SIGGRAPH 2020 S2020.SIGGRAPH.ORG THINK BEYOND

LARGE VOXEL LANDSCAPES ON MOBILE

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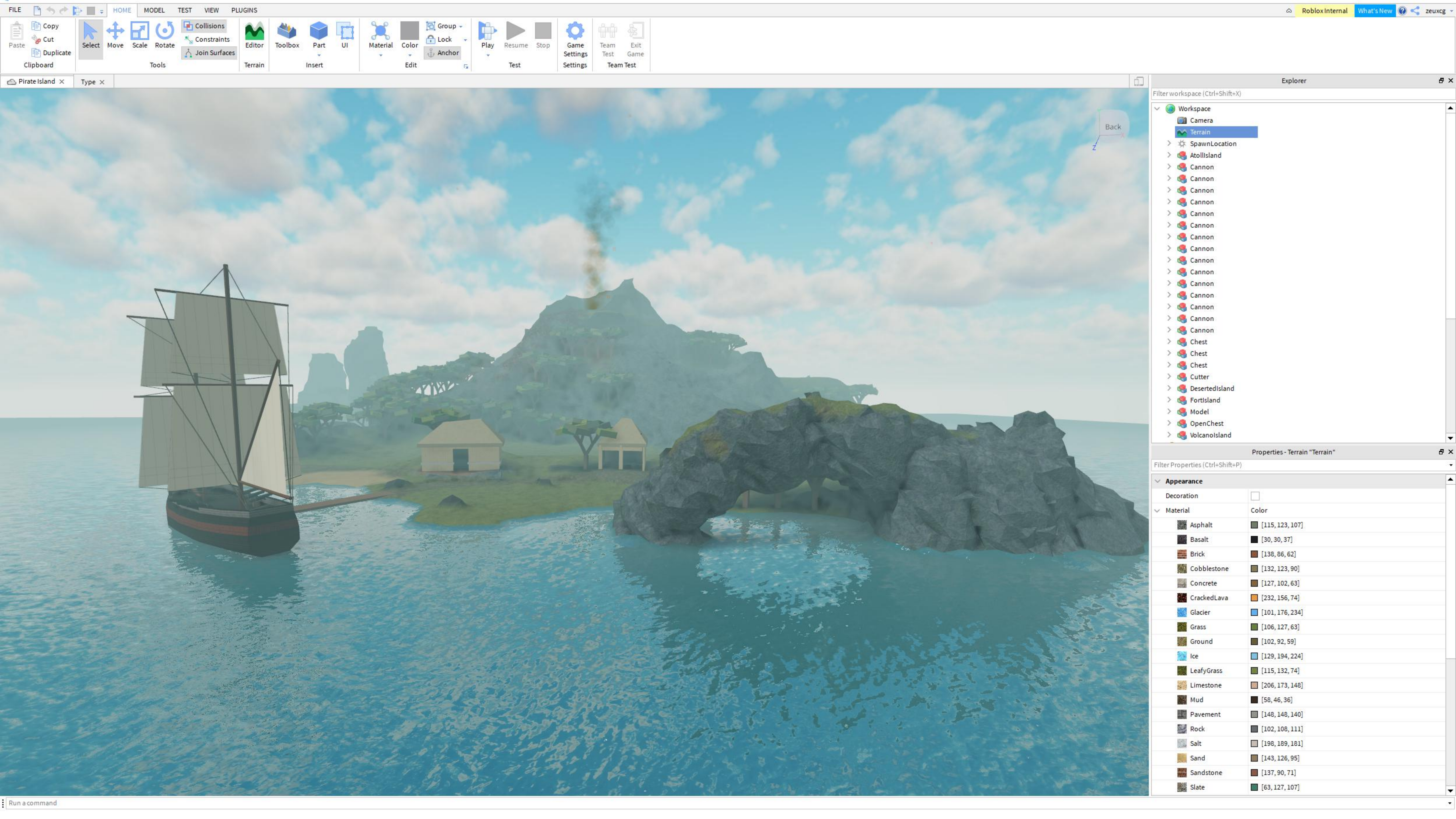
What is Roblox?

- Online multiplayer game creation platform
- All content is user generated
- 100M+ MAU, 5M+ CCU
- Windows, macOS, iOS, Android, Xbox One
- Direct3D 9/11, OpenGL 2/3, OpenGL ES 2/3, Metal, Vulkan


FILE
HOME
MODEL
TEST
VIEW
PLUGINS
Roblox Internal
What's New
zeuxcg
Paste
Copy
Cut
Duplicate
Clipboard
Select
Move
Scale
Rotate
Collisions
Constraints
Join Surfaces
Tools
Editor
Terrain
Toolbox
Part
UI
Insert
Material
Color
Group
Lock
Anchor
Edit
Play
Resume
Stop
Test
Game Settings
Settings
Team Test
Exit Game
Team Test
Pirate Island
Type
Back
Explorer
Filter workspace (Ctrl+Shift+X)
Workspace
Camera
Terrain
SpawnLocation
AtollIsland
Cannon
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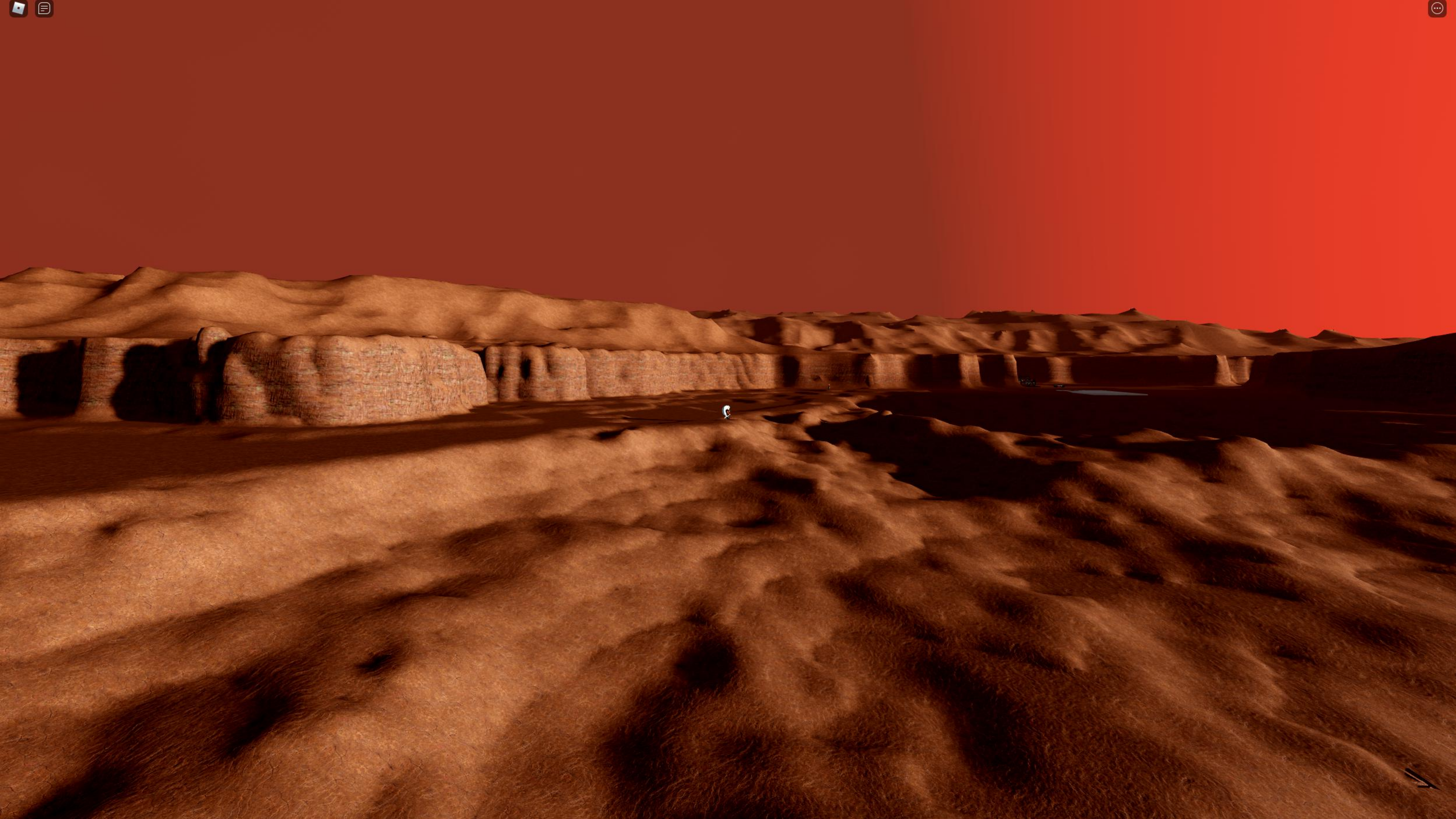
Cutter
DesertedIsland
FortIsland
Model
OpenChest
VolcanoIsland
Properties - Terrain "Terrain"
Filter Properties (Ctrl+Shift+P)
Appearance
Decoration
Material
Color
Asphalt [115, 123, 107]
Basalt [30, 30, 37]
Brick [138, 86, 62]
Cobblestone [132, 123, 90]
Concrete [127, 102, 63]
CrackedLava [232, 156, 74]
Glacier [101, 176, 234]
Grass [106, 127, 63]
Ground [102, 92, 59]
Ice [129, 194, 224]
LeafyGrass [115, 132, 74]
Limestone [206, 173, 148]
Mud [58, 46, 36]
Pavement [148, 148, 140]
Rock [102, 108, 111]
Salt [198, 189, 181]
Sand [143, 126, 95]
Sandstone [137, 90, 71]
Slate [63, 127, 107]
Run a command



Terrain system: goals

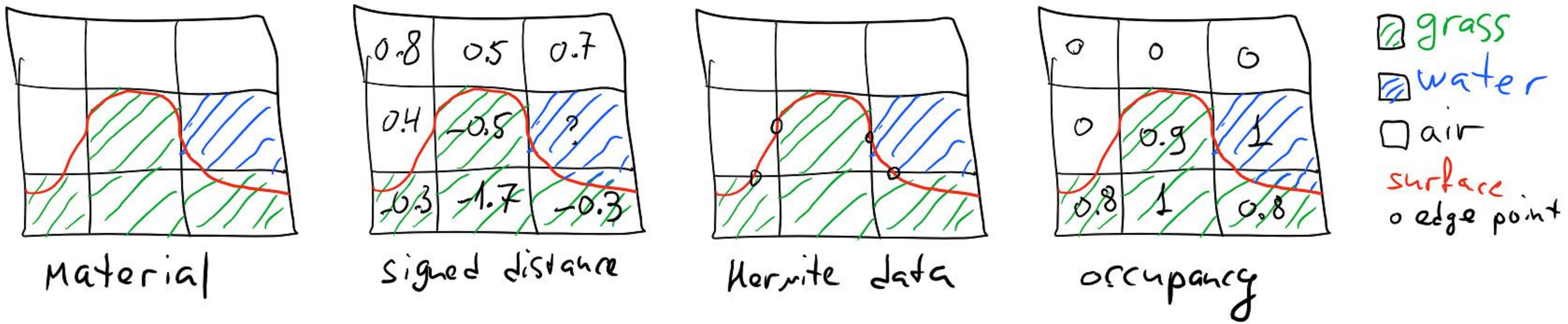
- No baking; any area can change at any point
- Fully 3D; caves, overhangs, bridges
- Scale up to reasonably large landscapes (10+ km^2)
- Scale down to very small devices (iPad 2)
- Easy to use tools and API
- Rich materials (semantics, not just visuals)

Voxel terrain

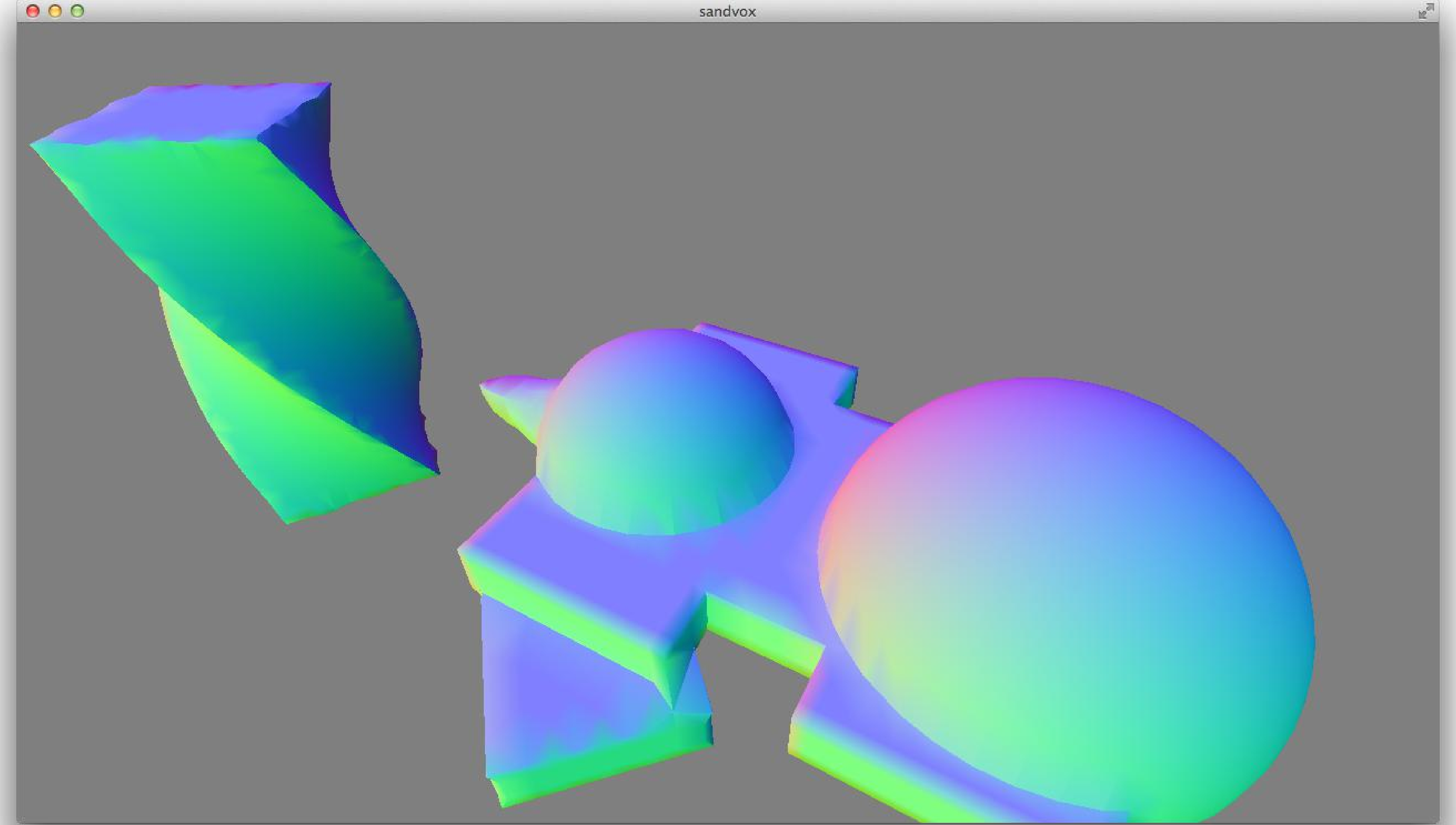
- Terrain is built out of voxels
- Voxels are sparse* and multiresolution*
- Each voxel has a material and occupancy
- All other controls are per material

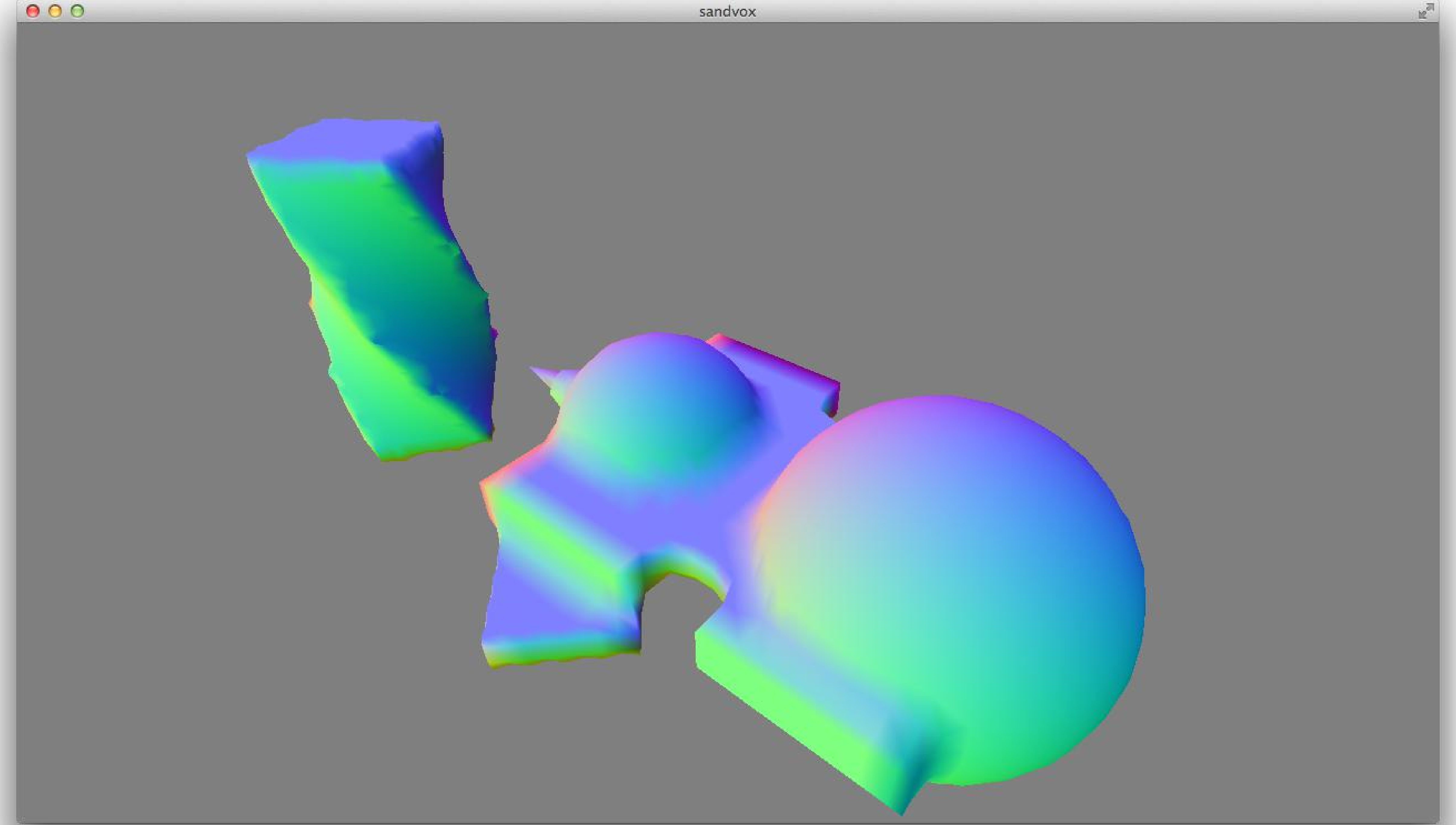
Voxel representation

- Early experiments with different types of data
- Occupancy over other representations for simplicity



ROBLOX


sandvox


sandvox

Voxel storage: grid

- Sparse set of fixed-size chunks
- Each chunk stores a mip pyramid (1^3 .. 32^3)
- Top levels can be skipped!
- Streaming mips in/out based on memory pressure

Voxel storage: mips

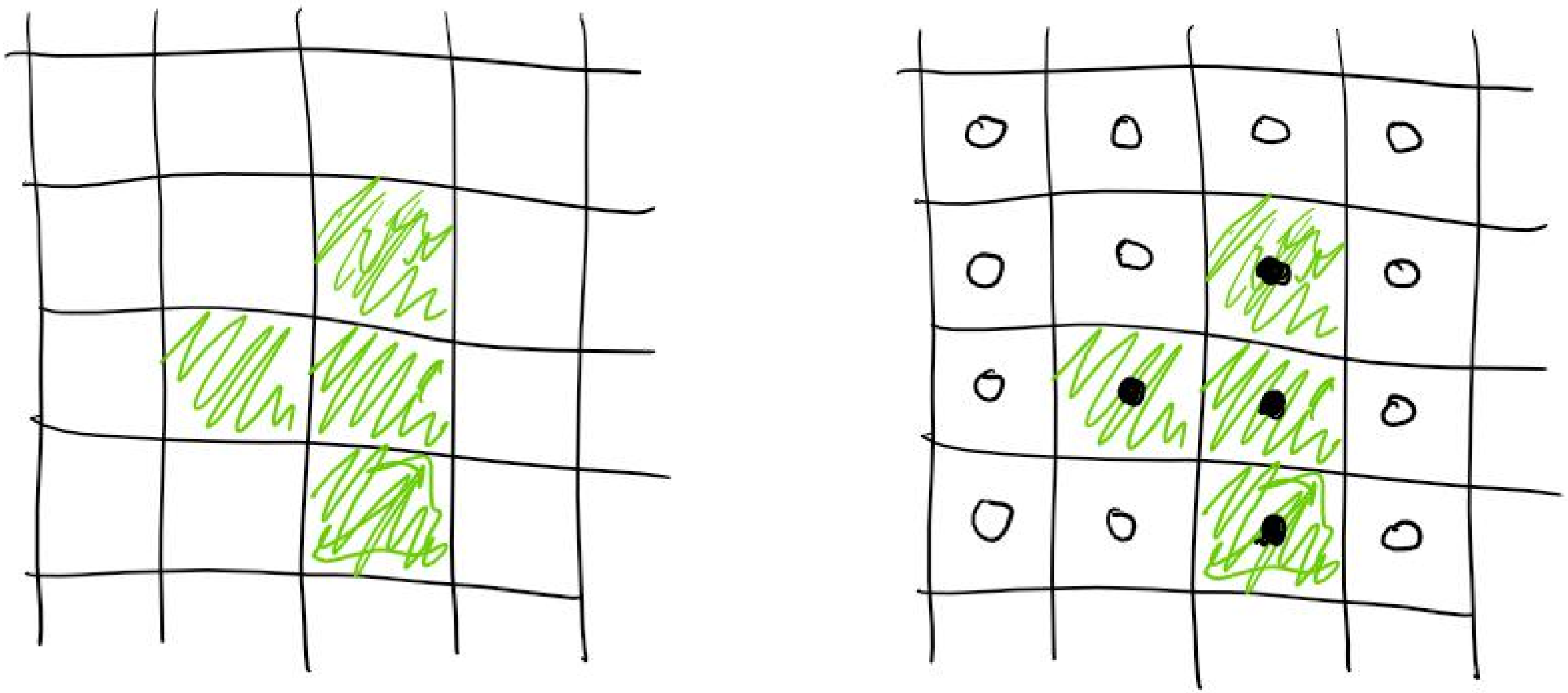
- Empty/full mip: 1 byte (material)
- Compressed rows: 1 byte (material) per row
- Uncompressed rows: 2 bytes (material + occupancy) per voxel
- Repack dynamically after voxel writes

Mesher: Marching Cubes?

- Non-uniform topology
- Needs tie breaking rules
- Non-intuitive and restrictive vertex placement

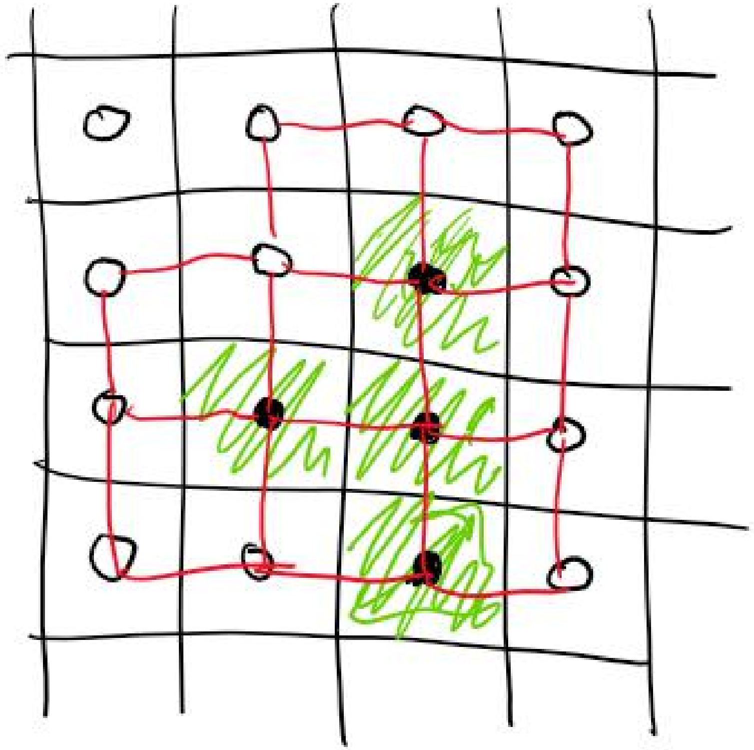
Mesher: dual method

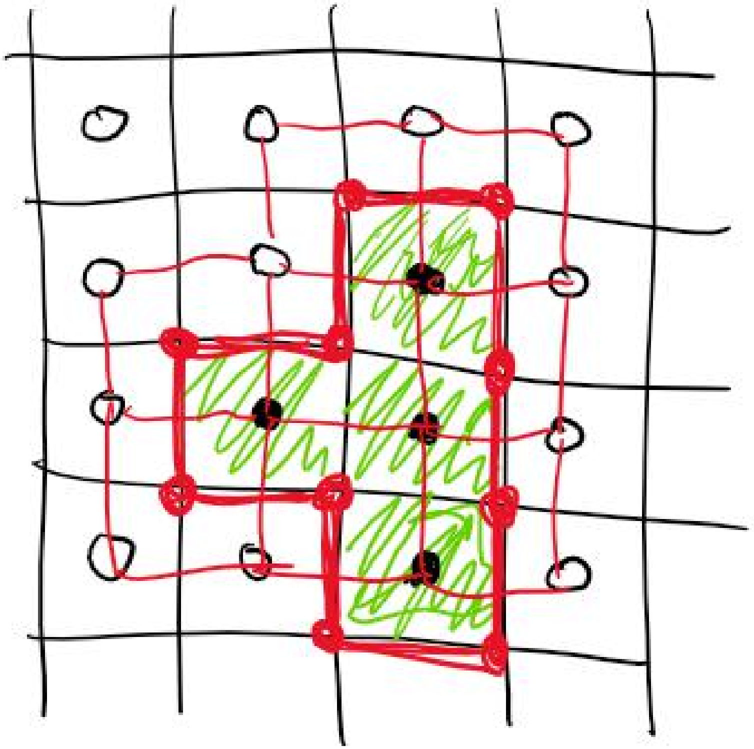
- Inspired by Dual Contouring and Naive Surface Nets
- Runs on CPU (carefully optimized)



Mesher: dual method

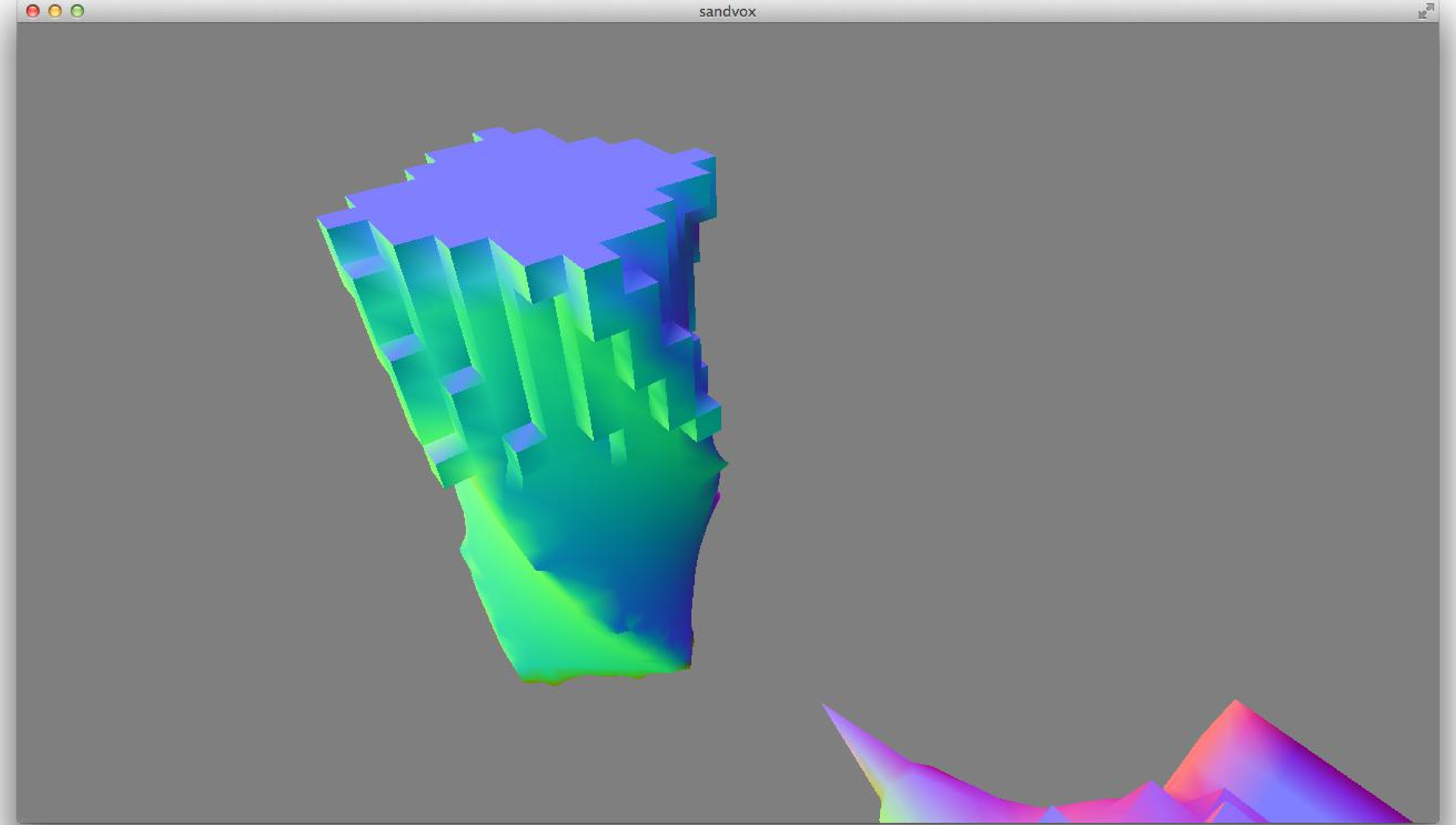
- One vertex per cell
- Neighboring cells are connected with quads





Mesher: vertex data

- For shading we decided to use 1 material per vertex
  - Dominant material based on occupancy from grid points
- Baseline position is computed as an average of edge points
  - See Naive Surface Nets
- Normal is computed as an average of triangle normals
- ... but we don't stop there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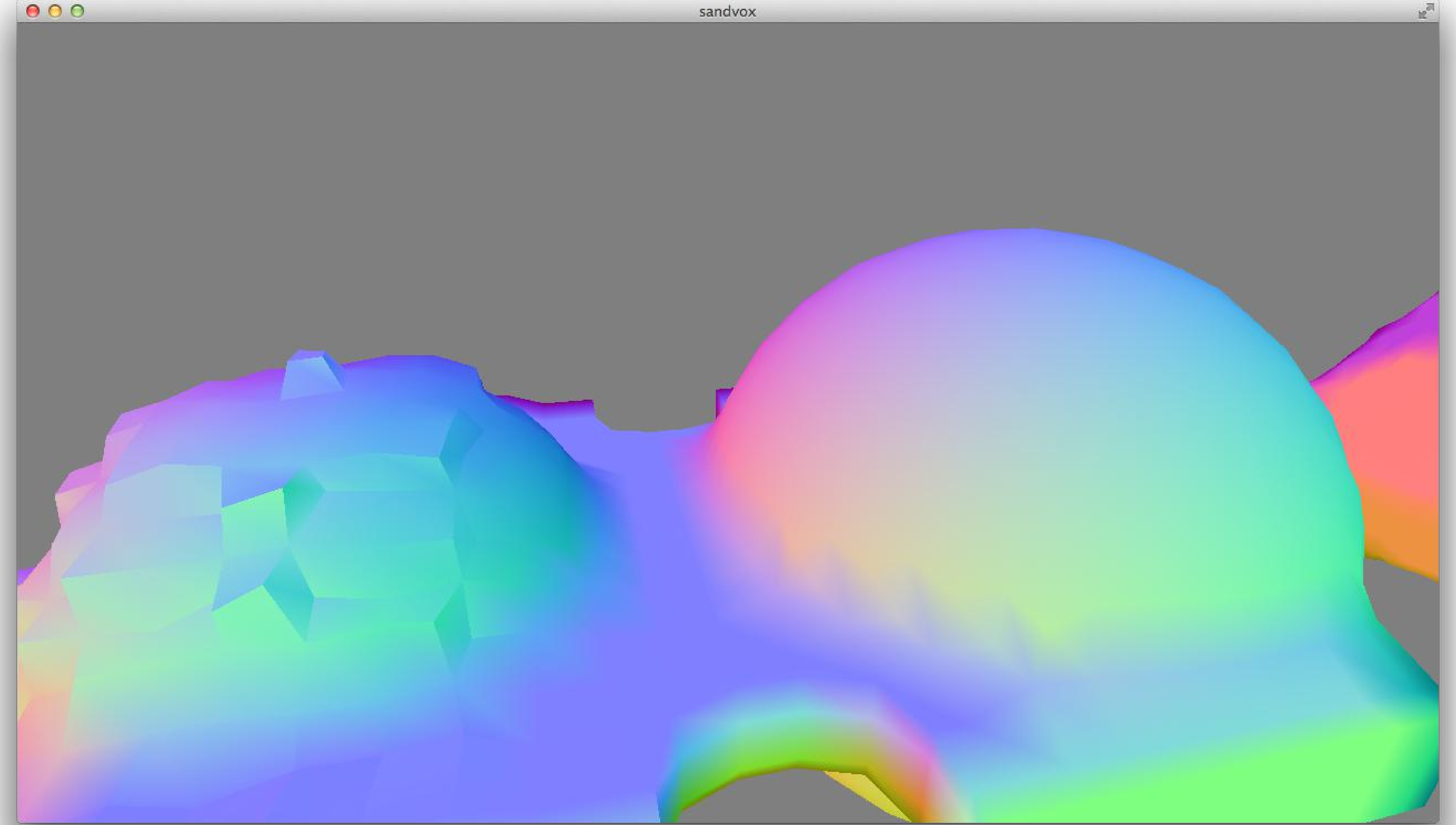

sandvox

Mesher: vertex deformation

- Materials define a procedural deformation:
  - Shift: pseudo-random offset
  - Cubify: lerp to box center
  - Quantize: round to a multiple of 1/K
  - Barrel: cubify along Y
  - ... and more (special math for water, etc.)
- Materials also define soft/hard edges for shading


Add
Subtract
Grow
Erode
Smooth
Flatten
Paint
Sea Level
Brush Settings
Base Size
5
Strength
1
Pivot Position
Bot
Cen
Top
Plane Lock
Snap to Grid
Ignore Water
Material Settings
Auto Material
Choose a material to apply
Left

Texture mapping

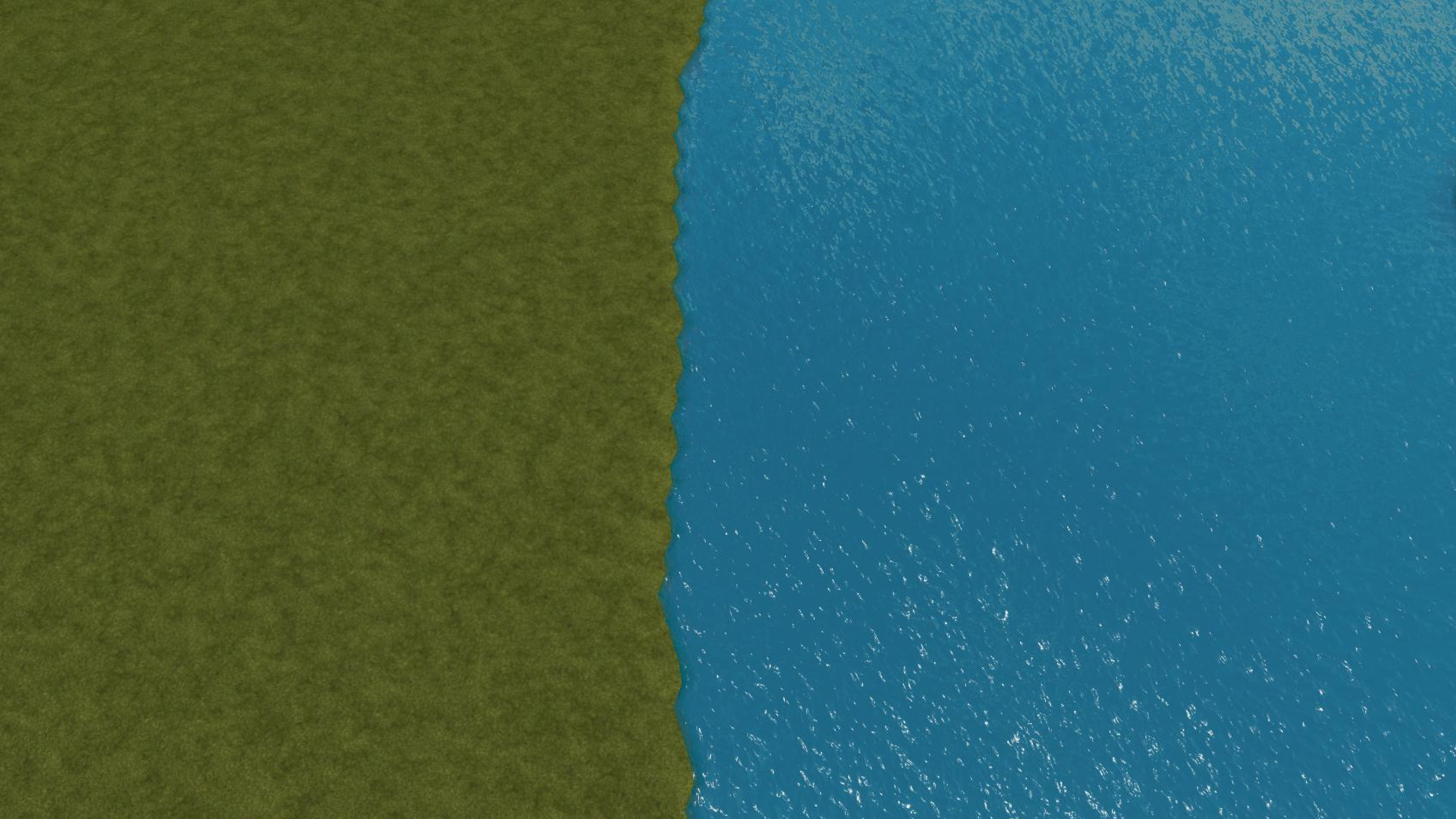
- Given a unique material per vertex, how do we shade a pixel?
- Sample textures from 3 materials, blend based on barycentrics
- Unclear how to project - perhaps triplanar?
- 3 material samples x 3 triplanar samples x 3 textures = 27 fetches
- ... no.

Texture mapping: quilting

- Idea: SIGGRAPH 2011, Real-time Image Quilting by Hugh Malan
- For each vertex, we're going to sample material just once
  - Total samples: 3 on low quality (albedo), 9 on high quality (PBR)
- We're going to pick a projection plane to minimize distortion
  - Not quite triplanar, but can be close enough!
  - We pick one of 18 planes and encode plane id in vertex

Texture mapping: detiling

- After projecting position on the UV plane, we apply random xform
  - Shift and rotate based on per-vertex seed
  - Material controls the transformation
- When all 3 materials are the same, this hides tiling artifacts



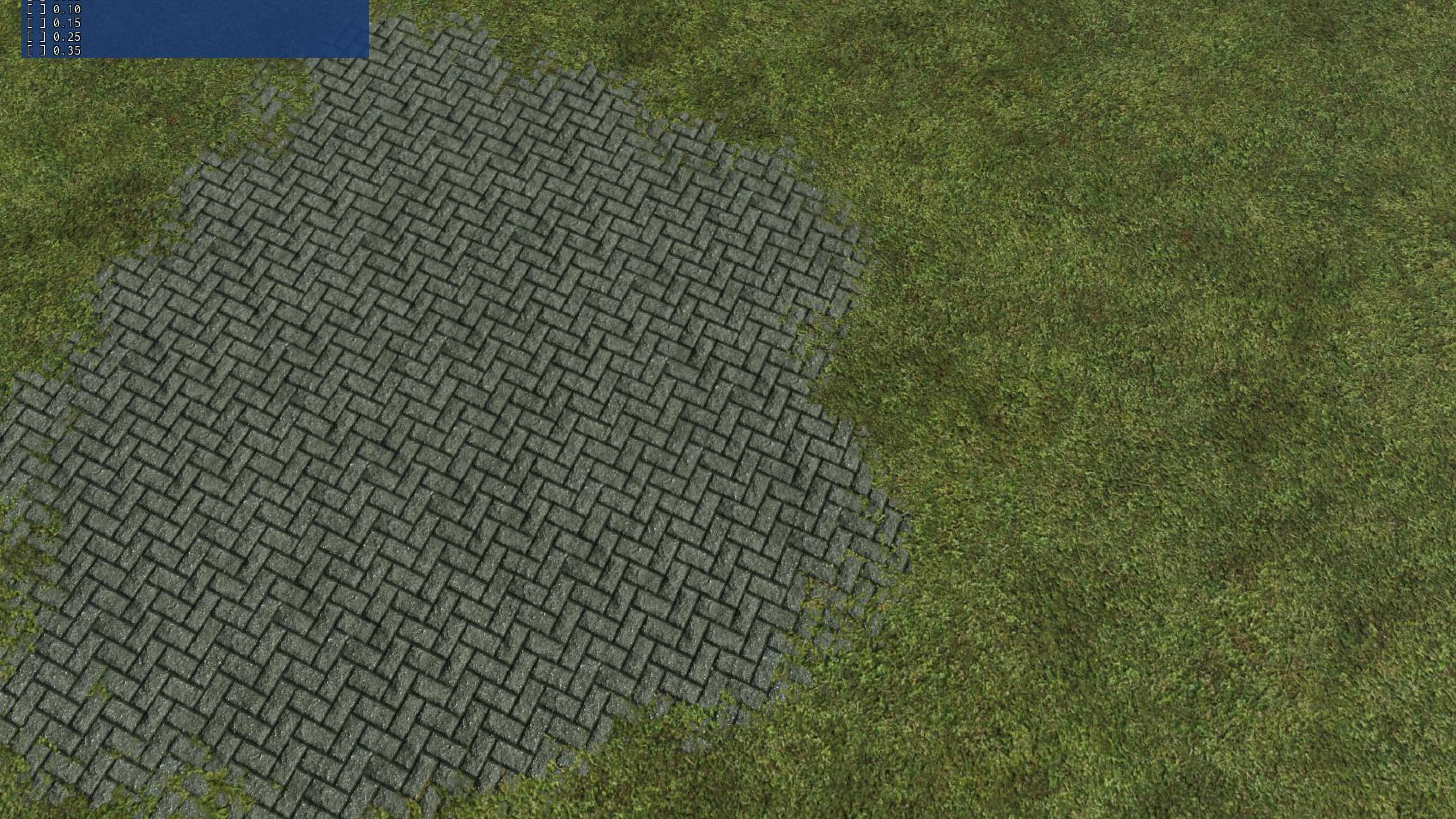
Texture mapping: scaling down

- Effectively each of 3 samples can act as:
  - Material sample (for 3-material blend)
  - Triplanar sample (for blend between material layers)
  - Detiling sample (to break up tiling)
- On low-quality we can only use one with largest weight
  - This results in sharp seams between materials

Texture mapping: scaling up

- Linear blend reduces contrast and results in unnatural blends
- Height-based blending (fixes blends)
- Histogram-preserving blending (fixes loss of contrast)


[ ] 0.10
[ ] 0.15
[ ] 0.25
[ ] 0.35


[ ] 0.10
[ ] 0.15
[ ] 0.25
[ ] 0.35

Vertex packing

- Unfortunately we need to store triangle material information
- Experimented with GS, promising results - future is mesh shaders?

```
// 20 bytes/vertex
struct Vertex
{
    int16_t position[3];
    int16_t id;             // vertex index (1-3)
    uint8_t normal[4];      // xyz = normal, w = random seed 0
    uint8_t material0[4]; // xyz = layer index (0-?), w = random seed 1
    uint8_t material1[4]; // xyz = normal segment (0-17), w = random seed 2
};
```

Draw calls

- On OpenGL ES draw calls are pretty expensive
- All material layers are packed into an atlas or texture array
- Single draw call per chunk
  - Nice side effect: material choice doesn't affect performance!
- Minimal setup per draw
  - Just need to update one uniform and vertex/index buffers

Level of detail

- We have to vary geometric detail for performance
- We also don't always have top mip available!
- Use octree to store render representation
- Split leaves into 2^3 when up close, merge leaves when far away
- Leaf size is 16^3 voxels (typically 500-1000 triangles)

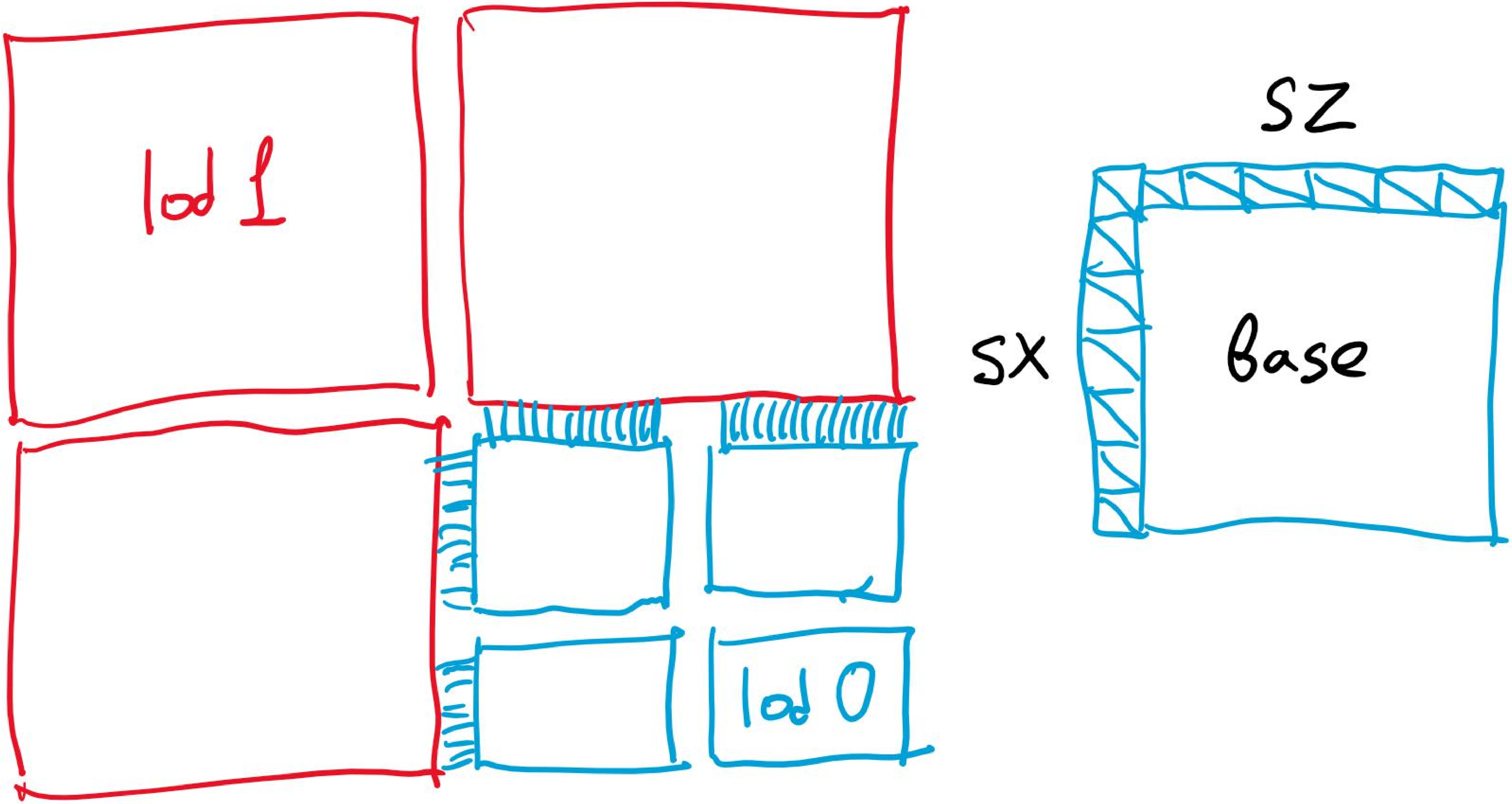
Level of detail: stitches

- Each node uses the meshing algorithm on a voxel mip
- We need to stitch geometry for neighboring chunks together
- Ideally, we'd generate triangles to match...
  - See "Dual Contouring of Hermite Data"
- ... but this is expensive and complicated

ROBLOX

Level of detail: skirts

- Instead, we generate extra overhang geometry
- Just one extra triangle is enough!
- An extra layer of voxels, patched to produce better skirts
- To avoid artifacts, we apply depth bias to skirt geometry
  - This makes sure skirts are only visible in gaps
- This is cheap enough to generate for every chunk



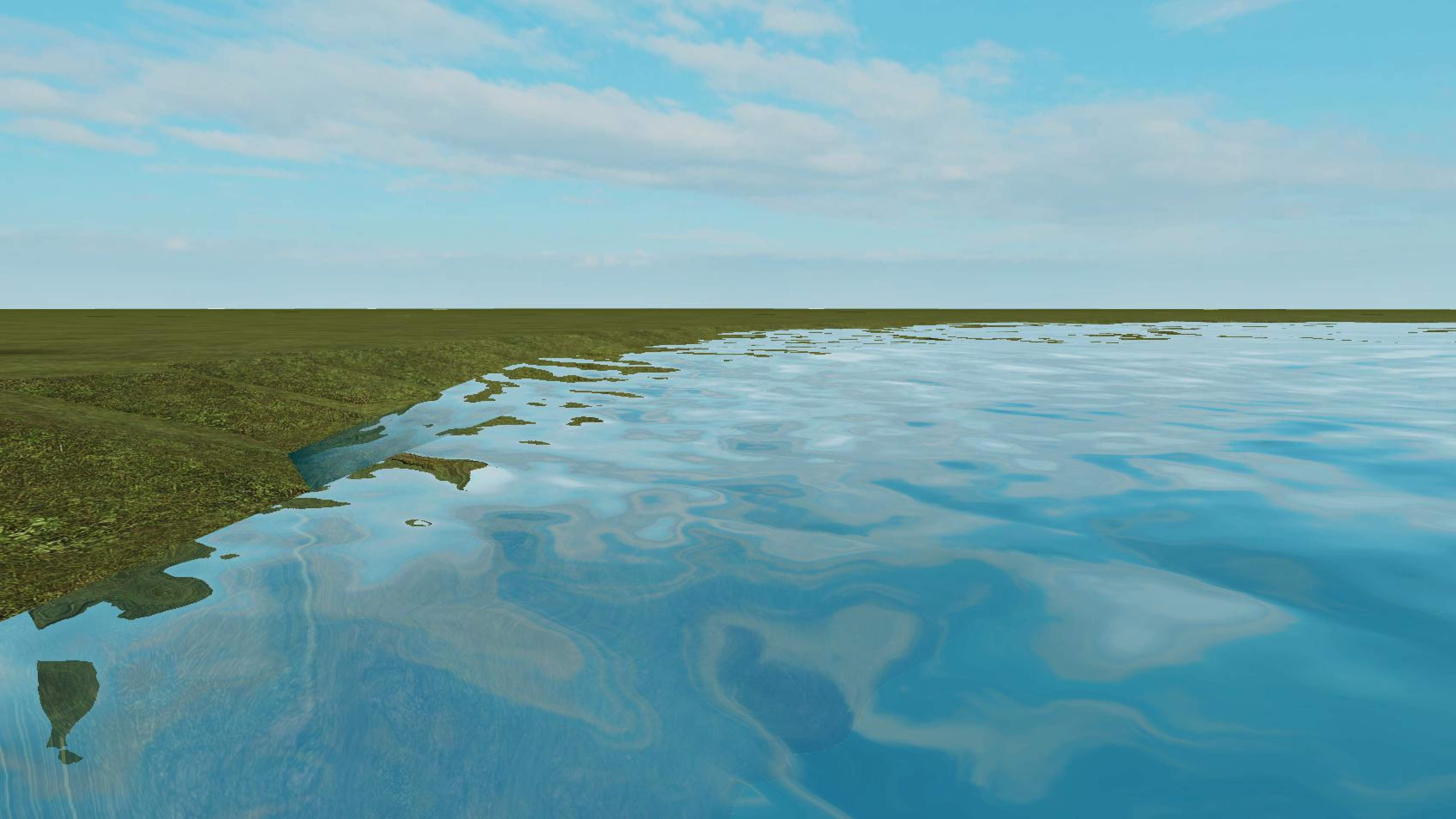
lod 1
SZ
SX
Base
lod 0

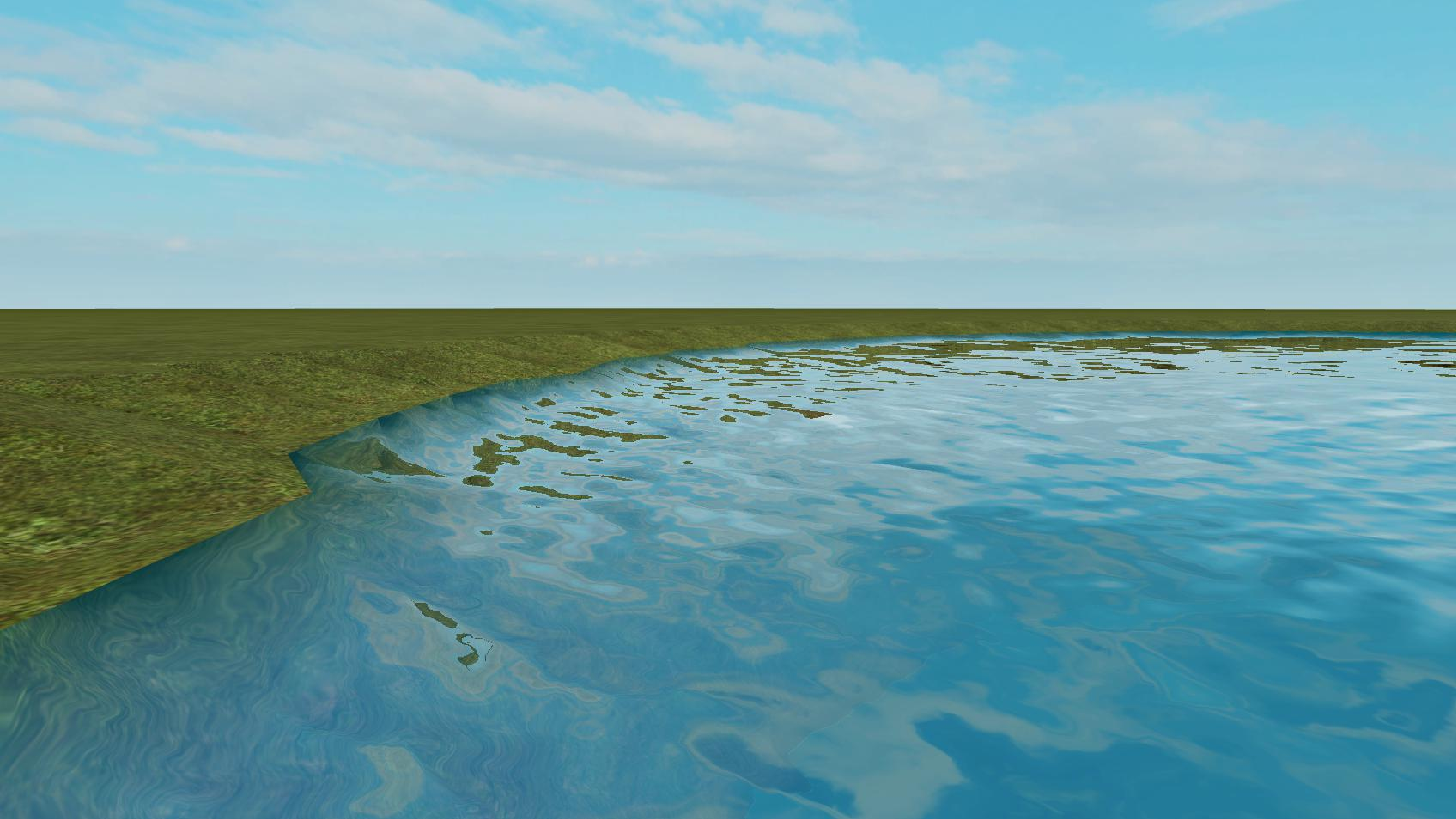
Level of detail: stitch rendering

- Conveniently, each chunk has up to 3 stitches to render
- … and Y stitch is almost never used
- Special index buffer layout: [stitchX] [base] [stitchZ] [stitchY]
- Single draw call to render base with any XZ stitches!
- Stitch vertices tagged in vertex data to apply depth bias in VS

Water

- Water is translucent and therefore needs special care...
- We mesh solid-air, solid-water and water-air interfaces
  - Done during a single meshing pass
- Water has special material-aware deformer to avoid bulging
- Water geometry is rendered separately



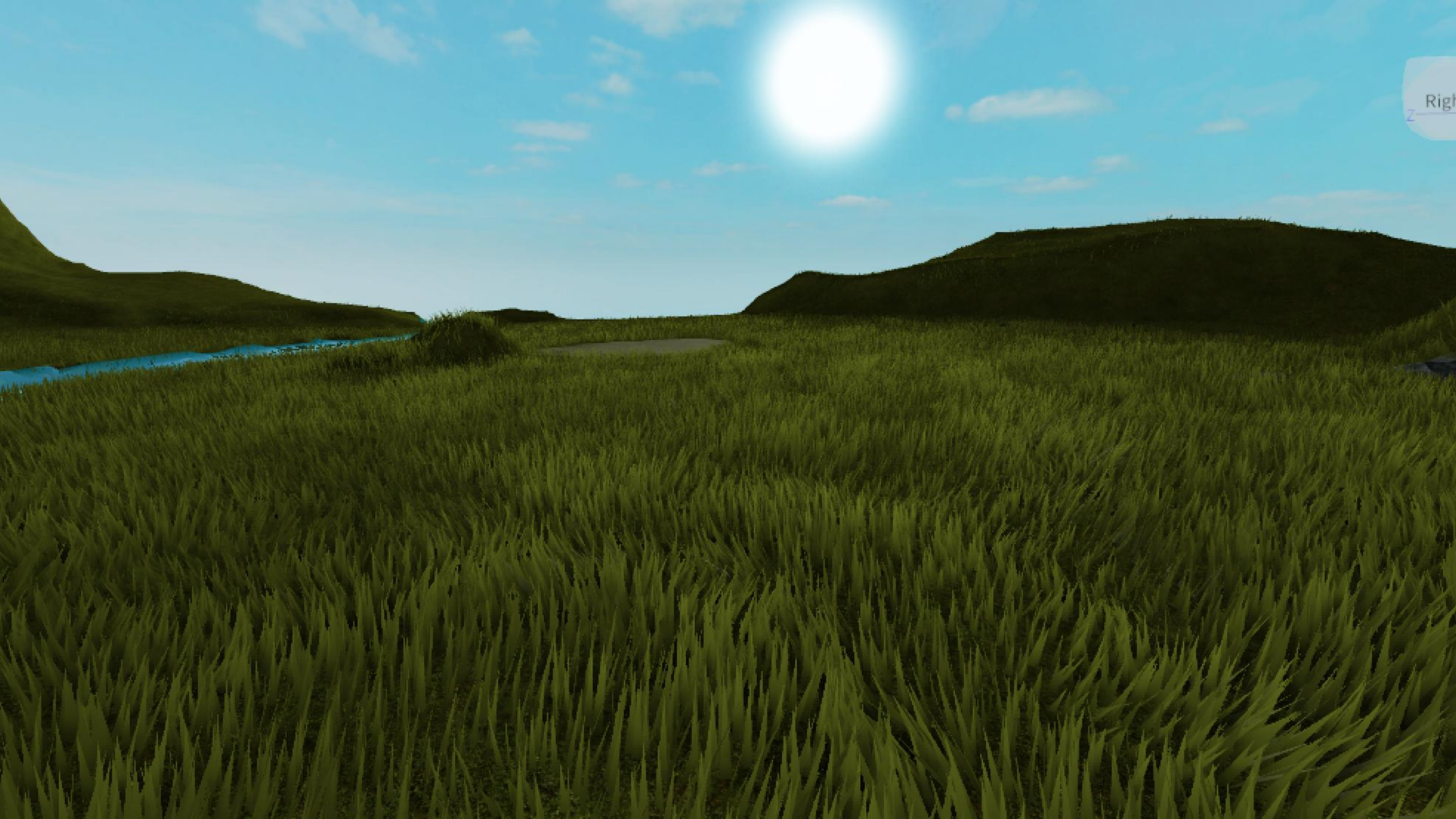


Water rendering

- Scrolling tiled animated normal maps (with detiling)
- Geometric waves
- Underwater fog
- On desktop:
  - Screen-space refraction
  - Screen-space reflection with 8-tap ray trace
- Future: better shorelines

Grass

- How can we make materials even smarter?
  - Future: higher fidelity geometric shaping?
  - Present: clutter
- Experimented with card-based and geometric grass
- Geometric grass was noticeably faster on tilers



Grass rendering

- 3-5 vertices per grass blade (level of detail)
- Grass points placed using vertex seeds (stable randomness)
- Very custom shading to "approximate" the look
  - Wrap diffuse
  - More translucency-related ~~hacks~~math
  - Height-based gradient for diffuse / specular


SAMSUNG
DUOS

Future work

- Higher fidelity geometry
- Higher fidelity shading
- Better texture mapping
- Scaling beyond 1B voxels

Thank you!