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Practical Metaballs and Implicit Surfaces

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Agenda

- The idea and motivation
- Implementation details
- Caveats & optimizations
- Where to go from here
- Conclusion

What are isosurfaces?

- Consider a function $f(x, y, z)$
  - Defines a *scalar field* in 3D-space
- *Isosurface* S is a set of points for which

$$f(x, y, z) = const$$

- $f(x, y, z) = const$ can be thought of as an *implicit* function relating x, y and z
  - Sometimes called *implicit* surfaces

What are isosurfaces?

- $f(x, y, z)$ can come from
  - Scattered data array
  - Mathematical formula
- Isosurfaces are important data visualization tool
  - Medical imaging
  - Science visualization
  - Hydrodynamics
  - Cool effects for games!

Metaballs

- A particularly interesting case
- Use implicit equation of the form

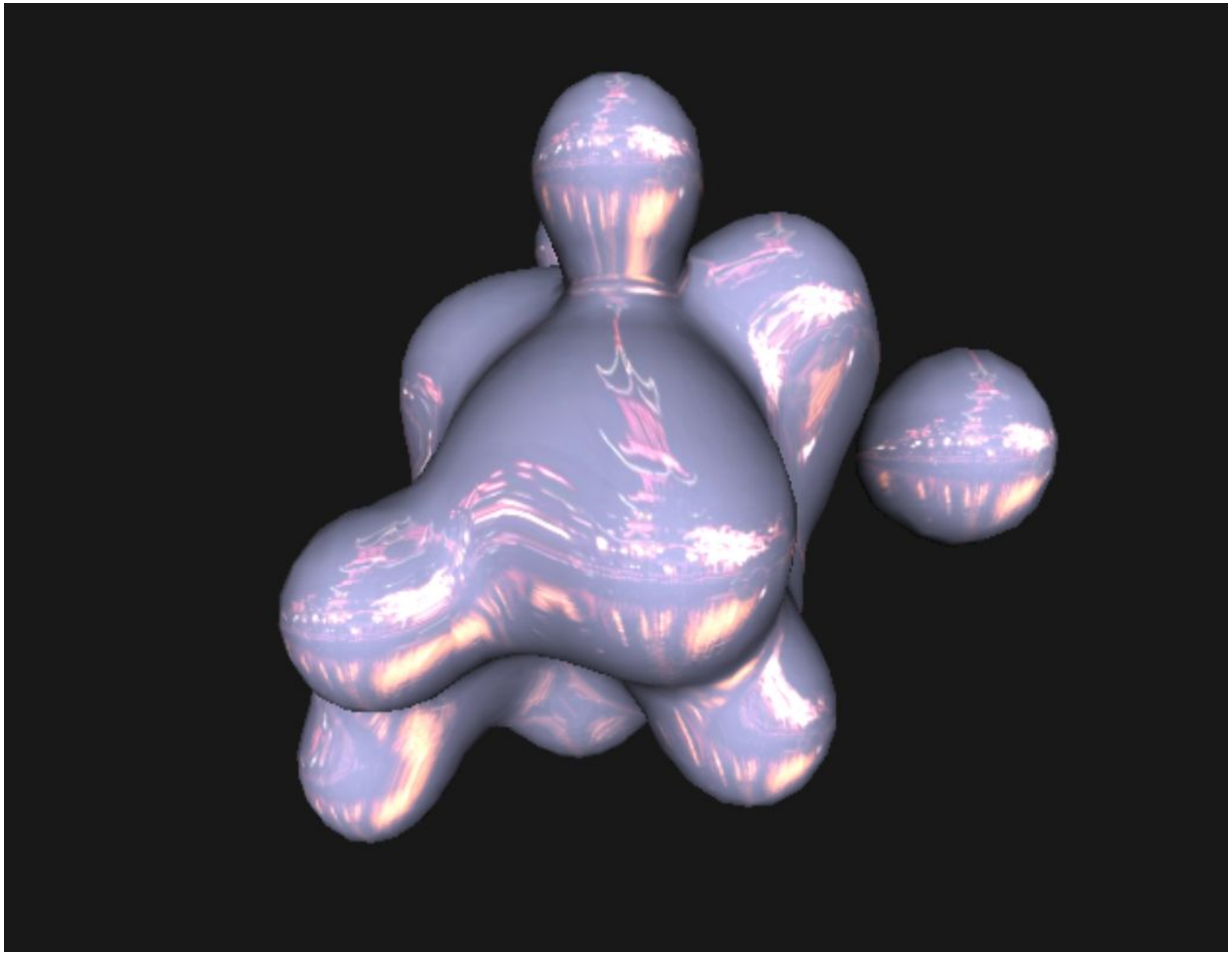
$$\sum_{i=1}^{N} \frac{r_i^2}{\left\|\mathbf{x}-\mathbf{p}_i\right\|^2} = 1$$

- Gradient can be computed directly

$$\mathbf{grad}(f) = -\sum_{i=1}^{N} \frac{2 \cdot r_i^2}{\left\|\mathbf{x}-\mathbf{p}_i\right\|^4} \cdot (\mathbf{x}-\mathbf{p}_i)$$

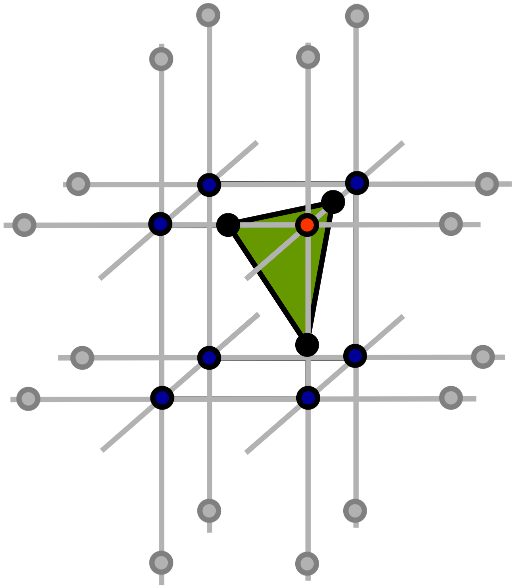
- Soft/blobby objects that blend into each other
  - Perfect for modelling fluids
  - T1000-like effects

Metaballs are cool!



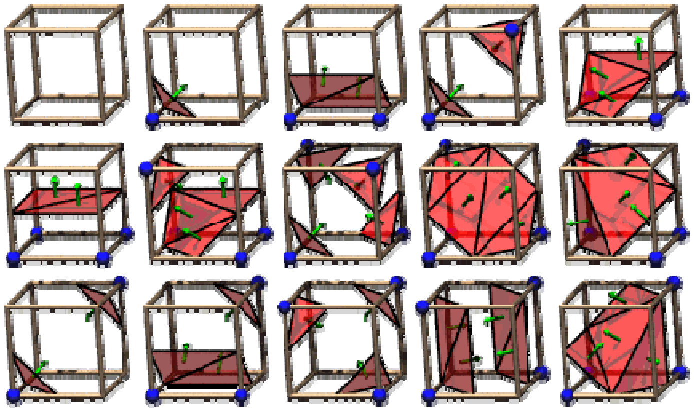
The marching cubes algorithm

- A well-known method for scalar field polygonization
- Sample f(x, y, z) on a cubic lattice
- For each cubic cell…
    - Estimate where isosurface intersects cell edges by linear interpolation
    - Tessellate depending on values of f() at cell vertices



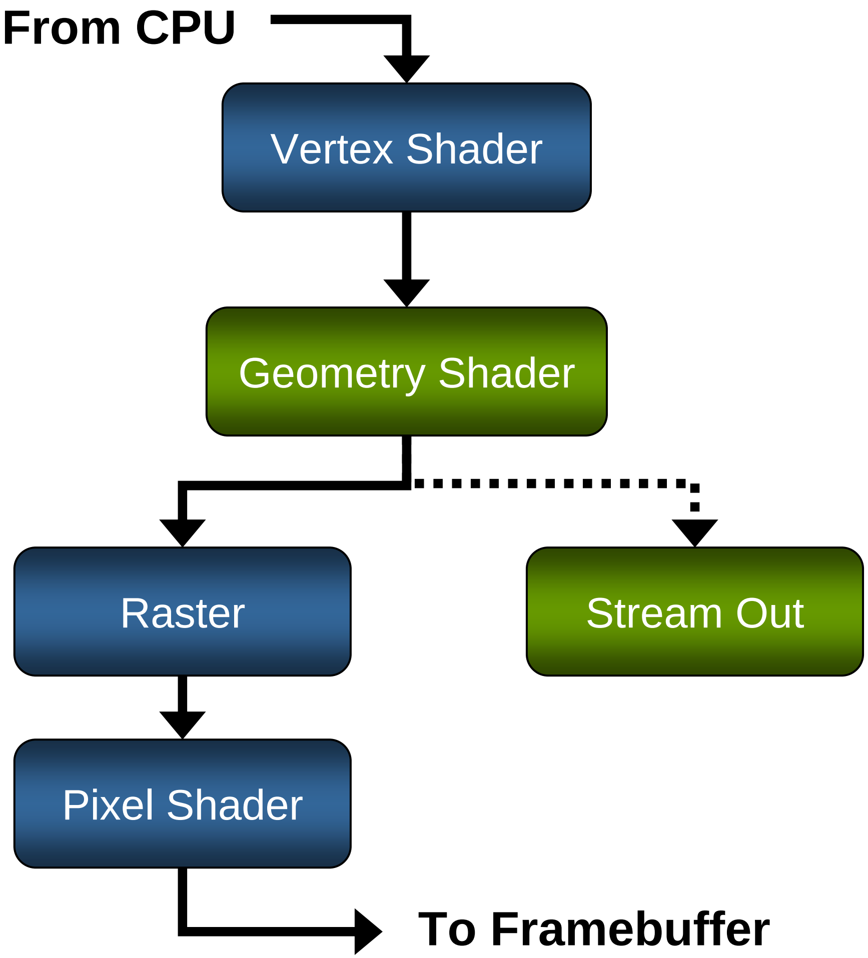
The marching cubes algorithm

- Each vertex can be either “inside” or “outside”
- For each cube cell there are 256 ways for isosurface to intersect it
    - Can be simplified down to 15 unique cases



The 15 Cube Combinations

Geometry shaders in DX10



From CPU

Vertex Shader

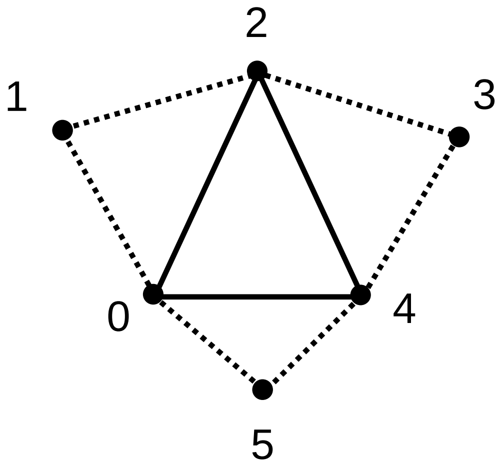
Geometry Shader

Raster

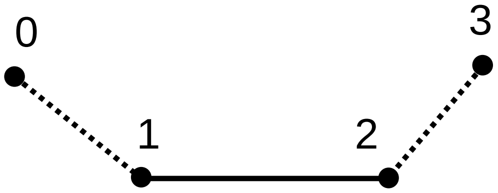
Stream Out

Pixel Shader

To Framebuffer

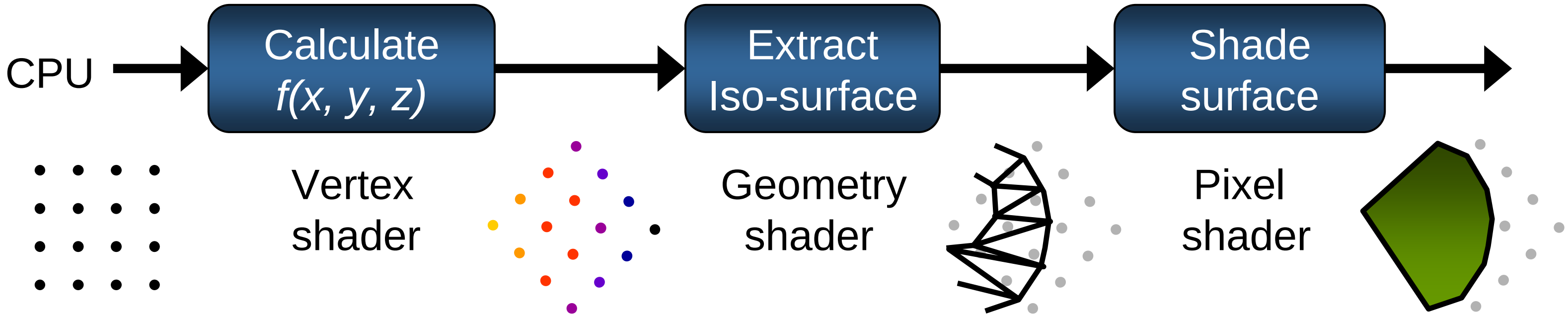


Triangles with adjacency



Lines with adjacency

Implementation - basic idea



CPU → Calculate *f(x, y, z)* → Extract Iso-surface → Shade surface →

Vertex shader

Geometry shader

Pixel shader

- App feeds a GPU with a grid of vertices
- VS transforms grid vertices and computes f(x, y, z), feeds to GS
- GS processes each cell in turn and emits triangles

A problem…

- Topology of GS input is restricted
  - Points
  - Lines
  - Triangles
  - with optional adjacency info
- Our “primitive” is a cubic cell

  Need to input 8 vertices to a GS

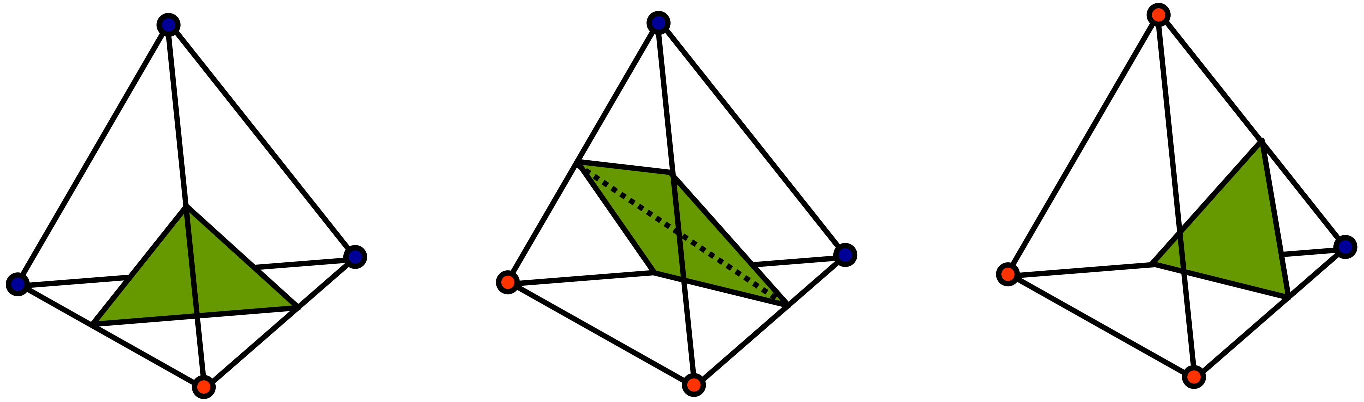
  A maximum we can input is 6 (with triangleadj)

Solution

- First, note that actual input topology is irrelevant for GS
  - E.g. lineadj can be treated as quad input
- Work at tetrahedra level
  - Tetrahedron is 4 vertices - perfect fit for lineadj!
- We'll subdivide each cell into tetrahedra

Marching Tetrahedra (MT)

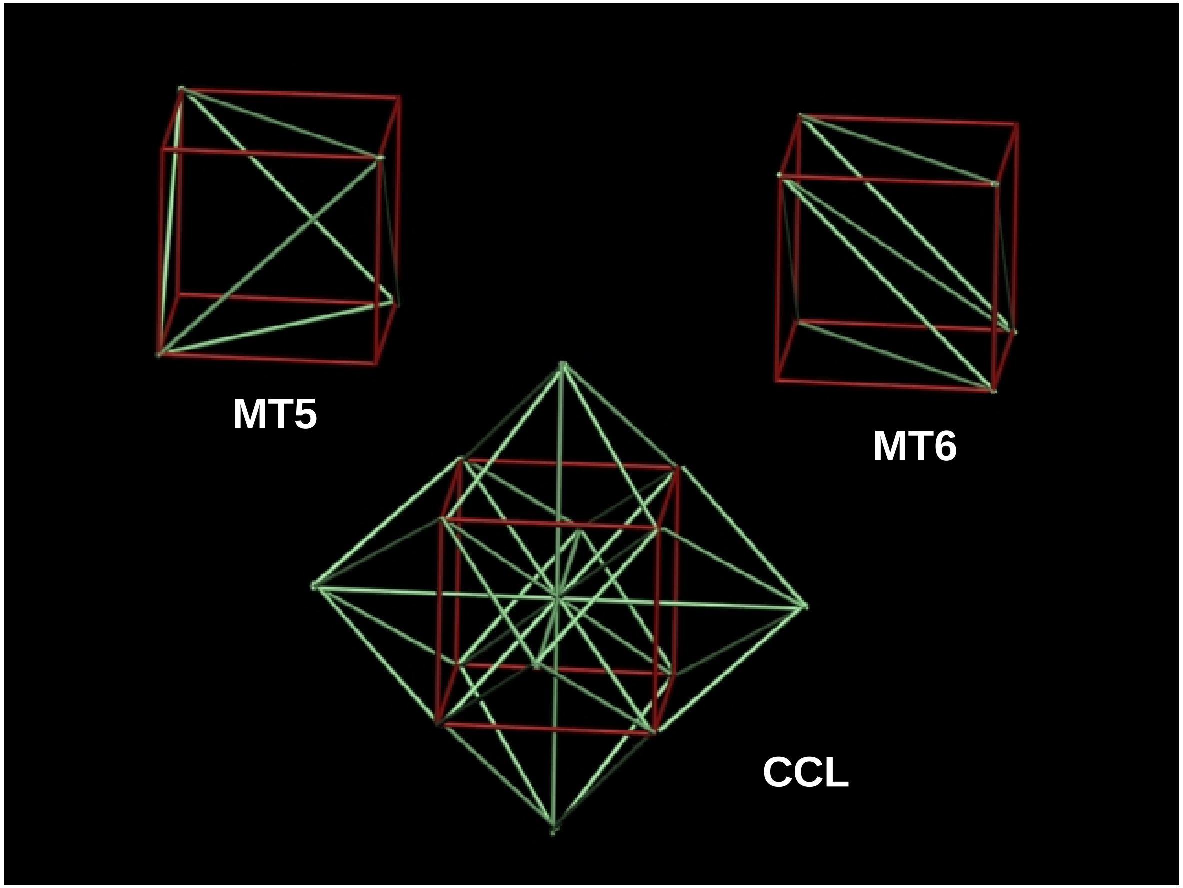
- Tetrahedra are easier to handle in GS
  - No ambiguities in isosurface reconstuction
  - Always output either 1 or 2 triangles



Generating a sampling grid

- There's a variety of ways to subdivide
  - Along main diagonal into 6 tetrahedra – MT6
  - Tessellate into 5 tetrahedra – MT5
  - Body-centered tessellation – CCL
- Can also generate tetrahedral grid directly
  - AKA simplex grid
  - Doesn't fit well within rectilinear volume

Sampling grids



Sampling grids comparison

	Generation Complexity	Sampling effectiveness	Regularity
MT5	Med	Med	Low
MT6	Low	Med	Low
CCL	High	High	Med
Simplex	Low	Med	High

VS/GS Input/output

```
// Grid vertex
struct SampleData
{
   float4 Pos : SV_POSITION;      // Sample position
   float3 N : NORMAL;             // Scalar field gradient
   float Field : TEXCOORD0;       // Scalar field value
   uint IsInside : TEXCOORD1;     // “Inside” flag
};

// Surface vertex
struct SurfaceVertex
{
   float4 Pos : SV_POSITION;      // Surface vertex position
   float3 N : NORMAL;             // Surface normal
};
```

Vertex Shader

```
// Metaball function
// Returns metaball function value in .w
// and its gradient in .xyz

float4 Metaball(float3 Pos, float3 Center, float RadiusSq)
{
   float4 o;

   float3 Dist = Pos - Center;
   float InvDistSq = 1 / dot(Dist, Dist);

   o.xyz = -2 * RadiusSq * InvDistSq * InvDistSq * Dist;
   o.w = RadiusSq * InvDistSq;

   return o;
}
```

Vertex Shader

```
#define MAX_METABALLS     32

SampleData VS_SampleField(float3 Pos : POSITION,
    uniform float4x4 WorldViewProj,
    uniform float3x3 WorldViewProjIT,
    uniform uint NumMetaballs, uniform float4 Metaballs[MAX_METABALLS])
{
    SampleData o;
    float4 Field = 0;

    for (uint i = 0; i<NumMetaballs; i++)
         Field += Metaball(Pos, Metaballs[i].xyz, Metaballs[i].w);

    o.Pos = mul(float4(Pos, 1), WorldViewProj);
    o.N = mul(Field.xyz, WorldViewProjIT);
    o.Field = Field.w;

    o.IsInside = Field.w > 1 ? 1 : 0;

    return o;
}
```

Geometry Shader

```
// Estimate where isosurface intersects grid edge
SurfaceVertex CalcIntersection(SampleData v0, SampleData v1)
{
   SurfaceVertex o;

   float t = (1.0 - v0.Field) / (v1.Field - v0.Field);

   o.Pos = lerp(v0.Pos, v1.Pos, t);
   o.N = lerp(v0.N, v1.N, t);

   return o;
}
```

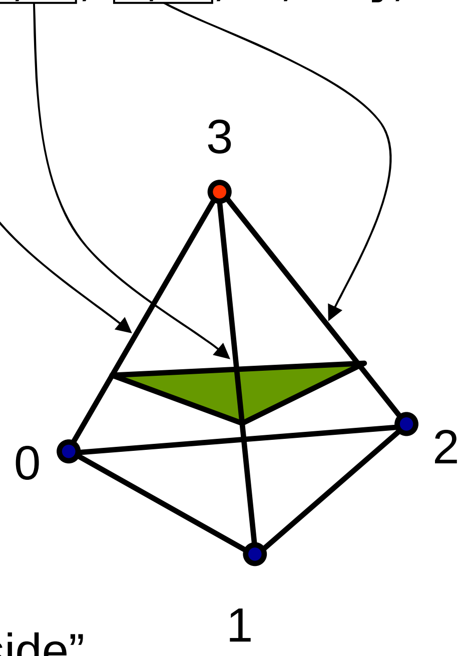
Geometry Shader

```
[MaxVertexCount(4)]
void GS_TesselateTetrahedra(lineadj SampleData In[4],
                              inout TriangleStream<SurfaceVertex> Stream)
{
    // construct index for this tetrahedron
    uint index =
          (In[0].IsInside << 3) | (In[1].IsInside << 2) |
          (In[2].IsInside << 1) | In[3].IsInside;

    const struct { uint4 e0; uint4 e1; } EdgeTable[] = {
          { 0, 0, 0, 0, 0, 0, 0, 1 },   // all vertices out
          { 3, 0, 3, 1, 3, 2, 0, 0 },   // 0001
          { 2, 1, 2, 0, 2, 3, 0, 0 },   // 0010
          { 2, 0, 3, 0, 2, 1, 3, 1 },   // 0011 - 2 triangles
          { 1, 2, 1, 3, 1, 0, 0, 0 },   // 0100
          { 1, 0, 1, 2, 3, 0, 3, 2 },   // 0101 - 2 triangles
          { 1, 0, 2, 0, 1, 3, 2, 3 },   // 0110 - 2 triangles
          { 3, 0, 1, 0, 2, 0, 0, 0 },   // 0111
          { 0, 2, 0, 1, 0, 3, 0, 0 },   // 1000
          { 0, 1, 3, 1, 0, 2, 3, 2 },   // 1001 - 2 triangles
          { 0, 1, 0, 3, 2, 1, 2, 3 },   // 1010 - 2 triangles
          { 3, 1, 2, 1, 0, 1, 0, 0 },   // 1011
          { 0, 2, 1, 2, 0, 3, 1, 3 },   // 1100 - 2 triangles
          { 1, 2, 3, 2, 0, 2, 0, 0 },   // 1101
          { 0, 3, 2, 3, 1, 3, 0, 0 }    // 1110
    };
```

Edge table construction

```
const struct { uint4 e0; uint4 e1; } EdgeTable[] = {
        // …
        { 3, 0, 3, 1, 3, 2, 0, 0 },         // index = 1
        // …
   };
```



Index = 0001,
i.e. vertex 3 is “inside”

Geometry Shader

```
   // … continued
   // don't bother if all vertices out or all vertices in
   if (index > 0 && index < 15)
   {
         uint4 e0 = EdgeTable[index].e0;
         uint4 e1 = EdgeTable[index].e1;

         // Emit a triangle
         Stream.Append(CalcIntersection(In[e0.x], In[e0.y]));
         Stream.Append(CalcIntersection(In[e0.z], In[e0.w]));
         Stream.Append(CalcIntersection(In[e1.x], In[e1.y]));

         // Emit additional triangle, if necessary
         if (e1.z != 0)
         Stream.Append(CalcIntersection(In[e1.z], In[e1.w]));
   }
}
```

Respect your vertex cache!

- f(x, y, z) can be arbitrary complex
    - E.g., many metaballs influencing a vertex
- Need to be careful about walk order
    - Worst case is 4x more work than necessary!
    - Straightforward linear work is not particularly cache friendly either
- Alternatively, can pre-transform with StreamOut

Respect your vertex cache!

- Can use space-filling fractal curves
  - Hilbert curve
  - Swizzled walk
- We'll use swizzled walk
- To compute swizzled offset, just interleave x, y and z bits

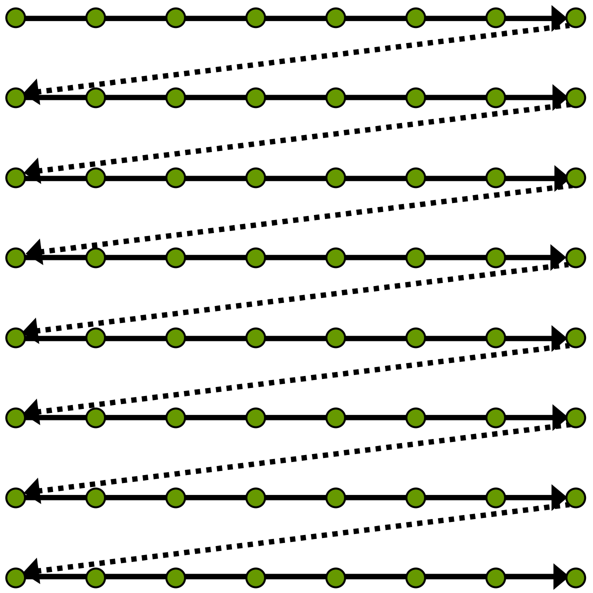
$$\mathbf{x} = x_1 x_0$$

$$\mathbf{y} = y_3 y_2 y_1 y_0$$

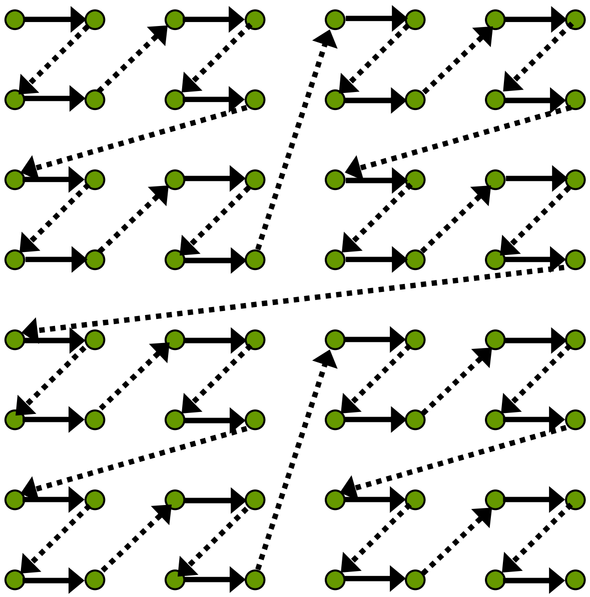
$$\mathbf{z} = z_2 z_1 z_0$$

$$swizzle(\mathbf{x}, \mathbf{y}, \mathbf{z}) = y_3 z_2 y_2 z_1 y_1 x_1 z_0 y_0 x_0$$

Linear walk vs swizzled walk

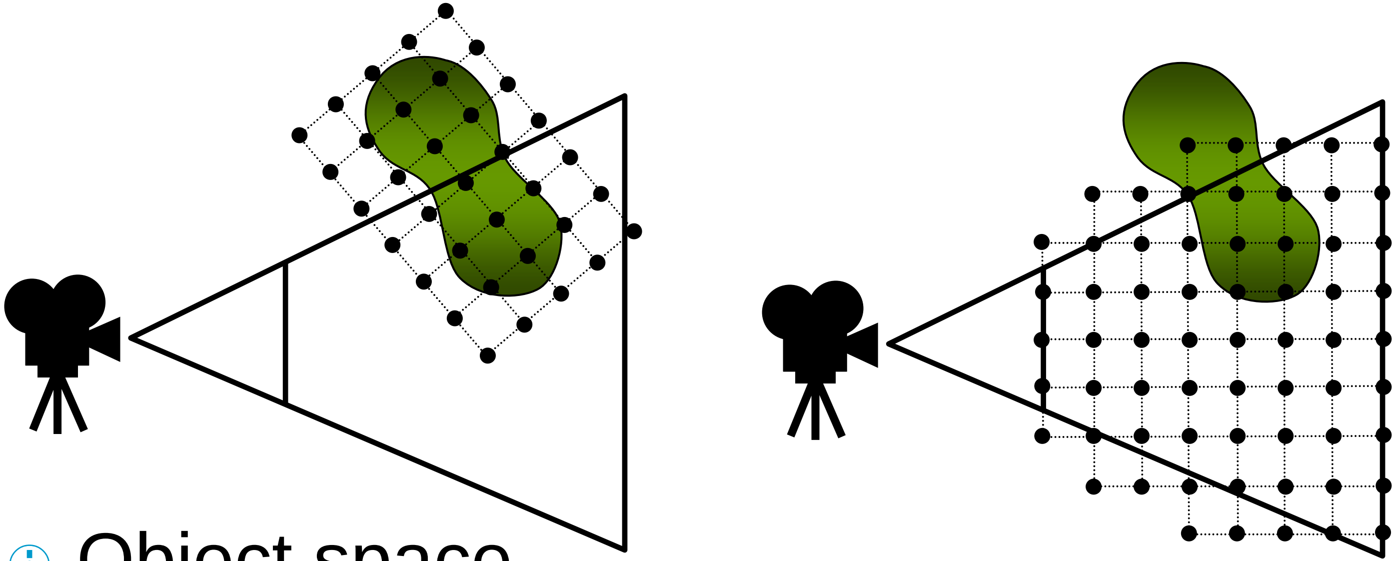


Linear walk



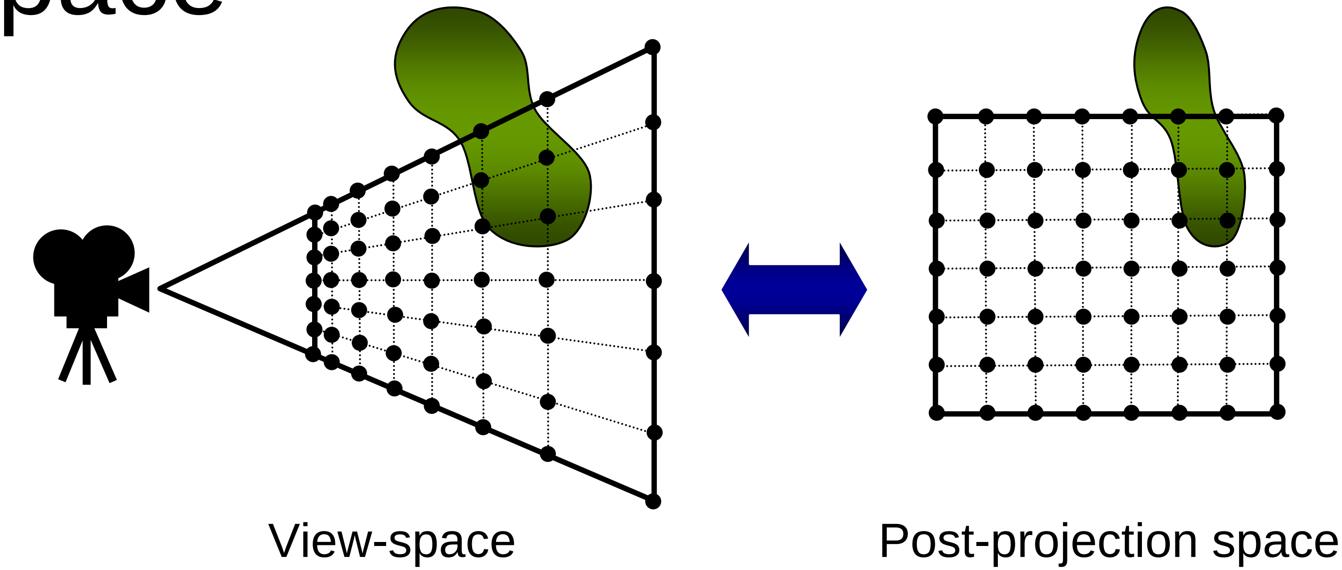
Swizzled walk

Tessellation space



- Object space
  - Works if you can calculate BB around your metaballs
- View space
  - Better, but sampling rate is distributed inadequately

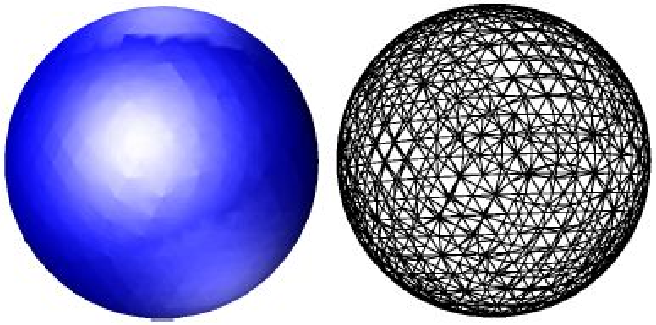
Tessellation in post-projection space



- Post-projective space
  - Probably the best option
  - We also get LOD for free!

Problems with current approach

- Generated mesh is over-tessellated
  - General problem with MT algorithms
- Many triangles end up irregular and skinny
  - Good sampling grid helps a bit



(a) MT, smooth (b) MT, triangles

Possible enhancements

- Regularized Marching Tetrahedra (RMT)
  - Vertex clustering prior to polygonization
  - Generated triangles are more regular
  - For details refer to [2]
- Need to run a pre-pass at vertex level, looking at immediate neighbors
  - For CCL, each vertex has 14 neighbors
  - GS input is too limited for this ☹

More speed optimizations

- Can cull metaballs based on ROI
    - Only 3 or 4 need to be computed per-vertex
- Can use bounding sphere tree to cull
    - Re-compute it dynamically on a GPU as metaballs move
- Cool effect idea – particle system metaballs
    - Mass-spring can also be interesting

Conclusion

- DX10 Geometry Shader can be efficiently used for isosurface extraction
- Allows for class of totally new cool effects
  - Organic forms with moving bulges
  - GPGPU to animate metaballs
  - Add noise to create turbulent fields
  - Terminator2 anyone?

References

- [1] J.Patera, V.Skala "Centered Cubic Lattice Method Comparison"
- [2] G.M.Treece, R.W.Prager and A.H.Gee "Regularised Marching Tetrahedra: improved iso-surface extraction"

Questions?

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