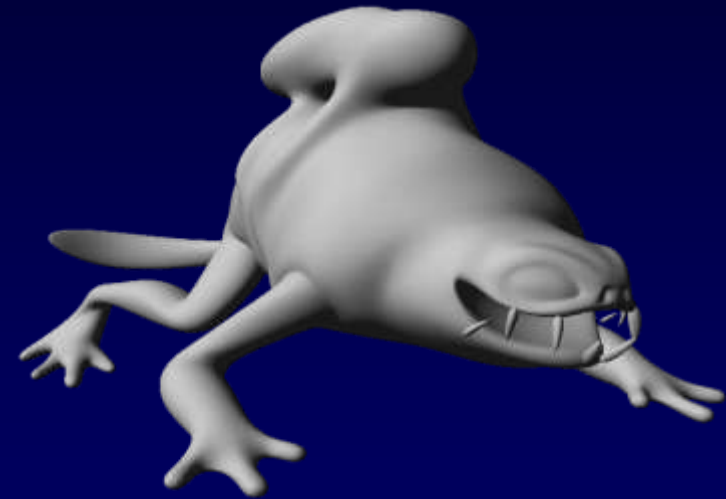
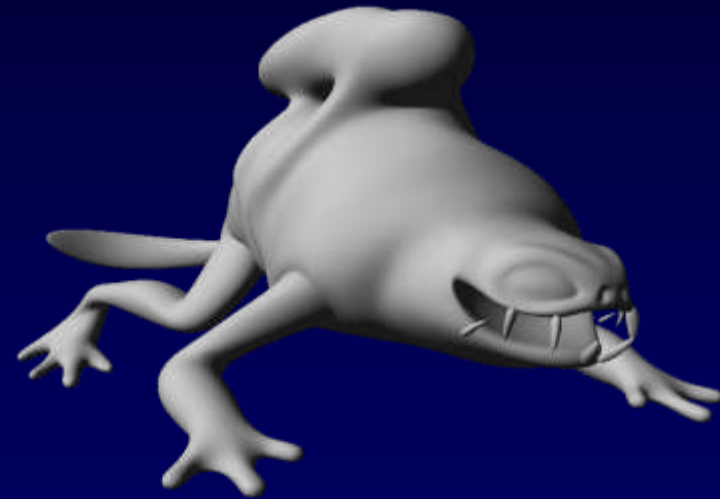


Approximate Catmull-Clark Patches

Scott Schaefer

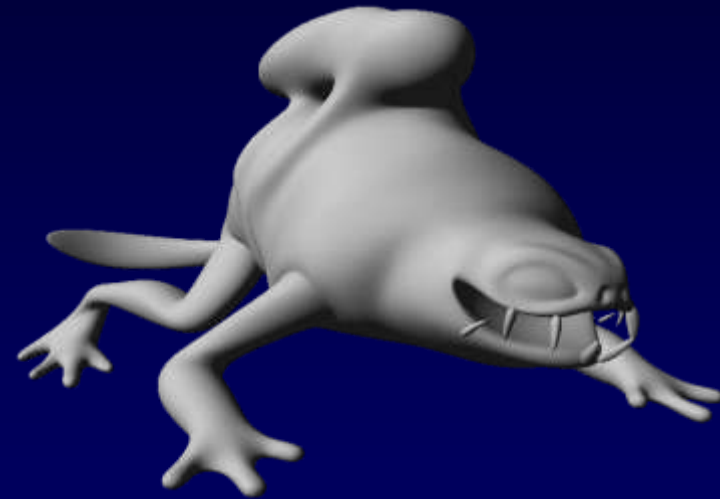
Charles Loop



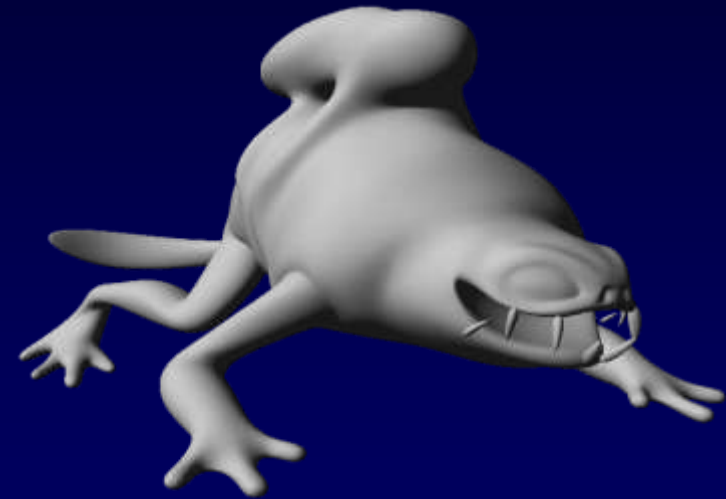
Approximate Catmull-Clark Patches

Scott Schaefer

Charles Loop



Catmull-Clark Surface



ACC-Patches

Polygon Models

- Prevalent in game industry
- Very fast to render
- Not smooth (faceted)
- Complicated LOD management
- High-resolution models require lots of band-width and computational resources



Goal: Fast Smooth Surfaces

- Eliminate faceting artifacts
- Animate low-res representation
- Let GPU worry about LOD

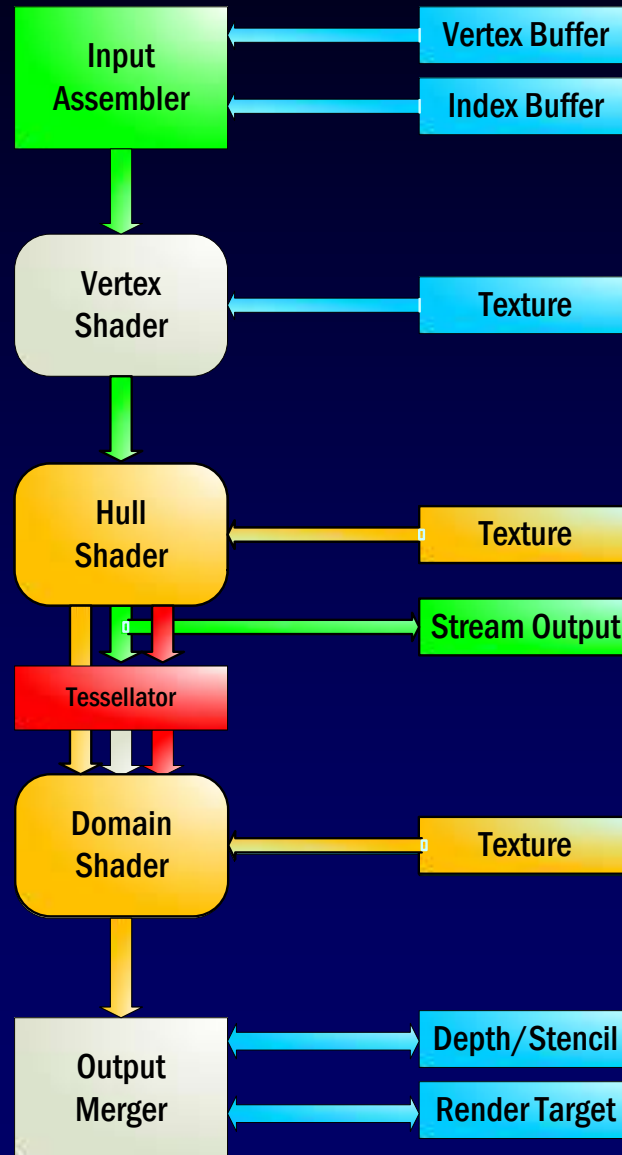


Current

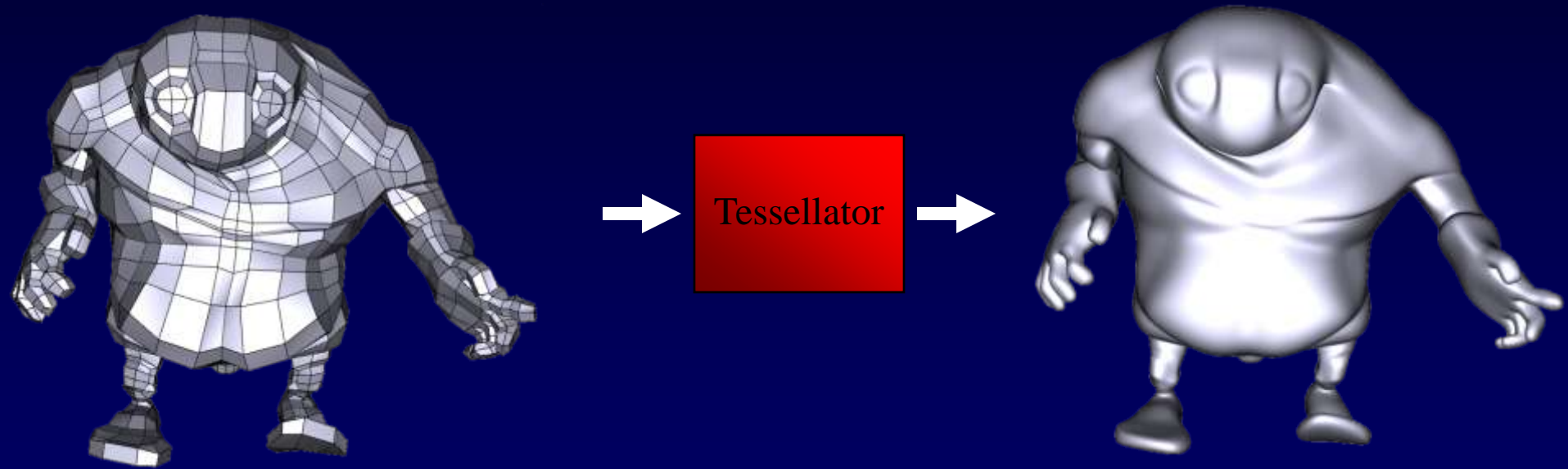


Future

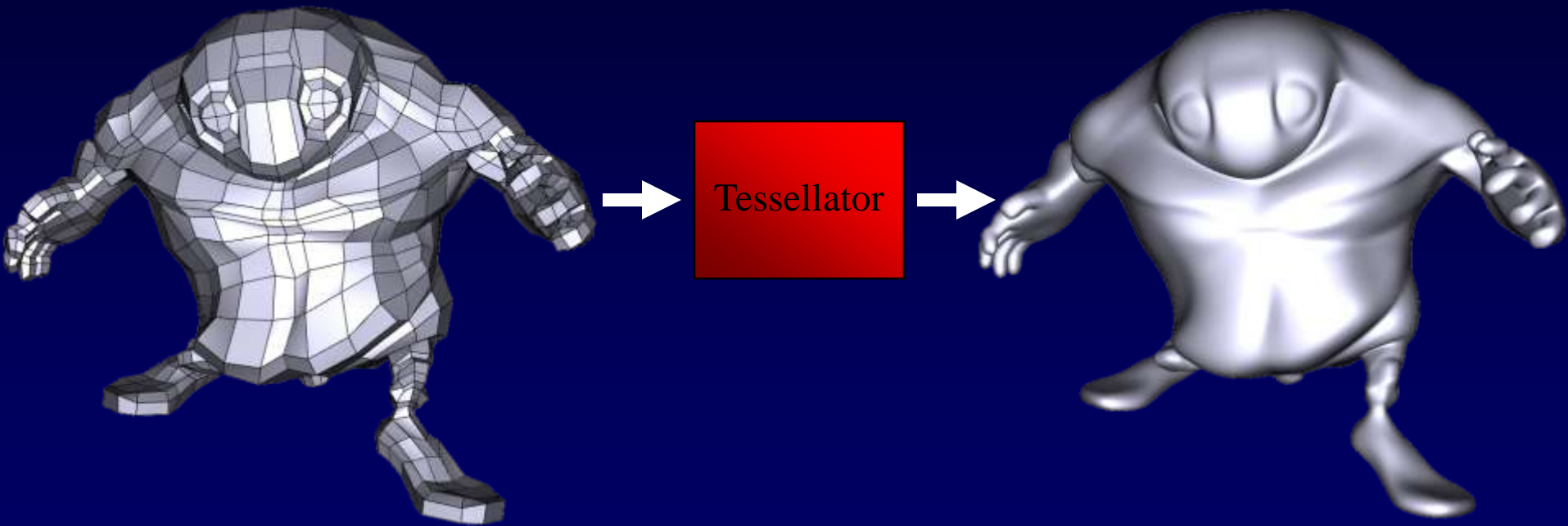
DirectX 10 Pipeline



Tessellator Unit

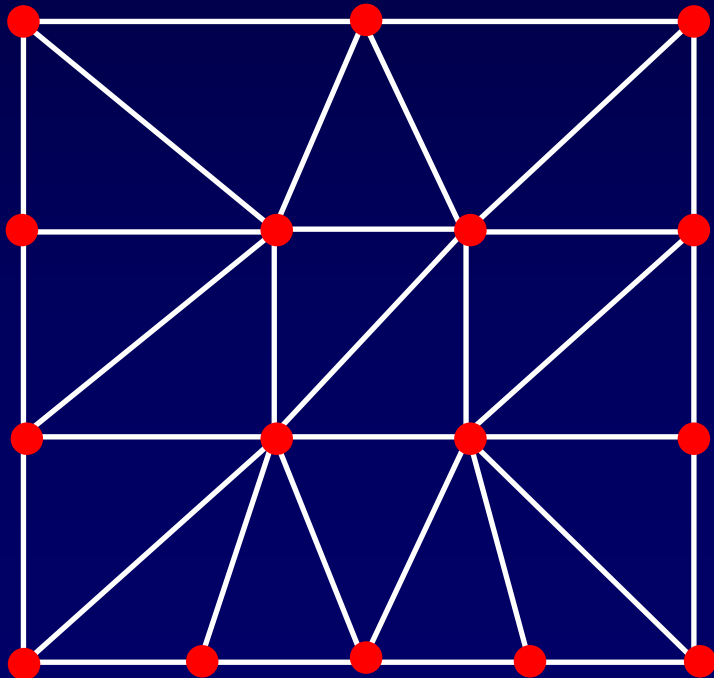


Tessellator Unit



Domain Shader

- Tessellation factor per edge
- Called for each vertex of the sample pattern
- Early form in the XBox 360



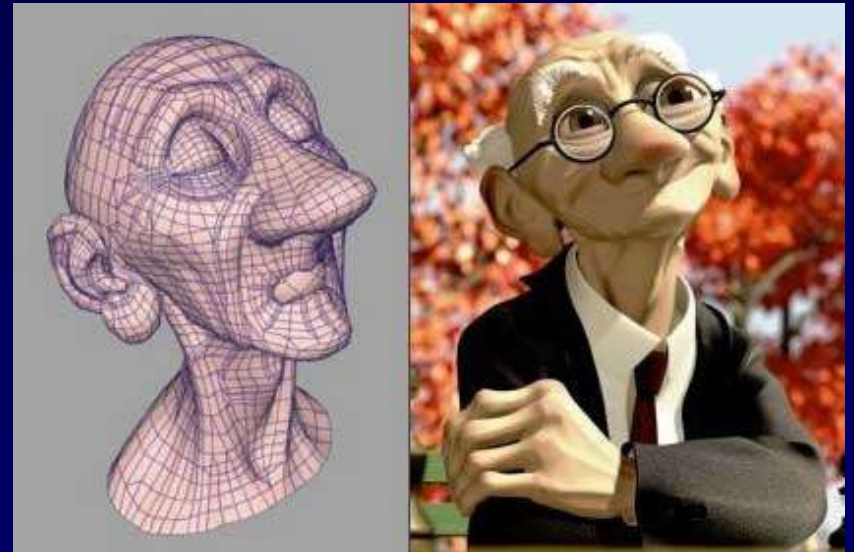
```
DS_OUT DS(float2 uv : BARYCENTRIC,  
          int patchInd : INDEX)  
{  
    DS_OUT Out = (DS_OUT)0;  
  
    // fetch data for patch #patchInd  
  
    // evaluate patch at uv  
  
    return Out;  
}
```

Subdivision Surfaces

- Used in movie and game industries
- Supported by most 3D modeling software



Toy Story © Disney / Pixar



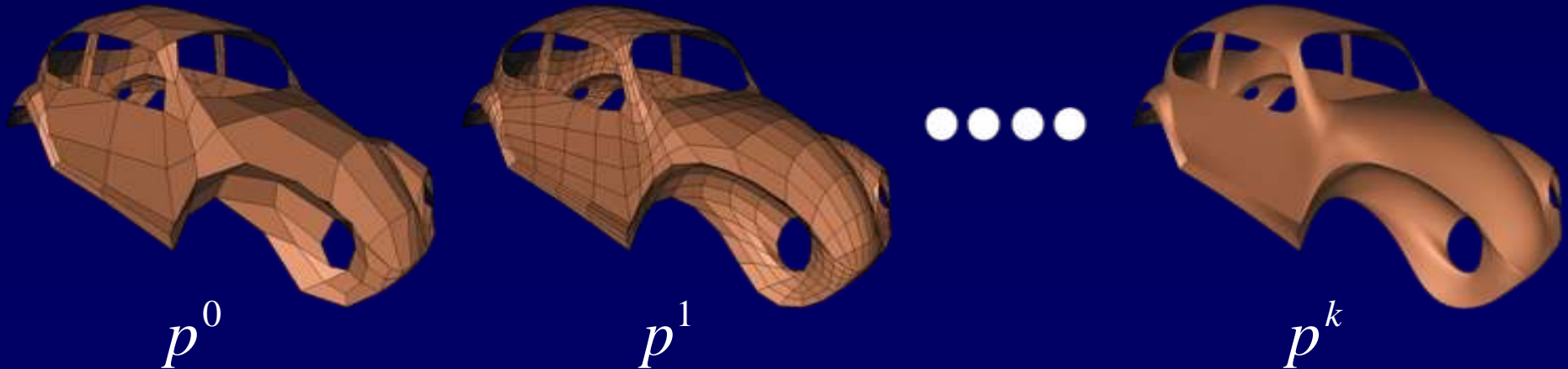
Geri's Game © Pixar Animation Studios

Subdivision Surfaces

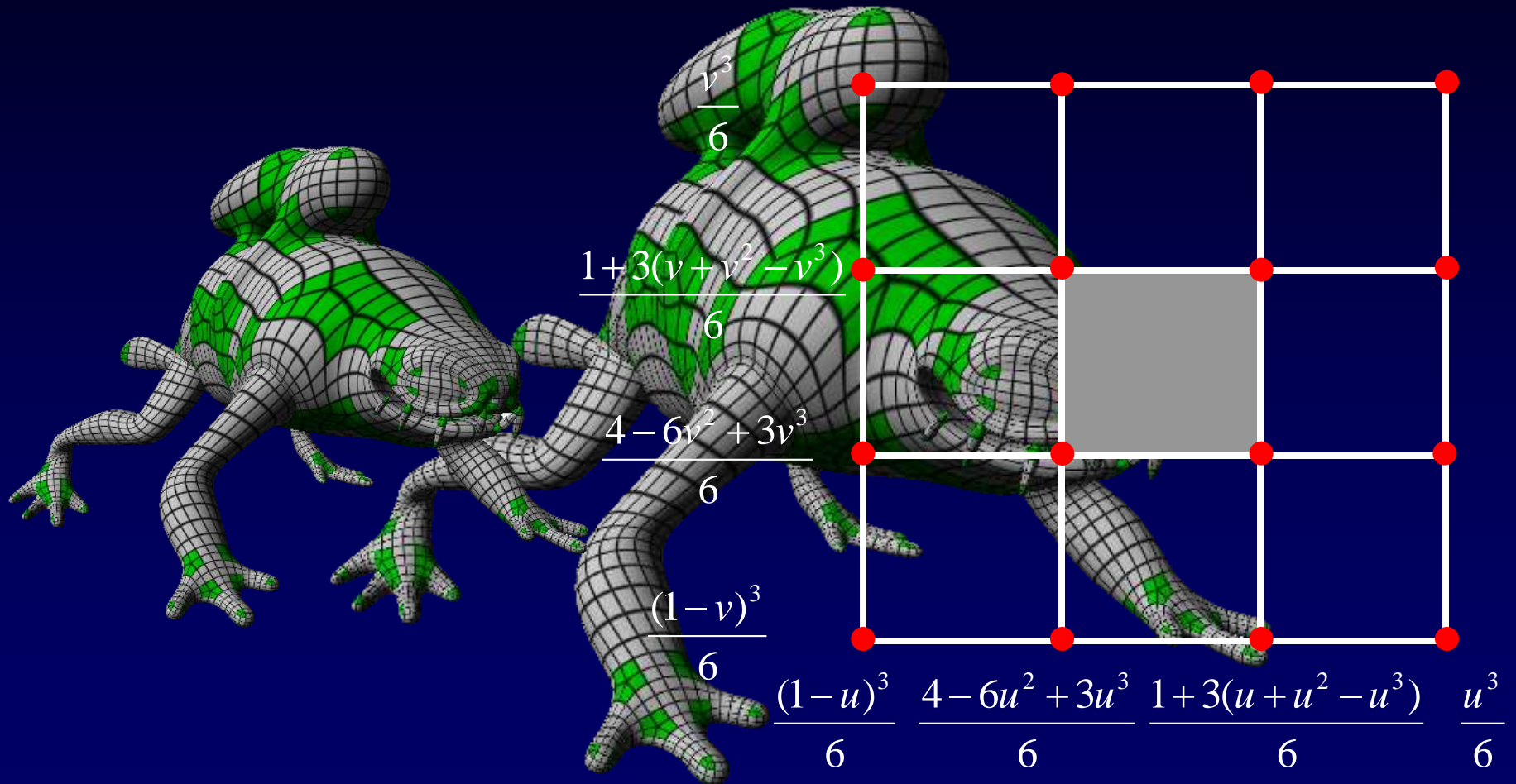
- Set of rules S that recursively act on a shape p^0

$$p^{k+1} = S p^k$$

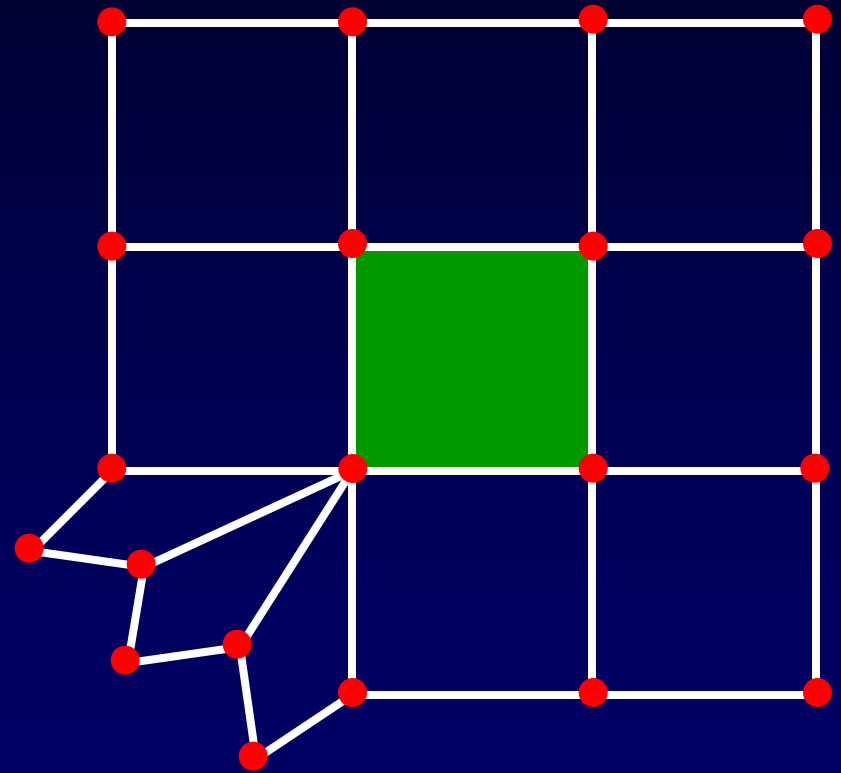
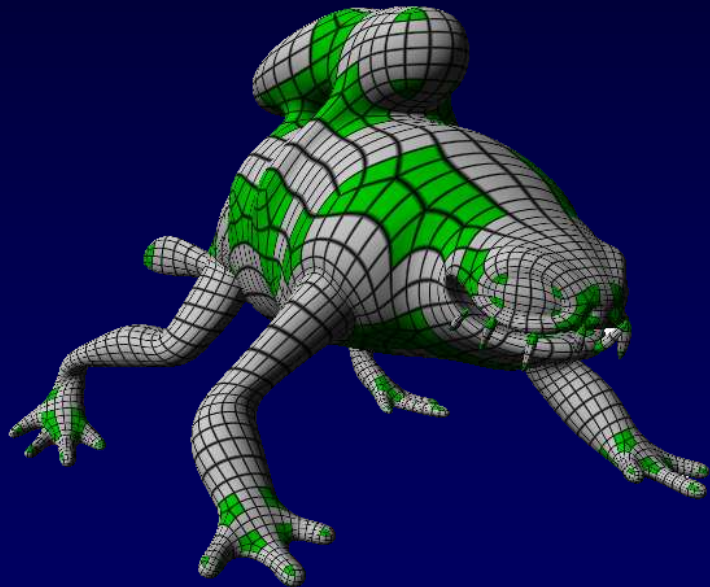
- Arbitrary topology surfaces
- Smooth everywhere



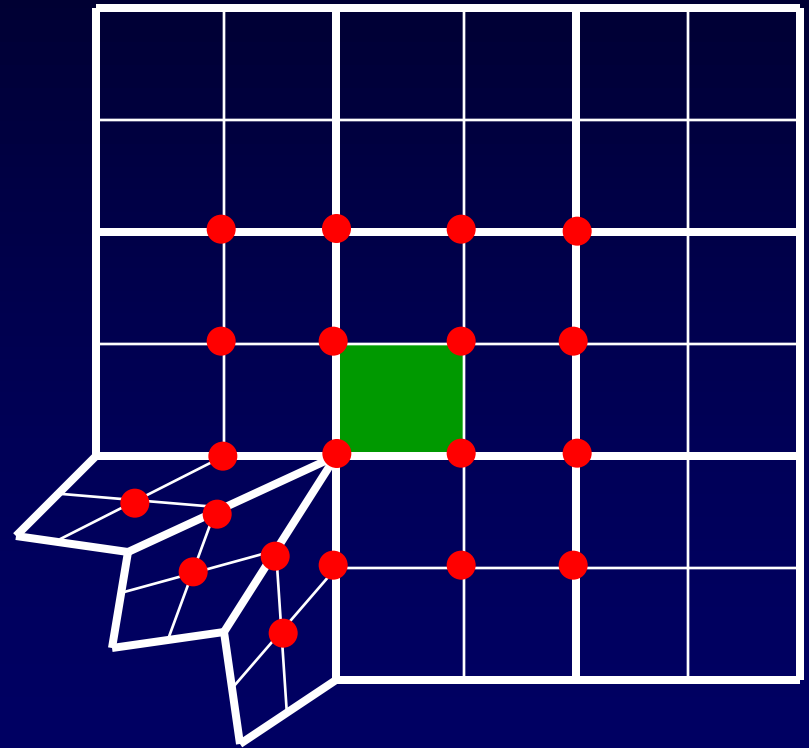
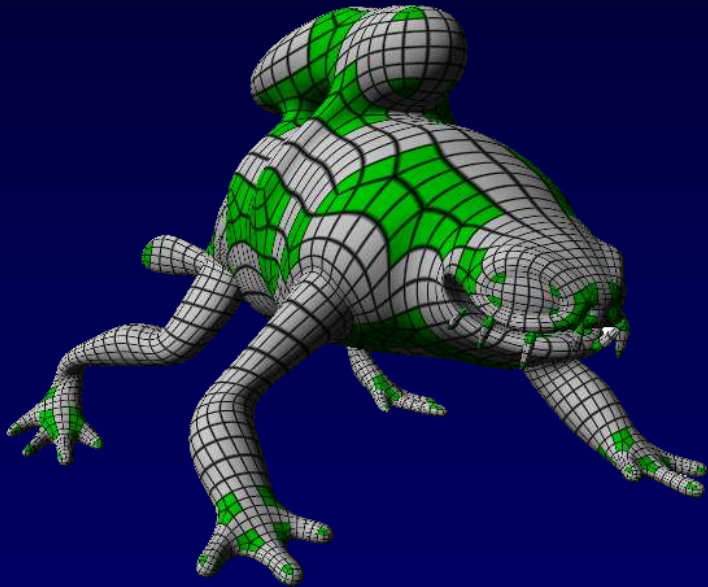
Catmull-Clark Surfaces



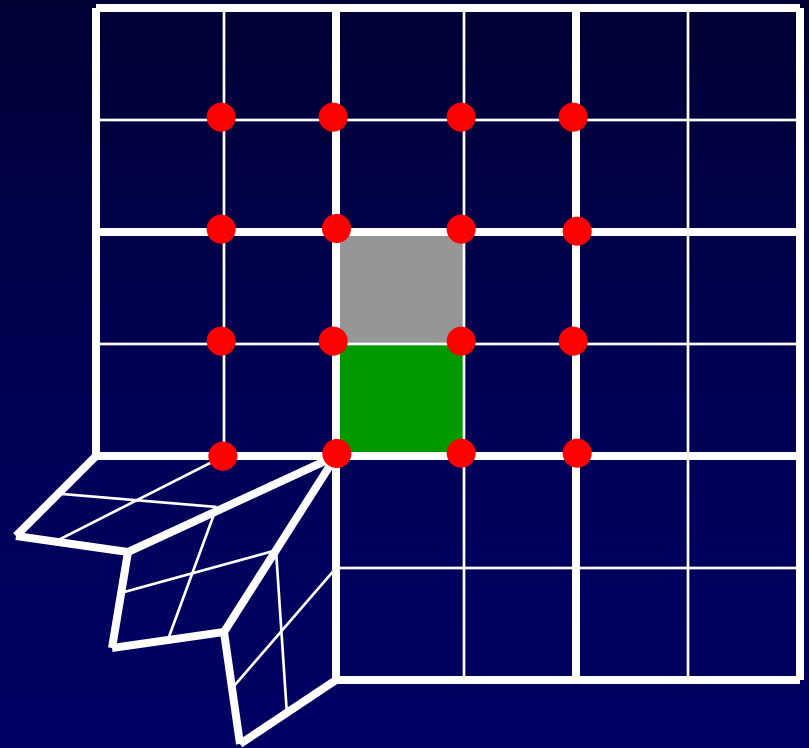
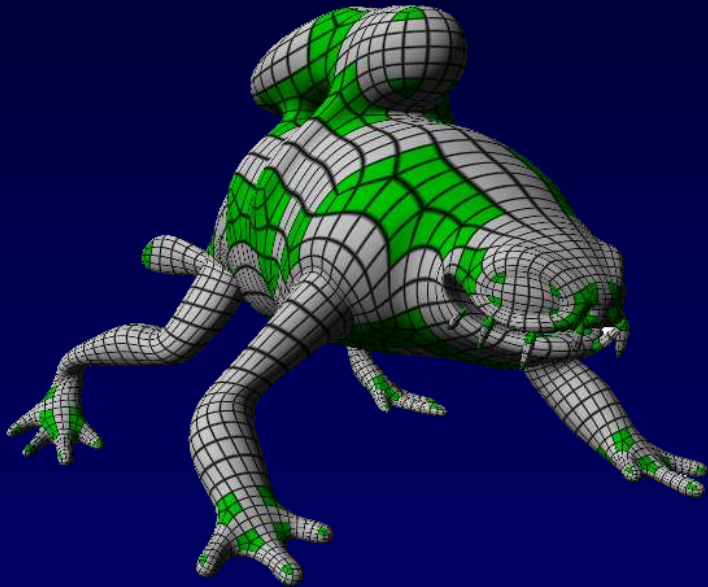
Catmull-Clark Surfaces



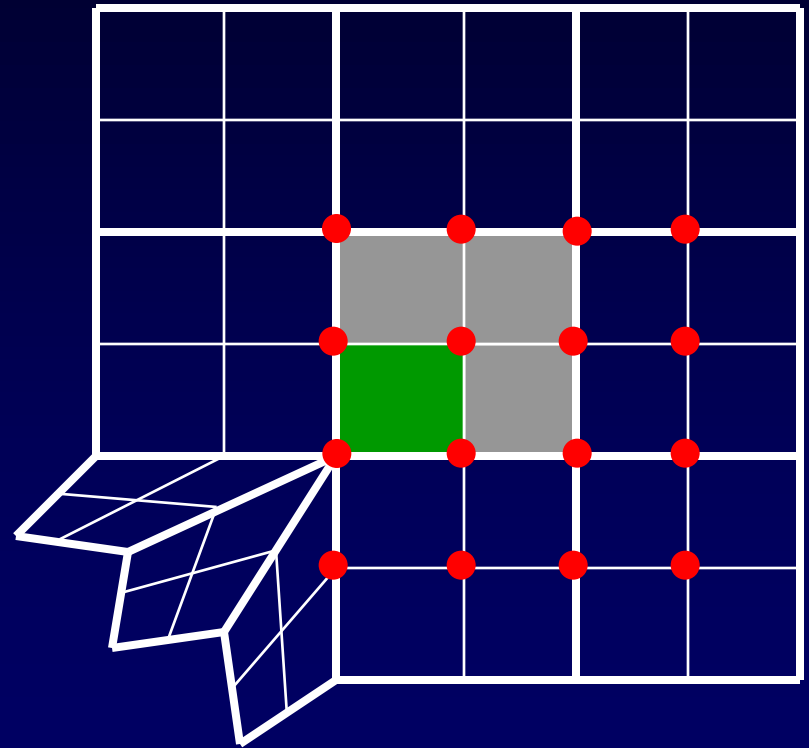
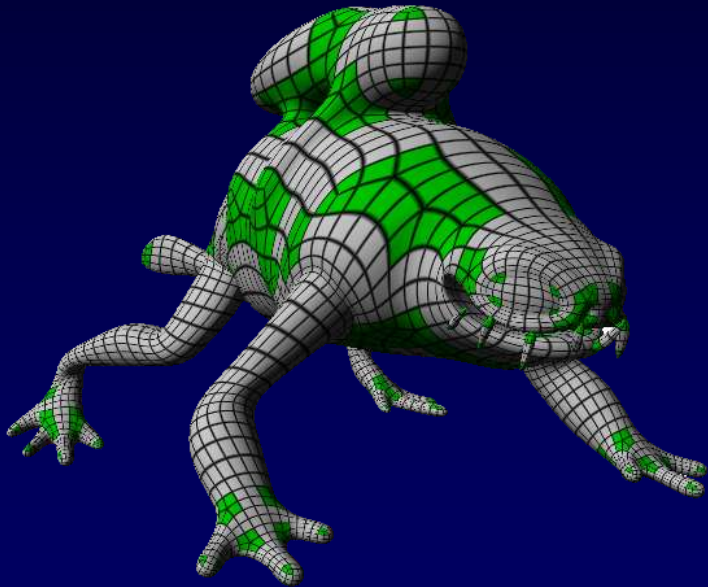
Catmull-Clark Surfaces



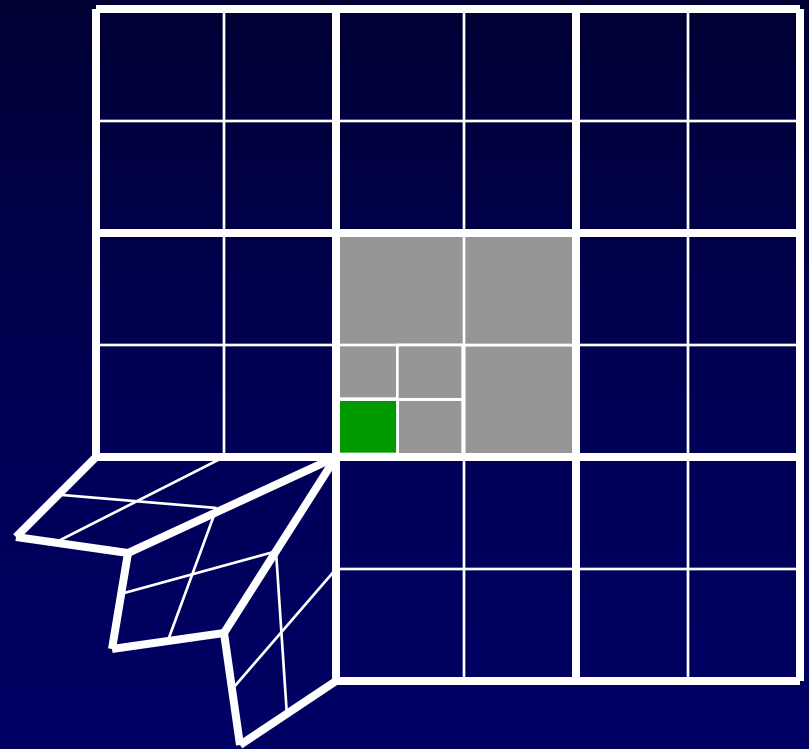
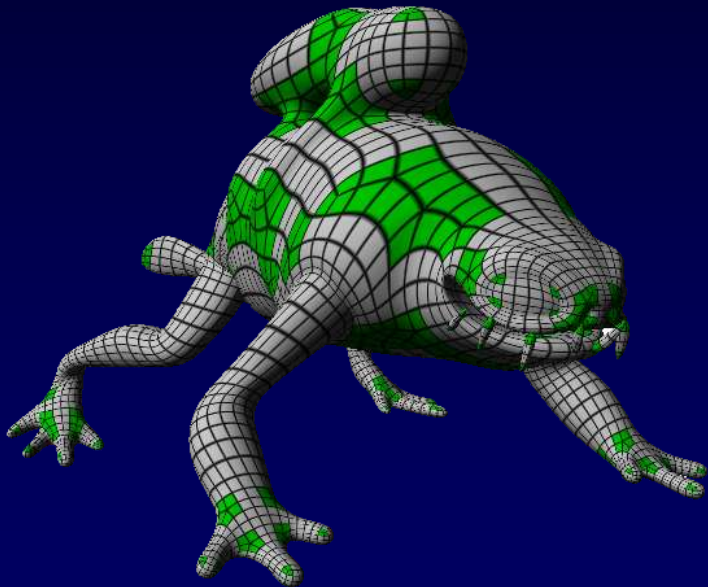
Catmull-Clark Surfaces



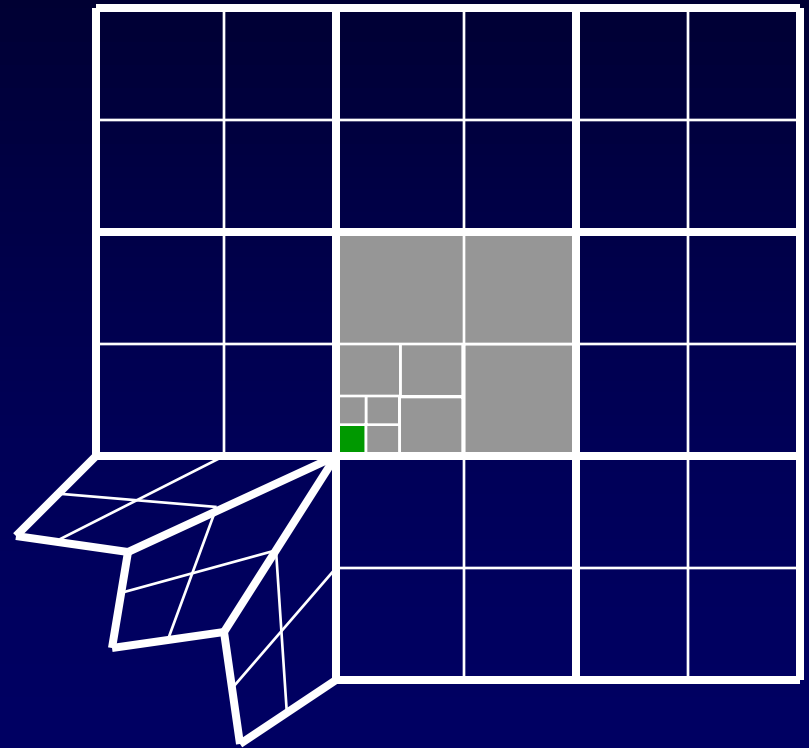
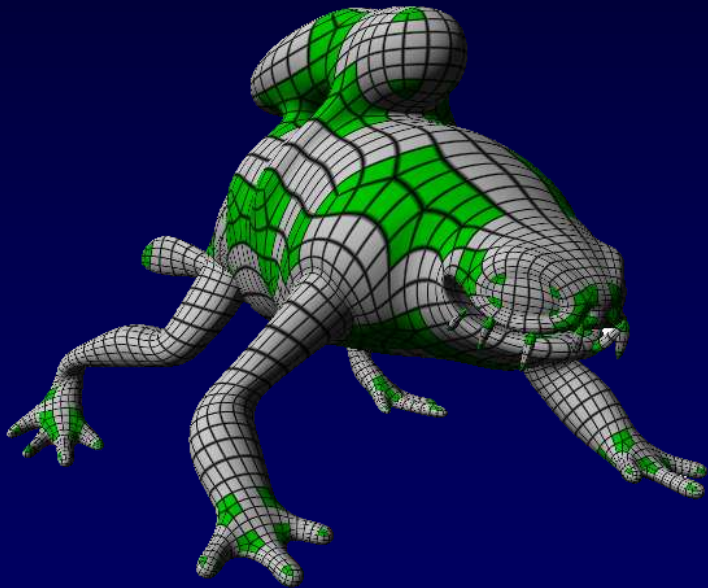
Catmull-Clark Surfaces



Catmull-Clark Surfaces



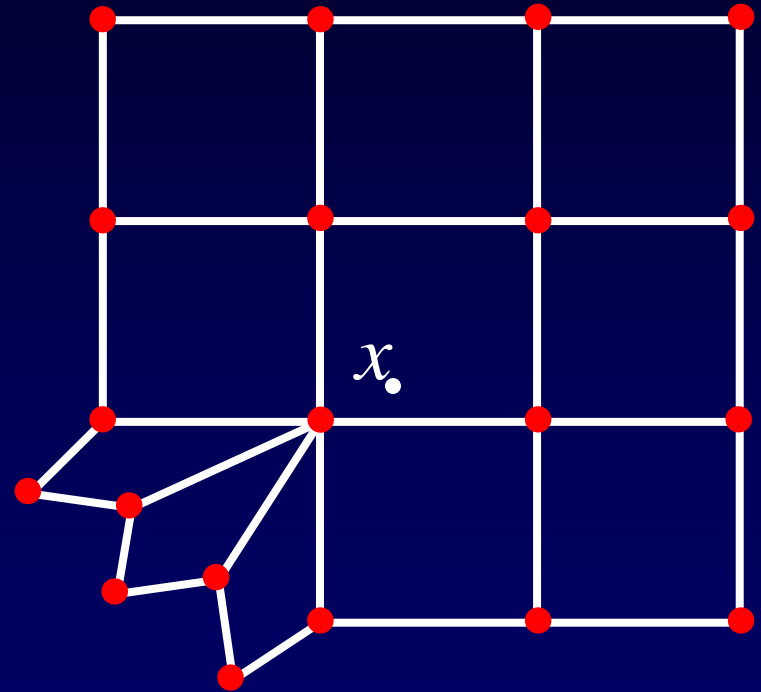
Catmull-Clark Surfaces



Stam's Exact Evaluation Algorithm

- Subdivide until x is in ordinary region

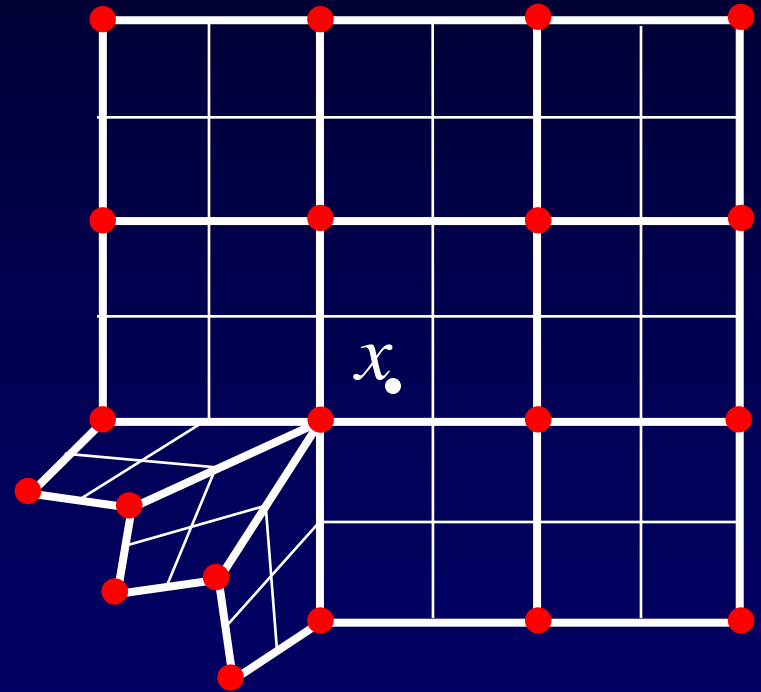
$S^i P$



Stam's Exact Evaluation Algorithm

- Subdivide until x is in ordinary region

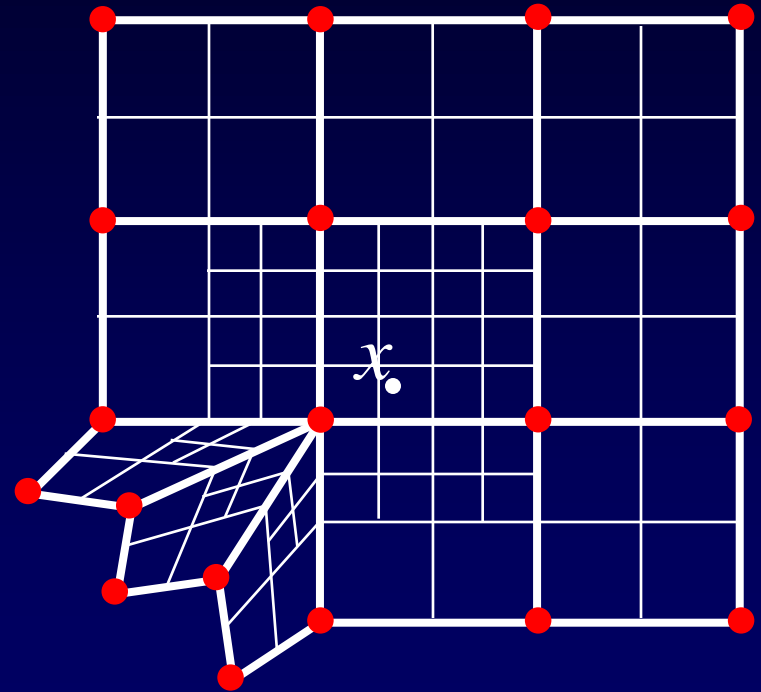
$S^i P$



Stam's Exact Evaluation Algorithm

- Subdivide until x is in ordinary region

$S^i P$

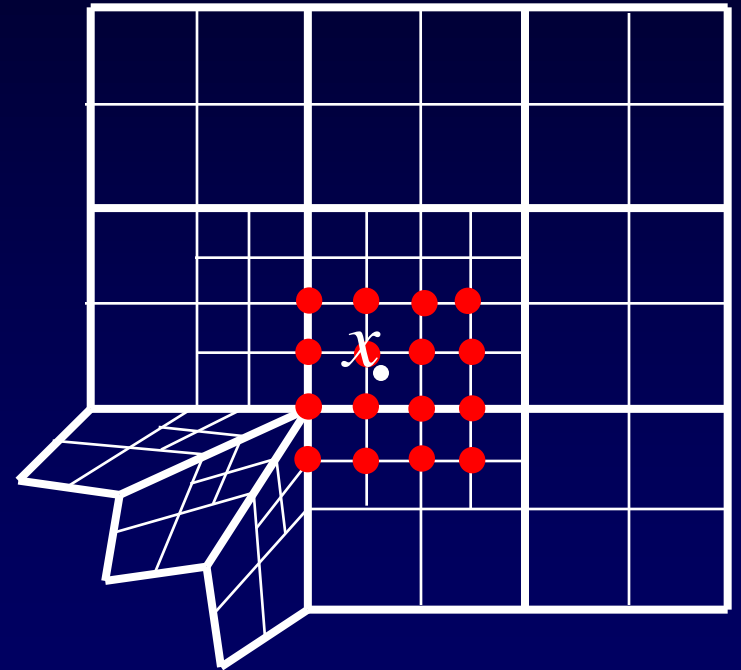


Stam's Exact Evaluation Algorithm

- Subdivide until x is in ordinary region

$$S^i P$$

- Extract B-spline control points and evaluate at x

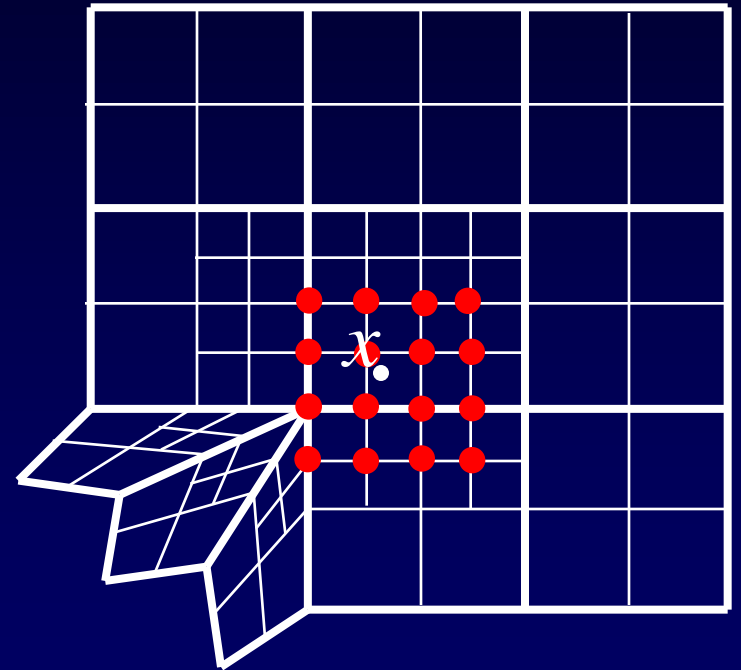


Stam's Exact Evaluation Algorithm

- Subdivide until x is in ordinary region

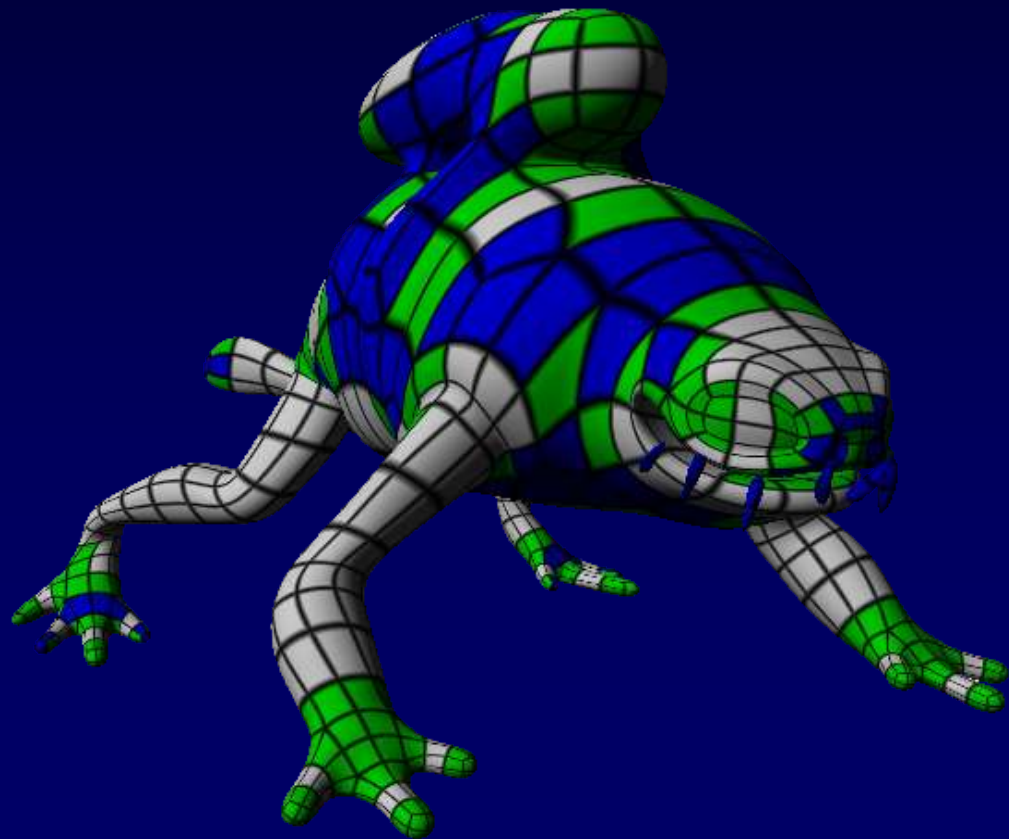
$$V\Lambda^iV^{-1}P$$

- Extract B-spline control points and evaluate at x



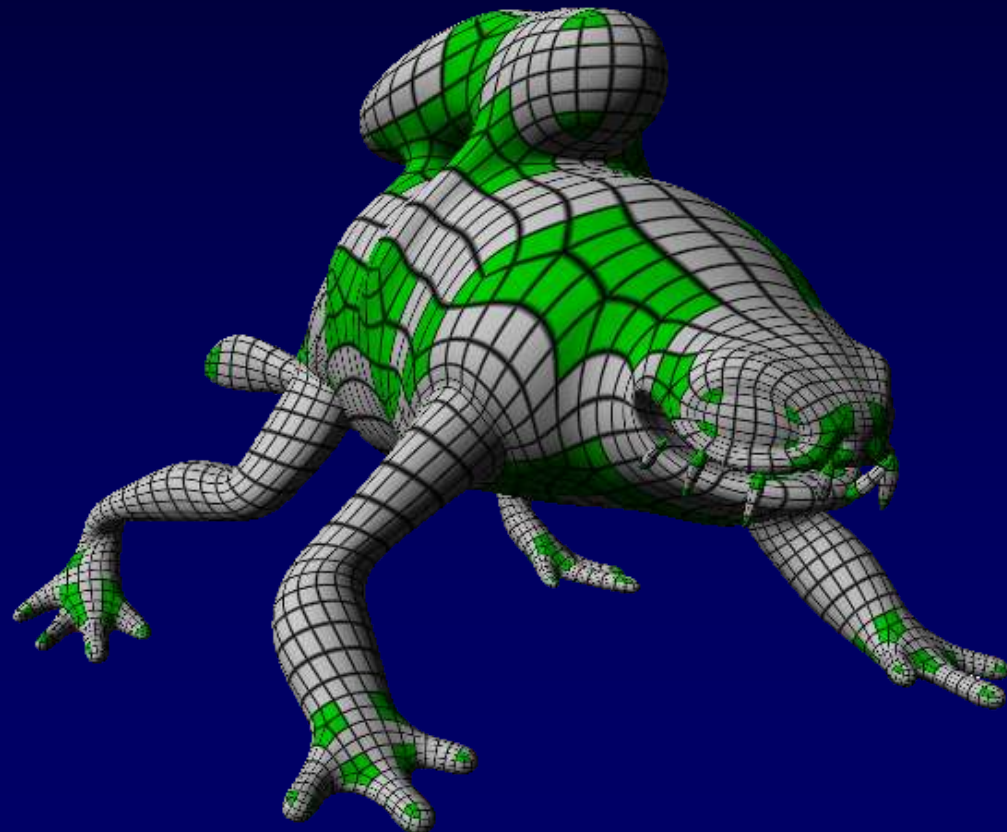
Performance Issues

- Limits # extraordinary verts



Performance Issues

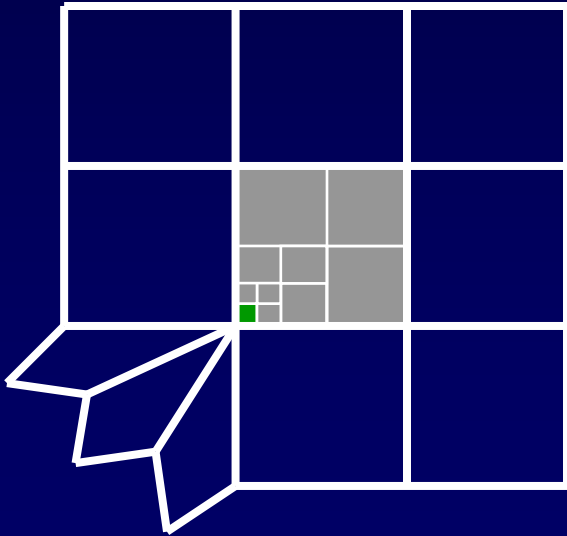
- Limits # extraordinary verts



Performance Issues

- Limits # extraordinary verts
- Lots of shader constants

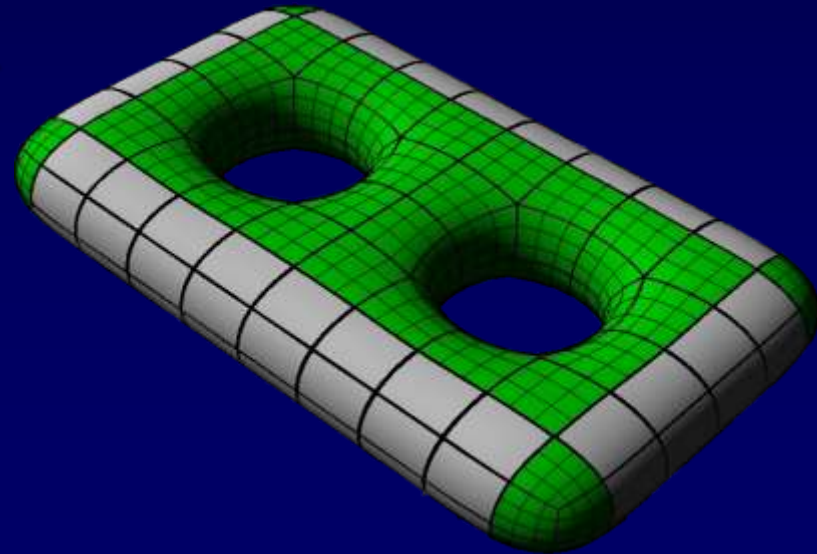
$$V\Lambda^i(V^{-1}P)$$



Valence	Constants
3	882
4	1040
5	1206
6	1380
7	1562
8	1752

Solution: Polynomial Patches

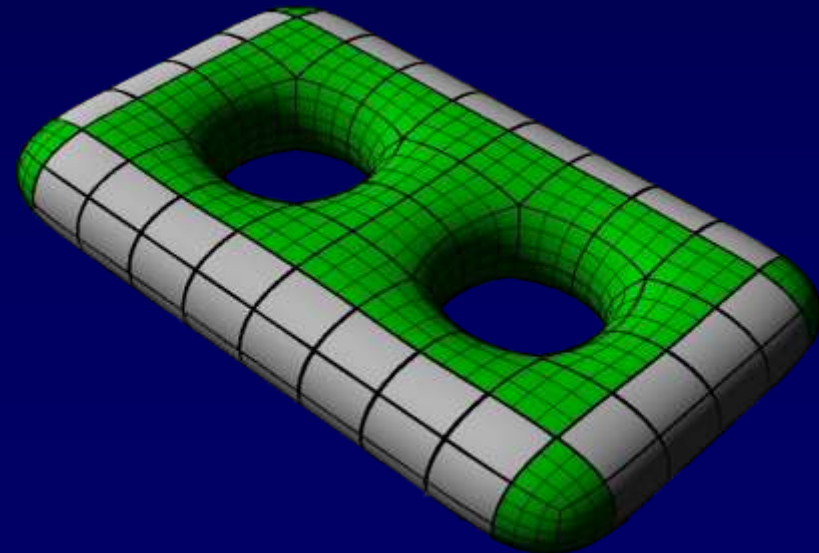
- Replace extraordinary patches with polynomials
 - ◆ Geometry patch (degree 3×3)
 - ◆ 2 Tangent patches (degree 3×2)
- Based on conversion from B-spline to Bezier form



Solution: Polynomial Patches

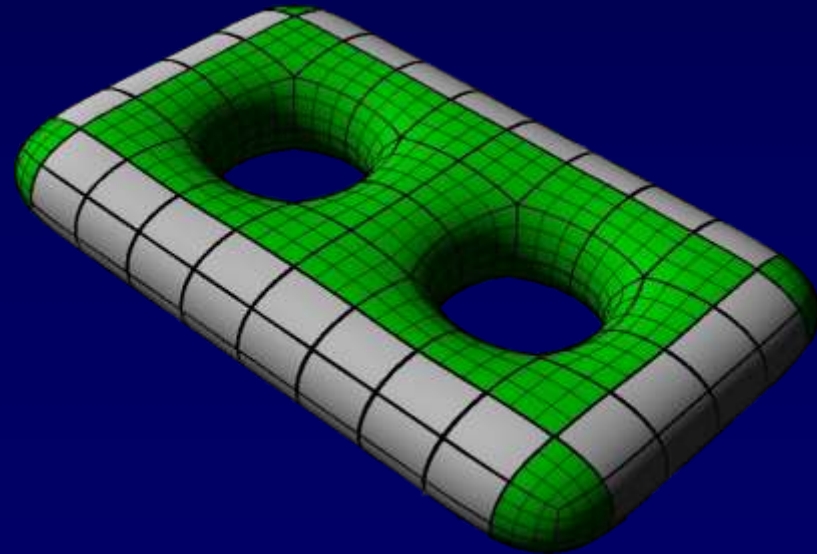
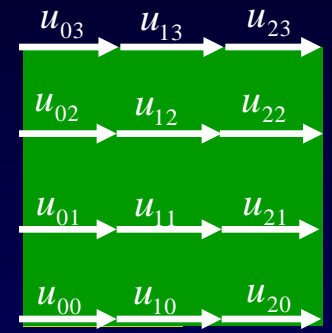
- Replace extraordinary patches with polynomials
 - ◆ **Geometry patch** (degree 3x3)
 - ◆ 2 Tangent patches (degree 3x2)
- Based on conversion from B-spline to Bezier form

b_{03}	b_{13}	b_{23}	b_{33}
b_{02}	b_{12}	b_{22}	b_{32}
b_{01}	b_{11}	b_{21}	b_{31}
b_{00}	b_{10}	b_{20}	b_{30}



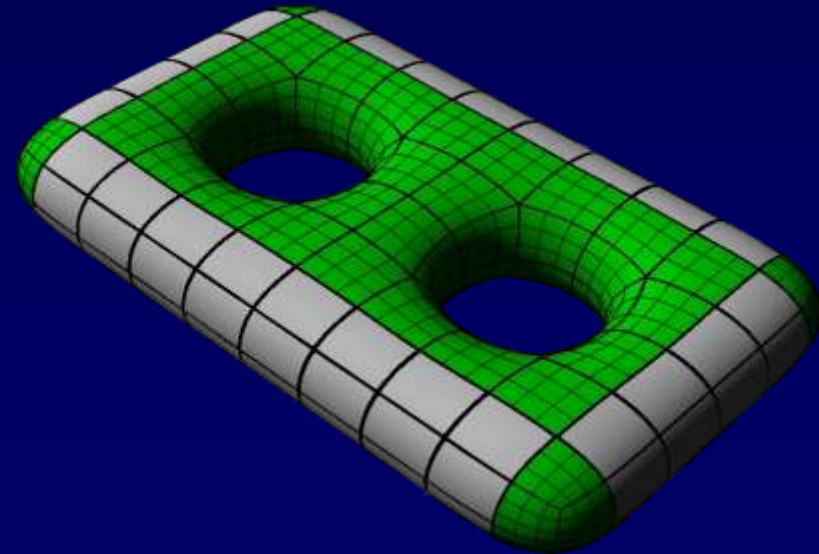
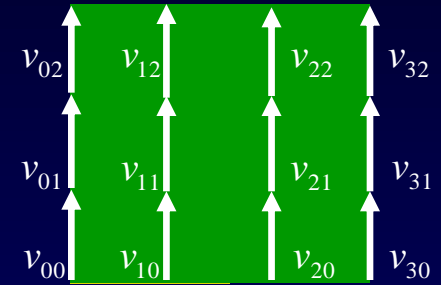
Solution: Polynomial Patches

- Replace extraordinary patches with polynomials
 - ◆ Geometry patch (degree 3x3)
 - ◆ **2 Tangent patches** (degree 3x2)
- Based on conversion from B-spline to Bezier form



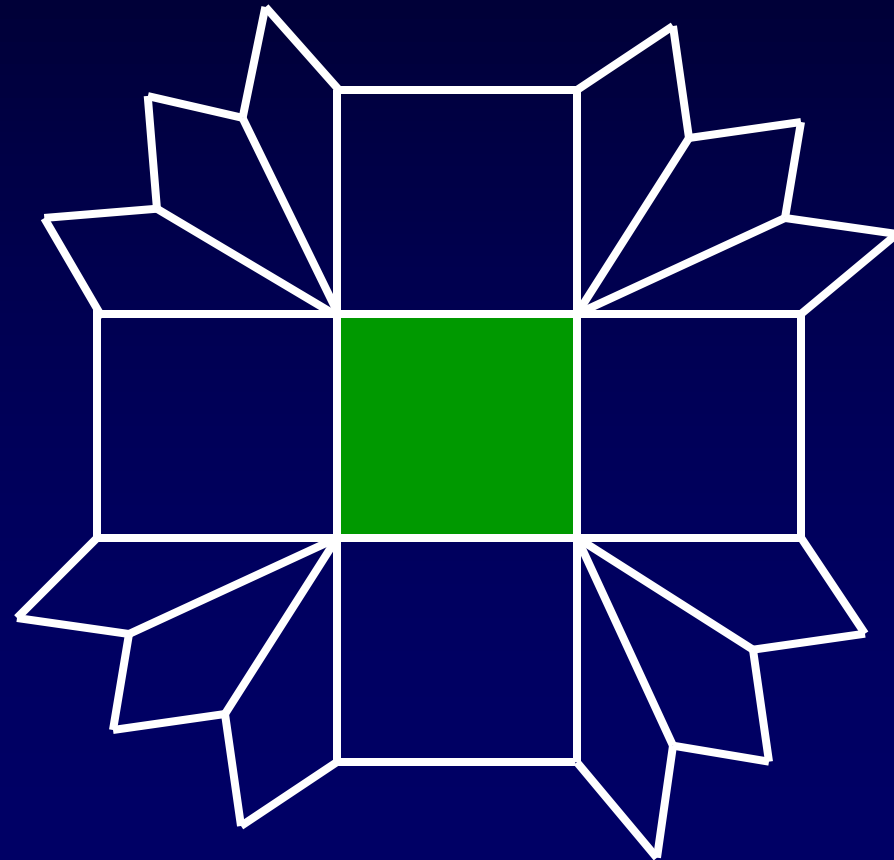
Solution: Polynomial Patches

- Replace extraordinary patches with polynomials
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 - ◆ **2 Tangent patches** (degree 3x2)
- Based on conversion from B-spline to Bezier form



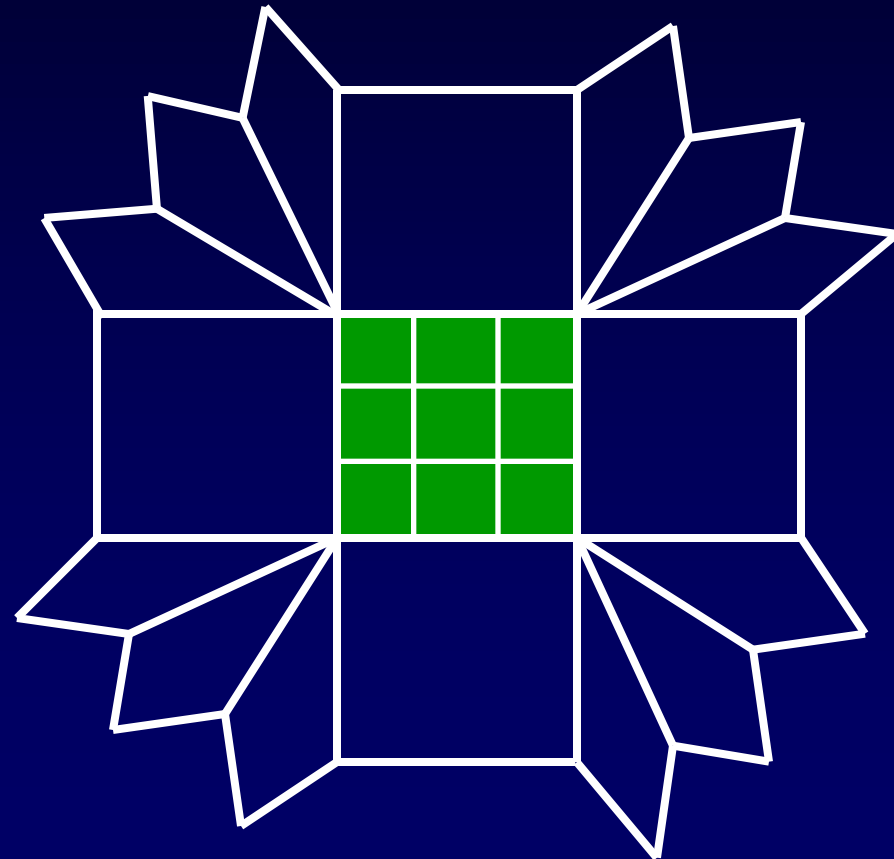
ACC Geometry Patches

- Use knot-insertion rules from ordinary case
- At corners, use limit masks



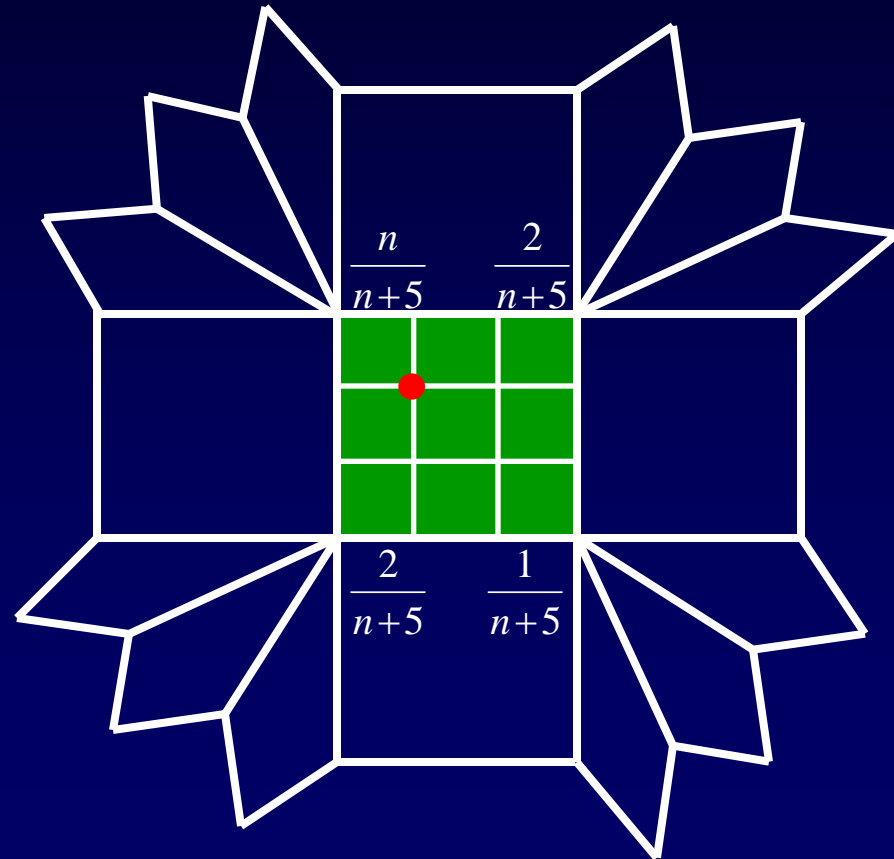
ACC Geometry Patches

- Use knot-insertion rules from ordinary case
- At corners, use limit masks



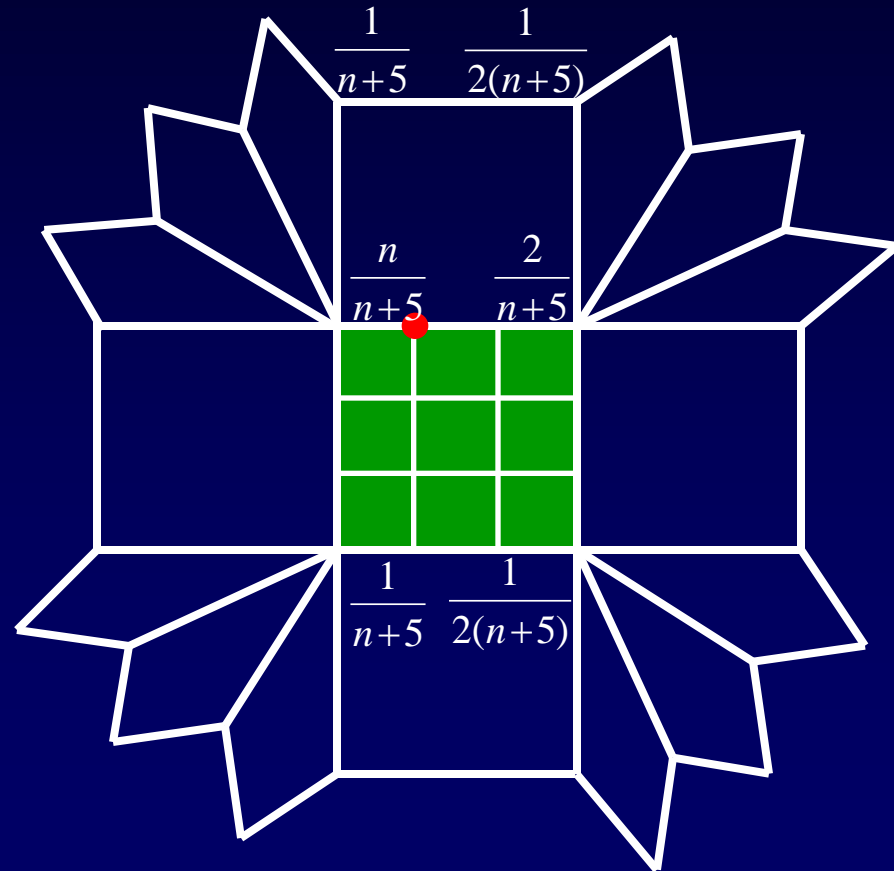
ACC Geometry Patches

- Use knot-insertion rules from ordinary case
- At corners, use limit masks



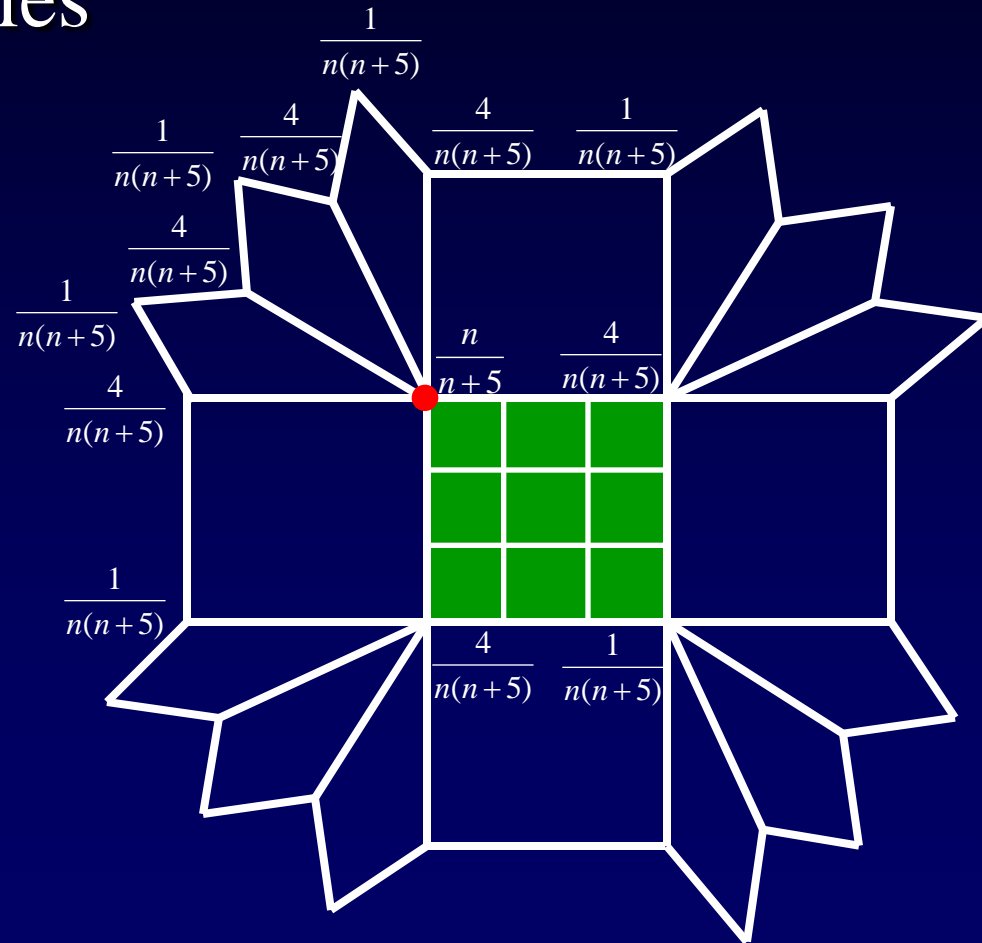
ACC Geometry Patches

- Use knot-insertion rules from ordinary case
- At corners, use limit masks



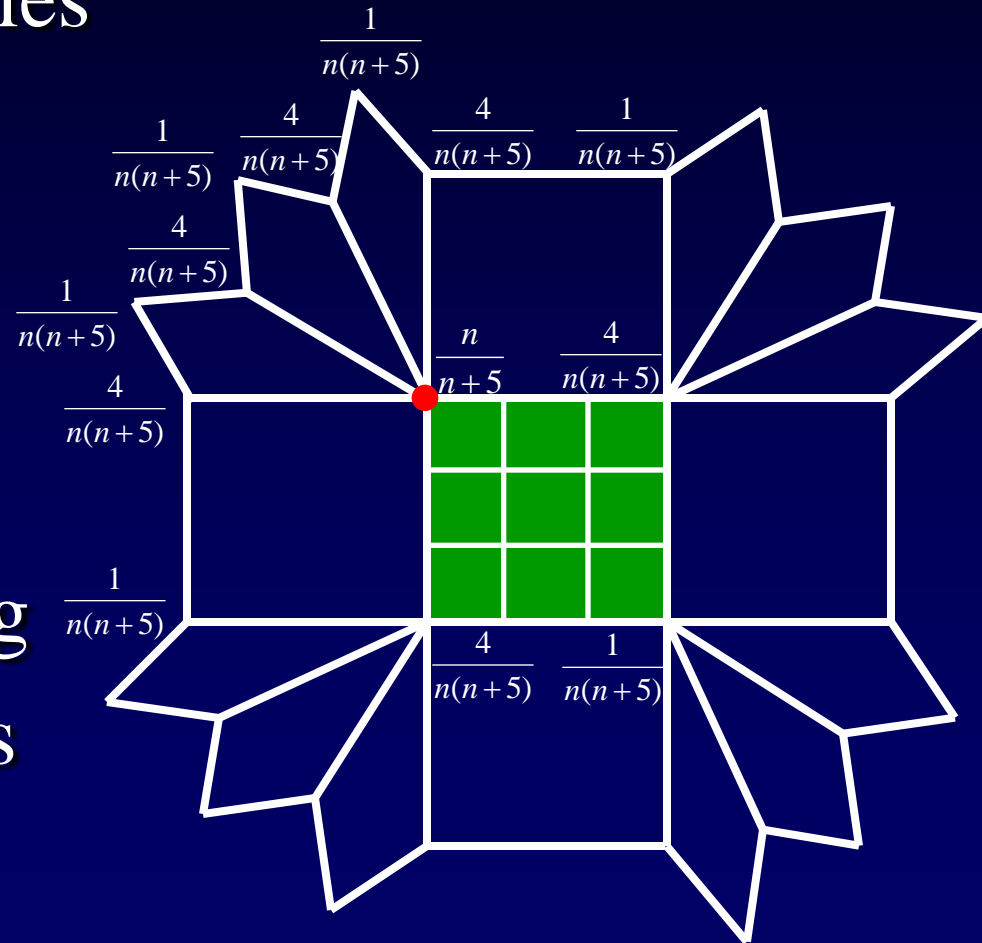
ACC Geometry Patches

- Use knot-insertion rules from ordinary case
- At corners, use limit masks



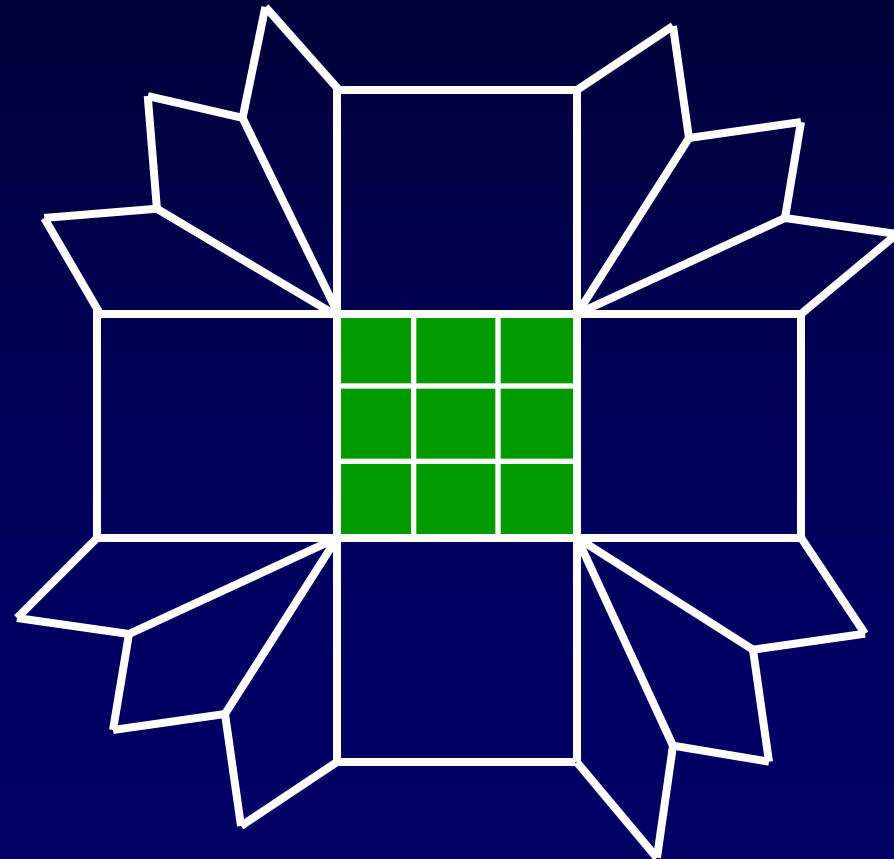
ACC Geometry Patches

- Use knot-insertion rules from ordinary case
- At corners, use limit masks
- Smooth everywhere except edges touching extraordinary vertices



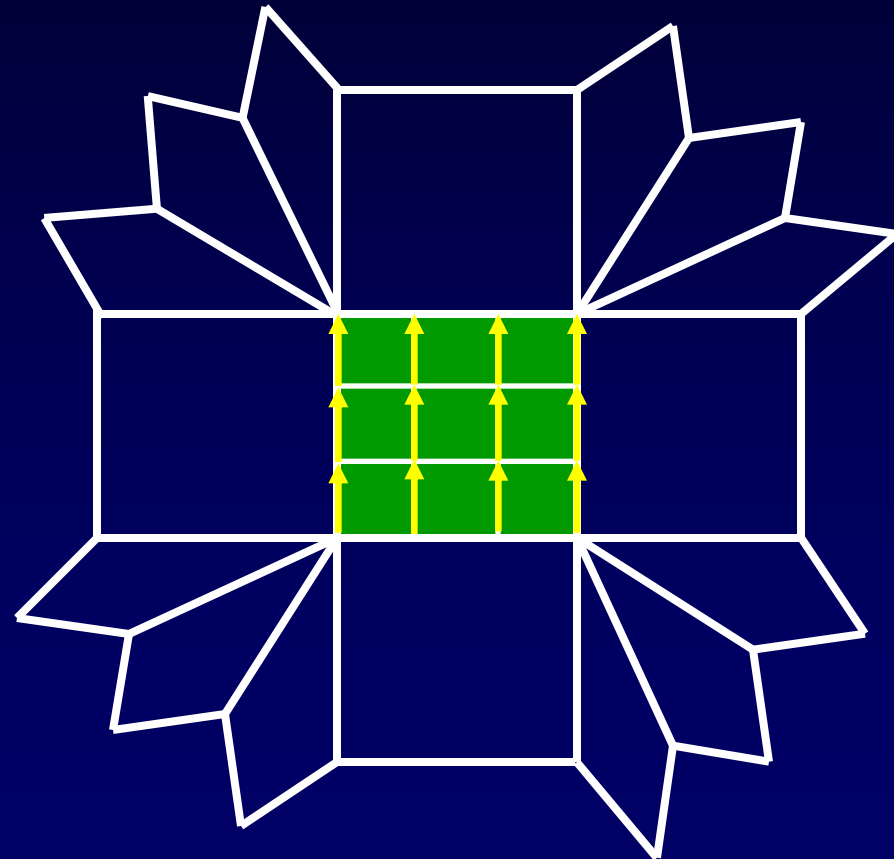
ACC Tangent Patches

- Continuous normal field needed for displacement mapping
- Create two tangent patches (u/v) for each position patch



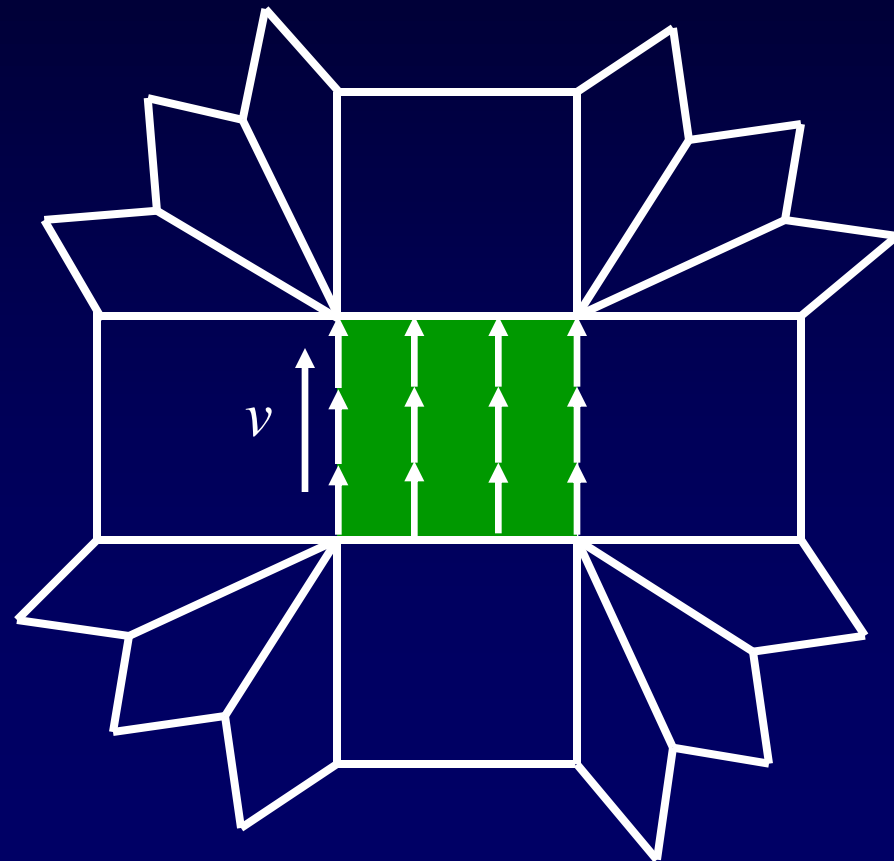
ACC Tangent Patches

- Continuous normal field needed for displacement mapping
- Create two tangent patches (u/v) for each position patch



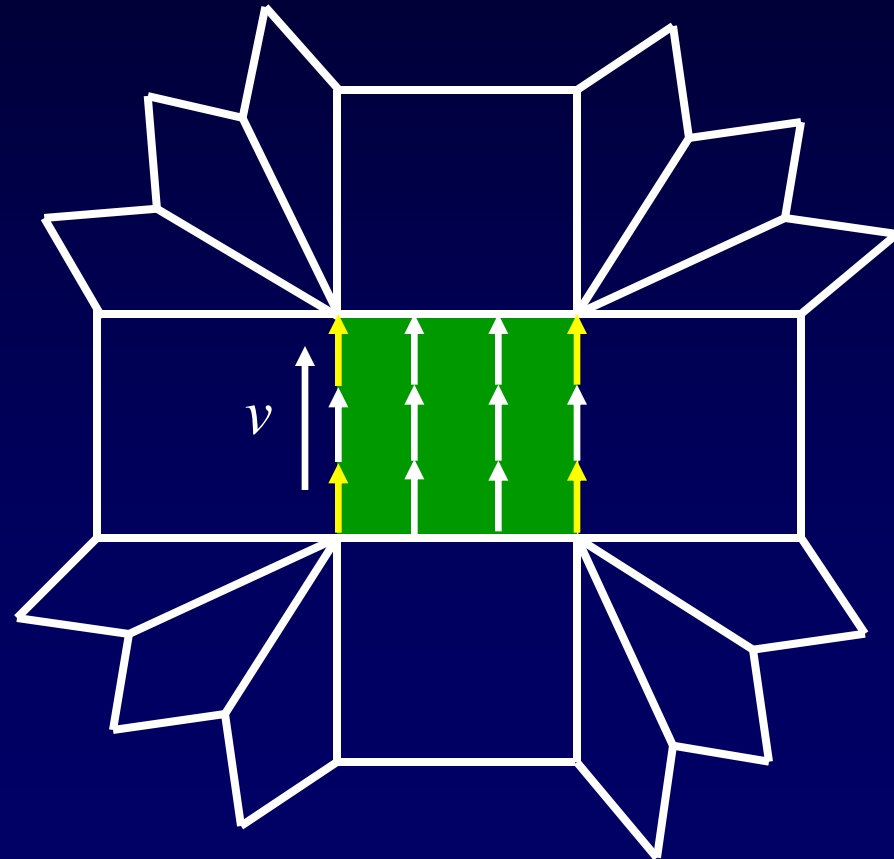
ACC Tangent Patches

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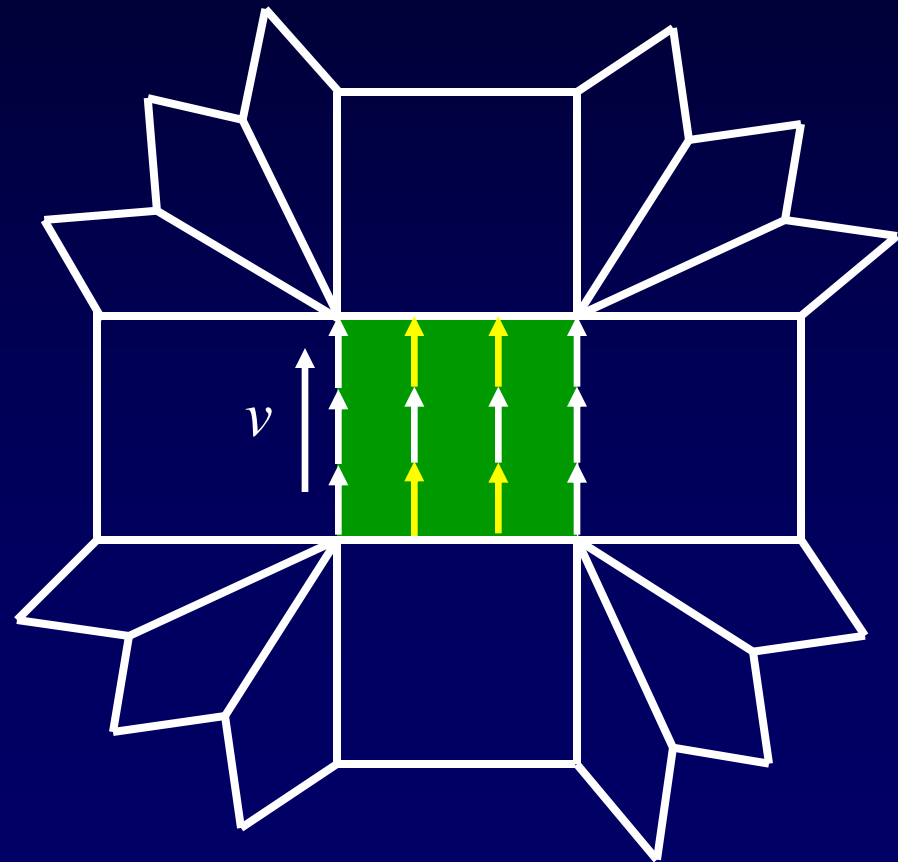
ACC Tangent Patches

- Continuous normal field needed for displacement mapping
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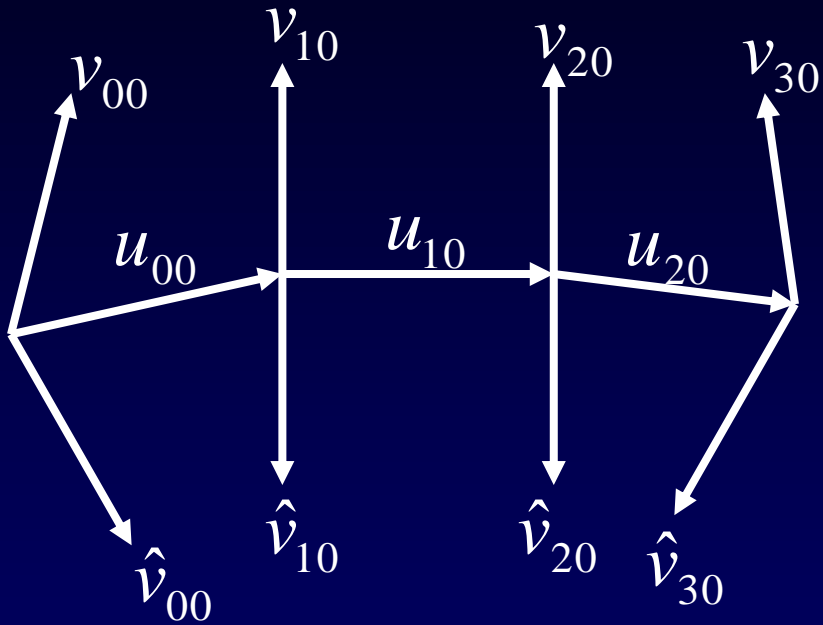


ACC Tangent Patches

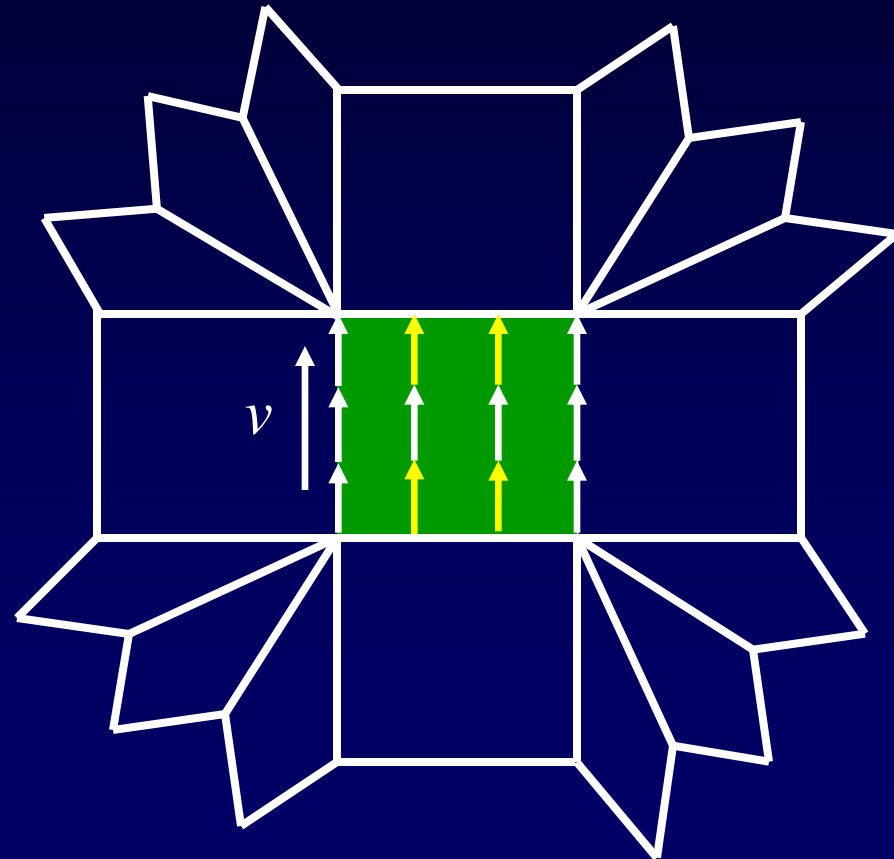
- Continuous normal field needed for displacement mapping
- Create two tangent patches (u/v) for each position patch



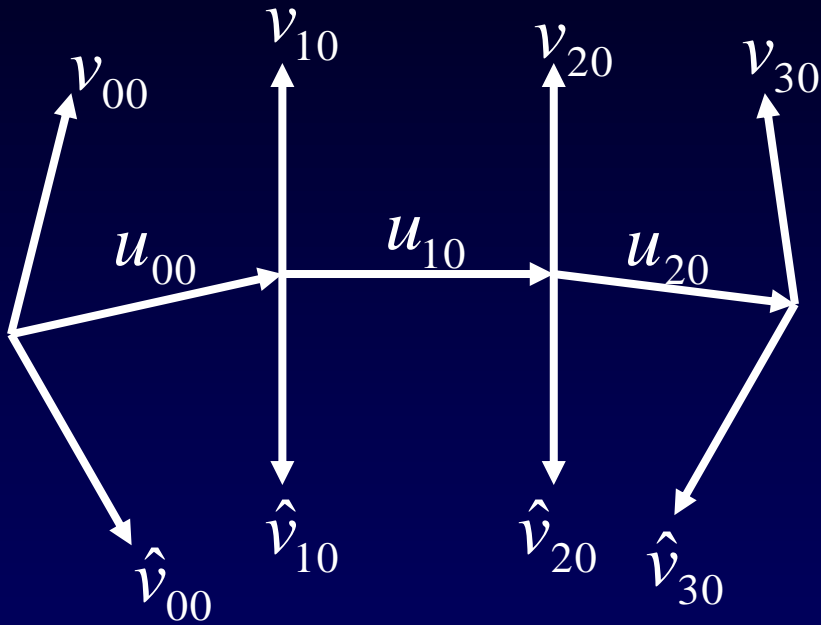
ACC Tangent Patches



$$v(t) \times u(t) \propto \hat{v}(t) \times u(t)$$



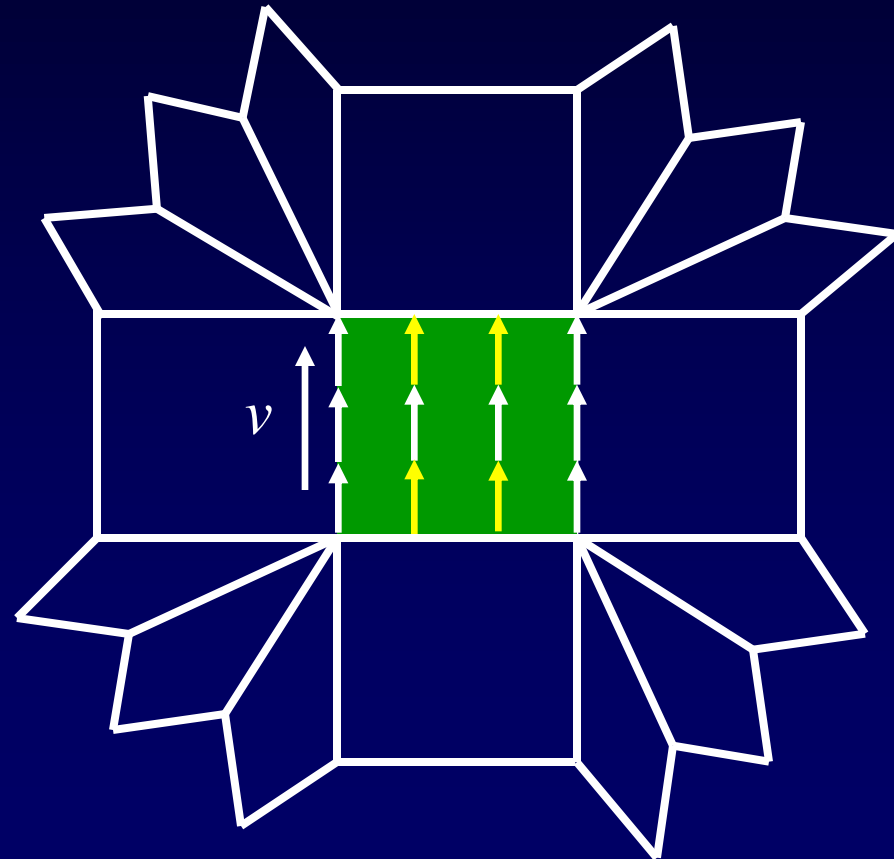
ACC Tangent Patches



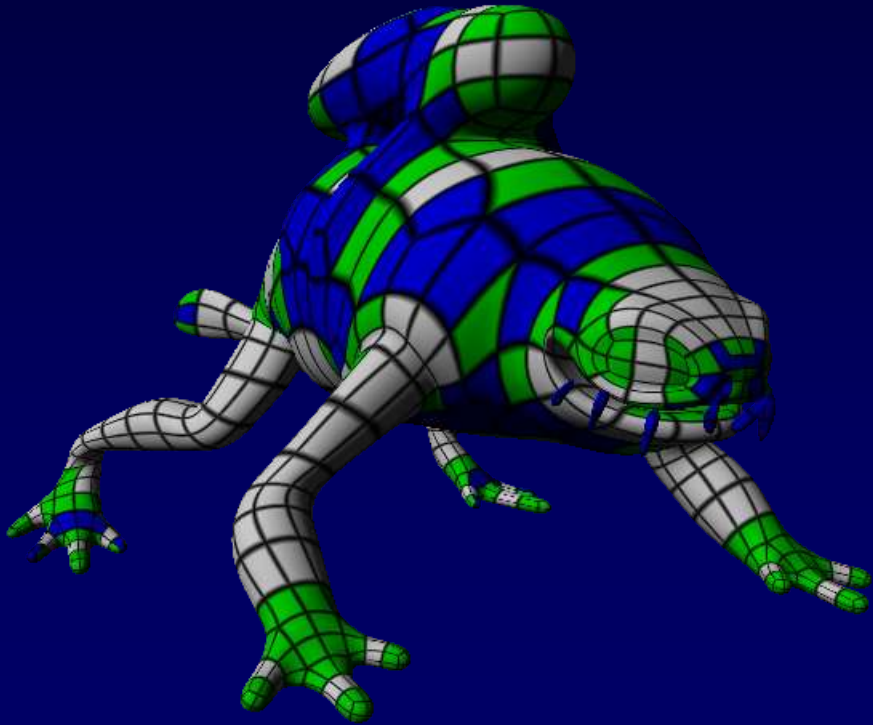
$$v_{10} + = \frac{2}{3}c_0 u_{10} - \frac{1}{3}c_1 u_{00}$$

$$v_{20} + = \frac{1}{3}c_0 u_{20} - \frac{2}{3}c_1 u_{10}$$

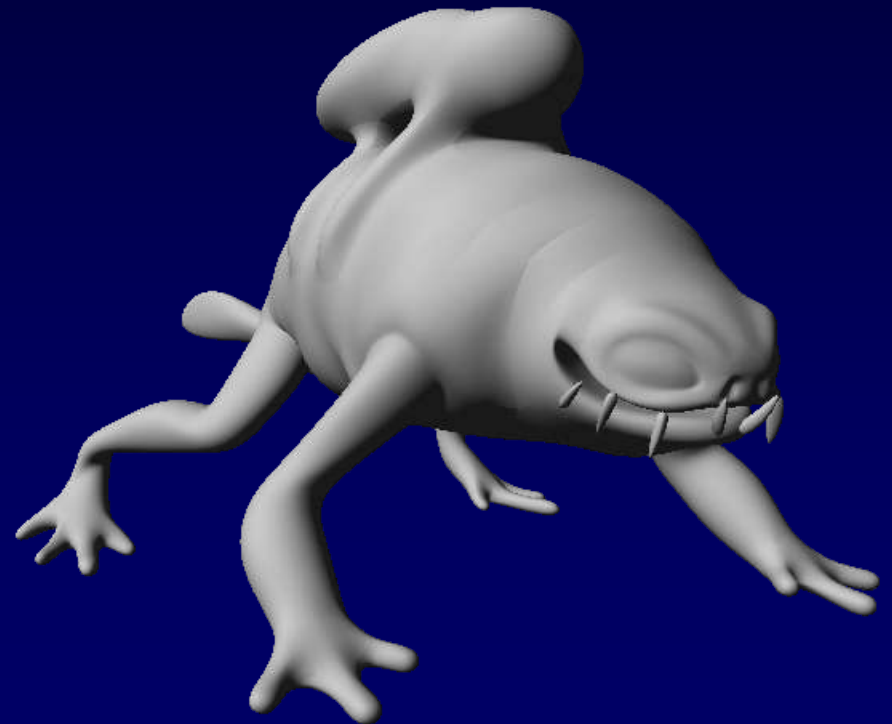
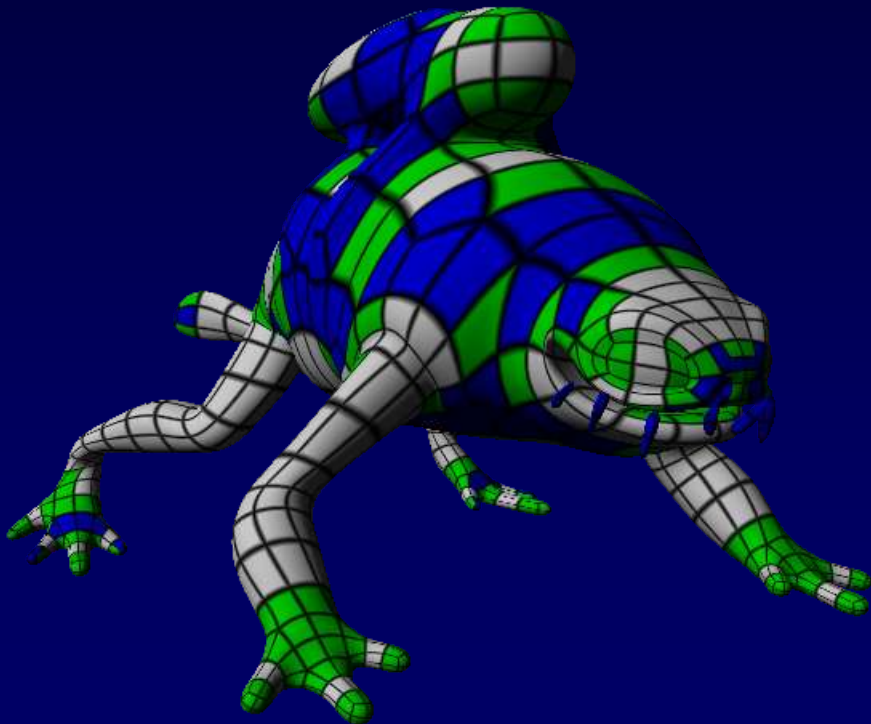
$$c_i = \cos\left(\frac{2\pi}{n_i}\right)$$



Examples

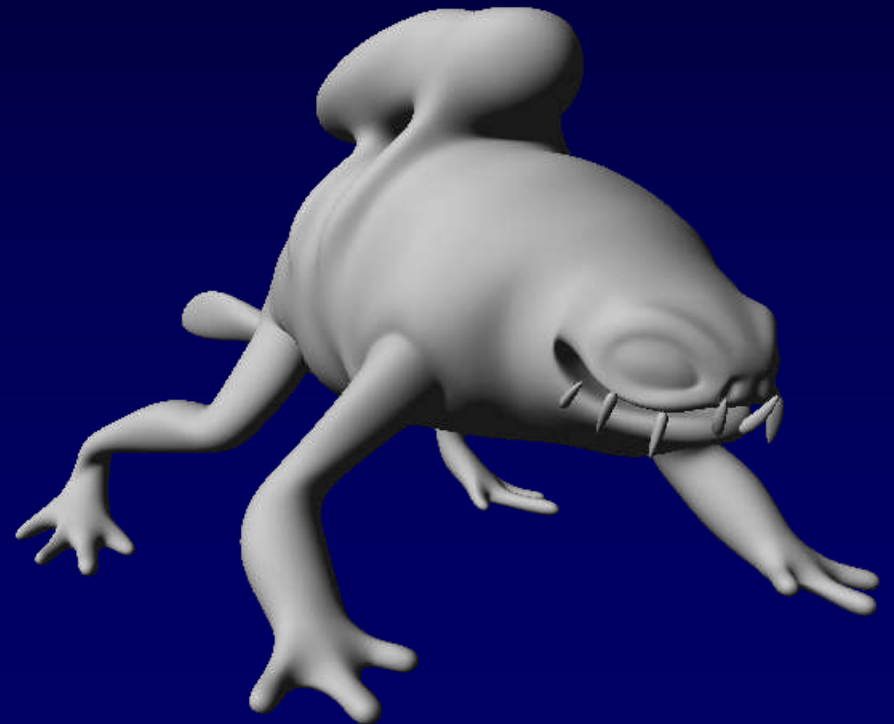
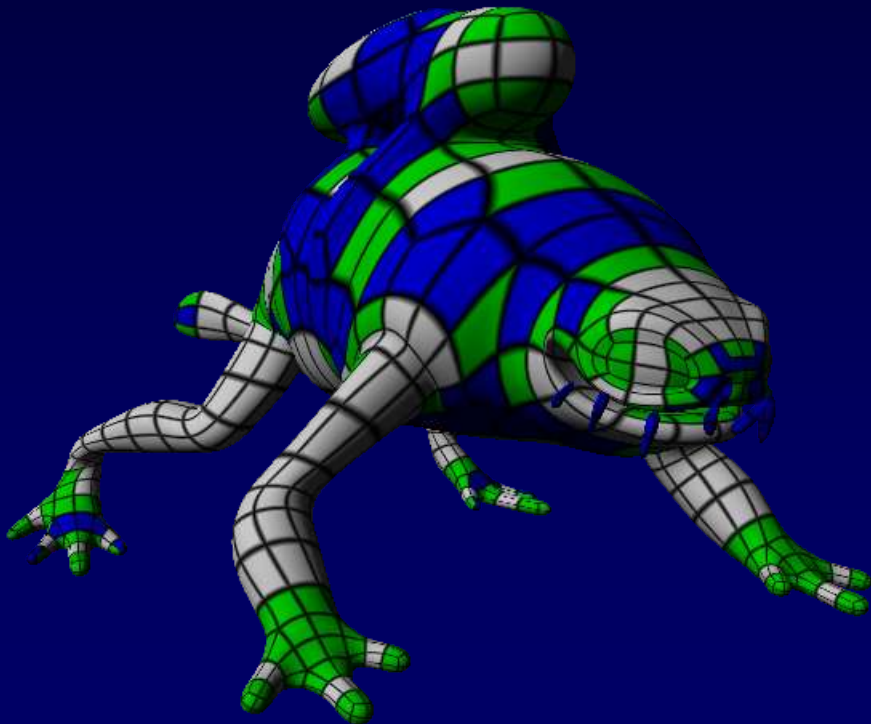


Examples



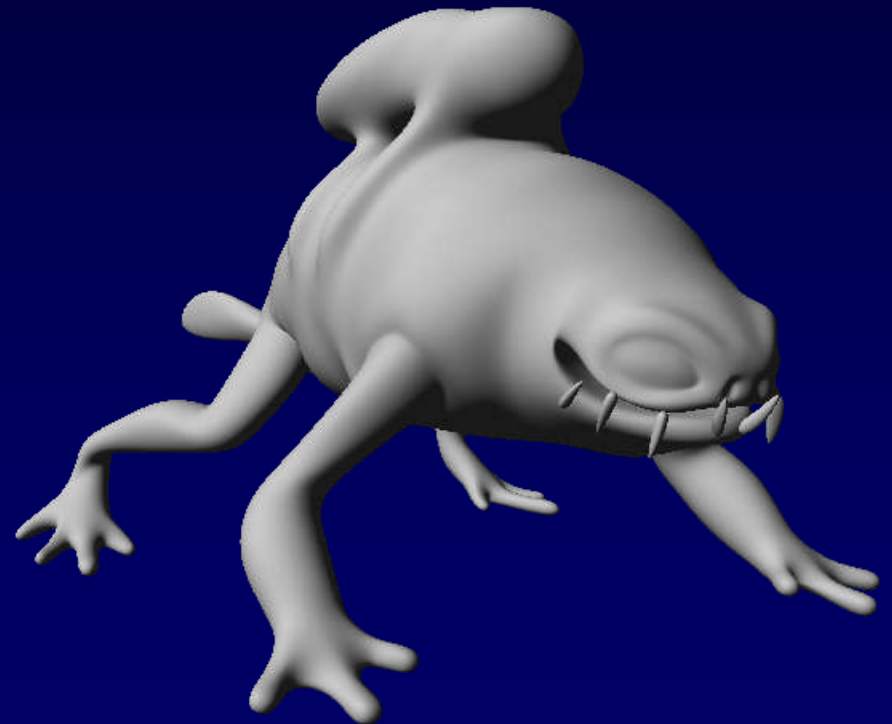
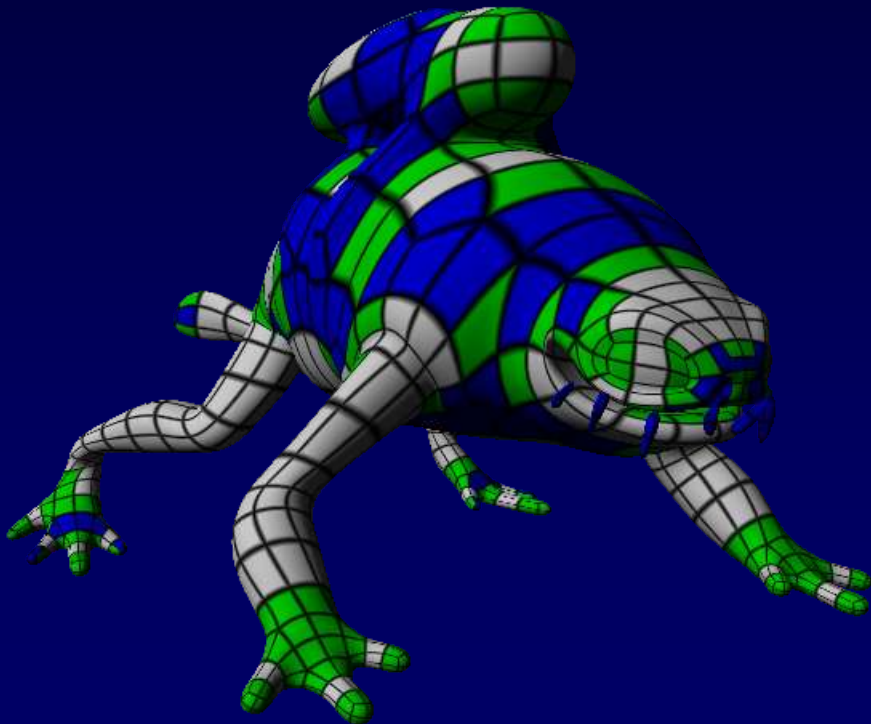
ACC Geometry Patches

Examples



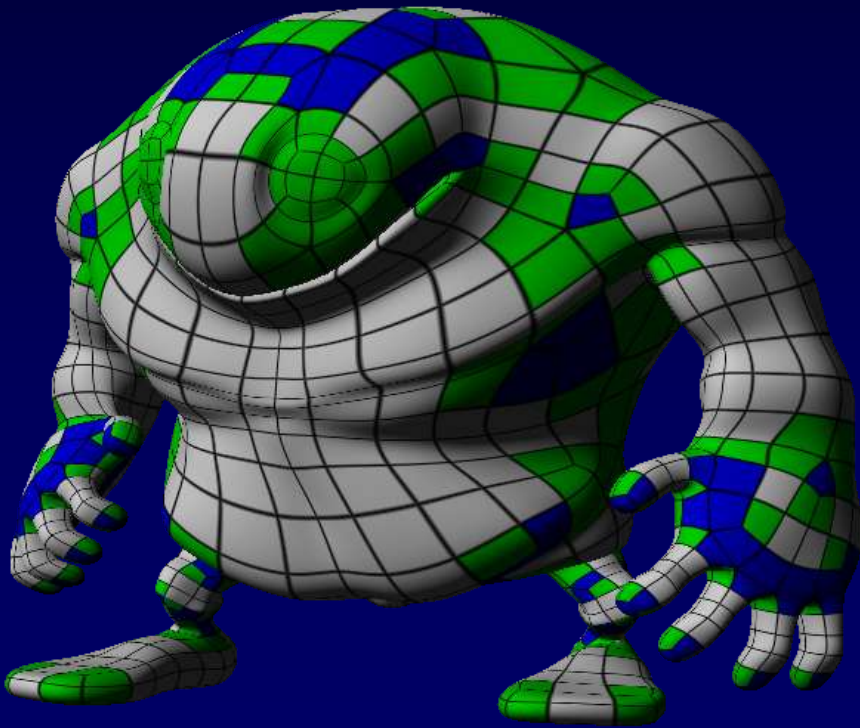
ACC Geo/Tan Patches

Examples

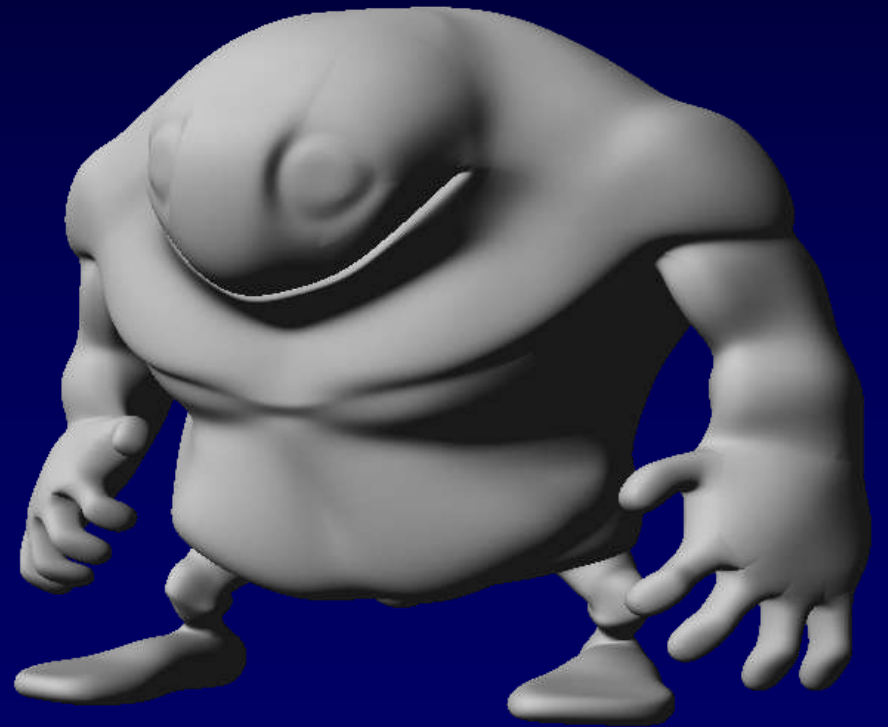
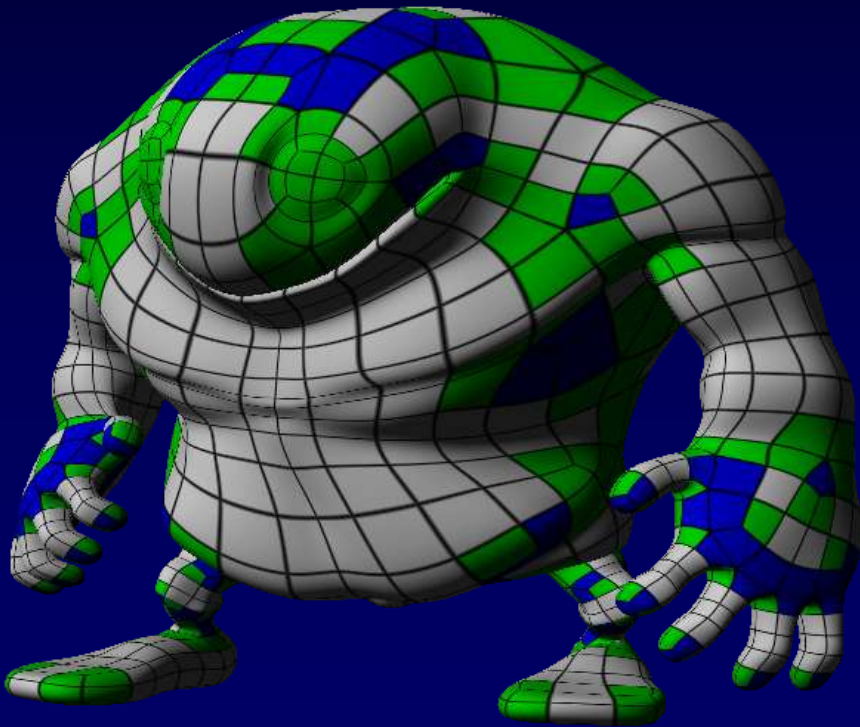


Catmull-Clark Surface

Examples

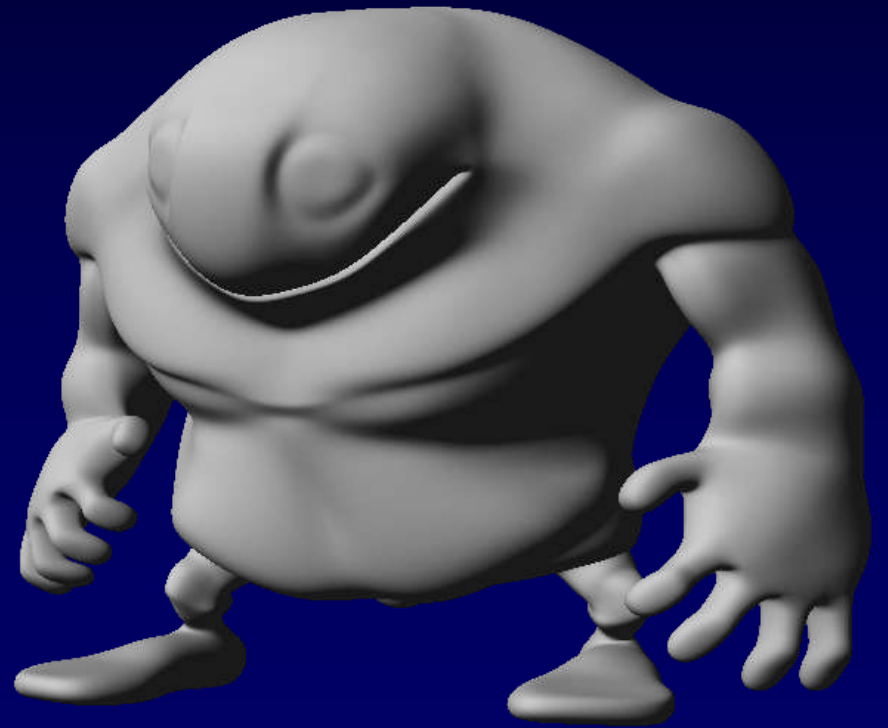
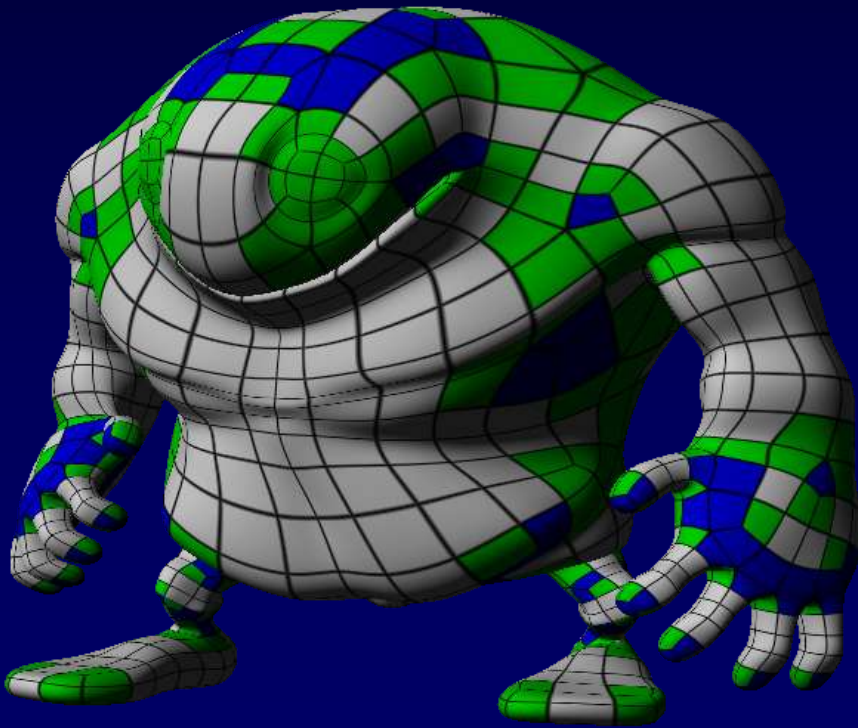


Examples



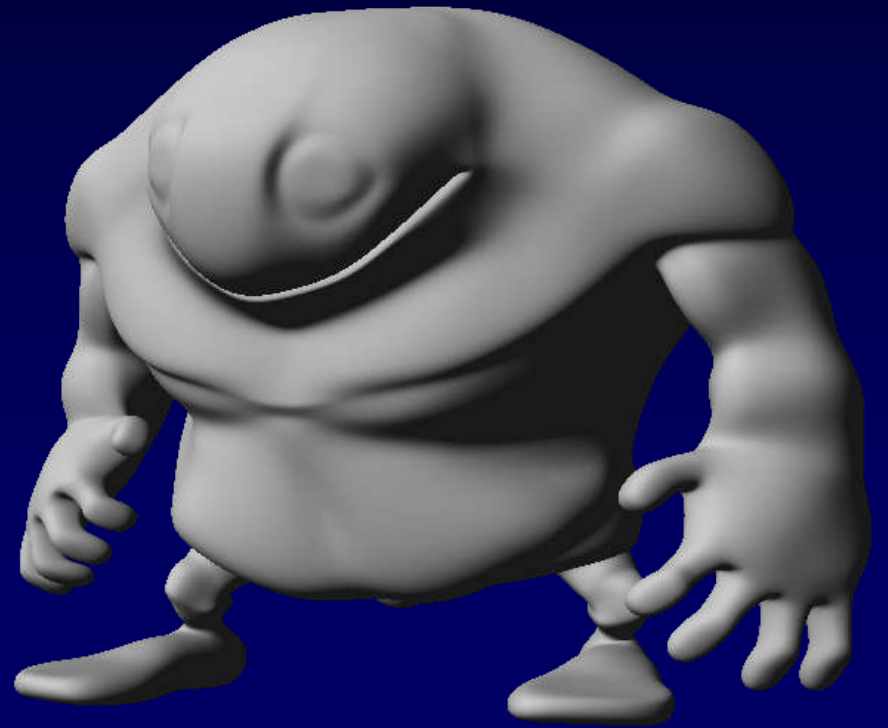
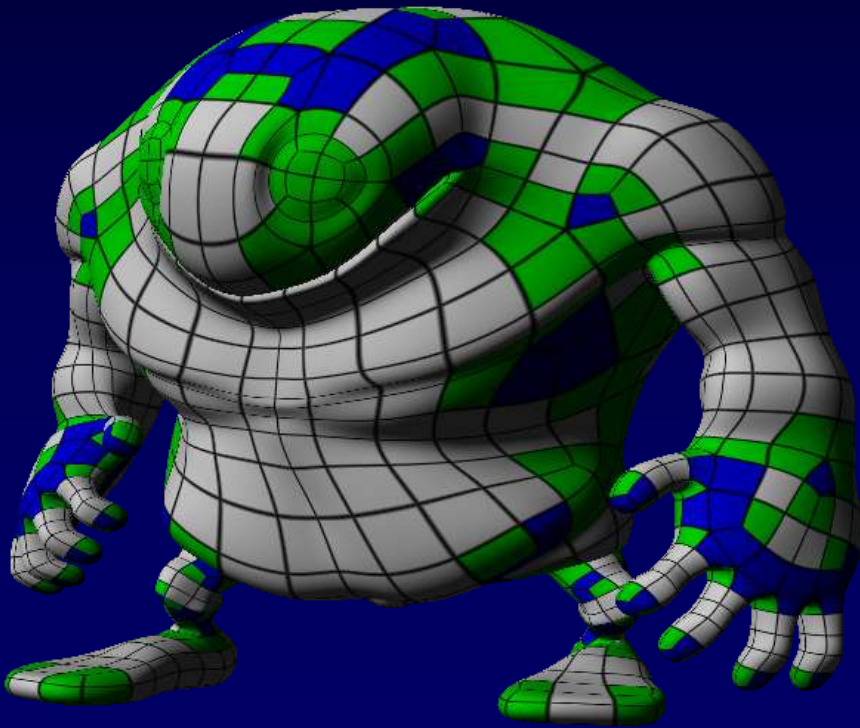
ACC Geometry Patches

Examples



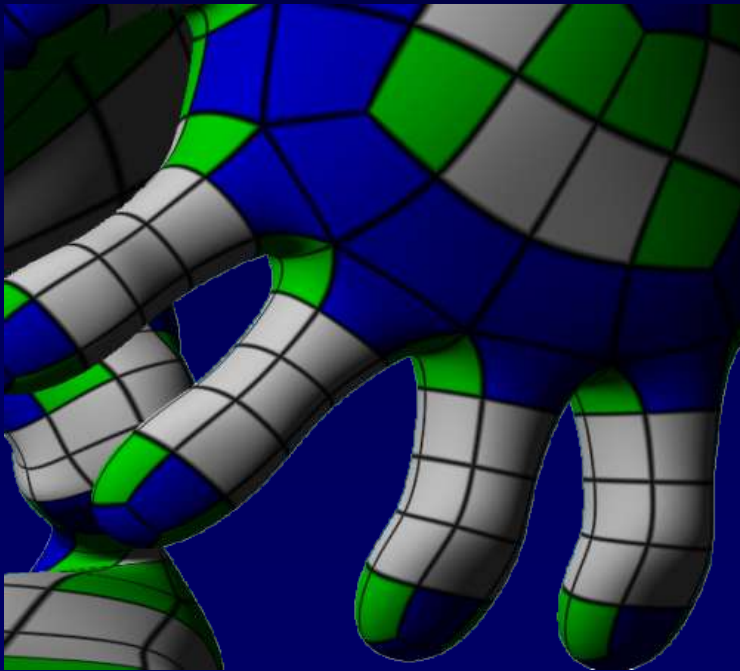
ACC Geo/Tan Patches

Examples

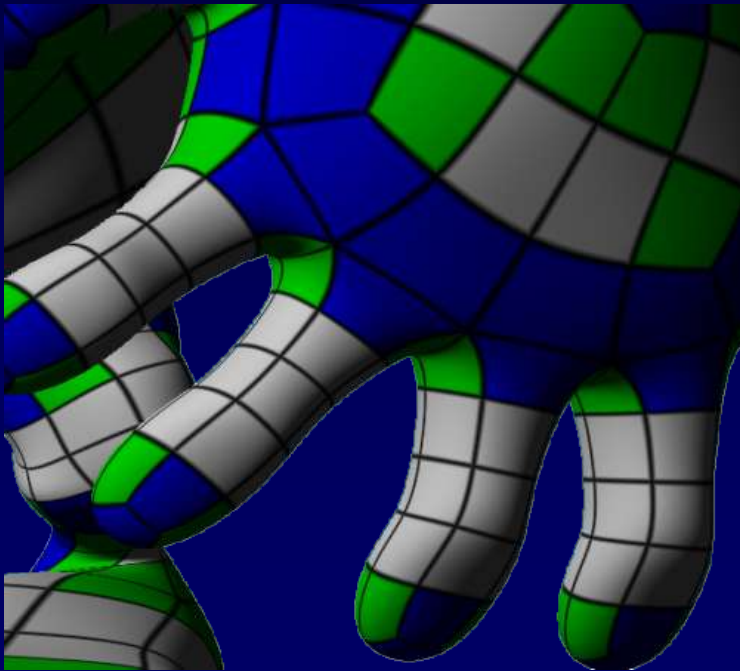


Catmull-Clark Surface

Examples

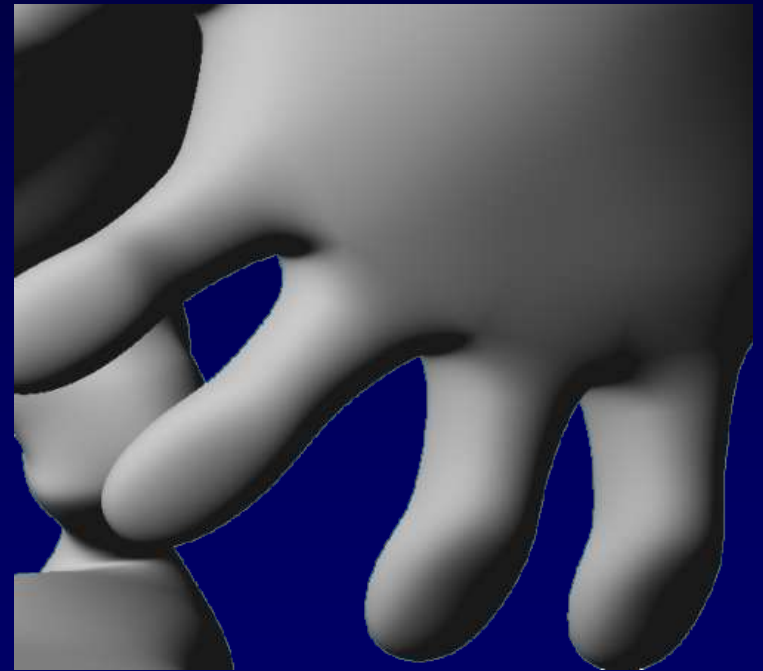
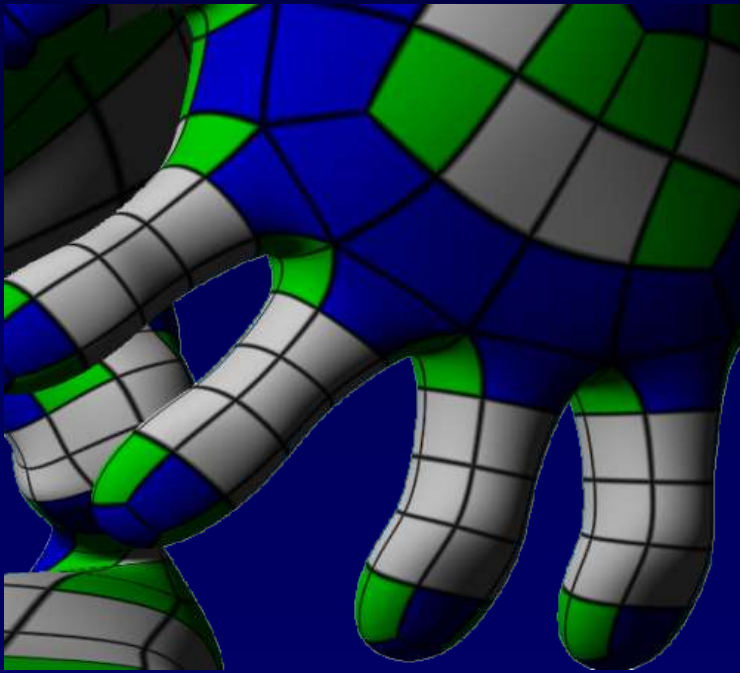


Examples



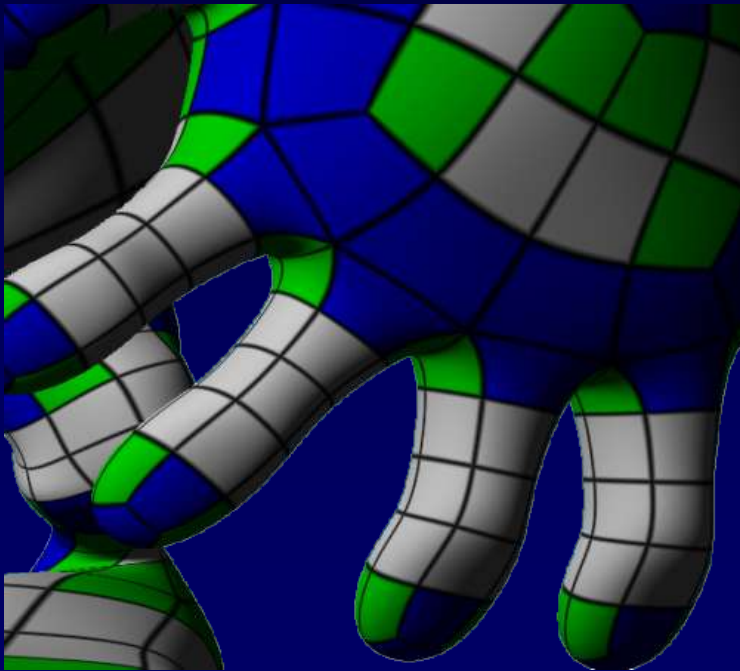
ACC Geometry Patches

Examples



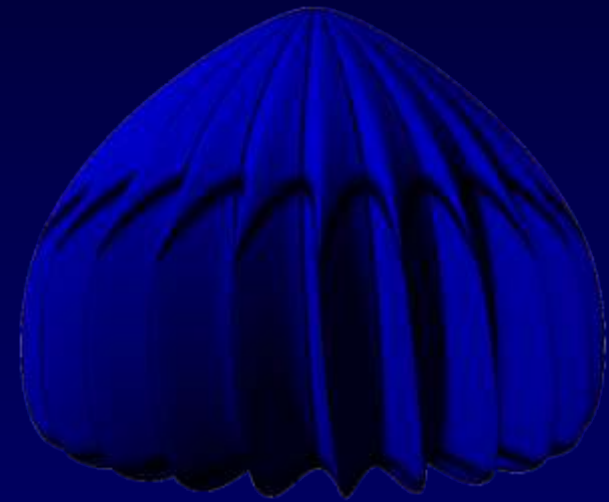
ACC Geo/Tan Patches

Examples

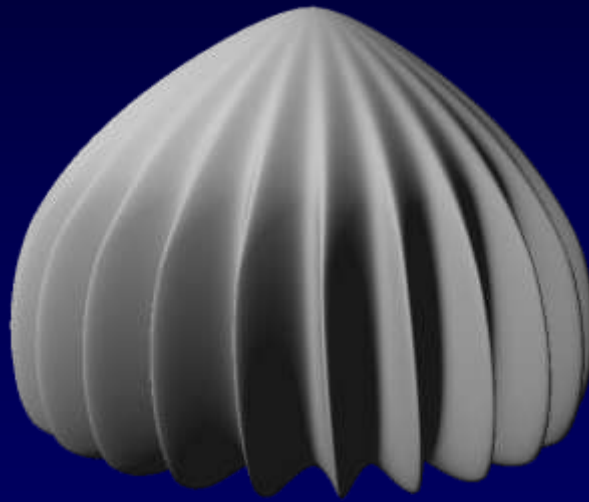


Catmull-Clark Surface

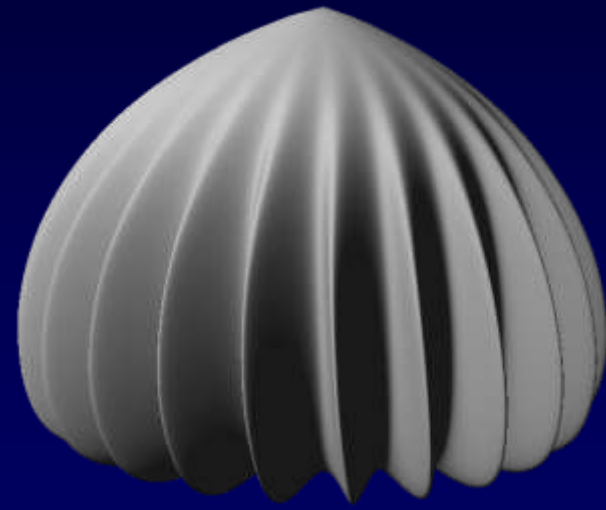
Examples



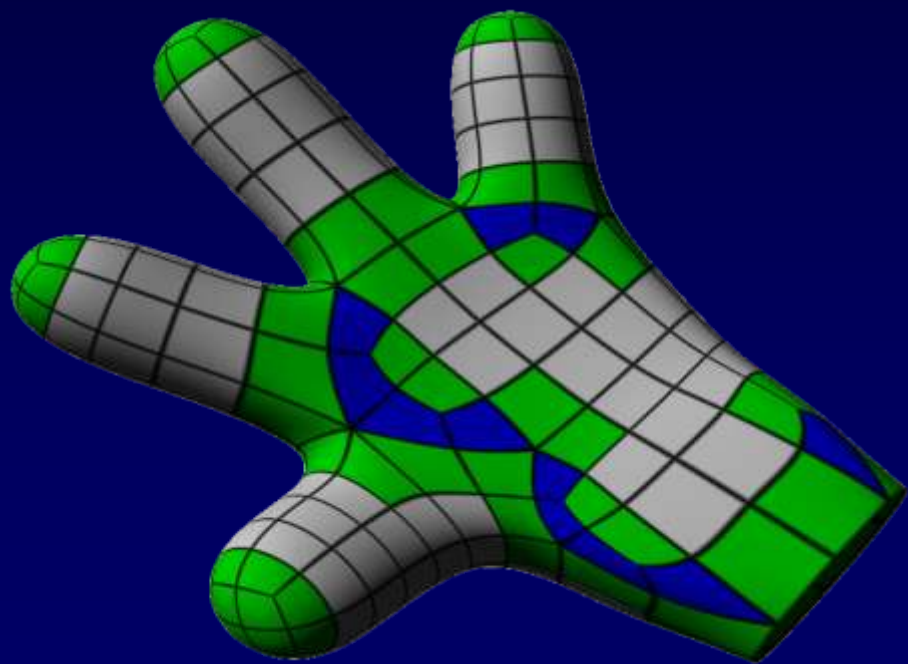
ACC Geo/Tan



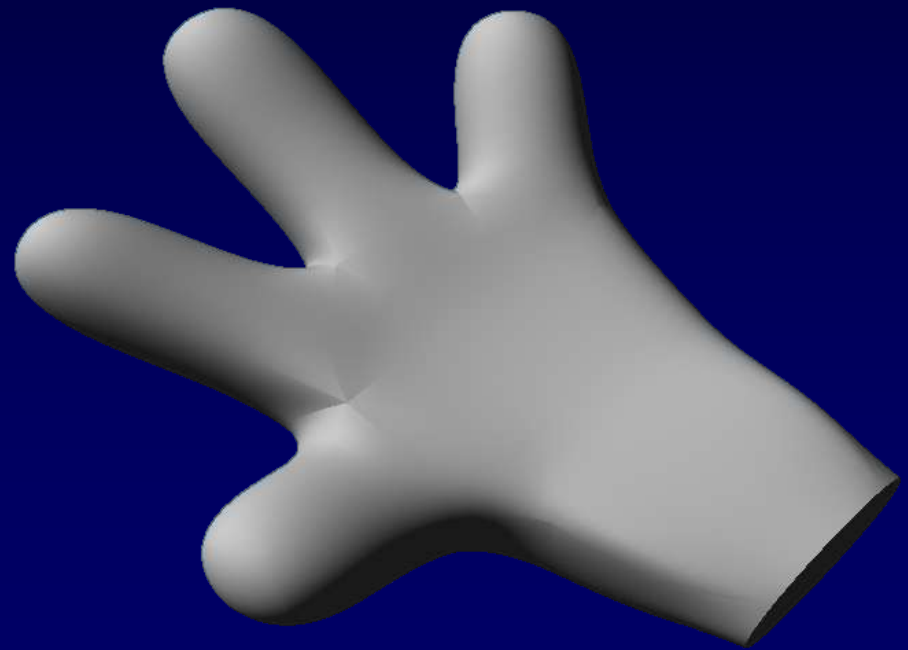
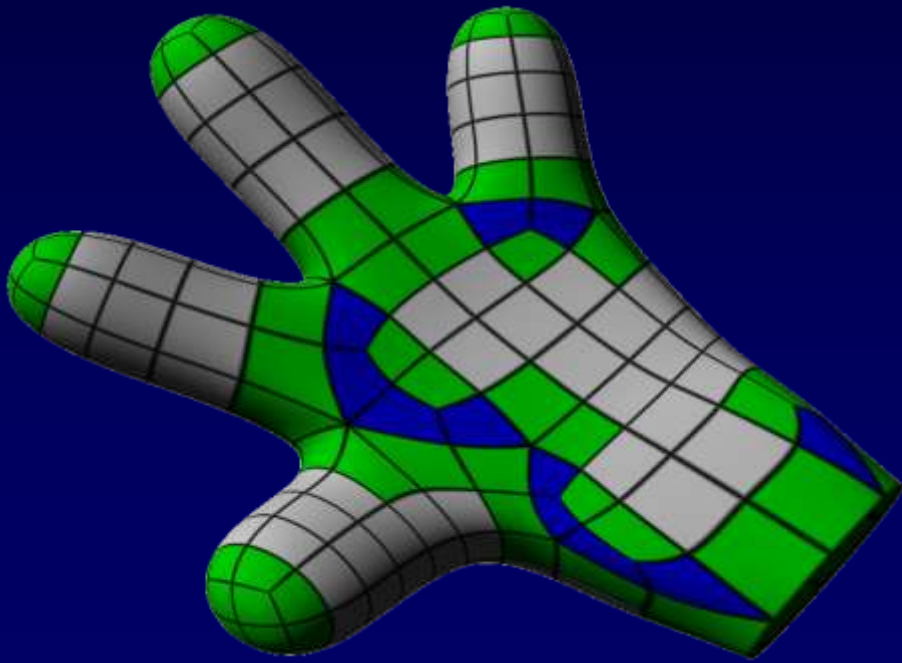
Catmull-Clark



Examples

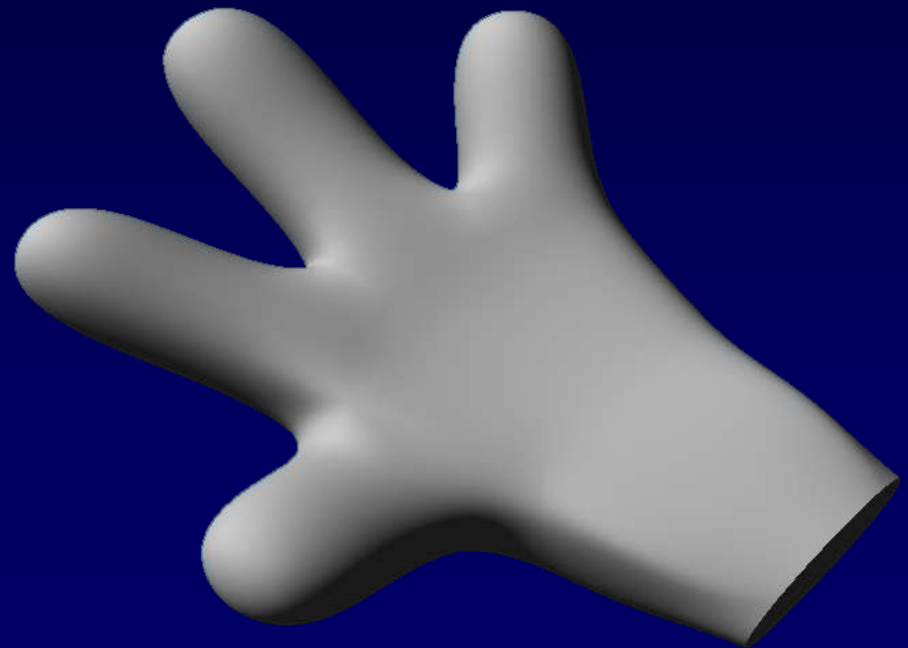
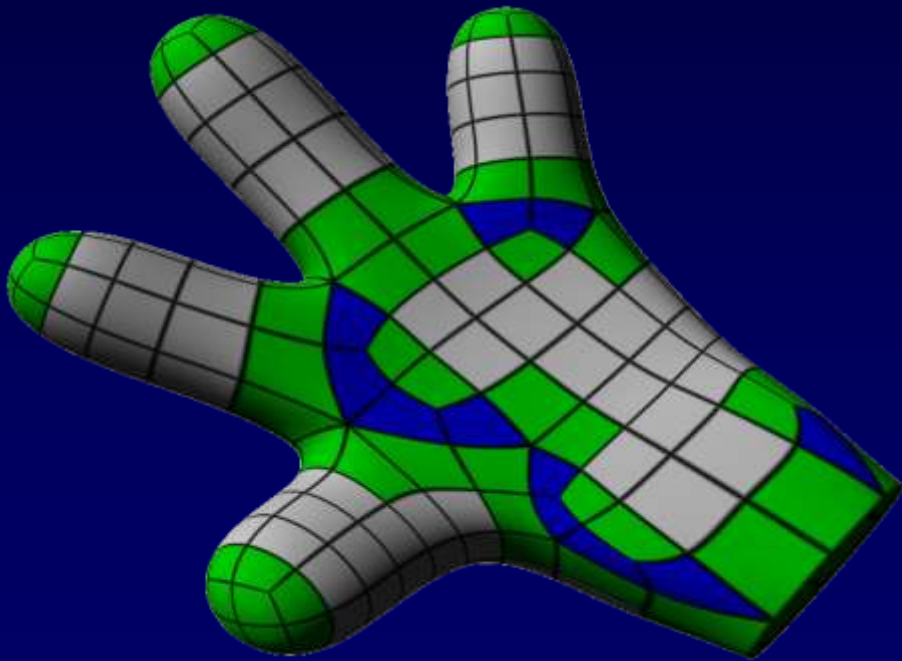


Examples



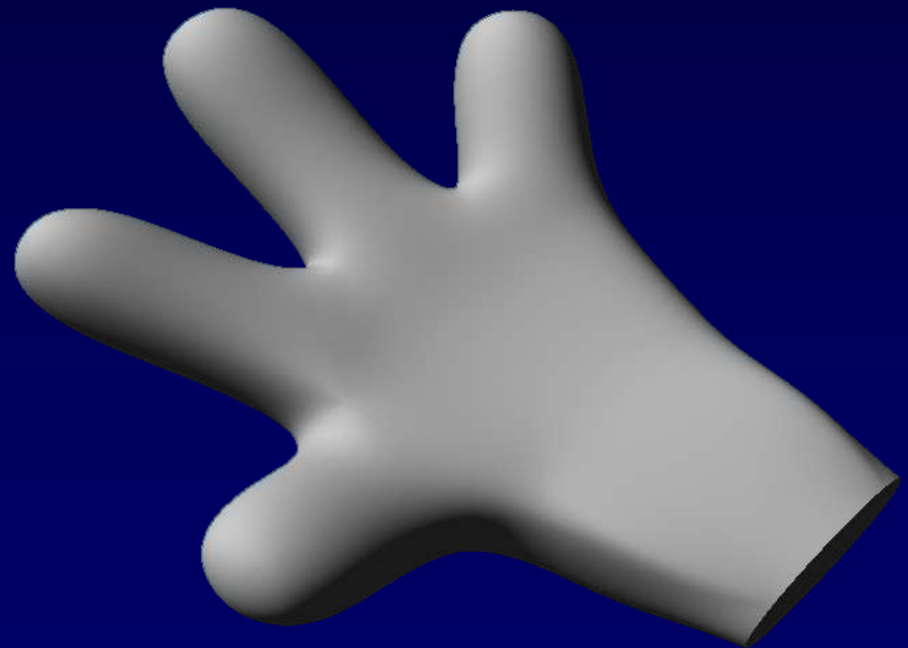
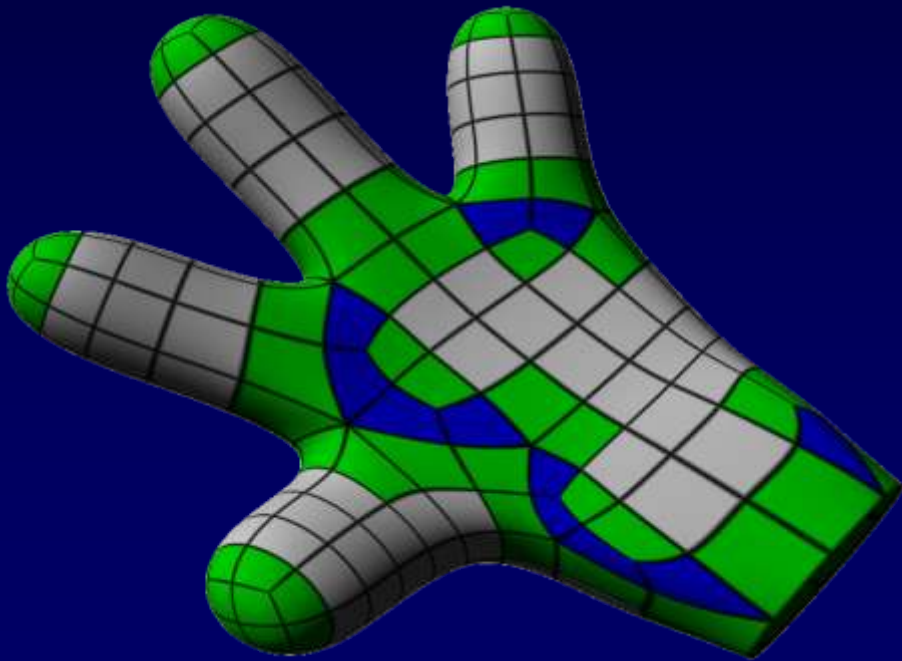
ACC Geometry Patches

Examples



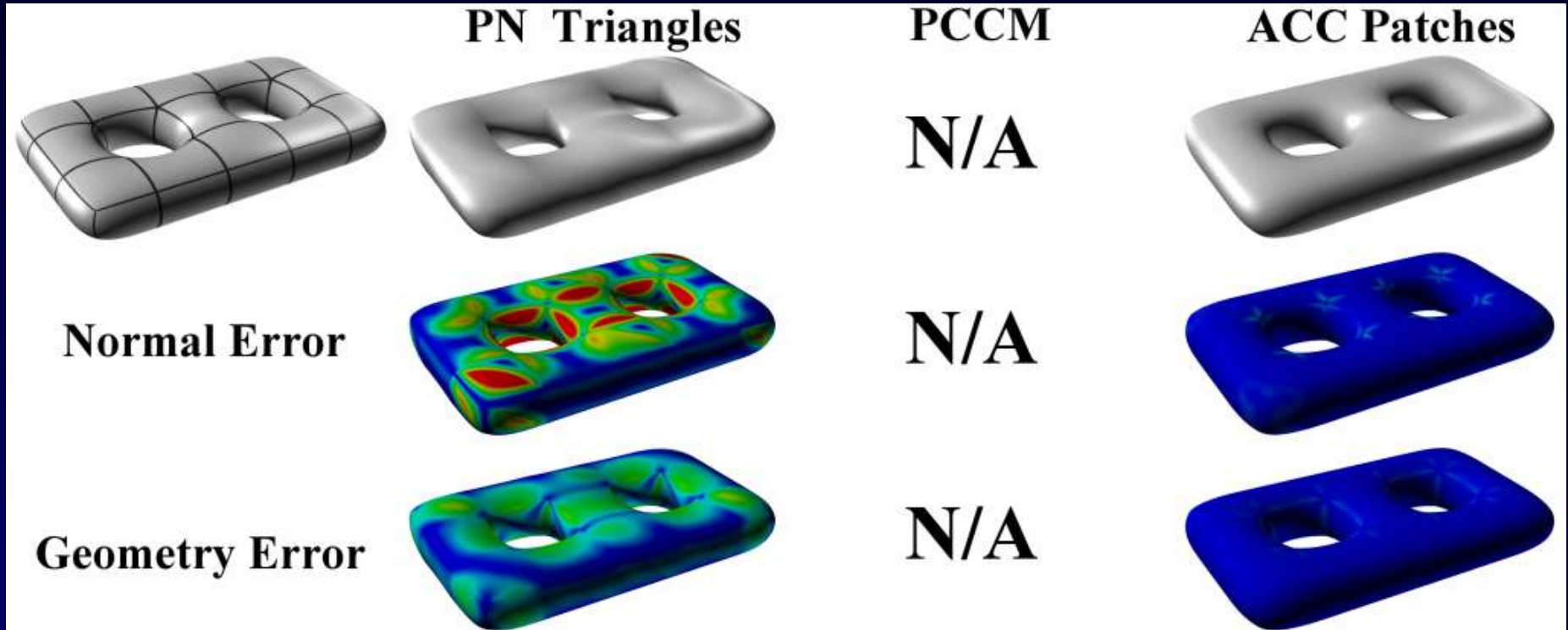
ACC Geo/Tan Patches

Examples



Catmull-Clark Surface

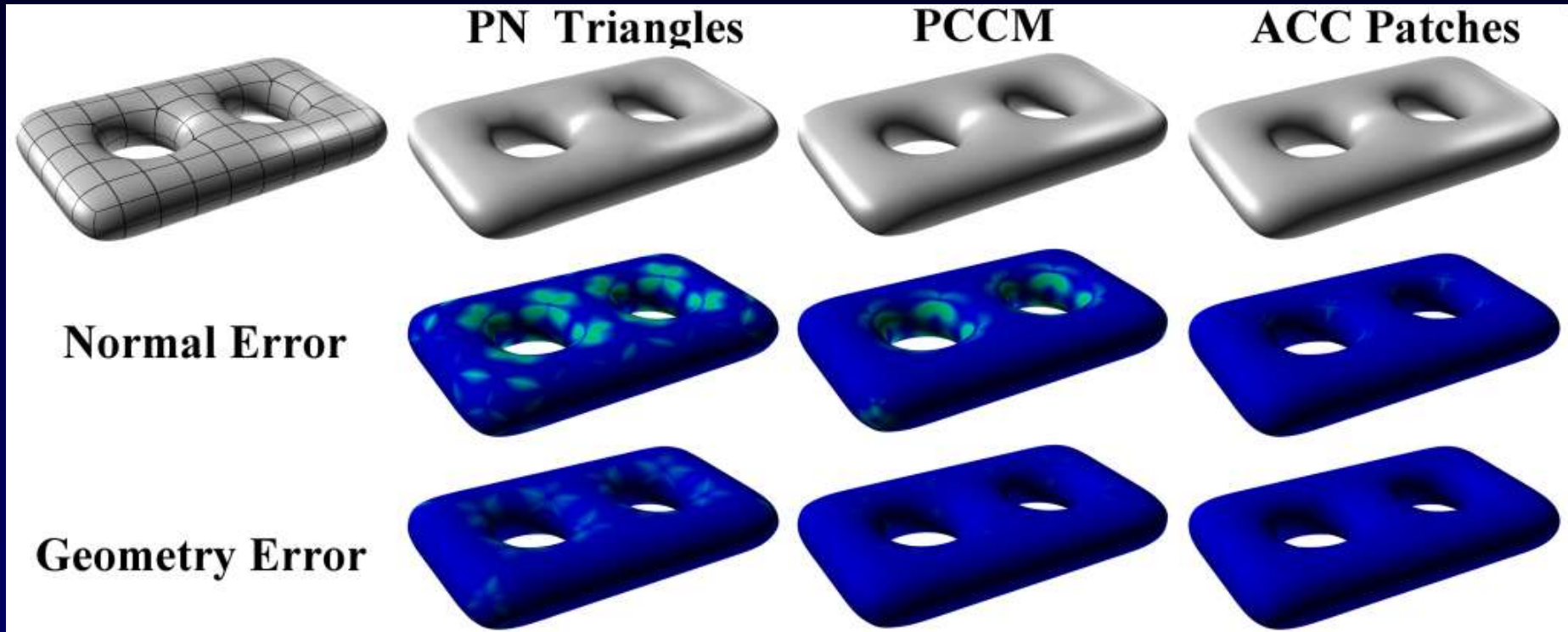
Comparison



Better

Worse

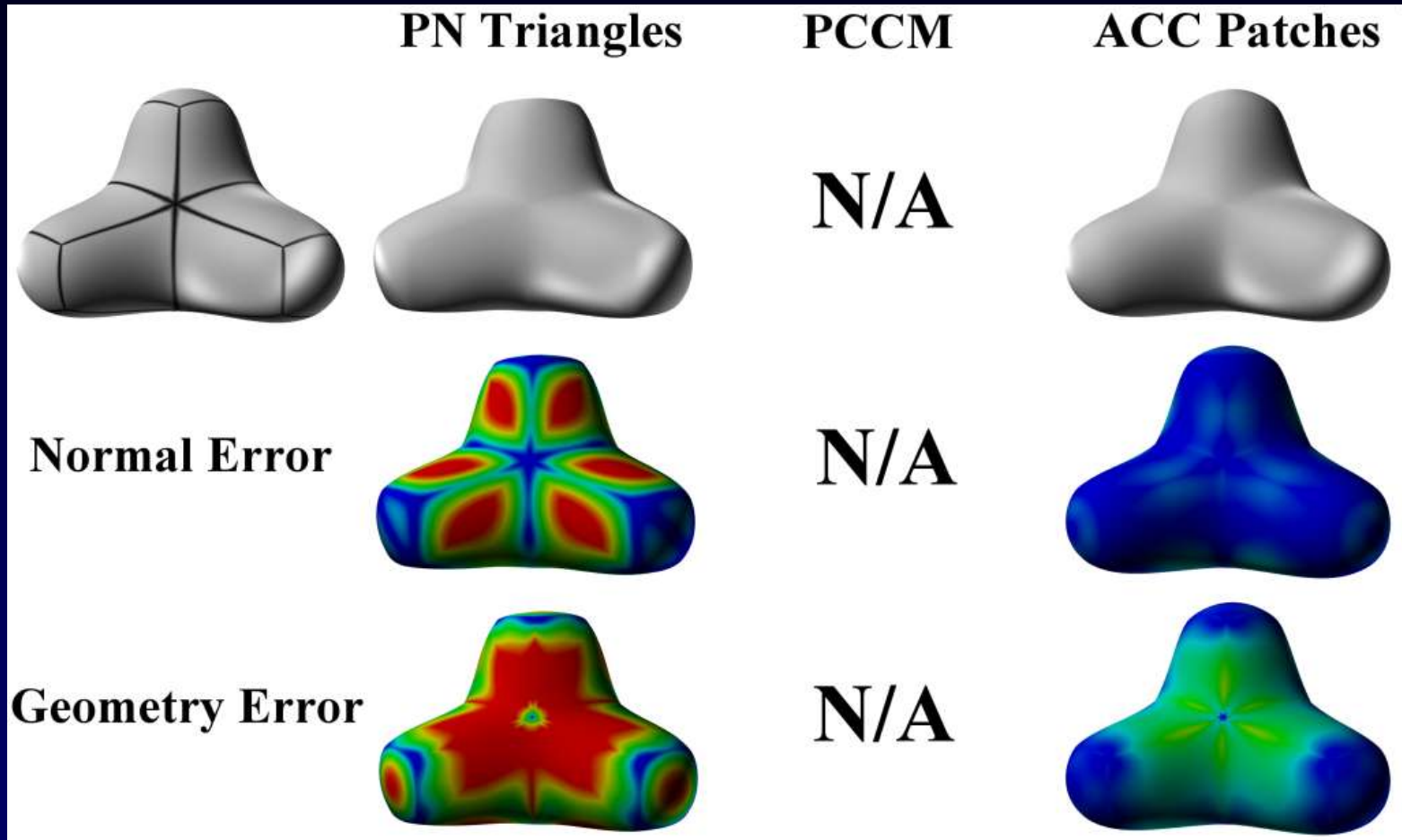
Comparison



Better

Worse

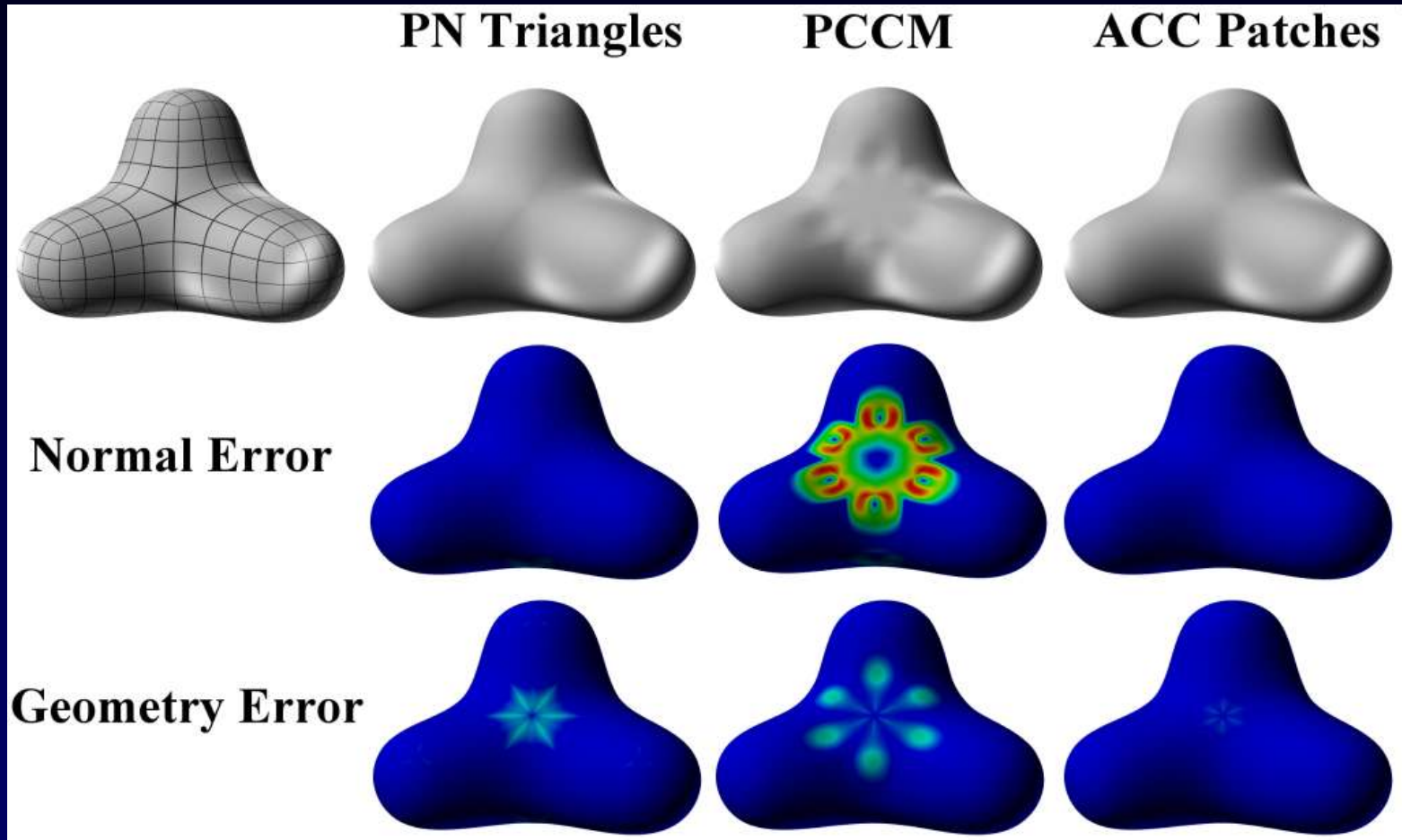
Comparison



Better

Worse

Comparison



Better

Worse

Conclusions

- Creates visually smooth surfaces
- Suitable for displacement/normal mapping
- Handles any number of extraordinary vertices
- Simple to evaluate
- Demo part of DirectX March 2008 SDK

