My Tessellation Has Cracks!

(and solutions to other tessellation related problems)

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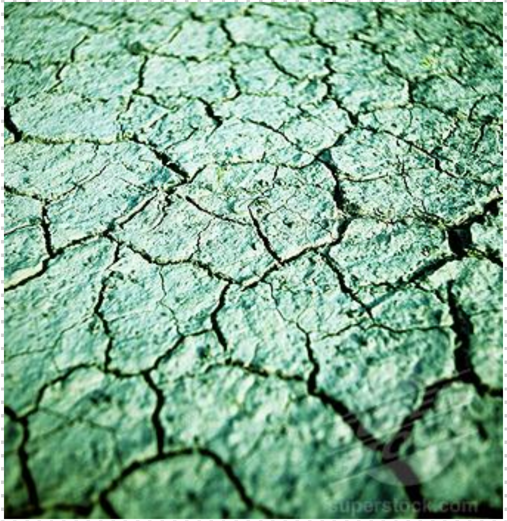
Developer Technology, **NVIDIA**



GAME DEVELOPERS CONFERENCE®

SAN FRANCISCO, CA
MARCH 5-9, 2012
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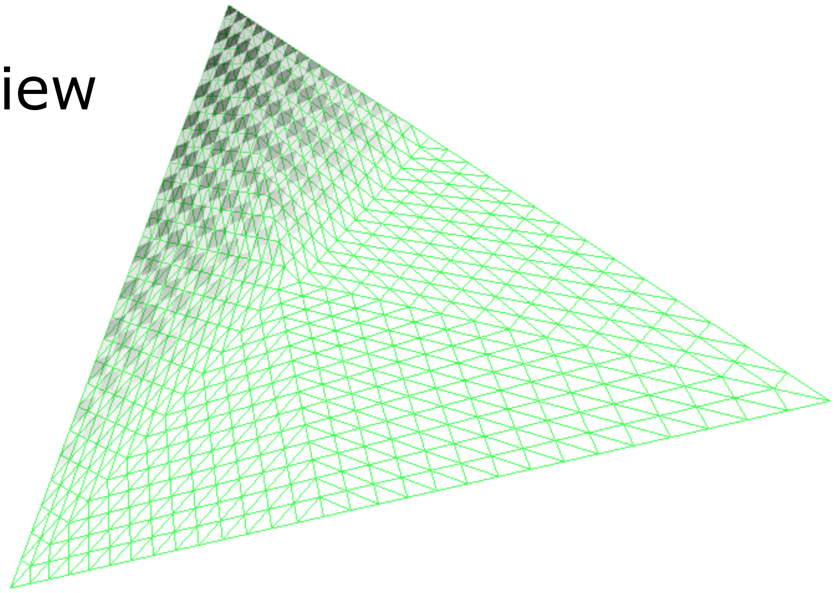
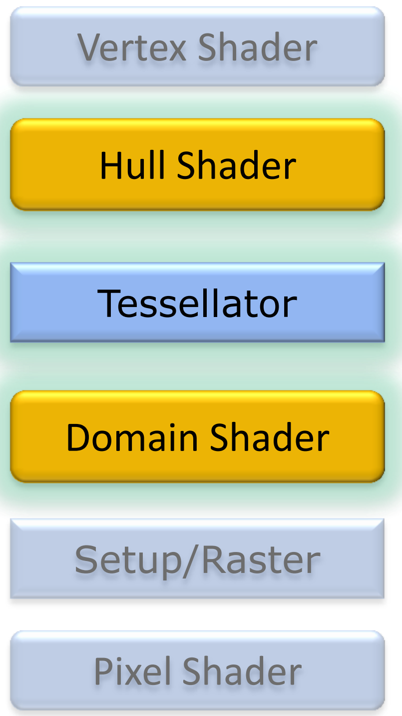
Agenda

- Super-Quick Tessellation Review
- How cracks/holes are born
- Specific examples
  - PN Triangles cracking
  - Displacement map cracking
- Other Tessellation Issues
- Debugging Techniques
- Ptex

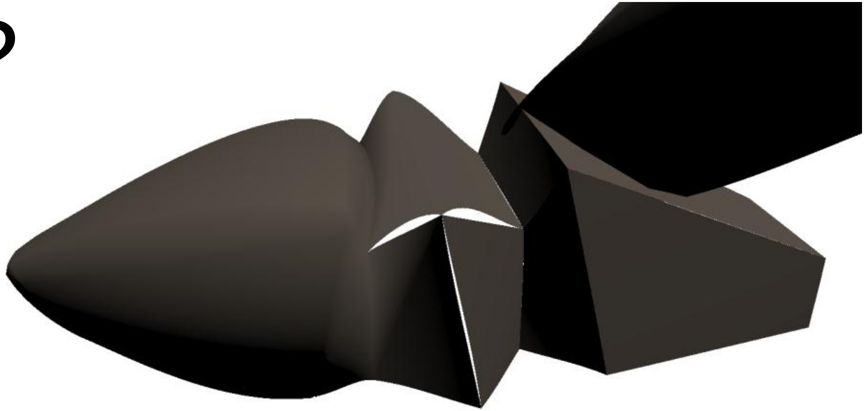


Super-Quick Tessellation Review

- Hull Shader
  - Processes control points
  - Decides tessellation factor
- Tessellator
  - Fixed function
  - Generates barycentric coords
  - Based on tess factors from HS
- Domain Shader
  - Calculates final tessellated vertices
  - Interpolates data using barycentric coords



What is a “crack”?



- Visible seam between edges in the mesh
  - Often large color variance on cracked pixels
  - Can see the background as backfaces are culled

- Vertices on shared edges that should <u>share a position</u> (along edge) are <u>offset such that they no longer share the same position</u>.

Holes: The other “crack”

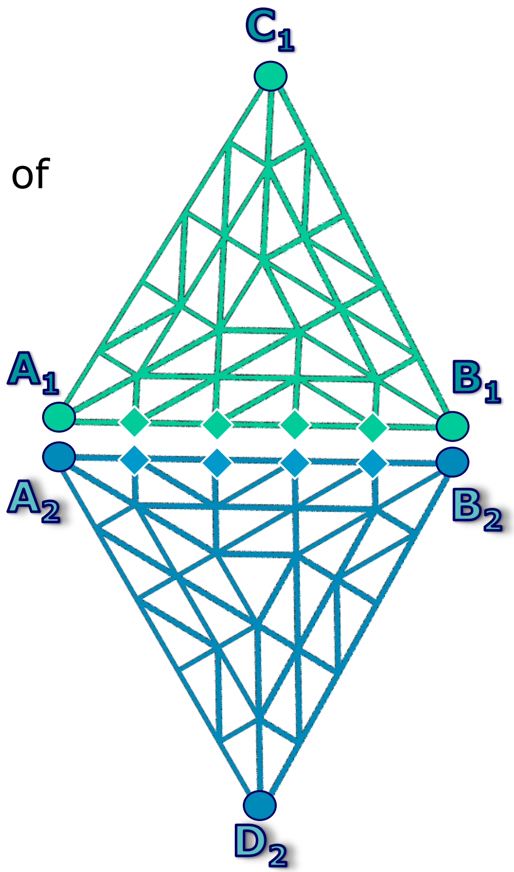
- A “hole” is when shared control vertices diverge position
  - Can think of this as multiple “cracks”

- Can result in much larger seams
  - Same avoidance methods as cracks

- Can cause holes without tessellation!
  - Different vertex offsets in VS per SV_PrimitiveID

How cracks are born

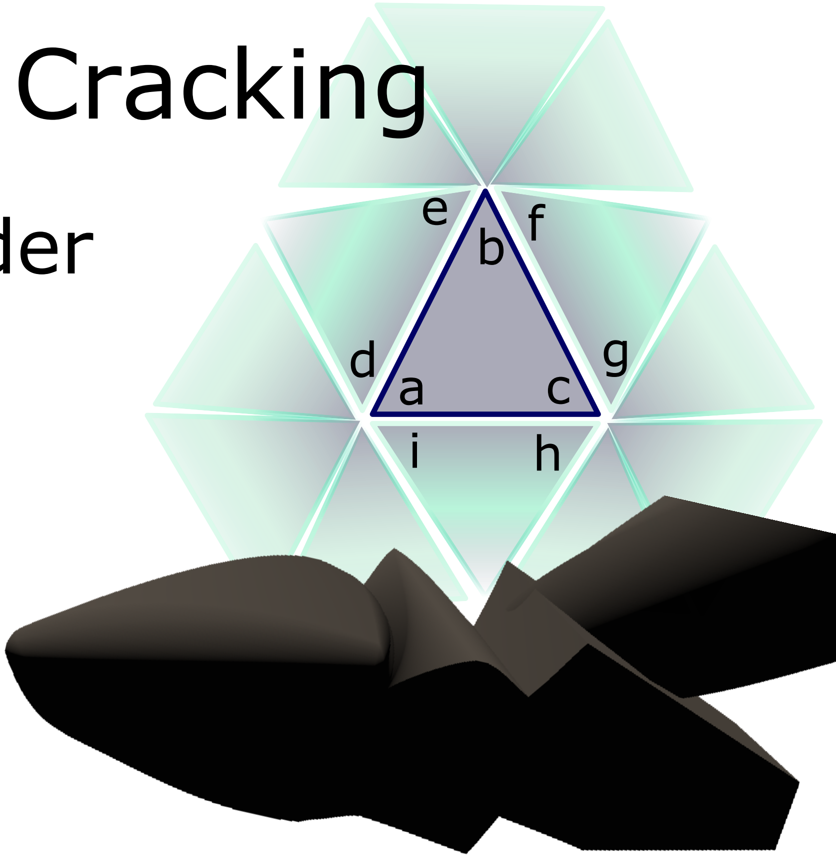
- Two primitives share an edge positionally, but the vertices of that edge have divergent data
  - Normal, UV, etc
- Domain Shader interpolates divergent data sets
  - Can result in large differences in tessellated positions
- Only along control edges/vertices
  - Interior edges are guaranteed not to crack
- In practice float LSB differences don't crack
  - Primitive winding means operations are in different order
  - Theoretically possible to have micro-cracking



General Solution to Cracking

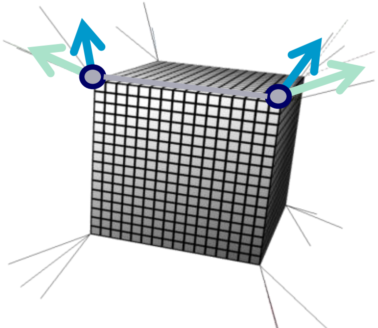
- Ensure the domain shader is using same input data
  - Shared Vertices
  - Shared Edges

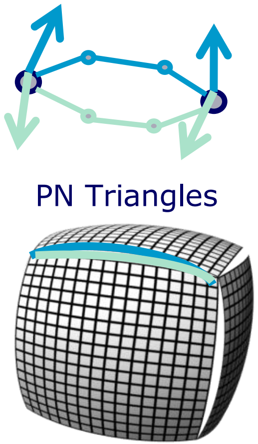
- What is "same data"?



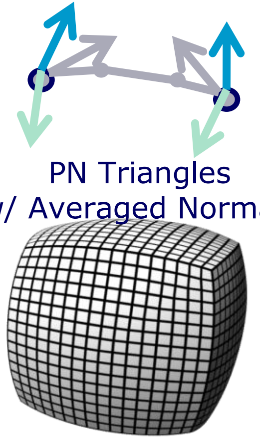
PN Triangles & PN-AEN

- Vertex normals used to calculate Bezier splines
  - offsets tessellated vertices
- Divergent normals = Divergent splines
  - Which leads to cracks
- Adjacent Edge Normals (AEN)
  - Average Normals along Edges
- Phong Tessellation
  - Same issue
  - Same solution





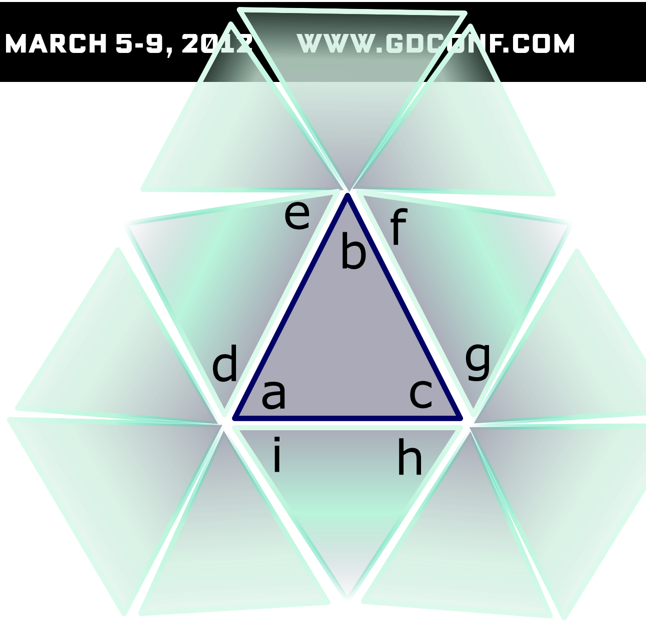
PN Triangles



PN Triangles
w/ Averaged Normals

Implementing AEN

- Method 1 : Index Buffer
  - Add extra indices per primitive
  - Point to adjacent edges
  - Average Normals in Shader
- Method 2 : Texture
  - Store Averaged Normals
    - "Smoothed Normals"
    - Two per edge
  - Load() in Shader
    - SV_VertexID



Index Buffer

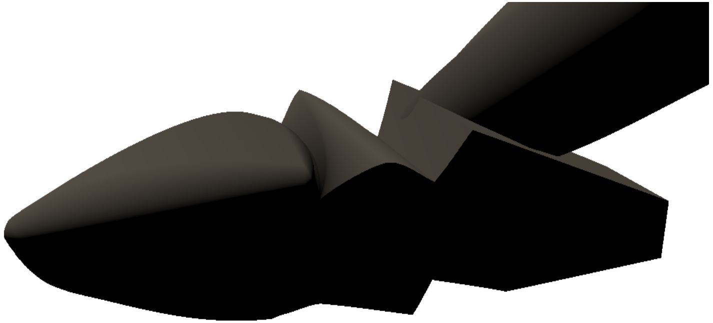
a	b	c	d	e	f	g	h	i

Texture

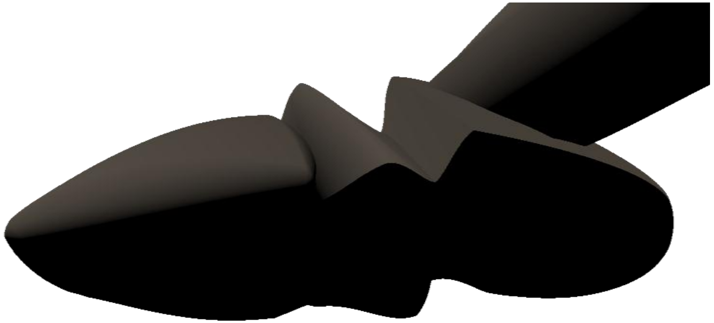
N_{ad}	N_{be}	N_{bf}	N_{cg}	N_{ch}	N_{ai}

AEN Alternative: Smoothed Normal

- Use average normals from entire mesh
  - PN "done right"?
  - Used only for PN/Phong interpolation
  - Averages all valence vertices
- Less "same data"
  - Only one tex sample per vertex
  - Could be integrated into VB
- Results in more "puffy" PN splines
  - Normals from irrelevant edges



PN-AEN



Smooth Normals

Displacement Map Cracking(1)

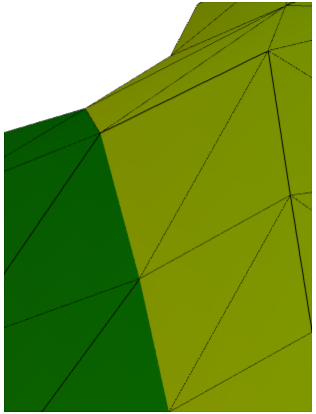
- UV coordinates are discontinuous
  - UV unwrap results in seams
  - Edge length in texture space also not identical
  - Edge direction in texure space divergent
- Historical “issue” for texture mapping
  - Divergent locations contain similar values
  - Normal mapping sometimes shows issues
- Displacement offsets along shared edges
  - Displacements interpolated along the edge and will pick up slightly varying values

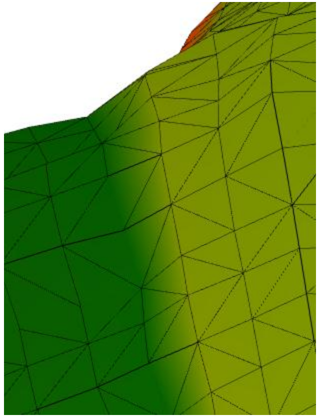
Solution: Dominant UVs

- Override UV for sampling displacement

- This is safe as we only override along the shared edge and control vertices
  - An edge will never crack from itself

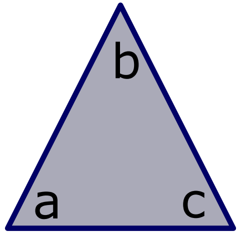
- Interior primitives uses the original UVs





Dominant Data

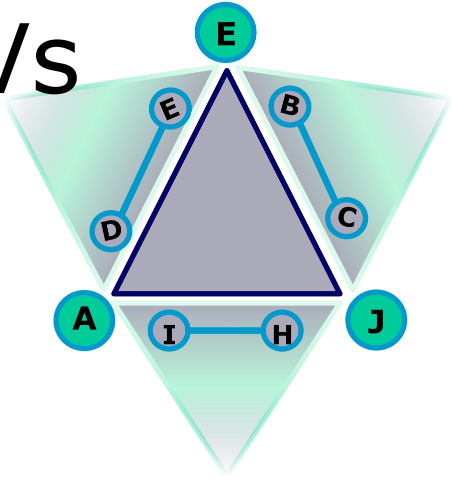
- Lookup at runtime into preprocessed data
  - Overridden IB
  - Data to stuff into texture
- Edges separate from Corners
  - Only 2 possible shared edges to pick from for any primitive
  - N shared “non edge” vertices
  - Dominant Vertex may or may not be on Dominant Edge
- Can be arbitrary
  - All shared vertices must have the same dominant data
  - Both edge vertices must be from the same primitive



Control Vertex	Dominant Vertex
a	A
b	E
c	H
Control Edge	**Dominant Edge**
a-b	D-E
b-c	B-C
c-a	H-I

Implementing Dominant UVs

- Method 1: Index Buffer
  - Add indices for dominant edge
    - Can use AEN edge data as well
  - Add indices for dominant vertex
- Method 2: Texture
  - Encode UV
  - 2 Samples per control point



Index Buffer

a	b	c	D	E	B	C	H	I	A	E	J

Texture

$U_dV_dU_e$	$V_eU_AV_A$

Dominant Data Generation

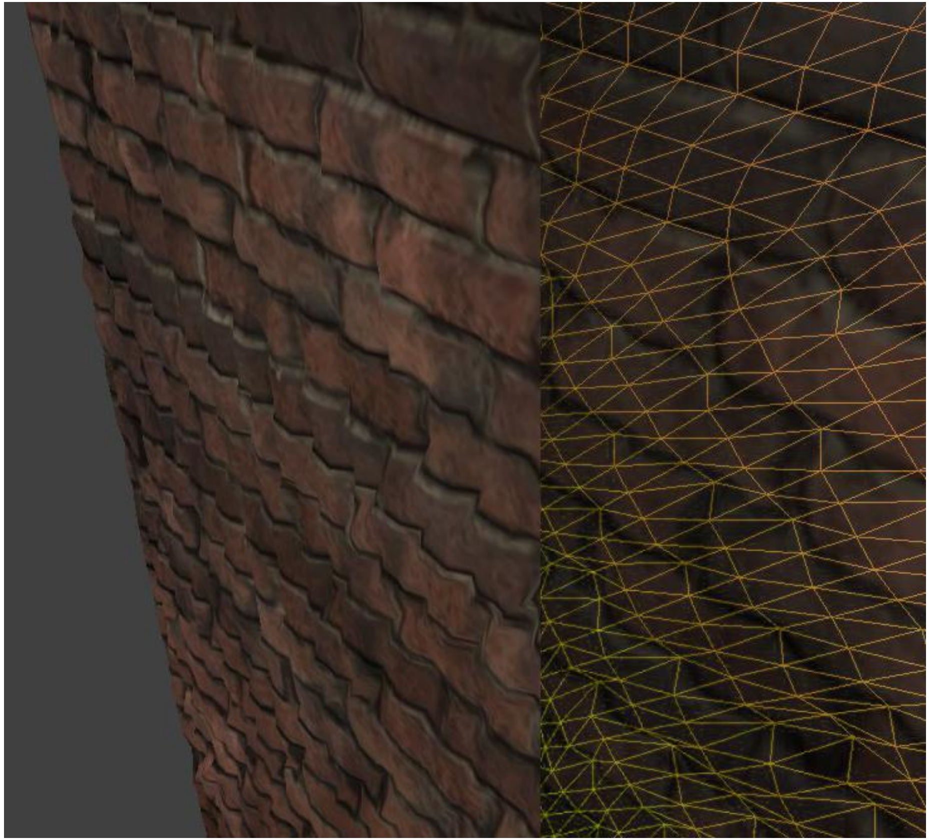
- CPU side pre-process
  - Typically done as part of a build/cook process
  - Can be done on mesh load as well
- Generate Packed Listing of shared position & edges
  - List of indices at each shared position
  - List of index tuple at each shared edge start
- Arbitrarily pick dominant data
  - First entry in the list
- It really is that simple

Intra-material cracking

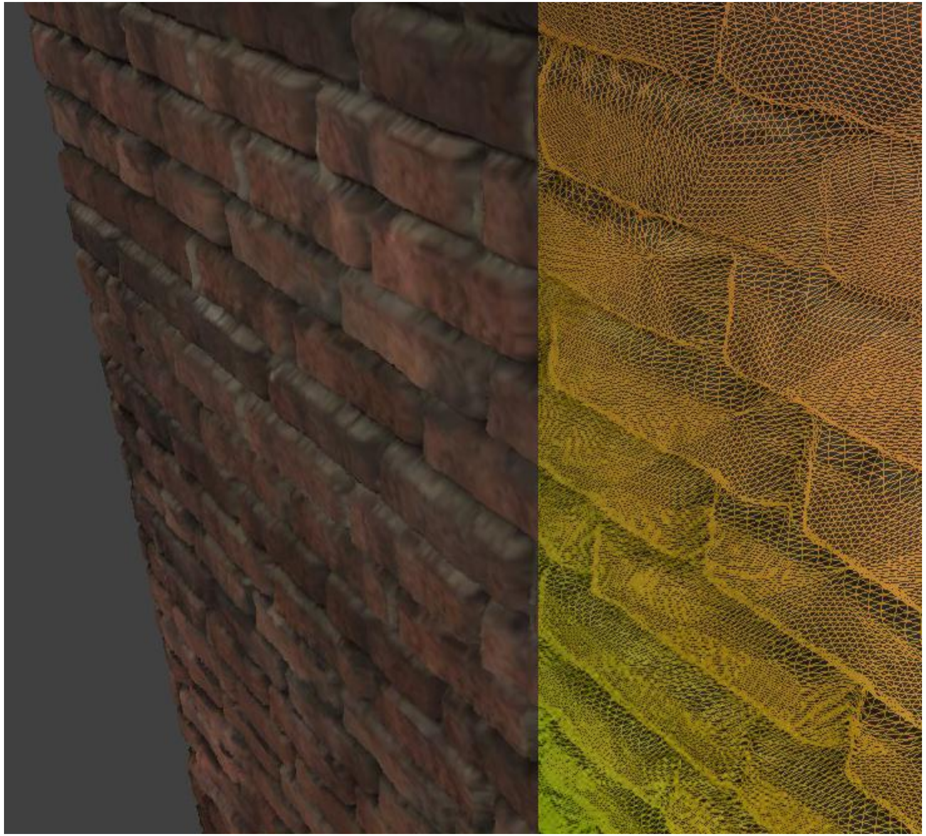
- Meshes in games often have multiple materials
  - Submeshes render as separate draws
  - With separate textures and UV spaces
  - No access to neighbor info across seams
- Solutions
  - If submeshes share a VB, then AEN style techniques can work
  - Smooth normal/Dominant UV texture can encode data from group of submeshes
  - Pin displacement to 0 at edge
    - May not look “right”
    - Alternative is mesh rework.

Virtual Dicing

- Tessellation factor limit of 64
  - 1 edge => 64 edges
  - This limit can be hit for coarse meshes with high zoom
- One solution is to pre-dice mesh in DCC tool
  - This requires artist time
  - Potentially not matched to displacement map resolution
- Alternative is to programmatically subdivide
  - Per primitive density control
  - Match mesh density to displacement map resolution
  - Add extra redundant indices into IB
  - Reposition duplicates on interior of original



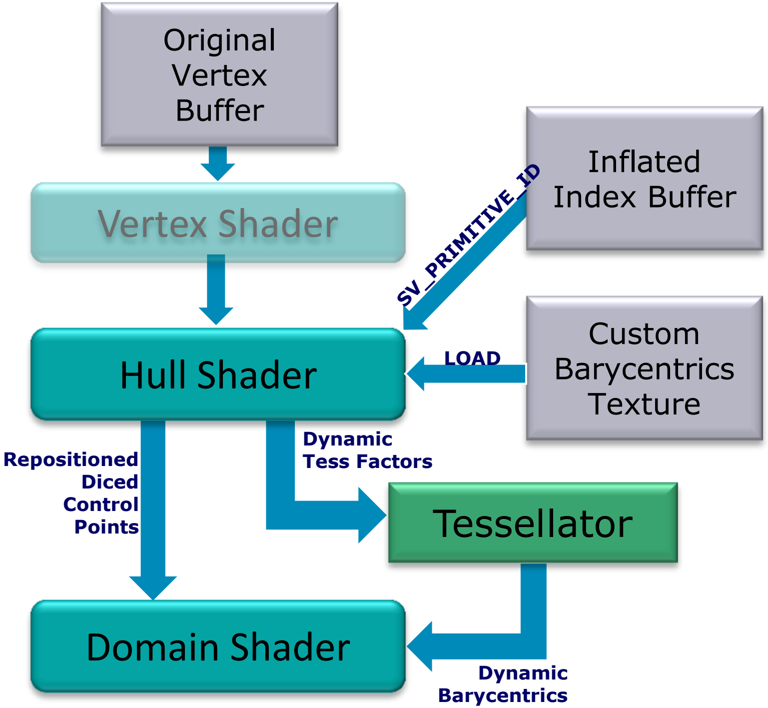
No Dicing – Dynamic Factor=64



12 Factor Diced – Dynamic Factor=32

Virtual Dicing Implementation

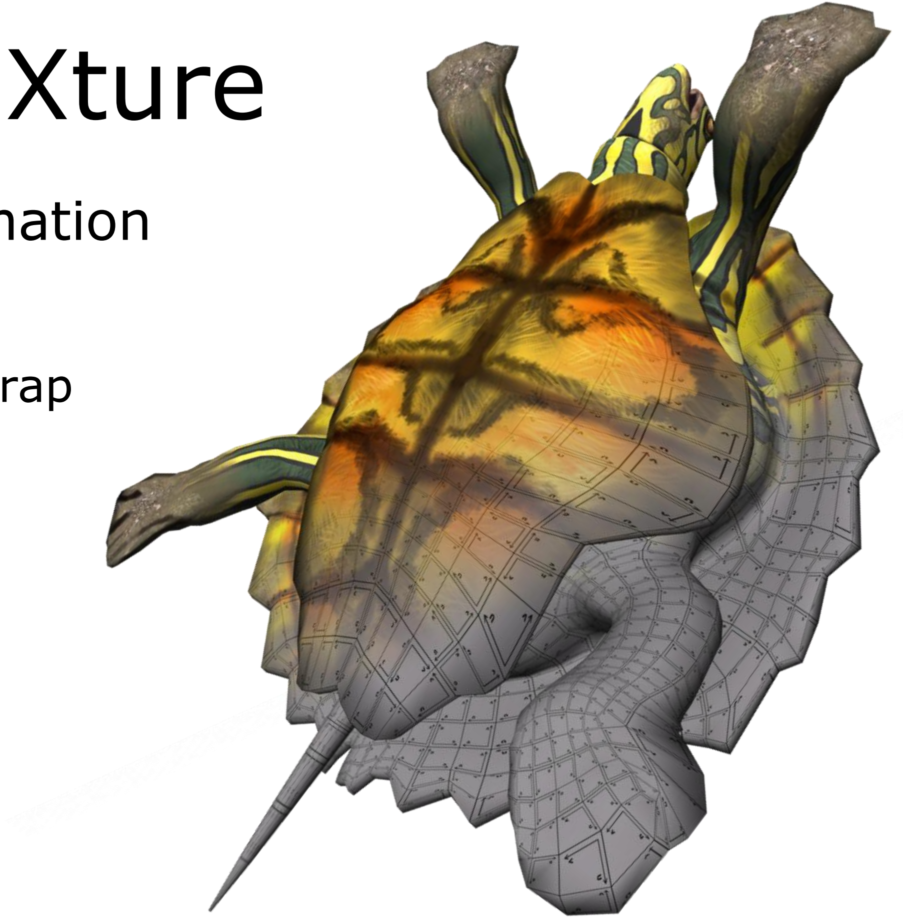
- Add duplicate primitives
  - "inflated" index buffer
  - # of addition varies per prim
- Barycentric coords texture
  - Remap of new control verts
  - Interpolation of originals
- Hull Shader repositions vertices
  - SV_PrimitiveID determines Load()



Ptex – Per-face TEXture

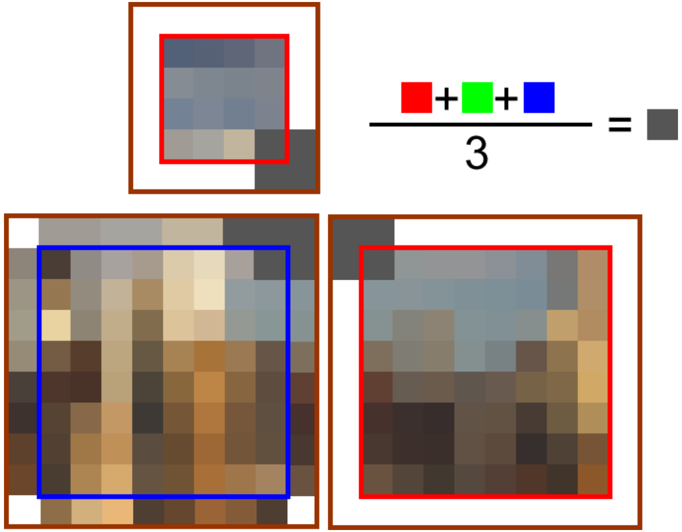
- Developed at Walt Disney Animation Studios
  - By Brent Burley in 2008
  - As a method to remove UV unwrap serialization in art pipeline

- Texturing with implicit UVs
  - One "texture" per primitive
  - Power of two textures
  - Quads only!



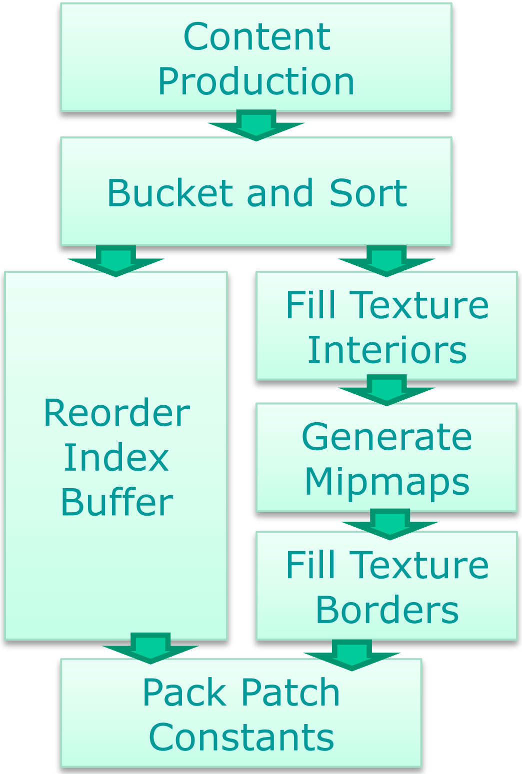
Ptex and Displacement Maps

- Ptex can be used with displacement maps
- No Holes
  - Corners pinned at texgen
- No Cracks
  - Edges all share common data
- Full Resolution Control
  - Per-face control



Realtime Ptex

- DCC support already in place
- Realtime Ptex with DirectX11!
  - Texture2DArray (also in D3D10)
  - Quad primitives
- For more info: http://ptex.us/
- "Practical Ptex for Games"
  - Game Developer Magazine: January 2012



Questions?

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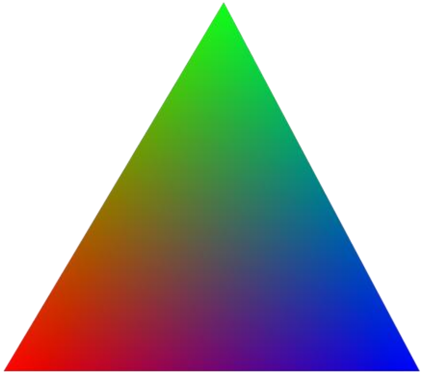
Appendix B: Debugging Techniques

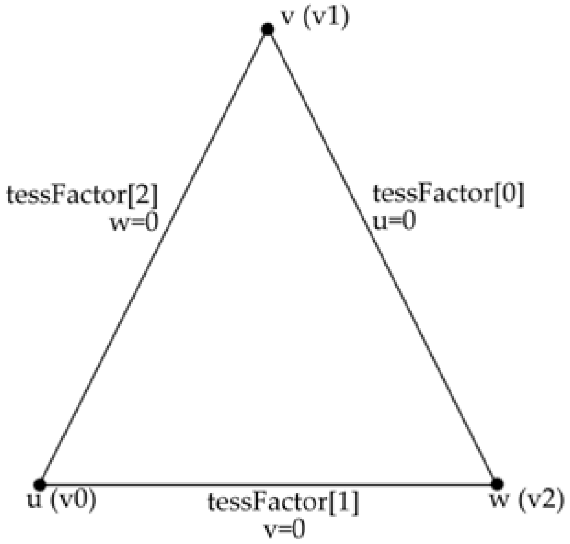
- Verify your conventions
  - Output Barycentric coordinates as diffuse color
- Reduce shader to flat tessellation
  - add pieces back
- Remove clipping & "clever" optimizations



Barycentric Coordinates as colors

Debugging Techniques cont'd

- Edge LOD specification
  - for triangles is surprising

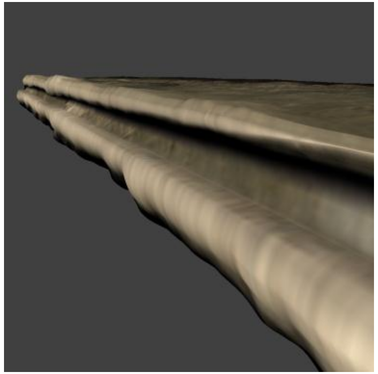


- Real-time graphics debugging tools
  - Introspect graphics state
  - Visualize mesh, texture and render target data
  - Debug your tessellation shader (Hull/Domain)
    - natively on the hardware

Appendix C :Texture Stretching

- UV space stretched when displacing
  - Edge length in texture space is constant
  - Physical edge length (world space) changes based on displacement
- Solution/Workaround
  - 2-pass approach
  - Reduce displacement of texels causing stretching on the second pass

Texture stretching



Reduced offsets