Fast Triangle Reordering for Vertex Locality and Reduced Overdraw

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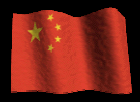
Hong Kong University of Science and Technology 

Diego Nehab

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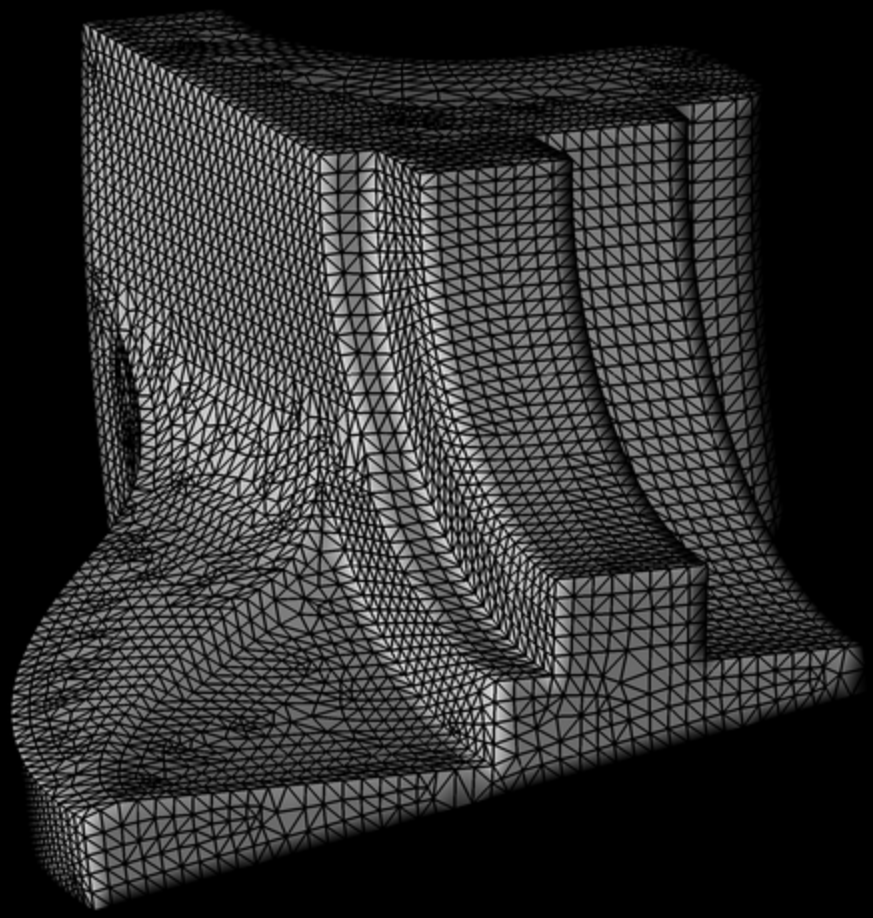
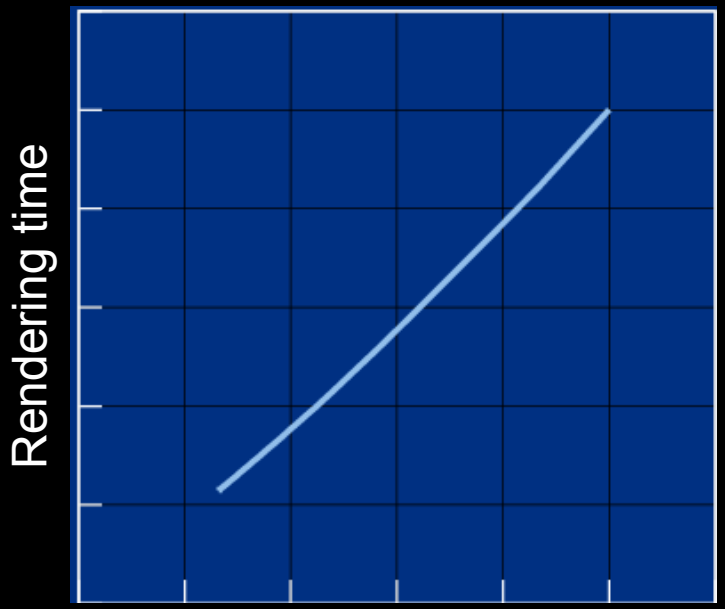
Triangle order optimization



Objective: Reorder triangles to render meshes faster

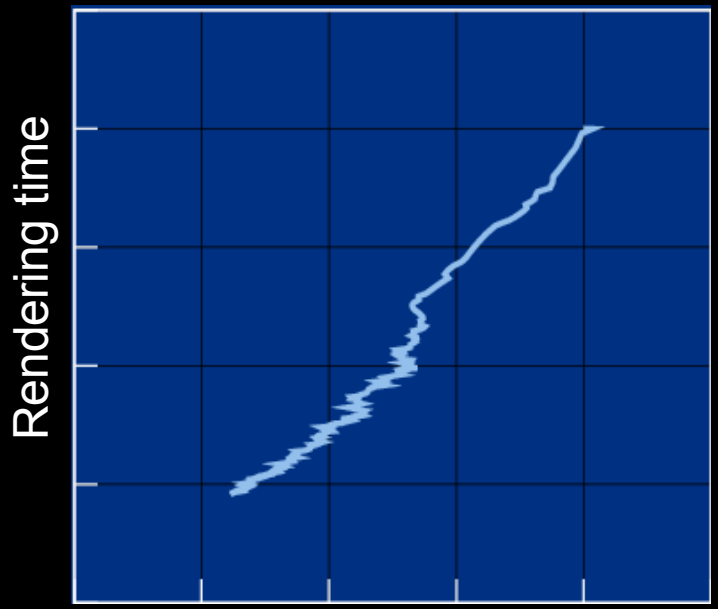
Motivation: Rendering time dependency

Vertex-bound scene



vertices processed

Pixel-bound scene



pixels processed

Reduce!
(transparently)

Goal

- Render faster
  - Two key hardware optimizations
    - Vertex caching (vertex processing)
    - Early-Z culling (pixel processing)
  - Reorder triangles efficiently at run-time
  - No changes in rendering loop
  - Improves rendering speed transparently

Algorithm overview

- Part I: Vertex cache optimization
- Part II: Overdraw minimization

Part I:
The Post-Transform Vertex cache

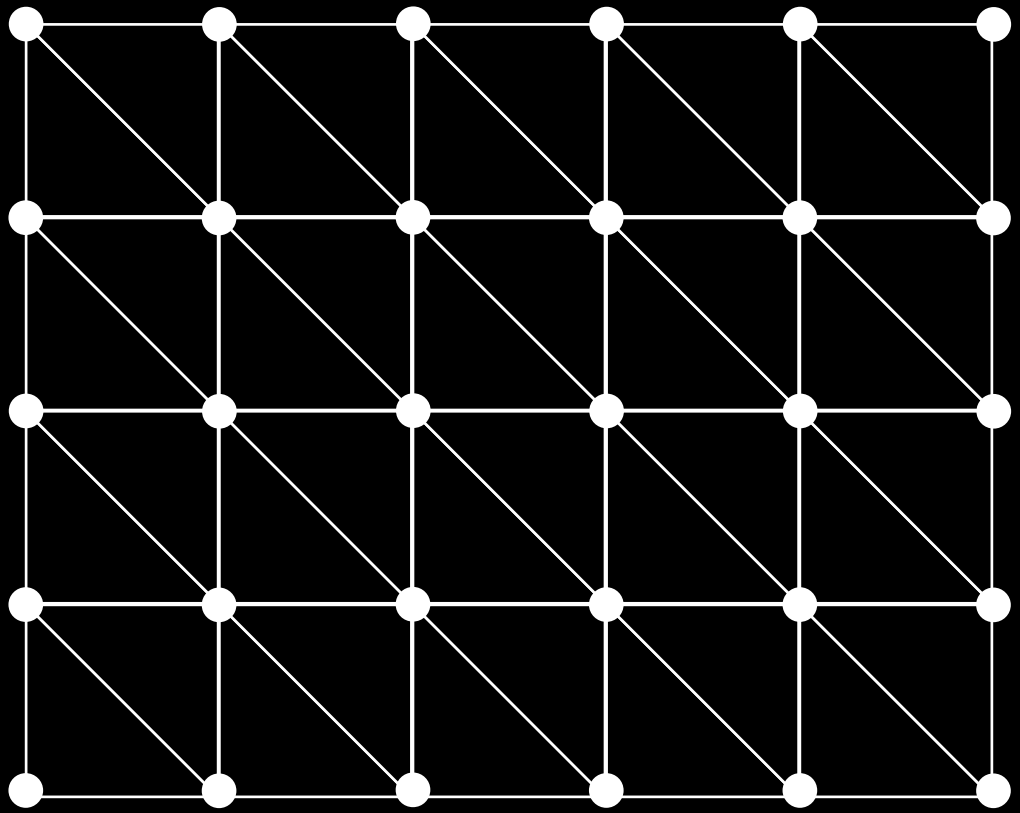
- Transforming vertices can be costly
- Hardware optimization:
  - Cache transformed vertices (FIFO)
- Software strategy:
  - Reorder triangles for vertex locality
- Average Cache Miss Ratio (ACMR)
  - # transformed vertices / # triangles
  - varies within [0.5–3]

ACMR Minimization

- NP-Complete problem
  - GAREY et. al [1976]
- Heuristics reach near-optimal results [0.6–0.7]
  - Hardware cache sizes range within [4–64]
- *Substantial* impact on rendering cost
  - From 3 to 0.6 !
  - Everybody does it

Parallel short strips

Very close to optimal!



~0.5 ACMR

Previous work

- Algorithms sensitive to cache size
  - MeshReorder and D3DXMesh [HOPPE 1999]
  - K-Cache-Reorder [LIN and YU 2006]
  - Many others…
  - Recent independent work [CHHUGANI and KUMAR 2007]

Previous work

- Algorithms oblivious to cache size
  - dfsrendseq [Bogomjakov et al. 2001]
  - OpenCCL [Yoon and Lindstrom 2006]
- Based on space filling curves
- Asymptotically optimal
  - Not as good as cache-specific methods
  - Long running time
- Do not help with CAD/CAM

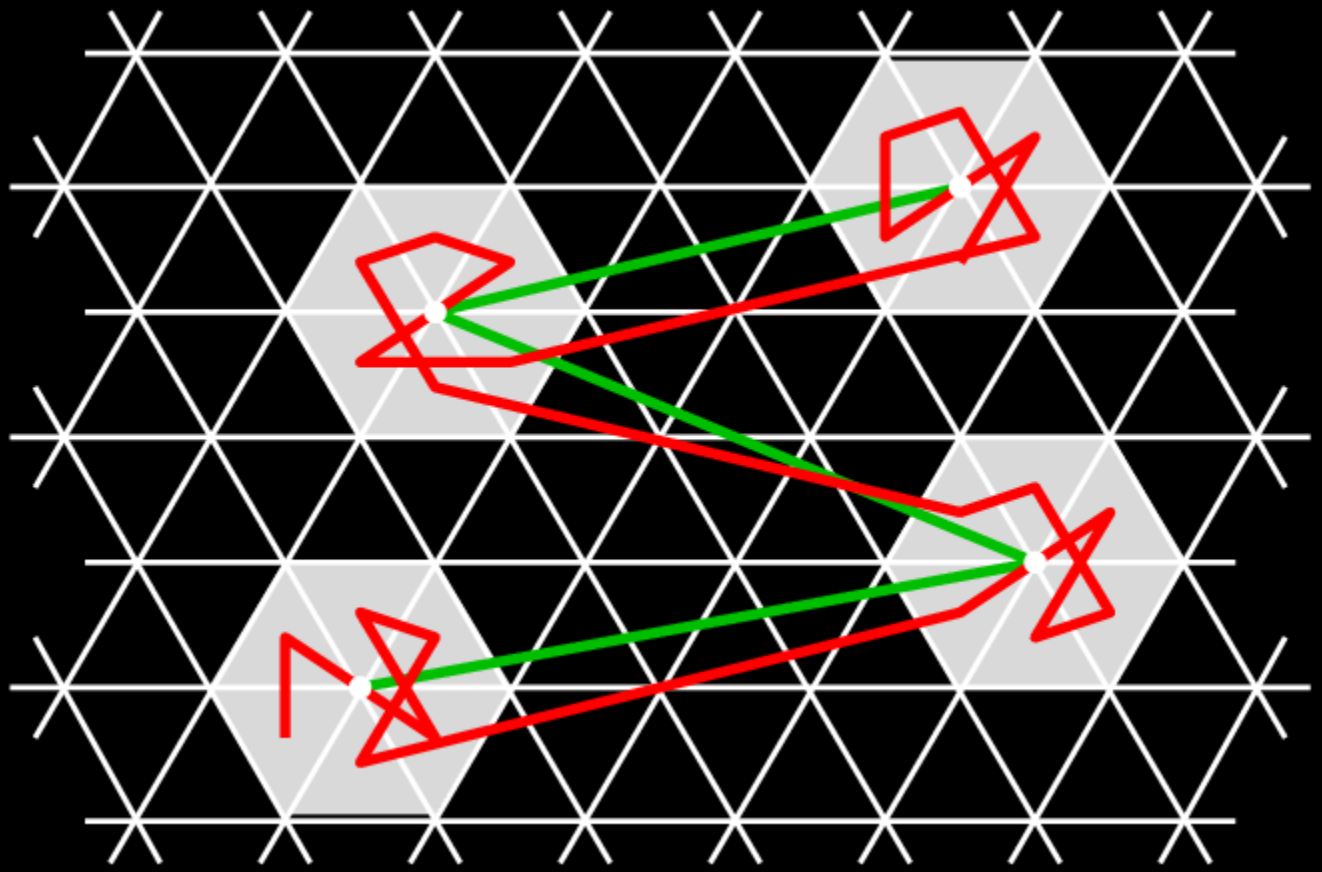
Our objective

- Optimize at run-time
  - We even have access to the *exact* cache size
- Faster than previous methods, i.e., O(t)
  - Must *not* depend on cache-size
- Should be easy to integrate
  - Run directly on index buffers
- Should be general
  - Run transparently on non-manifolds

“Triangle-triangle” adjacency unnecessary

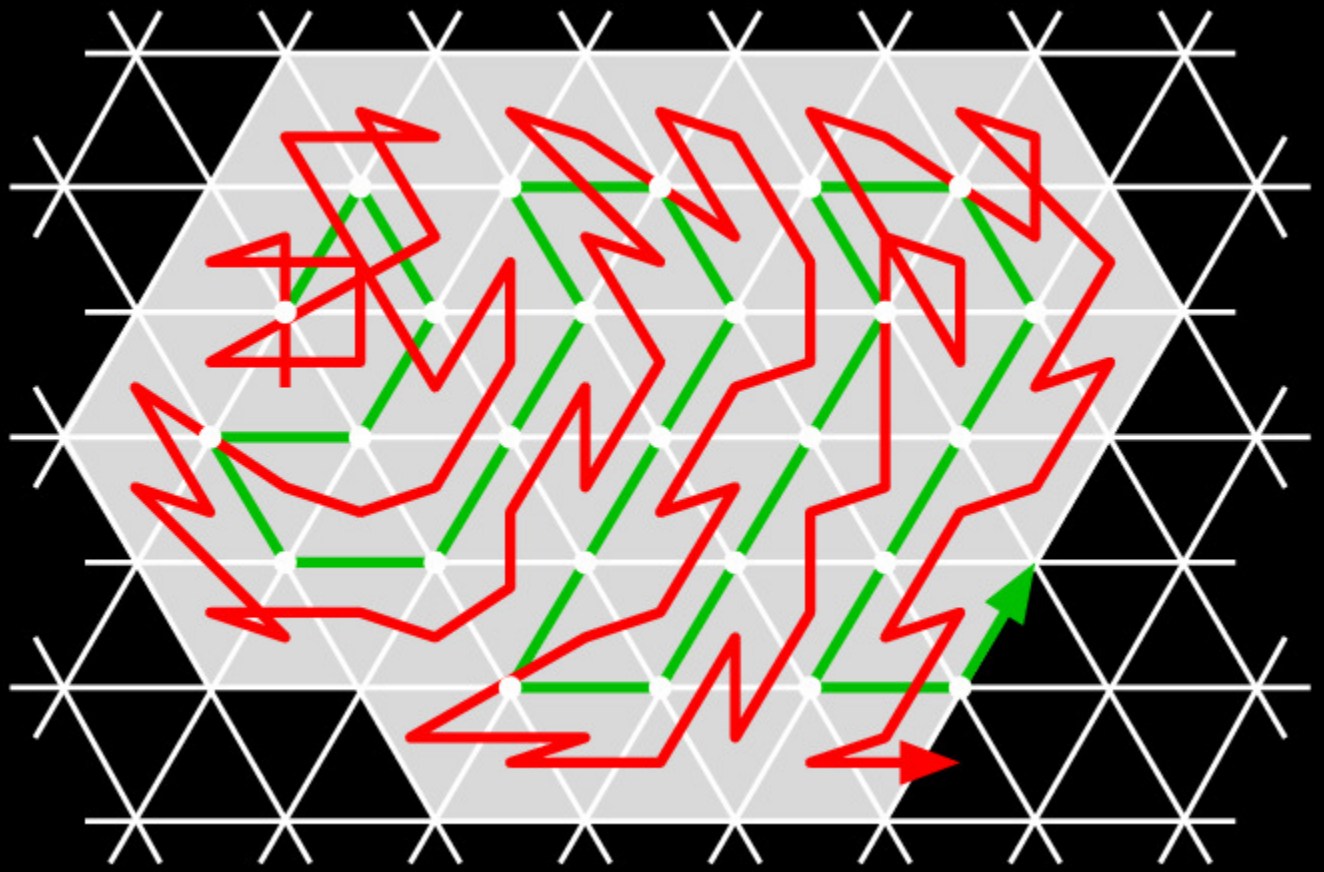
- Awkward to maintain on non-manifolds
- By the time this is computed, we should be *done*
- Use “vertex-triangle” adjacency instead
- Computed with 3 trivial linear passes

Simply output vertex adjacency lists



Tipsy (locally random) fans

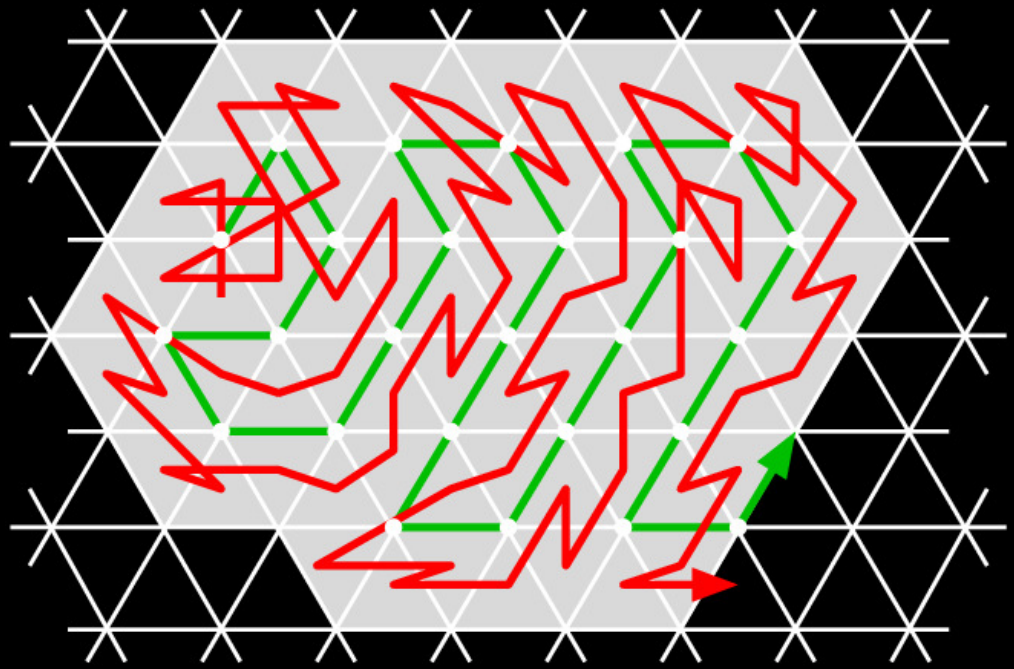
Choosing a better sequence



Tipsy strips

Selecting the next fanning vertex

- Must be a constant time operation
  - Select next vertex from 1-ring of previous
  - If none available, pick latest referenced
  - If none available, pick next in input order



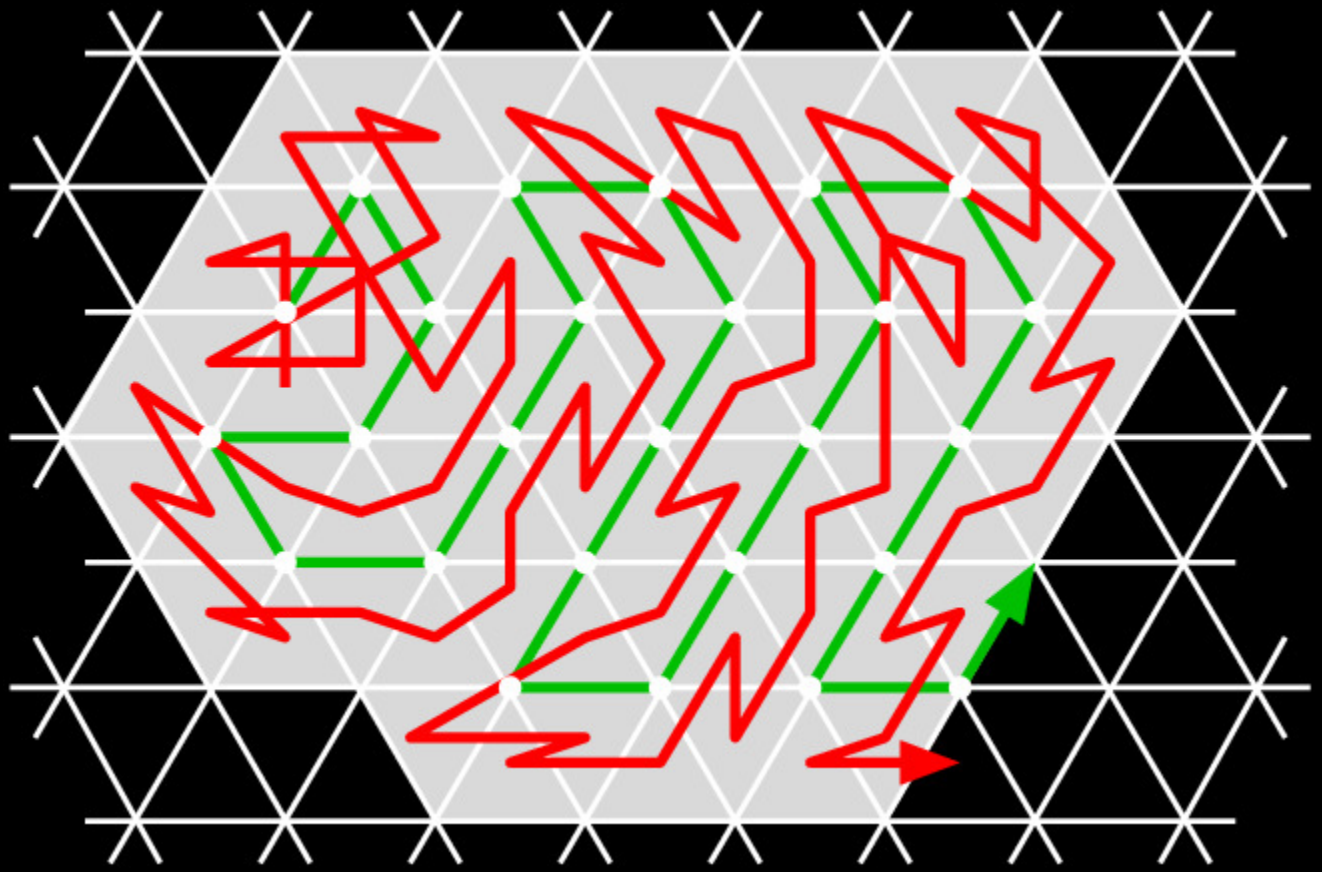
Best next fanning vertex within 1-ring

- Consider vertices referenced by emitted triangles

- Furthest in FIFO that would *remain* in cache

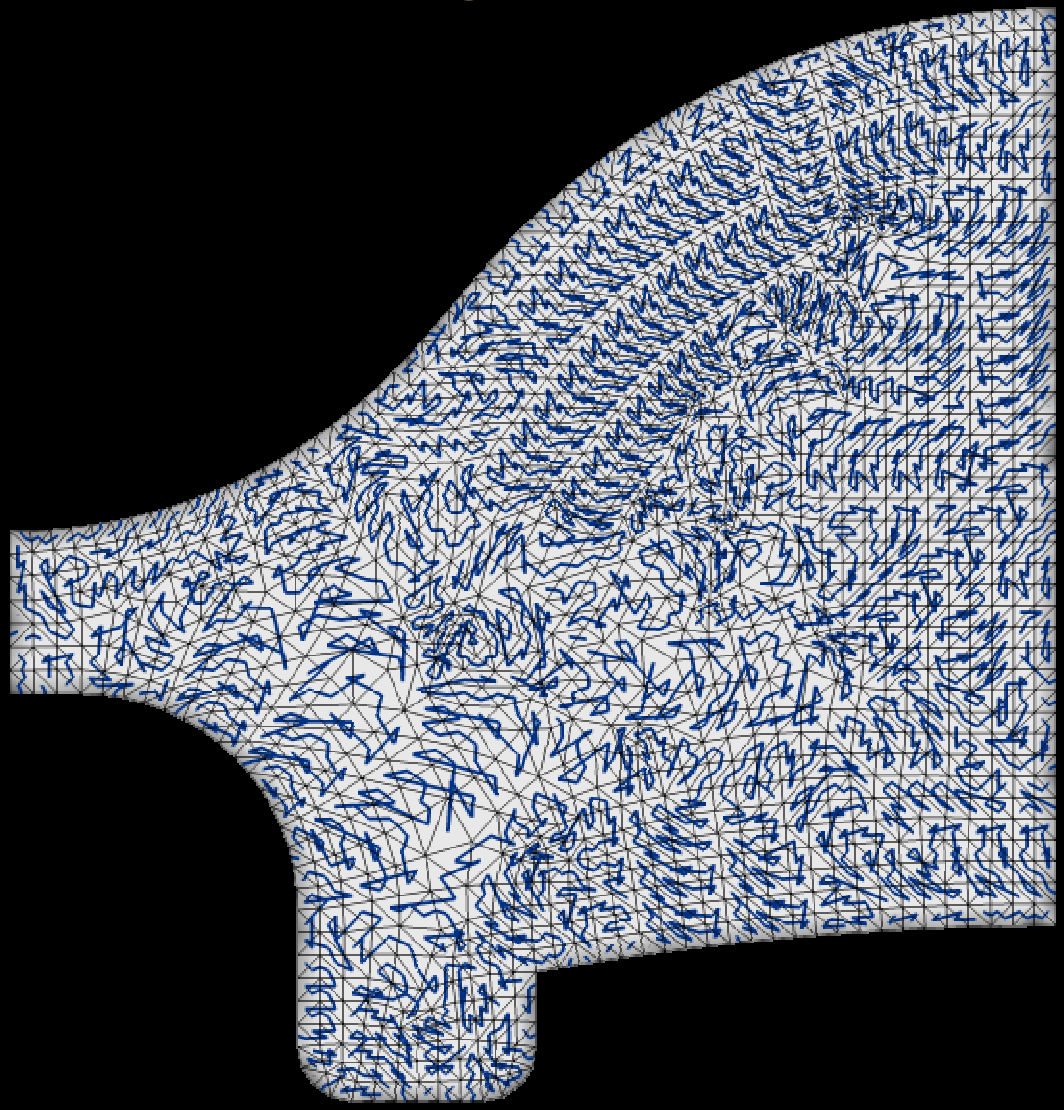
s	cache time stamp	how far is *u* in the cache?	$s - C[u]$
$C[u]$	caching time stamp of *u*	is *u* still in the cache?	$s - C[u] \leq k$
$L[u]$	# of live triangles in *u*	would *u* remain in cache?	$s - C[u] - 2L[u] \leq k$

Tipsy pattern



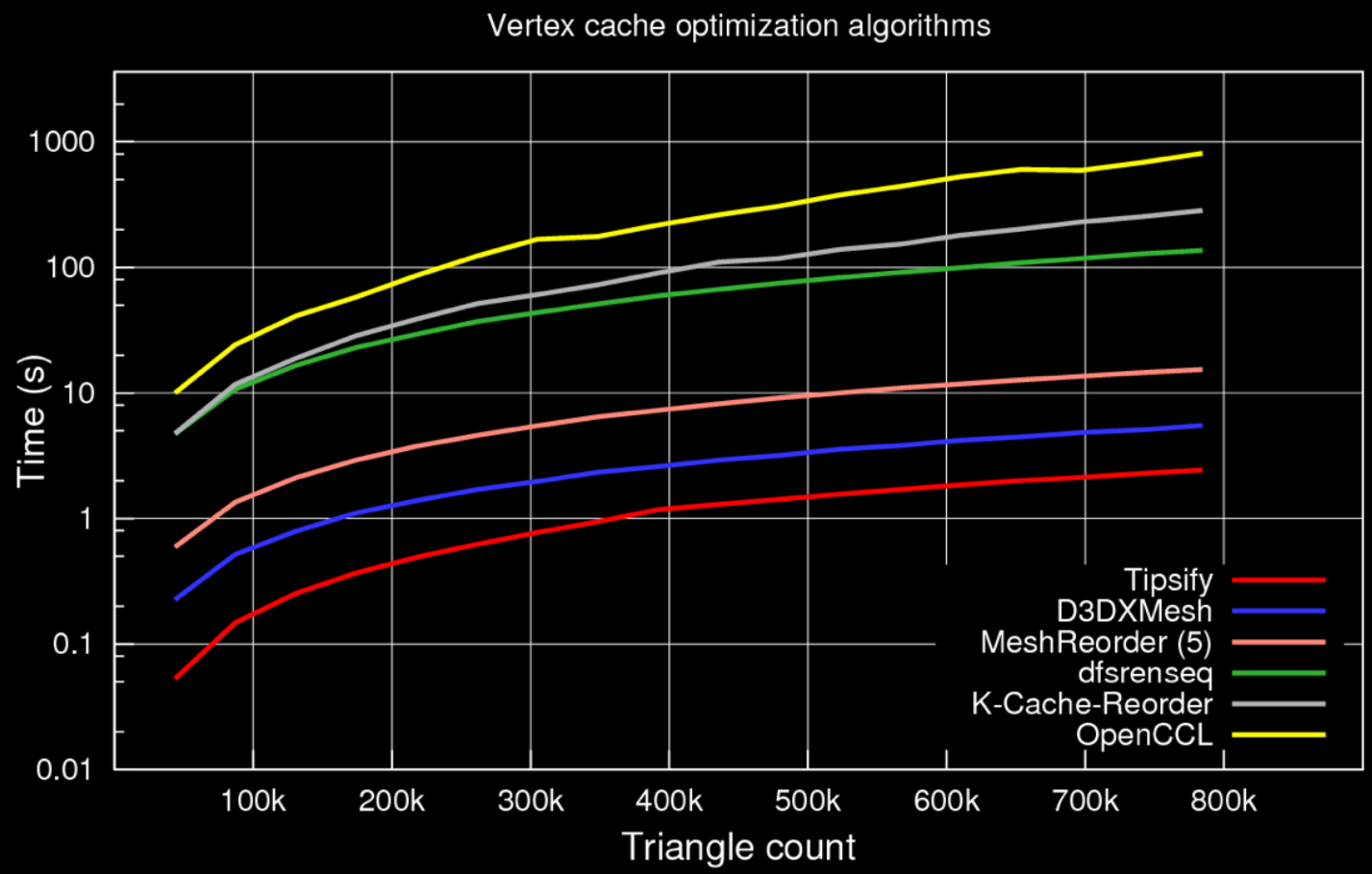
Tipsy strips

Tipsy pattern

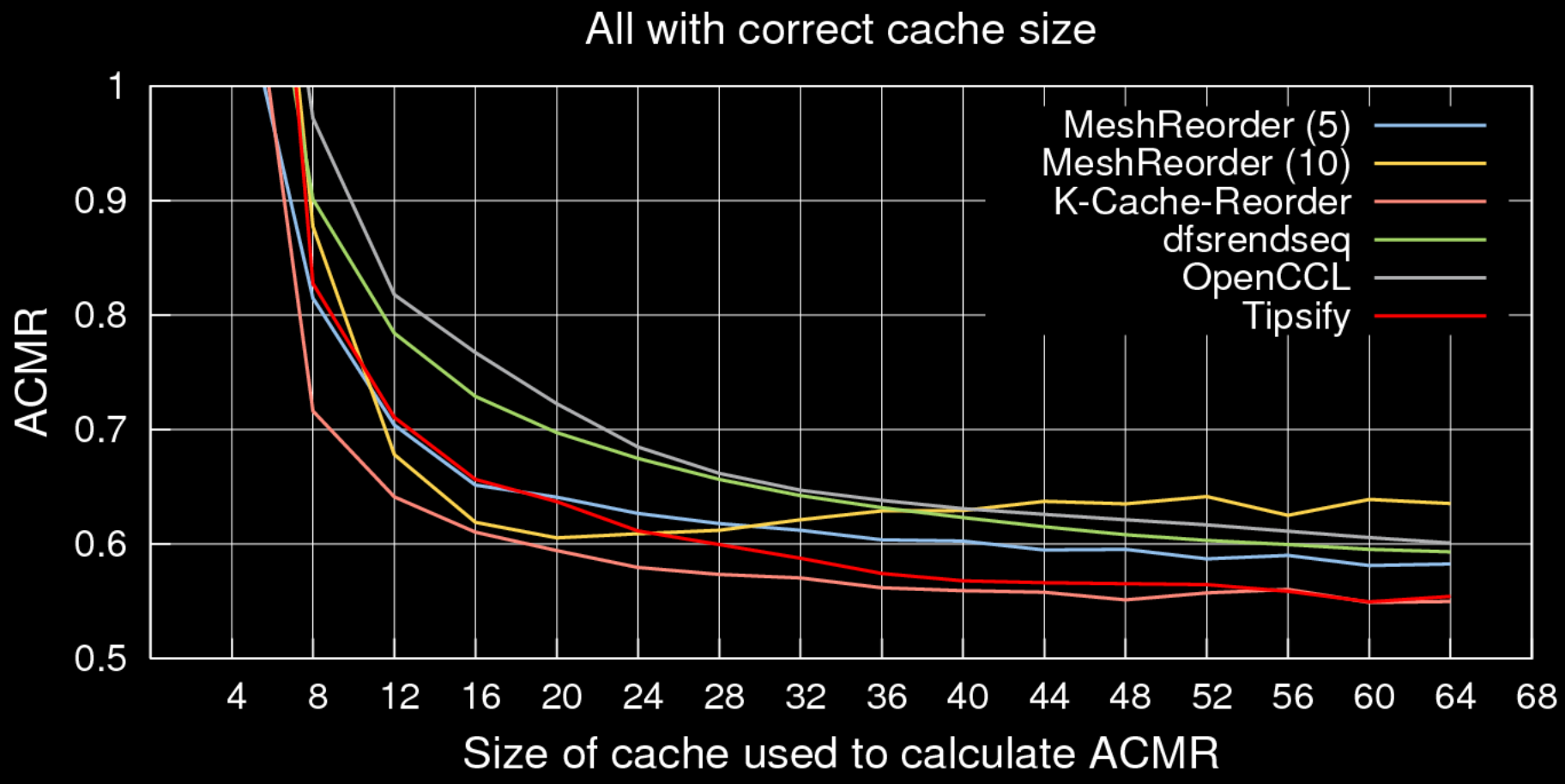


Tipsify

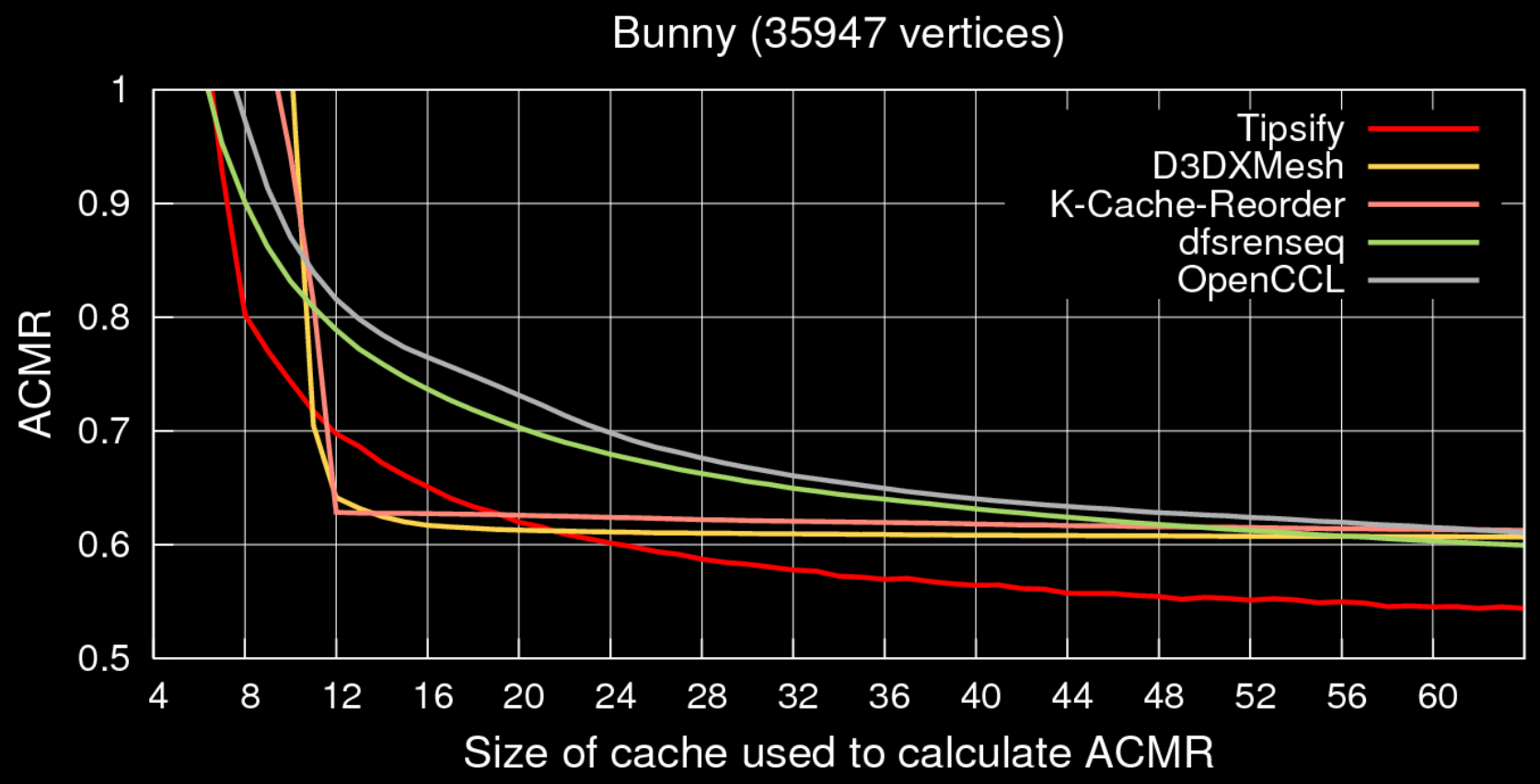
Typical running times



Preprocessing comparison

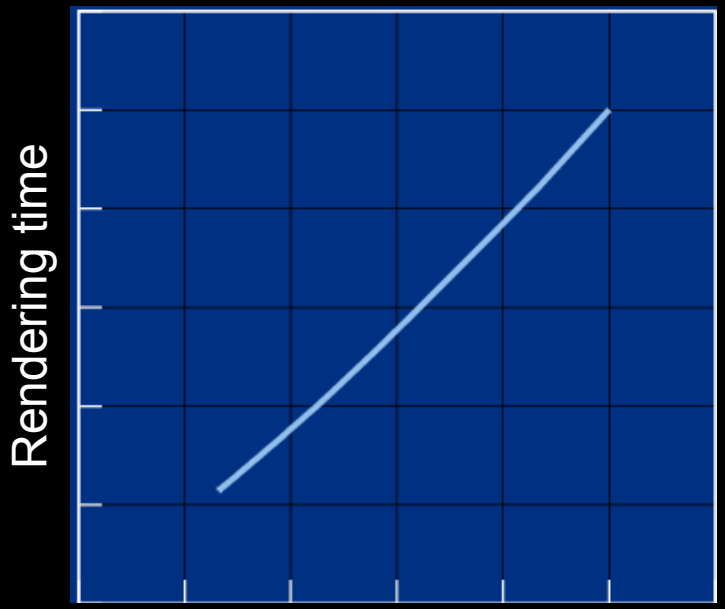


Typical ACMR comparison
Cache size of 12

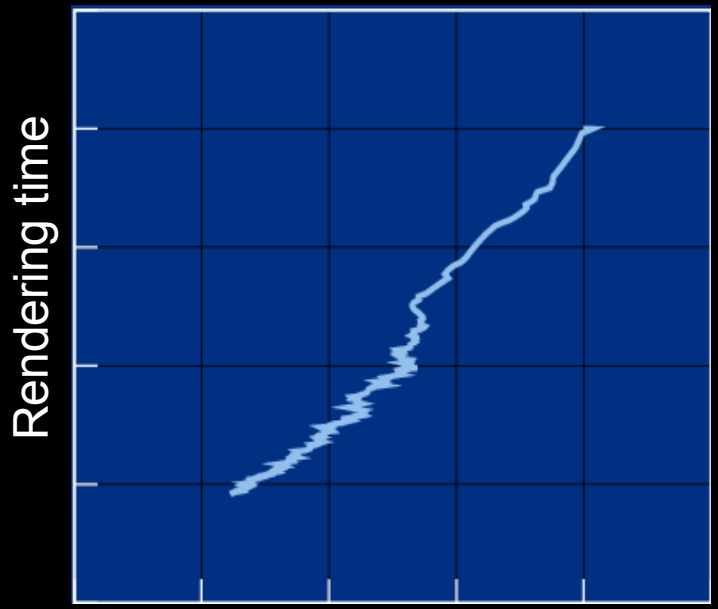


Motivation: Rendering time dependency

Vertex-bound scene



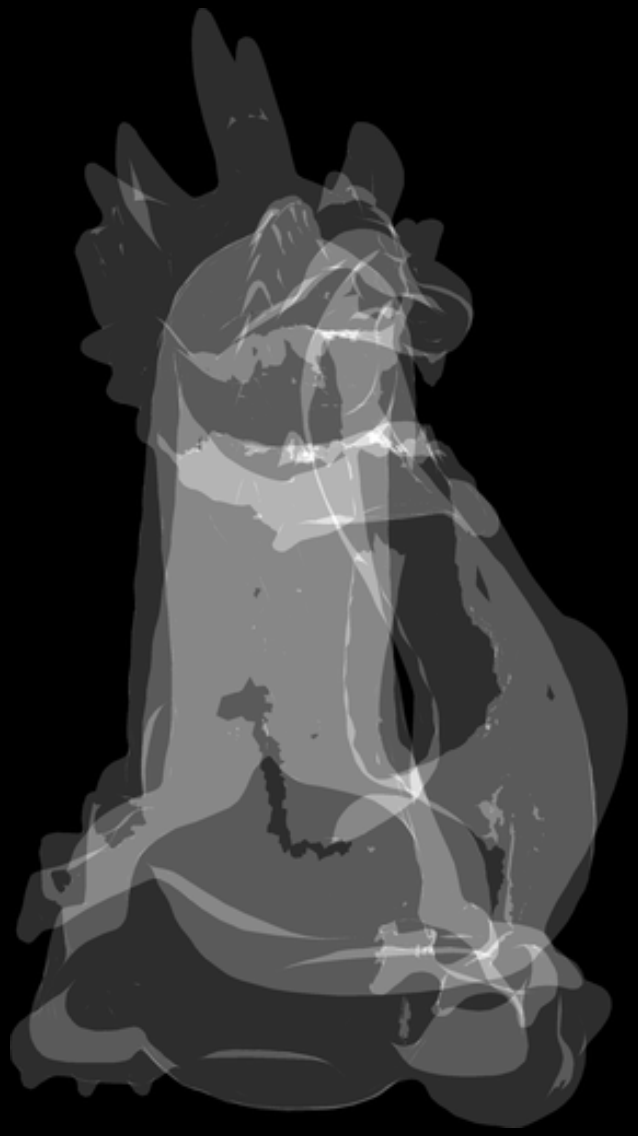
Pixel-bound scene



Reduce!
(transparently)

Part 2: Overdraw

- Expensive pixel shaders
- High overdraw
- Use early-z culling



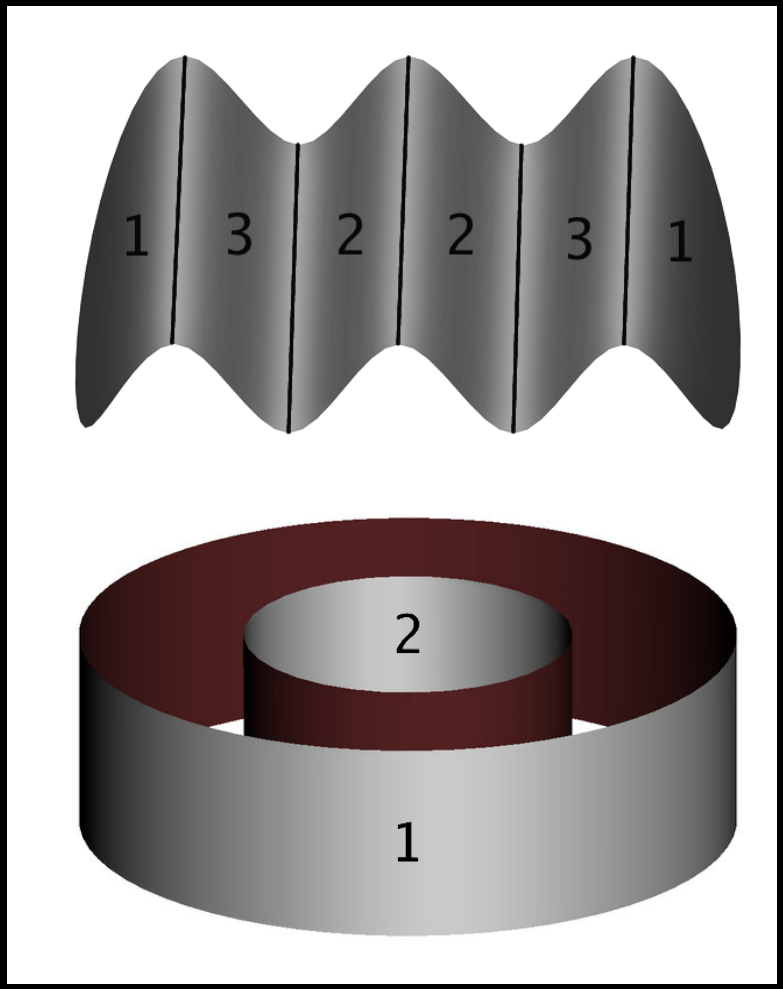
Options

- Dynamic depth-sort
  - Can be too expensive
  - Destroys mesh locality
- Z-buffer priming
  - Can be too expensive
- Sorting per object
  - E.g. GOVINDARAJU et al. 2005
  - Does not eliminate intra-object overdraw
  - Not transparent to application
  - Requires CPU work
  - Orthogonal method

Objective

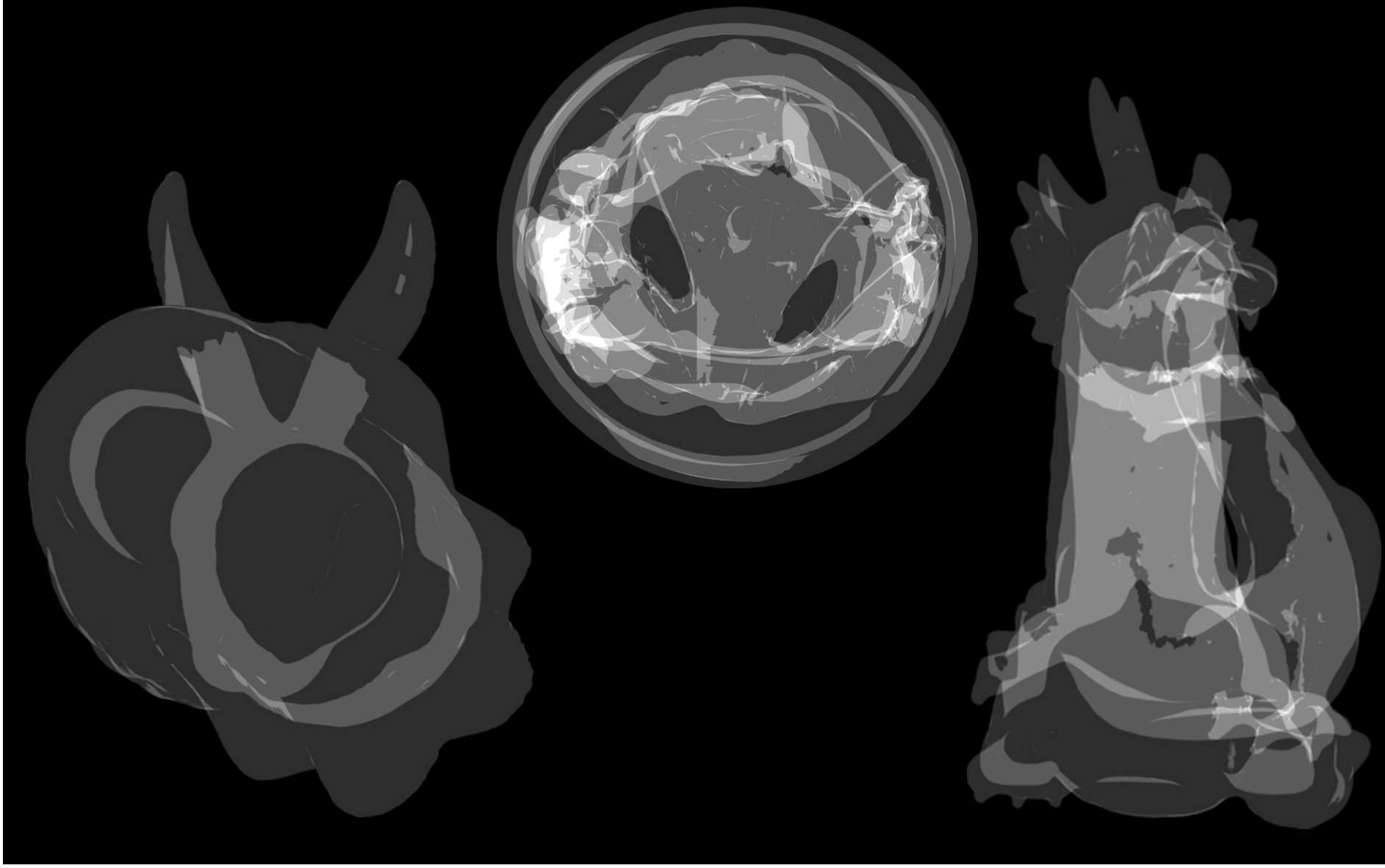
- Simple solution
- Single draw call
- Transparent to application
- Good in both vertex and pixel bound scenarios
- Fast to optimize

Insight: View Independent Ordering [Nehab et al. 06]

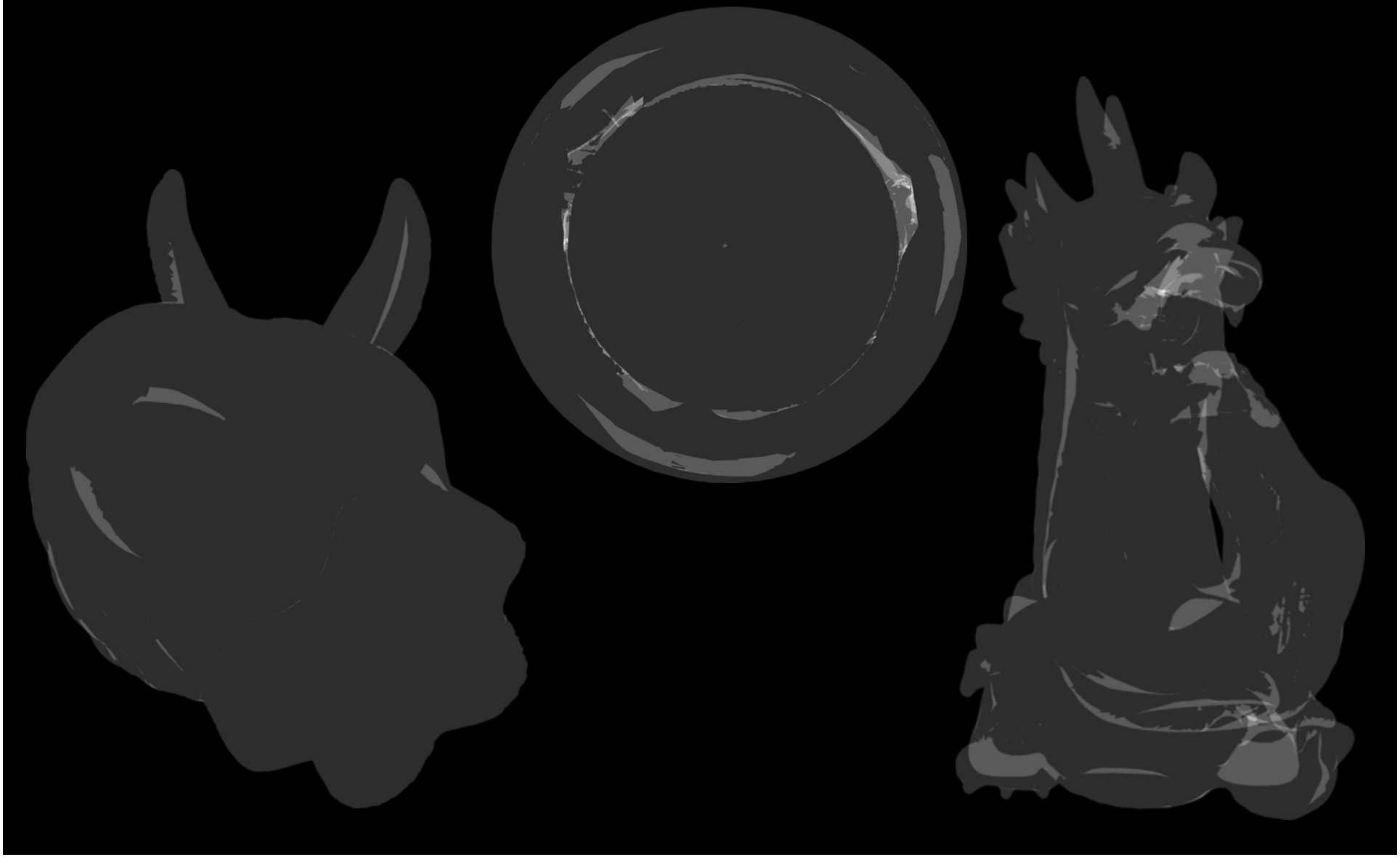


- Back-face culling is often used
- Convex objects have *no* overdraw, regardless of viewpoint
- Might be possible even for concave objects!

Overdraw (before)



Overdraw (after)



Our algorithm

- Can we do it at load-time or interactively?
- Yes! ☺ (order of milliseconds)
  - Quality on par with previous method
  - Can be immediately executed after vertex cache optimization (Part 1)
  - Like tipsy, operates on vertex and index buffers

Algorithm overview

1. Vertex cache optimization
   - Optimize for vertex cache ***first*** (Tipsify)
2. Linear clustering
   - Segment the index buffer into clusters
3. Overdraw sorting
   - Sort clusters to minimize overdraw

2. Linear clustering

During tipsy optimization:

- Maintaining the current ACMR
- Insert cluster boundary when:
  - A cache flush is detected
  - The ACMR reaches above a particular threshold λ

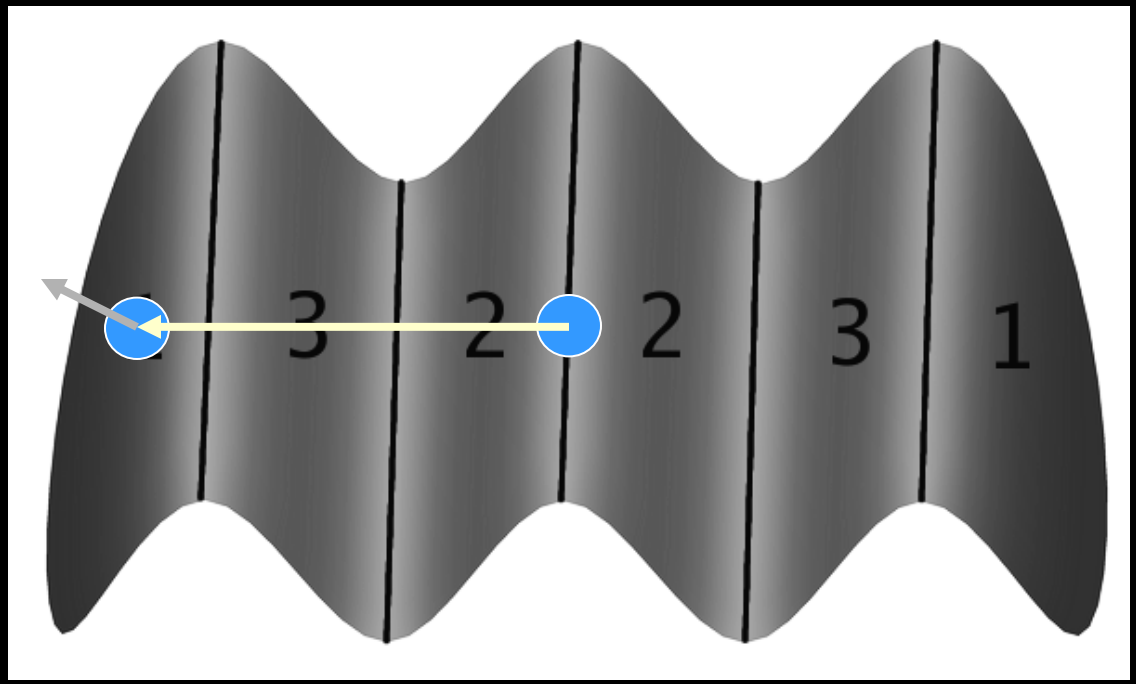
Threshold λ trades off
cache efficiency vs. ***overdraw***

If we care about both, use λ **= 0.75** on all meshes

- Good enough vertex cache gains
- More than enough clusters to reduce overdraw

3. Sorting: The DotRule

- How do we sort the clusters?
- Intuition: Clusters *facing out* have a higher *occluder potential*



$(C_p - M_p) \cdot C_n$

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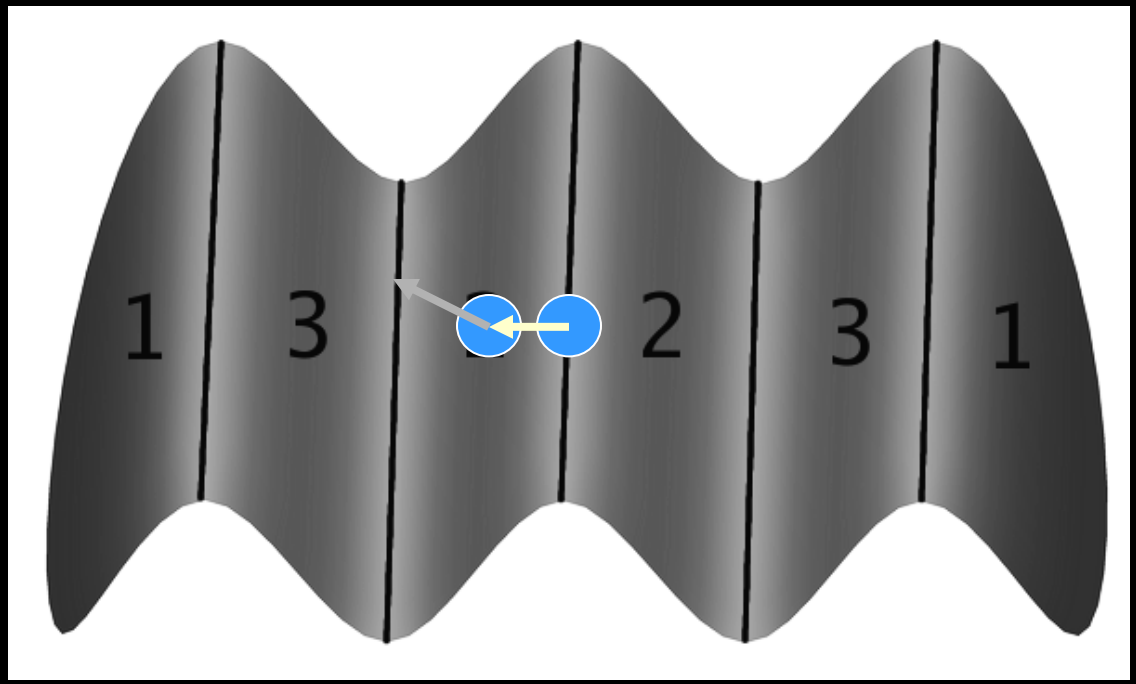

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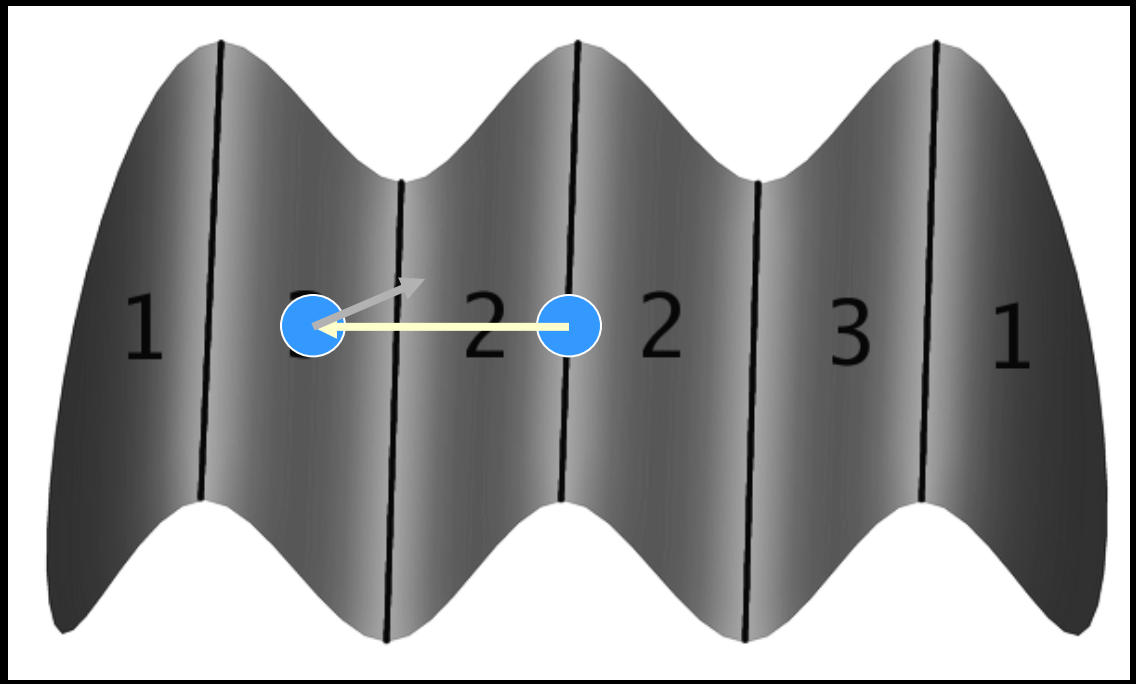
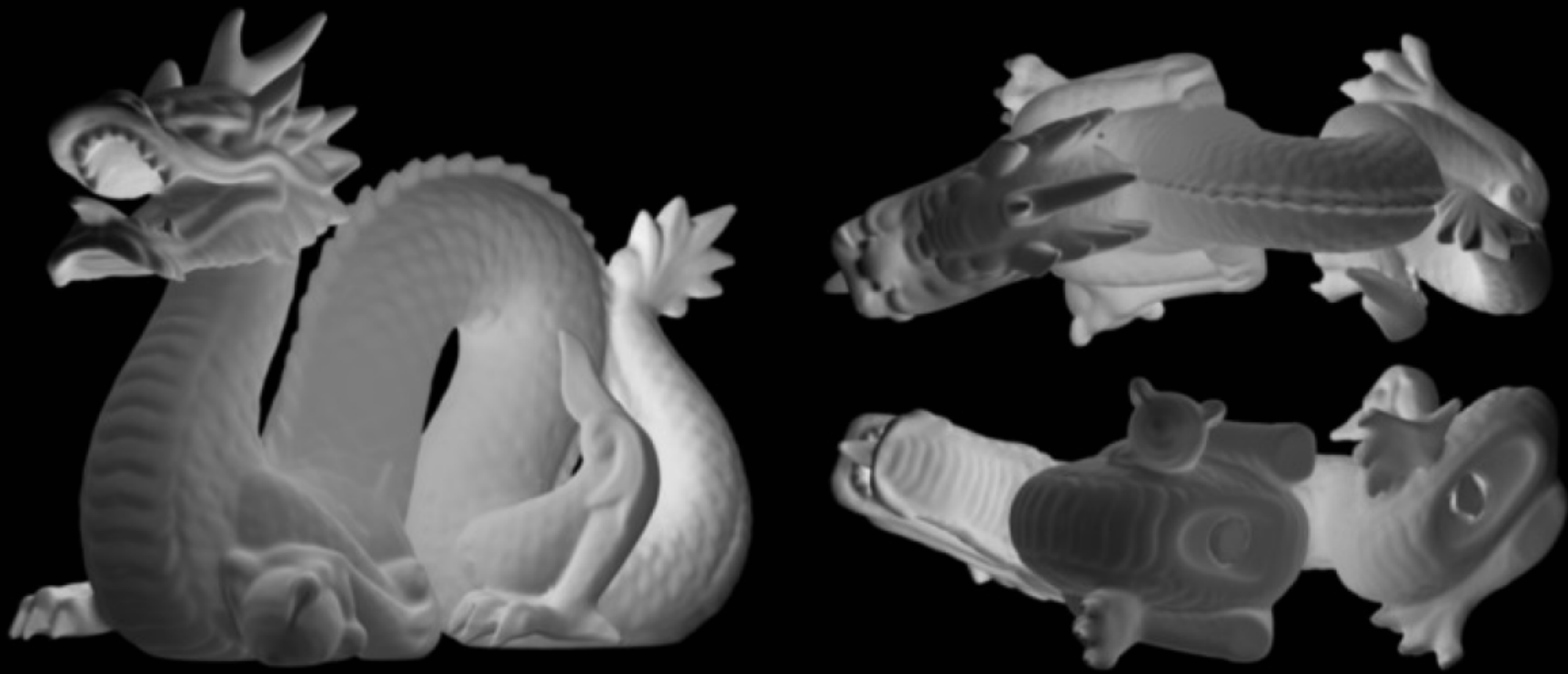
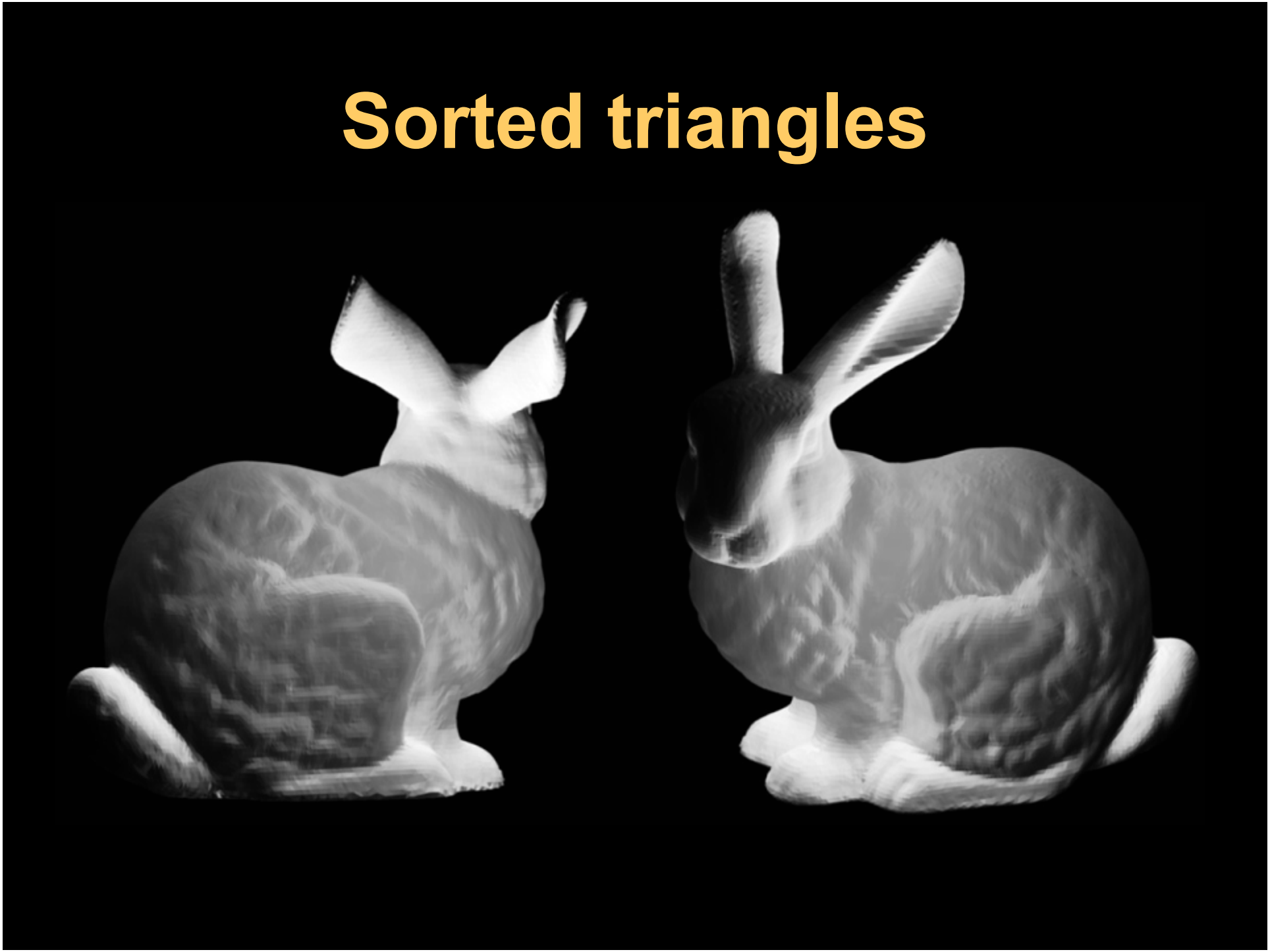


$(C_p - M_p) \cdot C_n$

Sorted triangles



Sorted triangles



Sorted clusters

Comparison to Nehab et al. 06

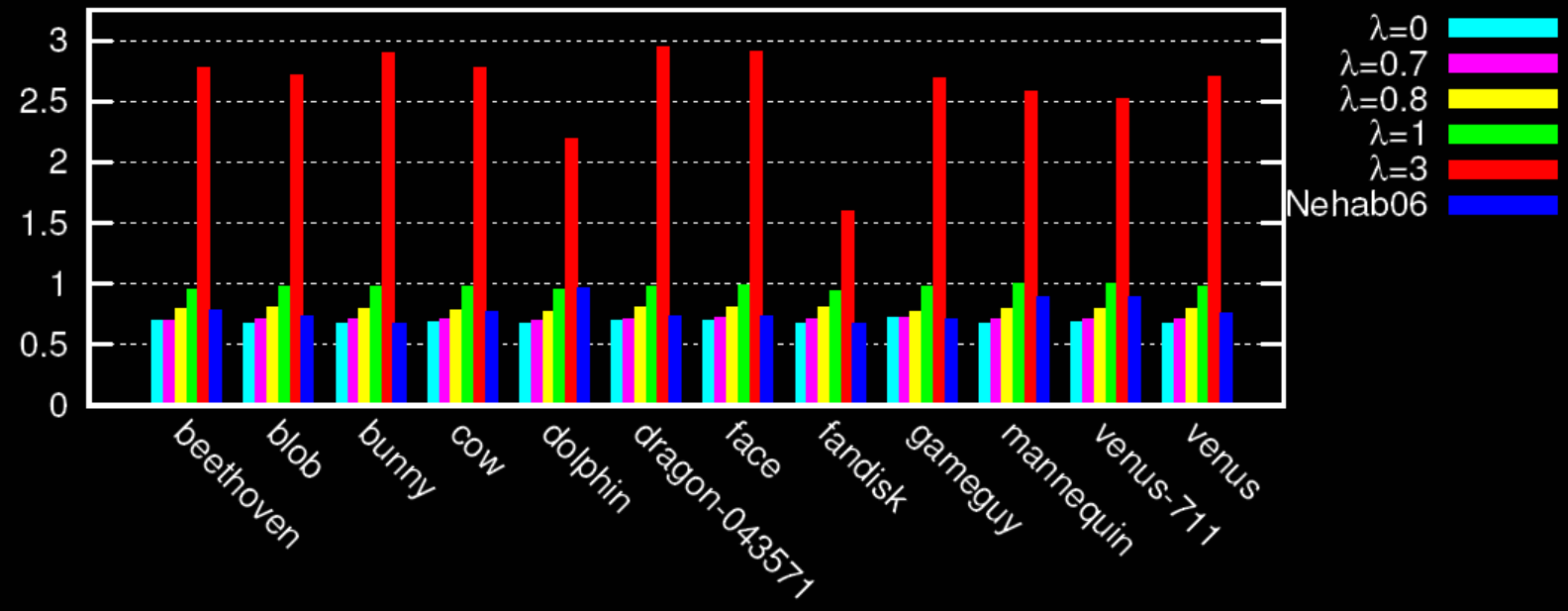
- We optimize for vertex cache first
- Allows for ***significantly*** more clusters
- Clusters not as planar, but we can afford more
- New heuristic to sort clusters very fast
- Tradeoff vertex vs. pixel processing at runtime

Timing comparisons

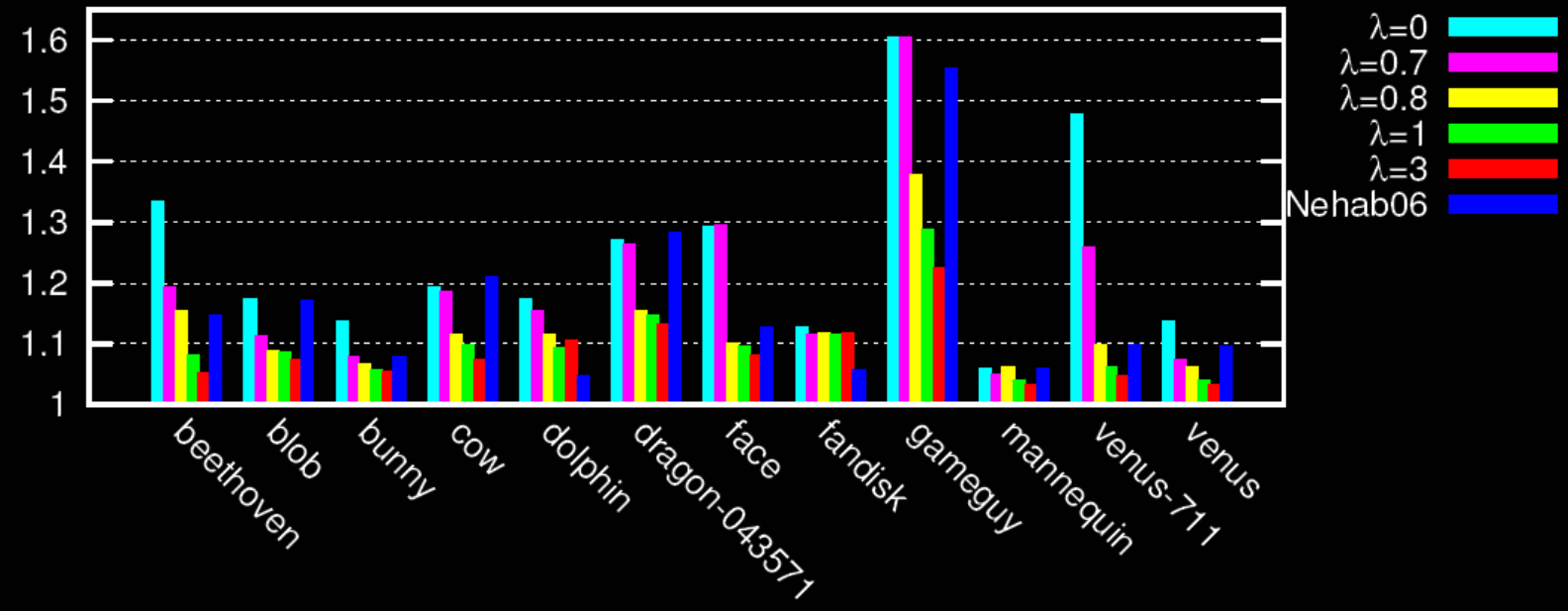
Mesh	Sander 07 (s)		New:Nehab 06
beethoven.m	0.0030		2712x
blob.m	0.0125		1359x
bunny.m	0.0749		321x
cow.m	0.0047		641x
dolphin.m	0.0003		10054x
dragon-043571.m	0.0434		253x
face.m	0.0199		251x
fandisk.m	0.0098		1024x
gameguy.m	0.0424		354x
mannequin.m	0.0007		13699x
venus.m	0.0033		1529x
Average			**3129x**

Overdraw comparison

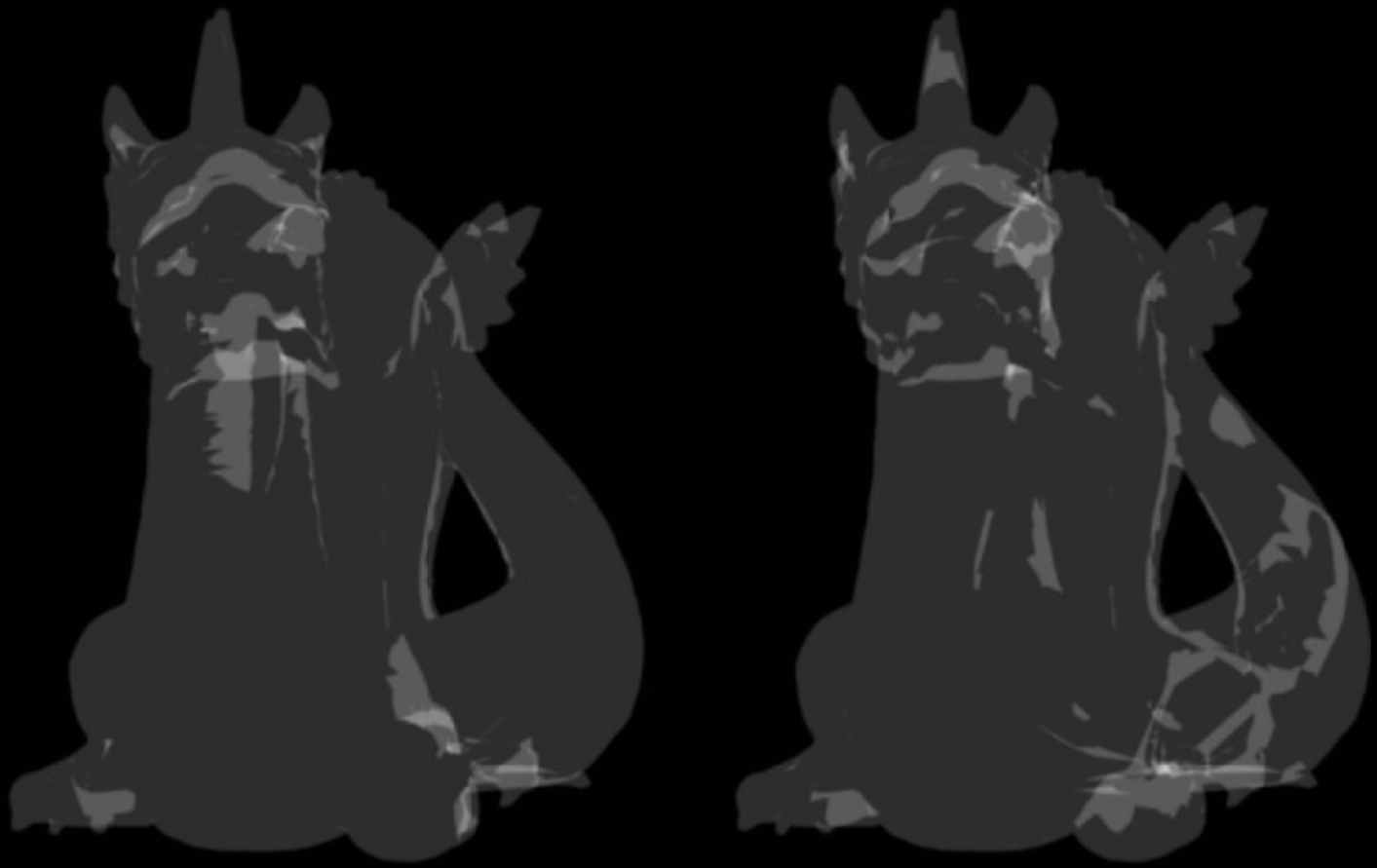
ACMR



MOVR



Comparison



Nehab et al. 06
40sec

Tipsy + DotRule
0.076sec

Summary

- Run-time vertex cache optimization
- Run-time overdraw reduction

- Operates on vertex and index buffers directly
- Works on non-manifolds
- Orders of magnitude faster
- Allows for varying cache sizes and animated models
- Quality comparable with previous methods
- About 500 lines of code!
- Extremely easy to incorporate in a rendering pipeline

- Expect most game rendering pipelines will incorporate such an algorithm
- Expect CAD applications to use and re-compute ordering interactively as geometry changes

```
void OverdrawOrder(int *piIndexBufferIn,
            int *piIndexBufferOut,
            int iNumFaces,
            float *pfVertexPositionsIn,
            int iNumVertices,
            int *piClustersIn,
            int iNumClusters,
            int *piScratch,
                  int *piRemap = NULL)
{
  int i, j;
  int c=0, cstart=0;
  int cnext=piClustersIn[1];
  int *p = piIndexBufferIn;
  Vector *pvVertexPositionsIn = (Vector *)pfVertexPositionsIn;
  Vector vMeshPositions = Vector(0,0,0);
  float fMArea = 0.f;

  int *piScratchBase = piScratch;
  Vector *pvClusterPositions = (Vector *)piScratch;
  piScratch += iNumClusters * 3;

  Vector *pvClusterNormals = (Vector *)piScratch;
  piScratch += iNumClusters * 3;

  ClusterSort *cs = (ClusterSort *)piScratch;
  piScratch += iNumClusters * 2;

  for(i = 0; i < iNumClusters; i++)
  {
    pvClusterPositions[i] = Vector(0,0,0);
    pvClusterNormals[i] = Vector(0,0,0);
  }
  float fCArea = 0.f;
  for(i = 0; i <= iNumFaces; i++)
  {
    if(i == cnext)
    {
      pvClusterPositions[c] /= fCArea * 3.f;
      pvClusterNormals[c].normalize();
      c++;
      if(c == iNumClusters)
        break;
      cstart = i;
      cnext = piClustersIn[c+1];
      fCArea = 0.f;
    }

    Vector vNormal = cross(pvVertexPositionsIn[p[2]] -
                           pvVertexPositionsIn[p[0]],
                           pvVertexPositionsIn[p[1]] -
                           pvVertexPositionsIn[p[0]]);
    float fArea = vNormal.length();
    if(fArea > 0.f)
    {
      vNormal /= fArea;
    }
    else
    {
      fArea = 0.f;
      vNormal = Vector(0,0,0);
    }

    for(j = 0; j < 3; j++)
    {
      Vector *vp = (Vector *)&pfVertexPositionsIn[(*p) * 3];
      vMeshPositions += *vp * fArea;
      pvClusterPositions[c] += *vp * fArea;
      p++;
    }
    pvClusterNormals[c] += vNormal;

    fMArea += fArea;
    fCArea += fArea;
  }
  vMeshPositions /= fMArea * 3.f;

  for(i = 0; i < iNumClusters; i++)
  {
    cs[i].dp = dot(pvClusterPositions[i]-vMeshPositions,
                   pvClusterNormals[i]);
    if(cs[i].dp < -2e20 || cs[i].dp > 2e20)
    {
      cs[i].dp = 0.f;
    }
    cs[i].i = i;
  }

  std::sort(cs, cs+iNumClusters, sortfunc);

  int jj=0;
  for(i = 0; i < iNumClusters; i++)
  {
    for(j = piClustersIn[cs[i].i]*3; j < piClustersIn[cs[i].i+1]*3; j++)
      piIndexBufferOut[jj++] = piIndexBufferIn[j];
  }

  if(piRemap != NULL)
  {
     for(i = 0; i < iNumClusters; i++)
     {
        piRemap[i] = cs[i].i;
     }
  }

  memset(piScratchBase, 0, (piScratch - piScratchBase) * sizeof(int));
}
```

Summary

- Run-time triangle order optimization
- Run-time overdraw reduction

- Operates on vertex and index buffers directly
- Works on non-manifolds
- Allows for varying cache sizes and animated models
- Orders of magnitude faster
- Quality comparable with state of the art
- About 500 lines of code!
- Extremely easy to incorporate in a rendering pipeline

- Hope game rendering pipelines will incorporate such an algorithm
- Hope CAD applications to use and re-compute ordering interactively as geometry changes

Thanks

- Phil Rogers, AMD
- 3D Application Research Group, AMD

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