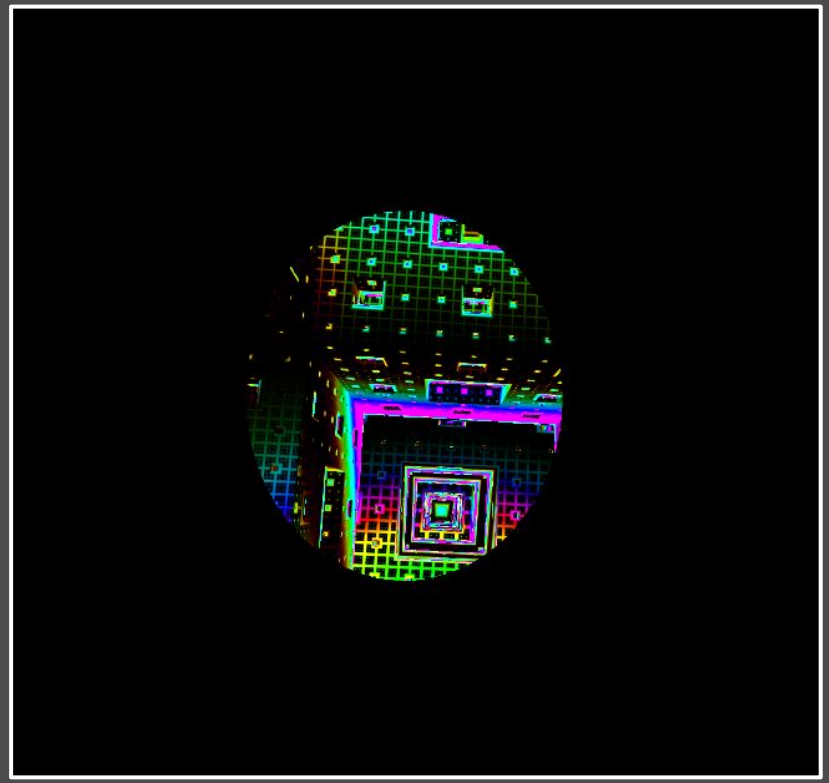
- Render at half res on the periphery, full resolution at the center and blend the edges



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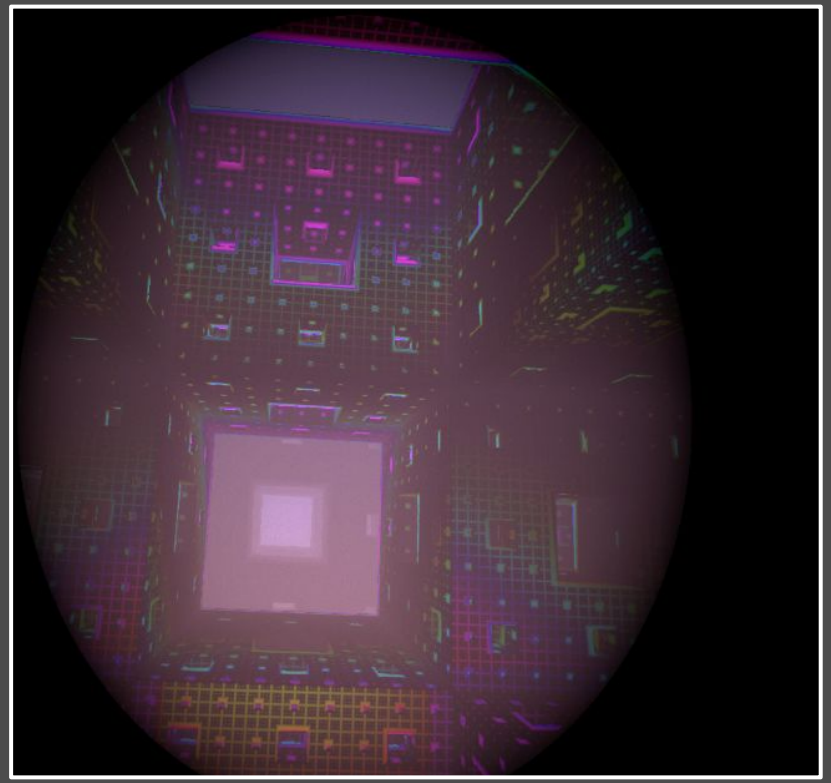

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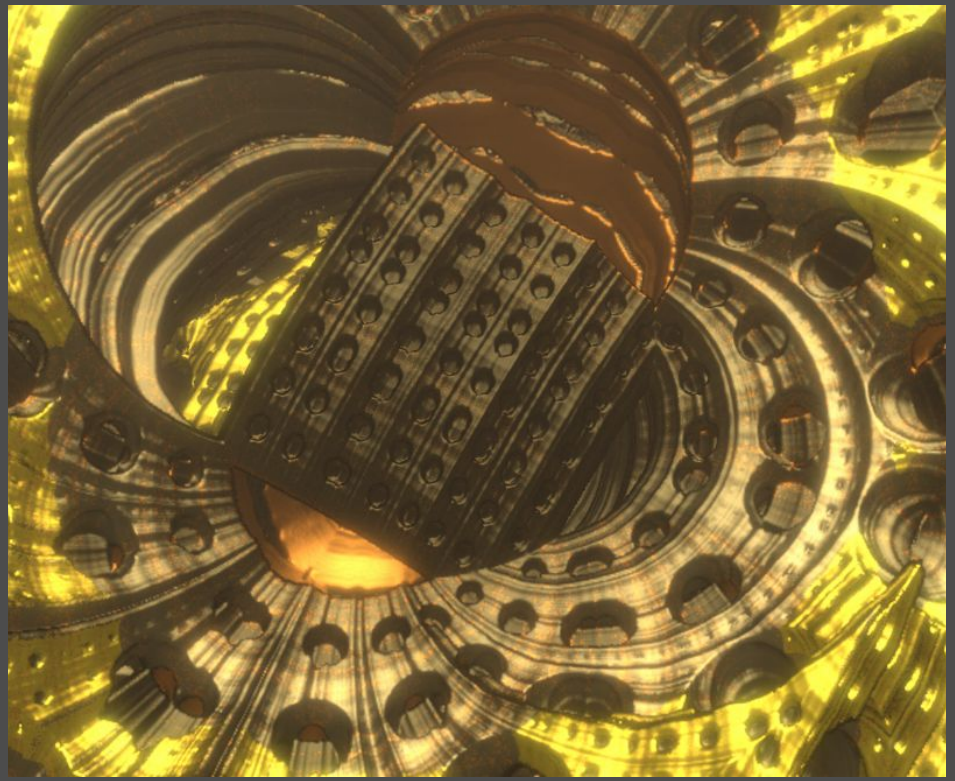
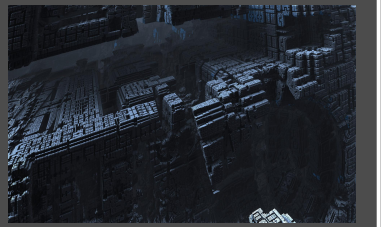
- We don’t need that much detail on the periphery
- We want something dynamic that can be scaled per fractal, and depending hardware
- Render at half res on the periphery, full resolution at the center and blend the edges
- Compose the result
  - Strong vignette saves us some computation time

THE SHADING CHALLENGE



HOW DO PEOPLE RENDER FRACTALS?



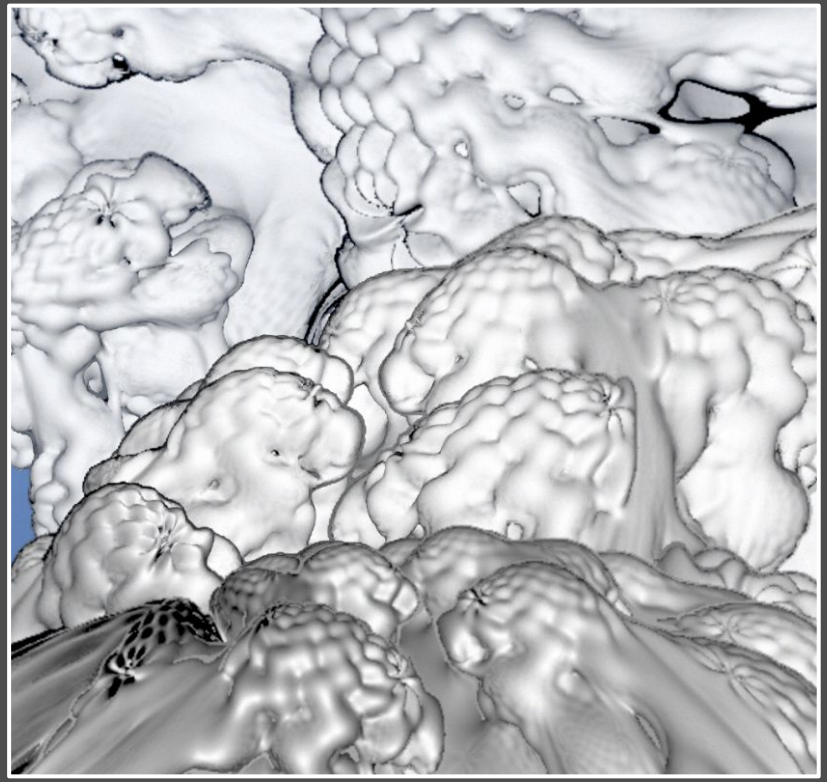
- How can we texture them?
  - We only have position and normal
- People generally use simple shading
  - Heavy use of shadows, occlusion and scattering to improve look
  - Heavy use of iteration glow
  - Orbit traps are not used cleverly
- We wanted to do something different

MORE CONSTRAINTS!

- Shadows are expensive!
- Normals are expensive!
- Occlusion is expensive!
- SSS is expensive!
- Our iteration glow is broken due to conemarching!

SHADING

- Experimented a lot with different ideas
  - Step the orbit traps to guide glowing elements
  - Warp the traps into themselves
  - Sample the fractal as the texture
    - Warp the fractal too!
  - Sample the derivative instead of the SDF
  - Use less iterations to fake SSS and AO
- Decided to design each fractal with a two color palette and heavy use of glowing sections.

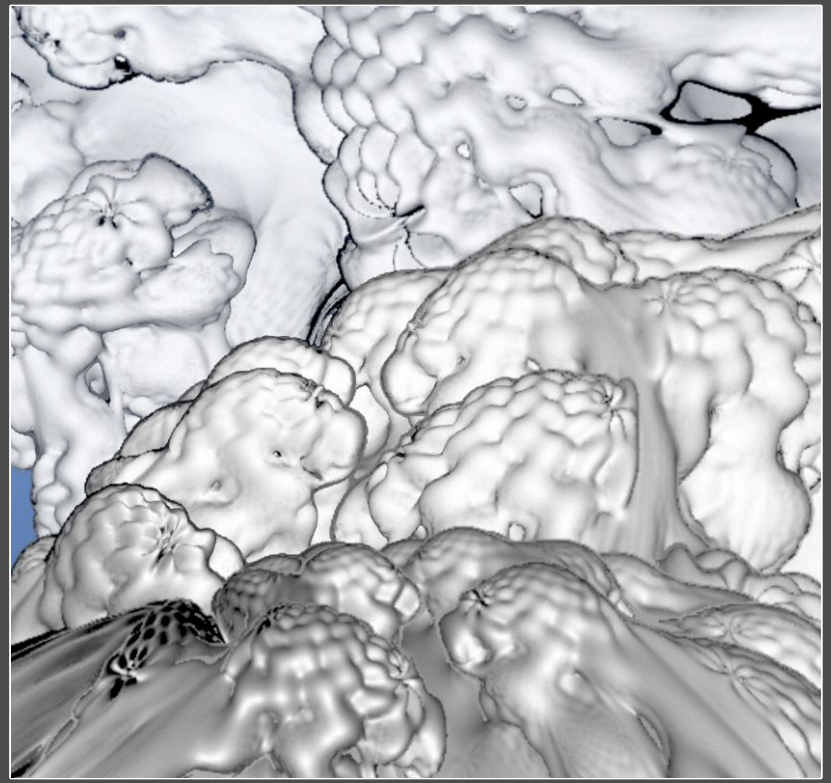


- Normal estimation generally uses finite differences

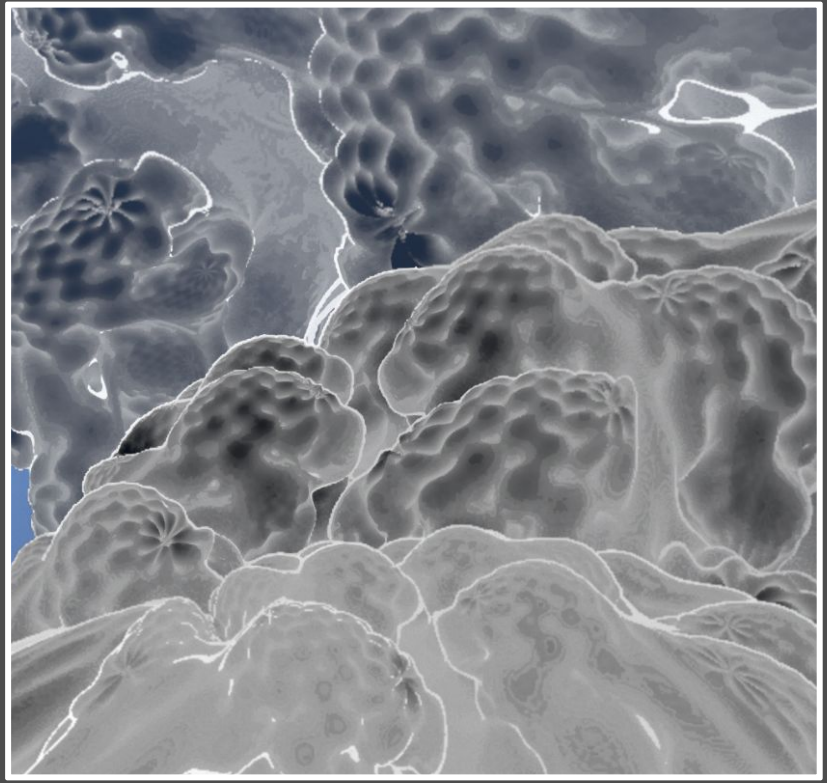
```
float3 normalEstimate(float3 p, float normalDistance)
{
    const float3 eps = float3(normalDistance, -normalDistance, 0.0);

    float dX = DEF(p + eps.xzz) - DEF(p + eps.yzz);
    float dY = DEF(p + eps.zxz) - DEF(p + eps.zyz);
    float dZ = DEF(p + eps.zzx) - DEF(p + eps.zzy);

    return normalize(float3(dX,dY,dZ));
}
```



- Normal estimation generally uses finite differences
- Requires 6 samples of the sdf
  - Can be reduced to 3 by losing some quality



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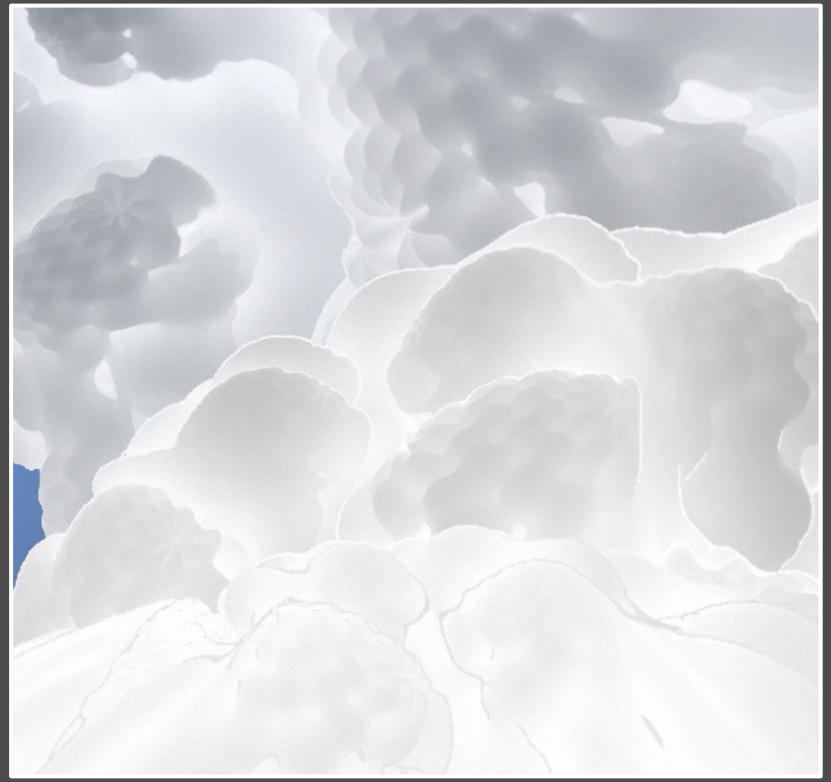
```
// Fast cosine estimation, reference: http://www.pouet.net/topic.php?which=7535&page=1
float estimateCosTheta(float3 pos, float3 lightDir, float eps)
{
    eps *= 2.25;
    float d = DEF(pos + lightDir * eps) / eps;
    return gain(d, .2);
}
```



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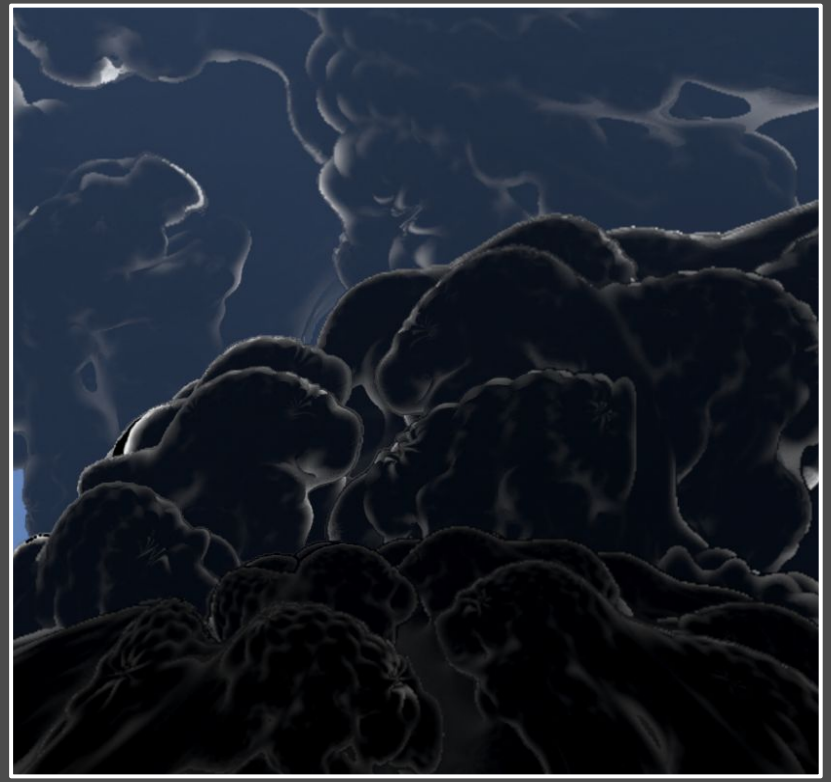
- Apply this trick to everything!
  - Reasonable fake AO!
  - Reasonable fake SSS!
  - Rim lighting?



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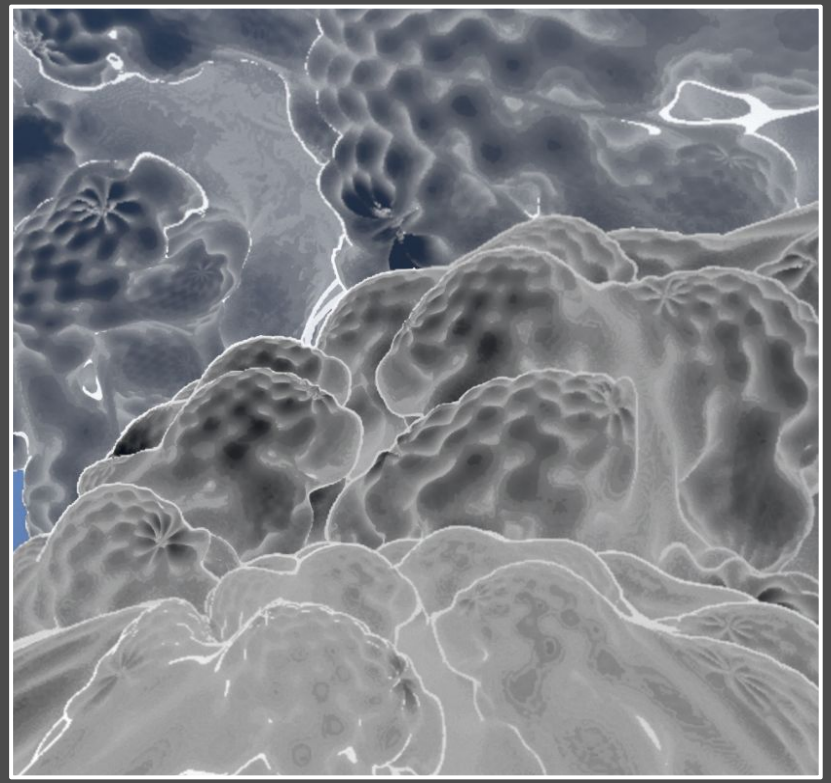

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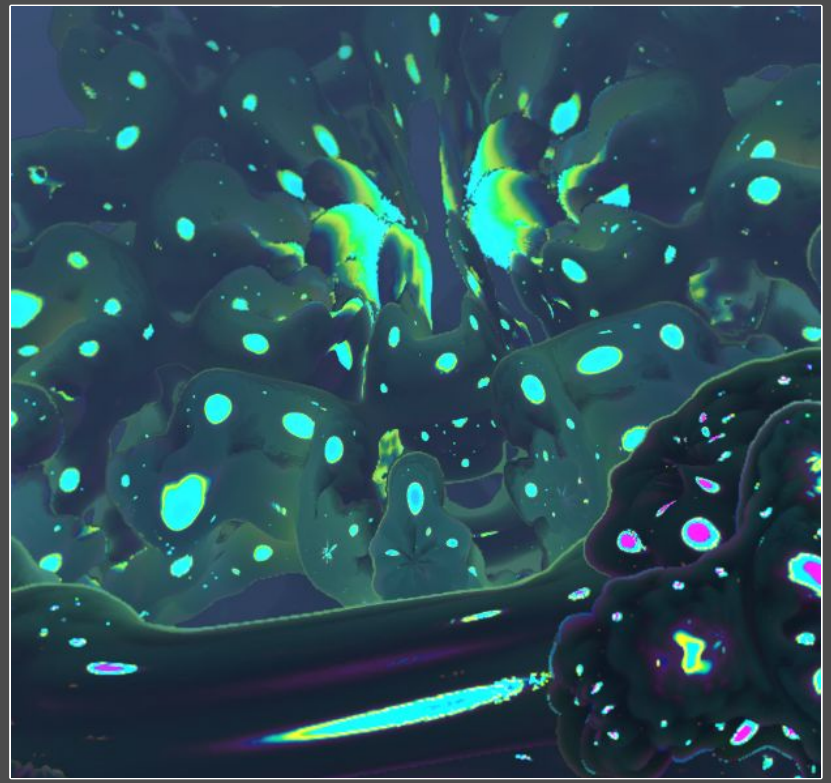
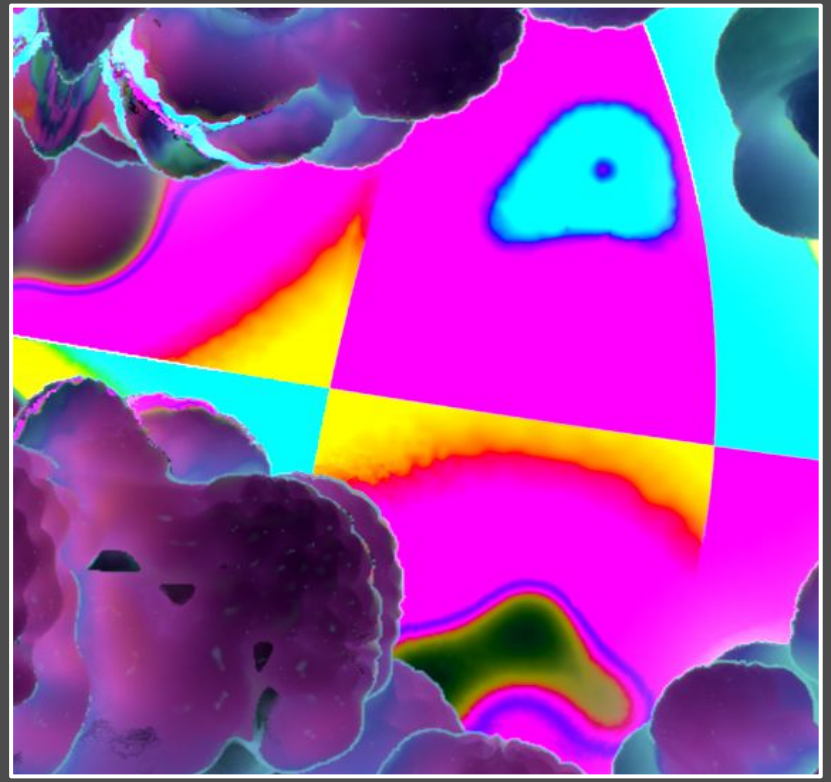
- Has some banding problems due to fractal epsilon
  - We still needed a proper normal for some fractals

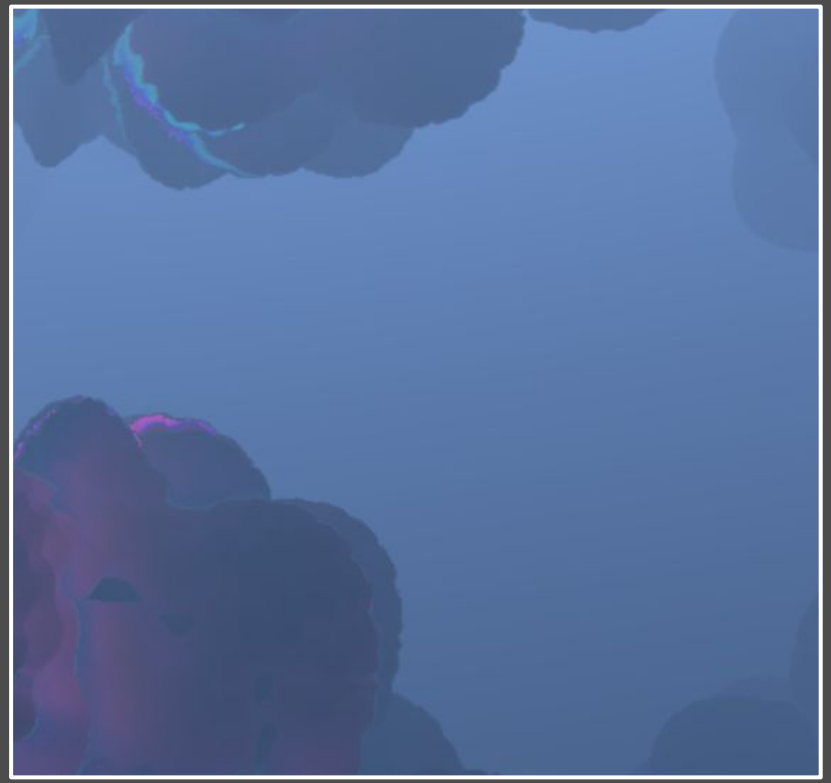


- Moving a little back to the camera instead generates a very interesting pattern
- Use an animated cosine palette that scrolls based on this function
- Heavy use of fake SSS
- Use of lower iteration Mandelbulb code for AO

```
75
76      float e = eps * 2.25;
77      float d = DEMandelbulb(pos + dir * e) / e;
78
```



- Don’t render very far

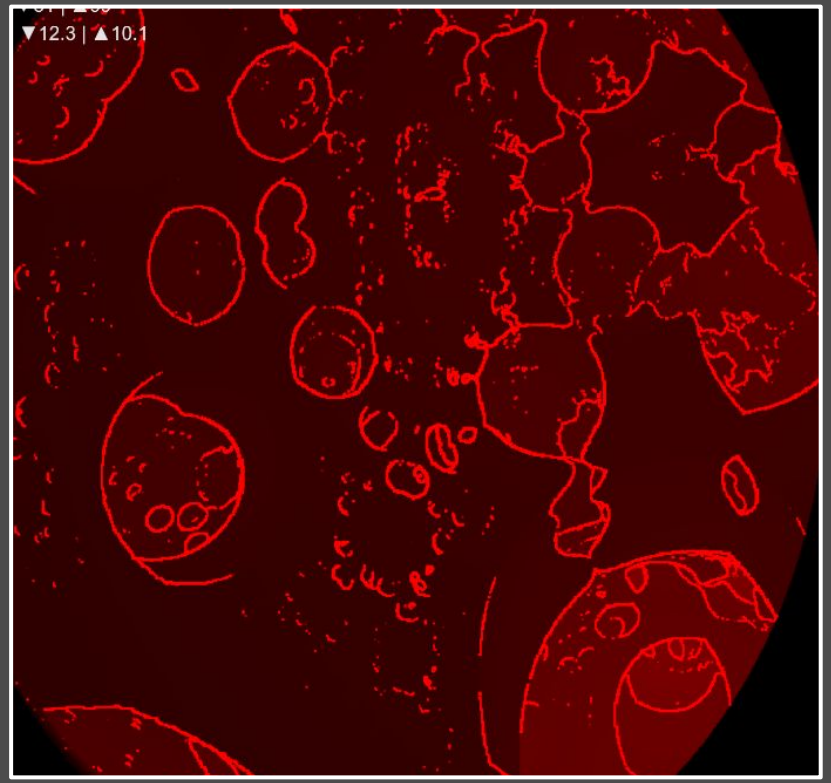


- Don’t render very far
- Use homogeneous scattering to hide it
  - This helps immersion, fortunately!

Acquiring Scattering Properties of Participating Media by Dilution
https://cseweb.ucsd.edu/~ravir/dilution.pdf

FUTURE WORK
(SHORT TERM)

- Temporal reprojection of depth estimation
- Reprojection of low frequency effects
- Use screen space normals to reduce shading complexity
  - Use lower quality shading on periphery
- Implement TAA + FXAA with the outlines provided by the stereo reprojection disparity



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FUTURE WORK
(LONG TERM)

- Implement stereo reprojection for shading (Oculus' approach)
- Optimize ray scheduling to maximize occupancy
  - **GPU Unchained (Timothy Lottes) from NVScene 2015**
- Experiment with low resolution voxel grid to accelerate depth estimation and other effects
- Alleviate strong aliasing artifacts

Thank you

coral-vr.com

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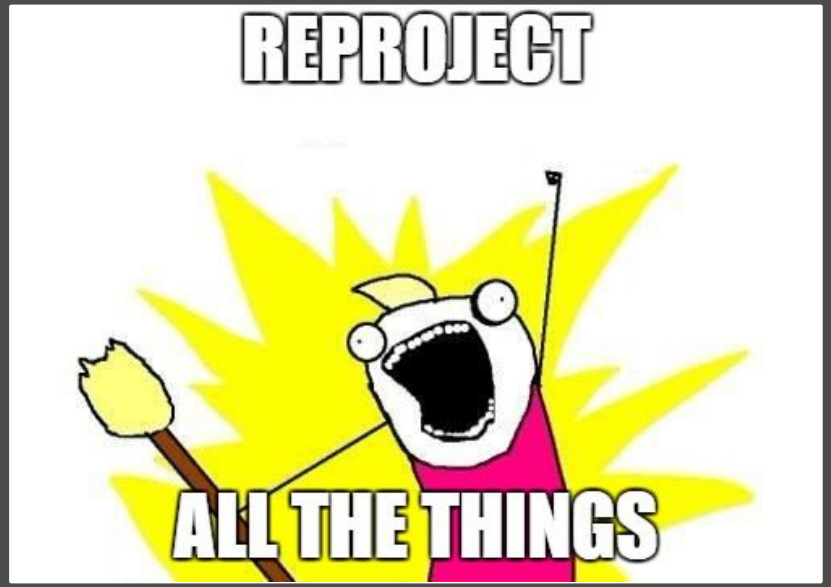
BONUS!



- We liked the reprojection results
- Can we reproject low frequency image effects?
  - Glow
  - Volumetric scattering (godrays)
- Still working on it!

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