Conemarching in VR
Developing a Fractal experience at 90 FPS

Johannes Saam
Mariano Merchante

FRAMESTORE
THE CONCEPT
THE CONCEPT

FRACTALS AND COLLISIONS
THE CONCEPT

FRACTALS AND COLLISIONS

RAYMARCHING AND VR
THE CONCEPT

FRACTALS AND COLLISIONS

RAYMARCHING AND VR

THE SHADING CHALLENGE
THE CONCEPT
THE CONCEPT

- Explore classic fractals in real-time VR
- Simple interaction model, sandbox feel
- Break a few rules!
Concept ○ Fractals ○ Collisions ○ Raymarching and VR ○ Shading tricks

HOW DO WE TRANSMIT SENSE OF SCALE?
Concept ○ Fractals ○ Collisions ○ Raymarching and VR ○ Shading tricks

HOW DO WE TRANSMIT SENSE OF SCALE?

THE LOCOMOTION CHALLENGE
**Concept**
- Fractals
- Collisions
- Raymarching and VR
- Shading tricks

**HOW DO WE TRANSMIT SENSE OF SCALE?**

- Scale the player’s eyes as they move around
HOW DO WE TRANSMIT SENSE OF SCALE?

- Scale the player’s eyes as they move around
- Make sure we smooth scale to prevent discontinuities

Concept
- Fractals
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- Make sure we smooth scale to prevent discontinuities
- Design shading such that there is enough size contrast
Concept ○ Fractals ○ Collisions ○ Raymarching and VR ○ Shading tricks

- Scale the player’s eyes as they move around
- 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
• Always move in the direction of your head...
• ... unless you prefer to strafe

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THE LOCOMOTION CHALLENGE
● Always move in the direction of your head...
● ... unless you prefer to strafe
● Velocity tied to scale and closest distance
● Option to rotate 90 degrees with fade
● Vignette intensity directly proportional to velocity and angular velocity.
FRACTALS AND COLLISIONS
Fractals

- Require a distance field to be marched
- Generally very expensive!
  - Usually have multiple iterations for a single estimation
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FRACTALS

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- Generally very expensive!
  - 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
We already use the fractal SDF for rendering
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We can use the same SDF for collisions!
  - R: distance, GBA: normal for bounce
- We already use the fractal SDF for rendering
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- Render a 1x1 texture and read it asynchronously (Thanks Unity!)
  - Prevent GPU stall due to VR context
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- Why not a compute shader?
  - Why not CPU?
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Render a 1x1 texture and read it asynchronously (Thanks Unity!)
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Why not a compute shader?
  ○ Why not CPU?

Predict a bit due to latency
FIRST STEPS: MANDELBULB
FIRST STEPS: Fractals ○ Collisions ○ Raymarching and VR ○ Shading tricks

- Famous 3D fractal developed by Daniel White and Paul Nylander
  - The fractalforums thread is amazing!
FIRST STEPS: **Fractals** ○ Collisions ○ Raymarching and VR ○ Shading tricks

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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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- Tweaked the formula to prevent these bubbles
  - Kept the maximum derivative as we iterate
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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
Concept ○ Fractals ○ Collisions ○ Raymarching and VR ○ Shading tricks

```cpp
float evaluateMandelbulb(in vec3 p, in bool conservative) {
    vec3 w = p;
    float m = dot(w, w);
    float dz = 1.0;
    vec3 J = vec3(0.2);
    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
Define a function that gives us the distance to a surface
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• 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!
Each step jump is proportional to the distance of the surface.
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Each step jump is proportional to the distance of the surface.
- 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
Each step jump is proportional to the distance of the surface.

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Preferred way to raymarch in modern approaches.
VIRTUAL REALITY CONSTRAINTS

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

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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
• Originally from the demoscene
  ○ Fractus by Fulcrum, Revision 2012

CONEMARCHING
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- Optimizing the number of iterations and passes is not trivial. Some emergent behaviour can appear!
Concept ○ Fractals ○ Collisions ○ **Raymarching and VR** ○ Shading tricks

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- 8 steps at highres
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- Two problems: depth estimation and shading
  - Maybe we can we reproject depth? Yes!
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Render the center eye with the conemarcher

Reproject to left and right eye
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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

// Iterate at different levels
let GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_0, 2, .2);
let GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_5, 4, .15);
let GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_3, 8, .075);
let GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_2, 4, .875);
let GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_1, 4, .075);
let GetReprojectedDistance(rayOrigin, rayDirection, t, _RaymarchingResultTex_0, 16, 0.025);
Original paper deals with rasterization and couldn’t fix the discontinuities

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

We can!
  - Just keep marching where there is a lot of stereo disparity
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
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We can!
  ○ Just keep marching where there is a lot of stereo disparity
  ○ Also, shift samples horizontally

Small artifacts, but can be masked
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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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- Now we can directly cut a huge part of the pipeline
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● Reprojection pass is usually fast
  ○ Performance improves proportionally to the conemarching pass
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- Now we can directly cut a huge part of the pipeline
- 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
Concept • Fractals • Collisions • Raymarching and VR • Shading tricks

- Still expensive to render the shading
Still expensive to render the shading

We don’t need that much detail on the periphery
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Still expensive to render the shading

We don’t need that much detail on the periphery

We want something dynamic that can be scaled per fractal, and depending on hardware

Render at half res on the periphery, full resolution at the center and blend the edges
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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!
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.
Concept  Fractals  Collisions  Raymarching and VR  Shading tricks

- Normal estimation generally uses finite differences

```c
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.zyx);
    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
- Normal estimation generally uses finite differences
- Requires 6 samples of the sdf
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- Iq proposed on pouet.net a way to fake diffuse lighting with only one sample

```c
float estimateCosTheta(float3 pos, float3 lightDir, float eps)
{
    eps *= 2.25;
    float d = DEF(pos + lightDir * eps) / eps;
    return gain(d, .2);
}
```
Normal estimation generally uses finite differences

Requires 6 samples of the sdf
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Iq proposed on pouet.net a way to fake diffuse lighting with only one sample

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

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 float e = eps * 2.25;
76 float d = DEMandelbulb(pos + dir * e) / e;
```
● Don’t render very far
Concept ○ Fractals ○ Collisions ○ Raymarching and VR ○ **Shading tricks**

- 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

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BONUS!
REPROJECT ALL THE THINGS!

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

- Can we reuse the previous frame’s distance estimation?
  - TAA deals with similar ideas, but only for shading
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- Can’t use simple eye reprojection technique because delta is both positional and rotational
  - Scatter vs gather
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| ● The conemarching passes serve as lower bounds  
  ○ So we can grab (dis)appearing objects! |
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- We’re still working on this!