Efficient GPU Rendering of Subdivision Surfaces

Tim Foley, 2017-03-02

Collaborators

- Activision
  - Wade Brainerd
- Stanford
  - Matthias Nießner
- NVIDIA
  - Manuel Kraemer
  - Henry Moreton

Subdivision surfaces are a powerful modelling primitive

Smooth surface (+creases)
Arbitrary input topology
Animation
Level of detail

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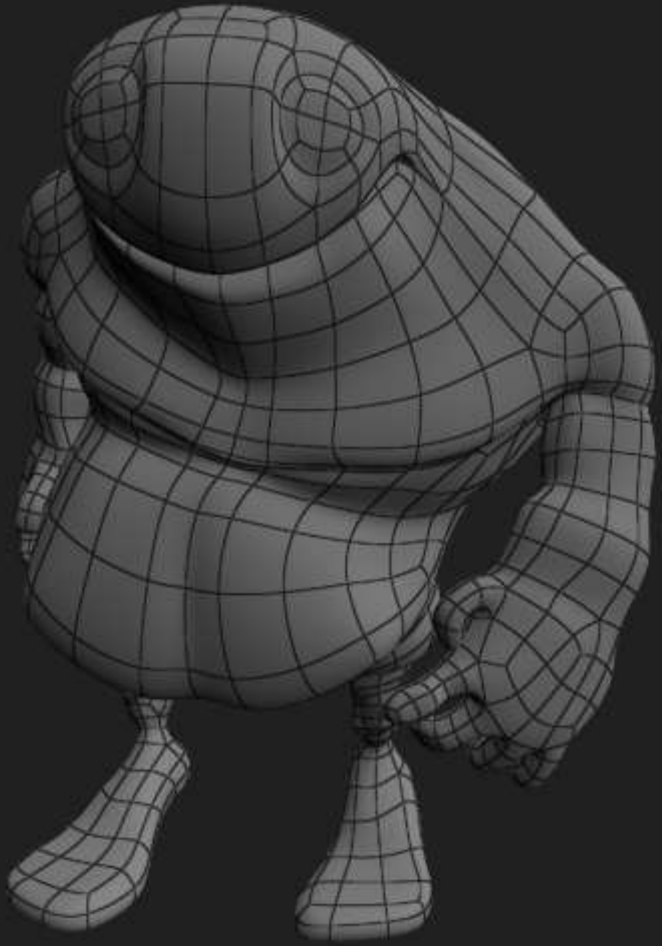

Subdivision surface rendering is not common in games

Performance

Ease of Integration

Performance

Our method is up to 3x faster than previous non-approximate schemes

Ease of Integration

Our method can work in a single draw pass (no compute)
Can use with existing vertex shaders for animation

Outline

- Background
  - Subdivision surfaces
  - GPU tessellation hardware
- Prior work
- Overview of our approach
- Performance evaluation
- Conclusion

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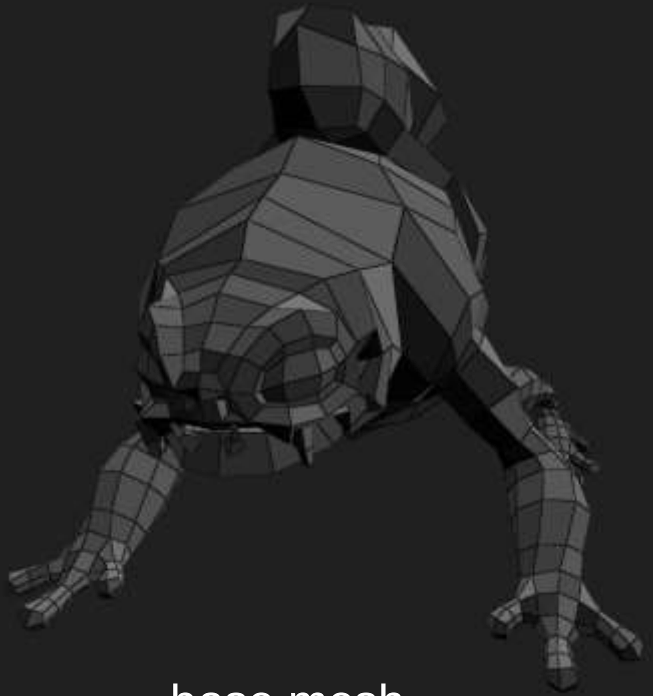
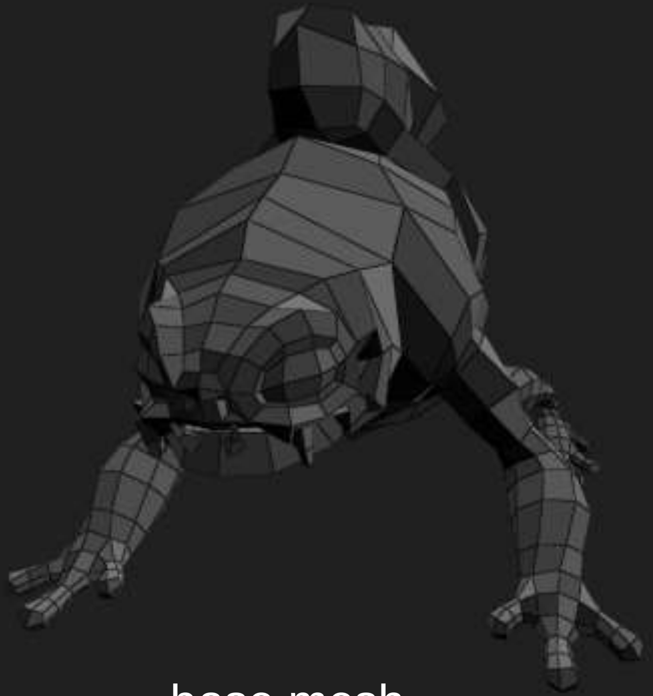
Catmull-Clark Subdivision



base mesh

Defined by repeated application of subdivision rules



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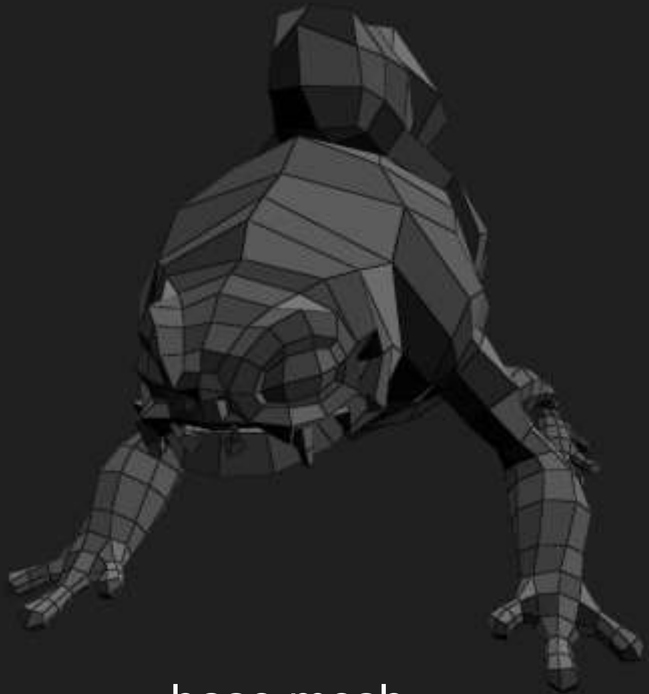

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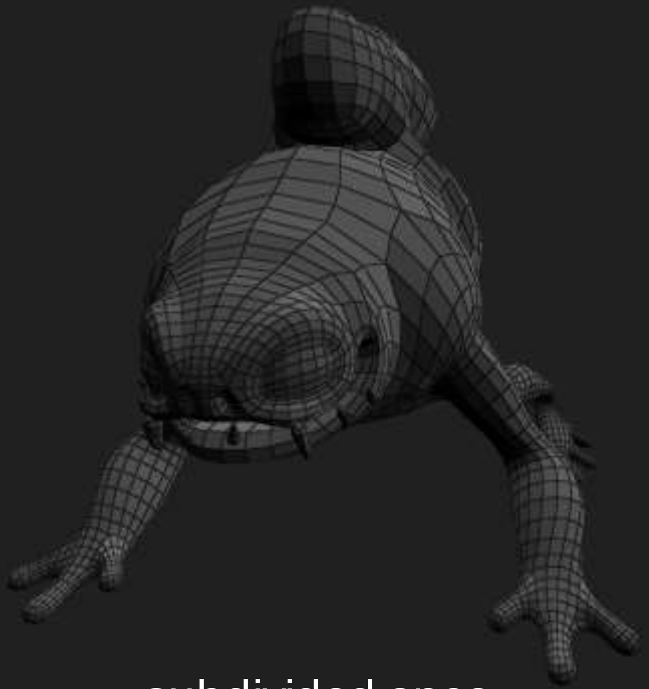
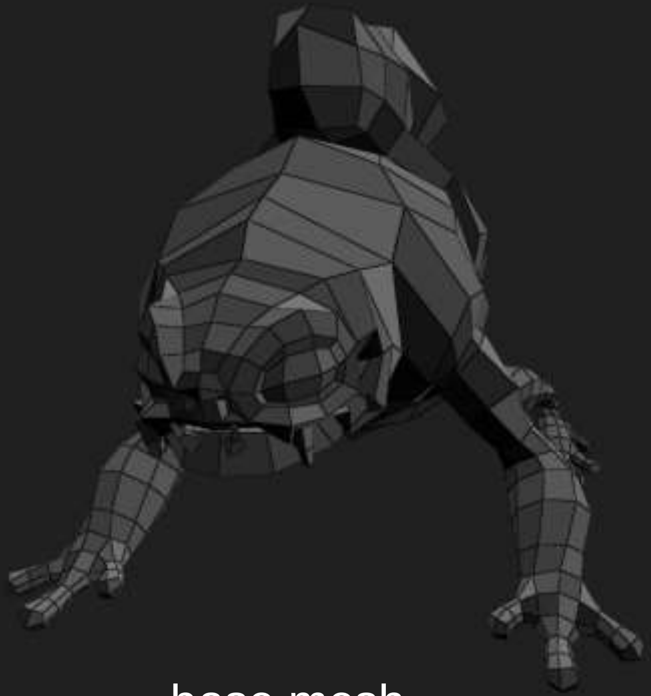


subdivided once

Defined by repeated application of subdivision rules



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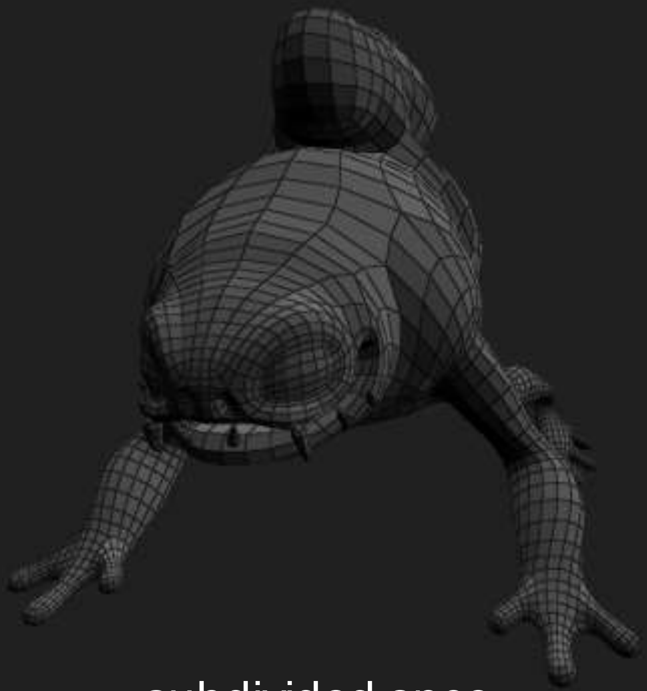

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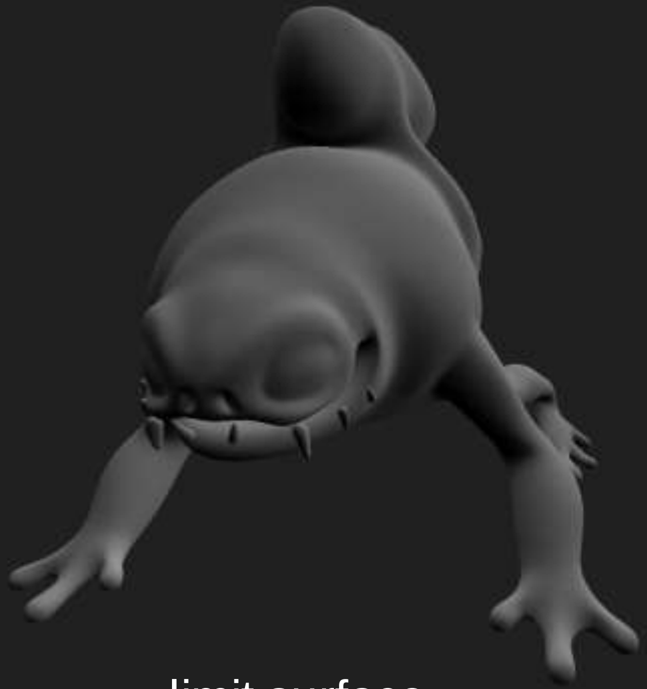
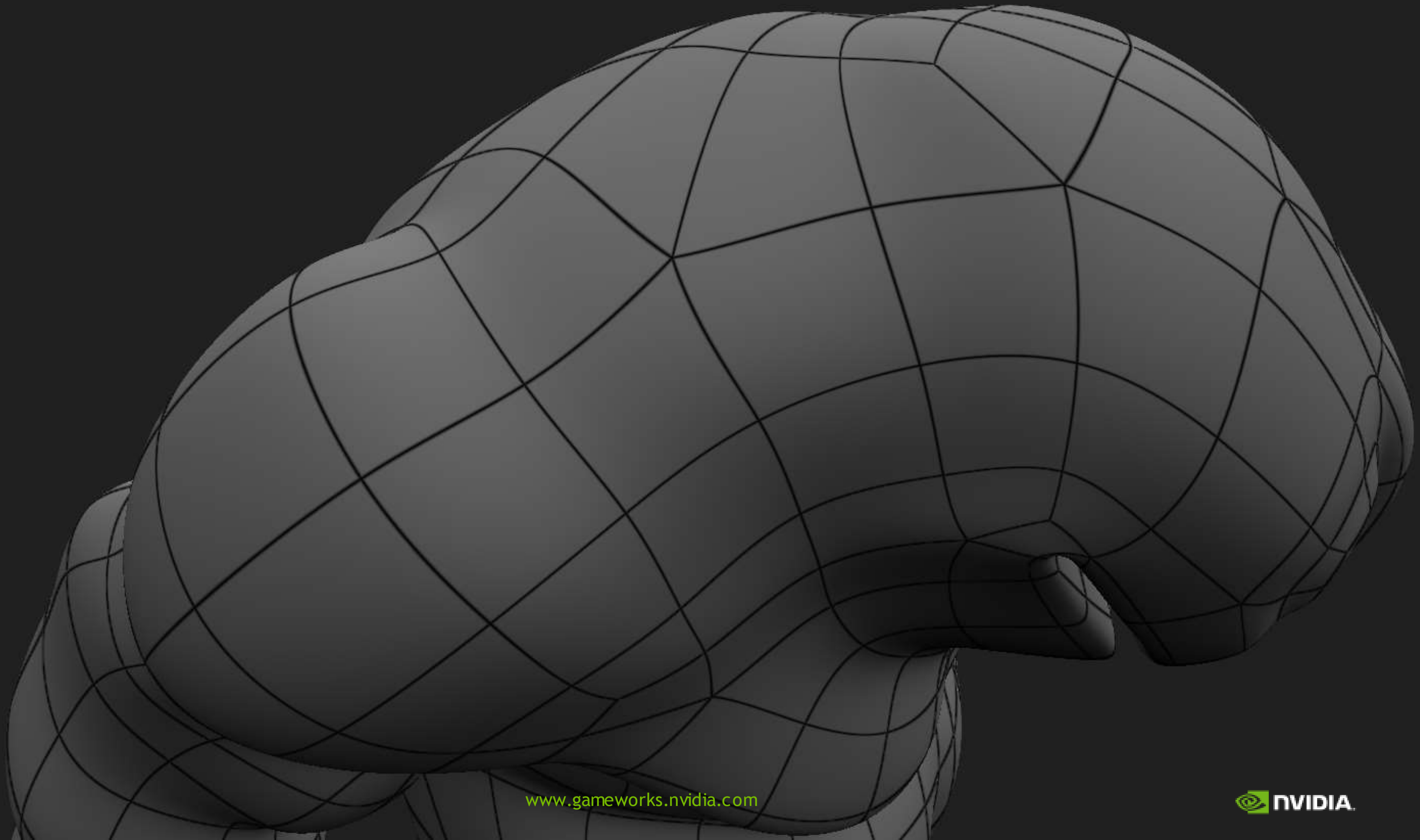
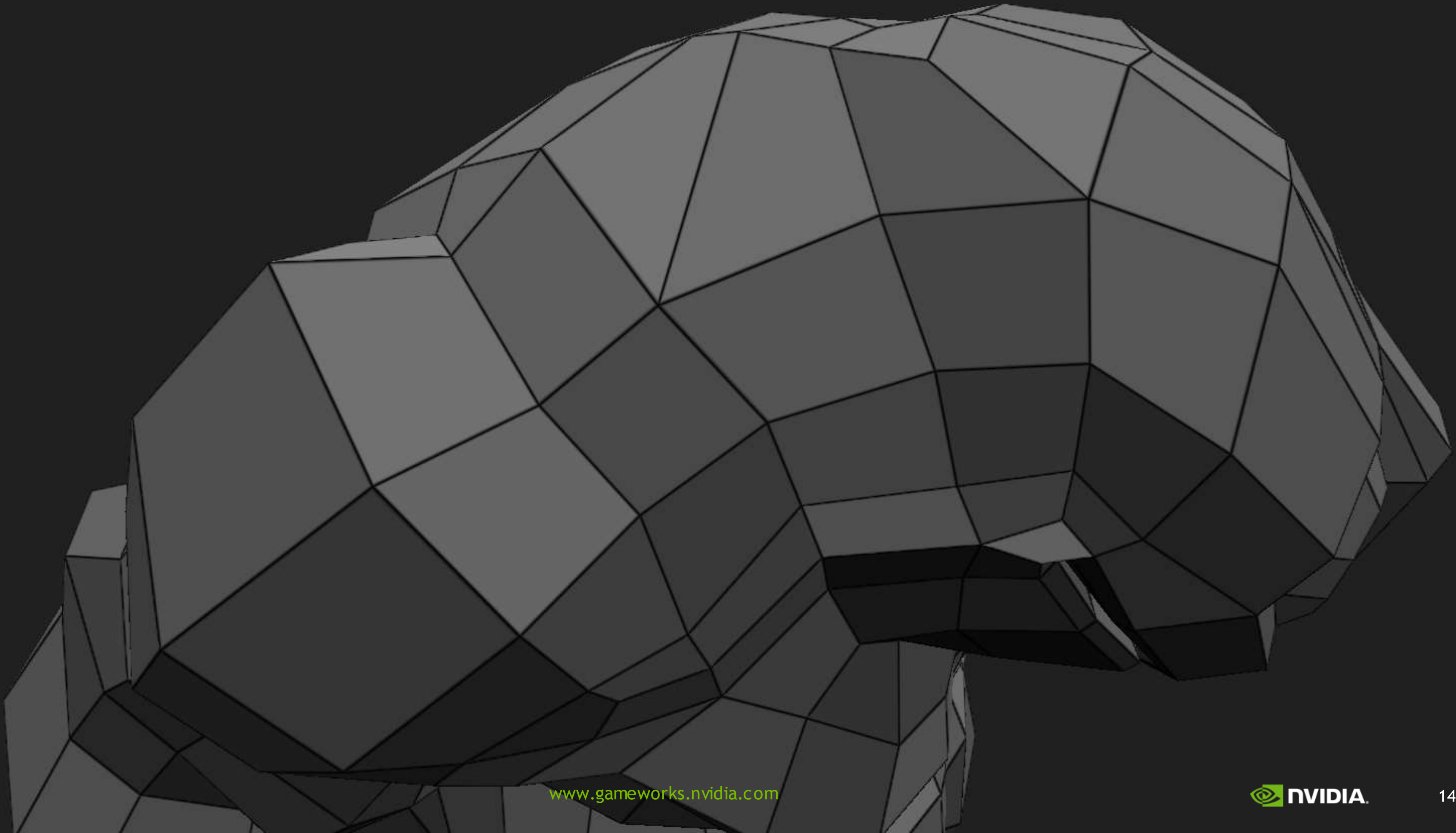


limit surface





Limit surface for face depends on local neighborhood

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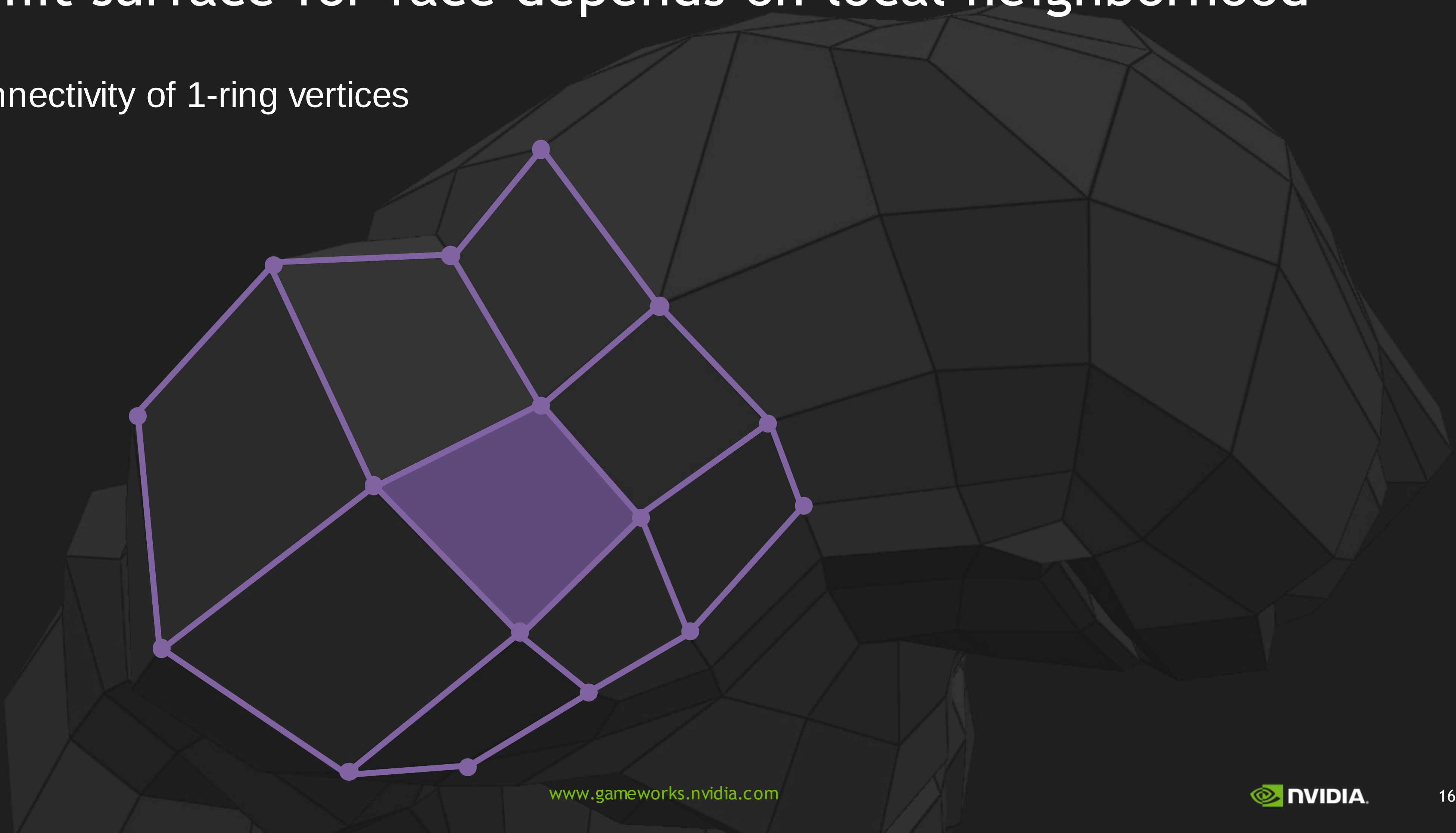
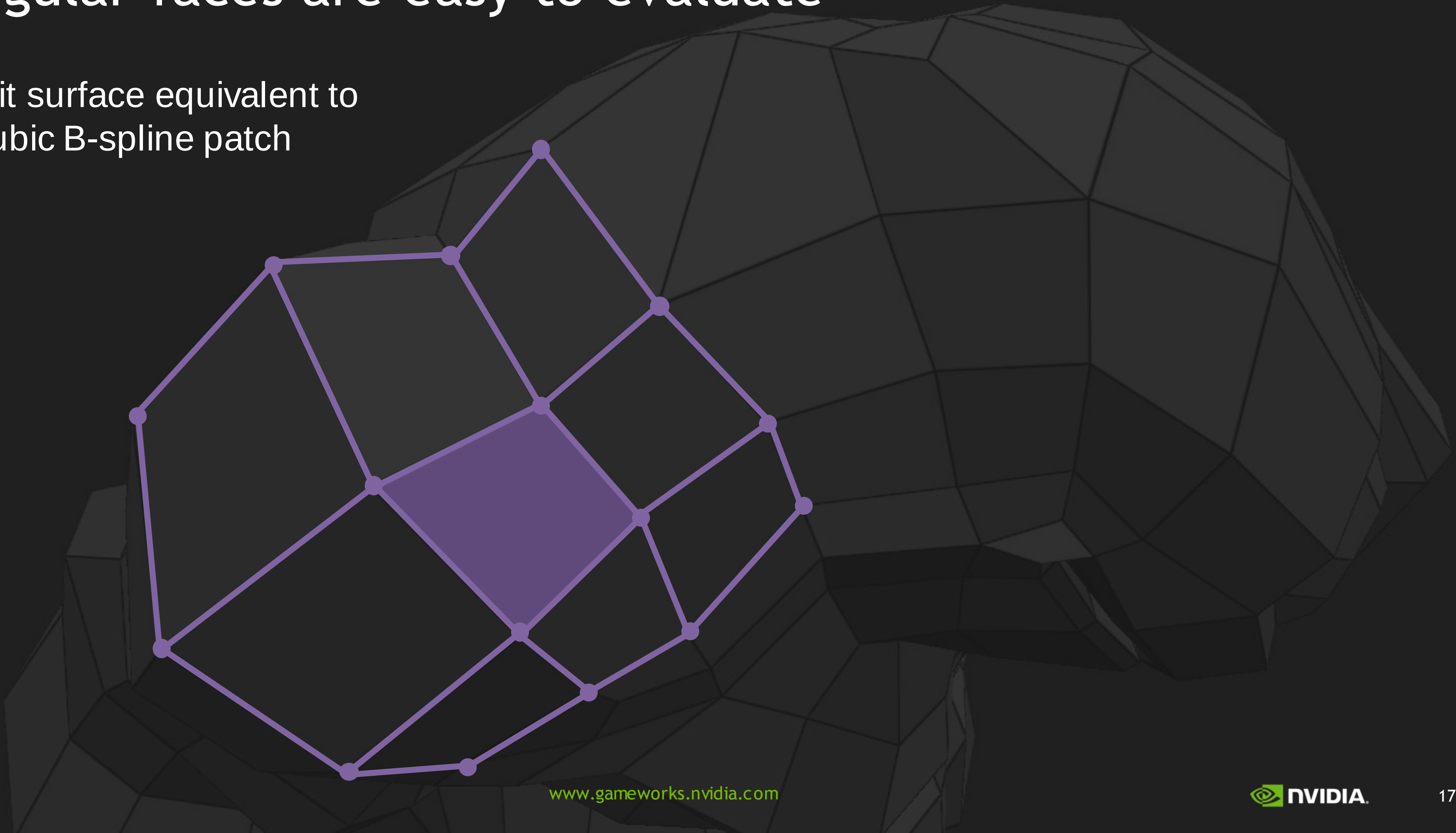
Connectivity of 1-ring vertices

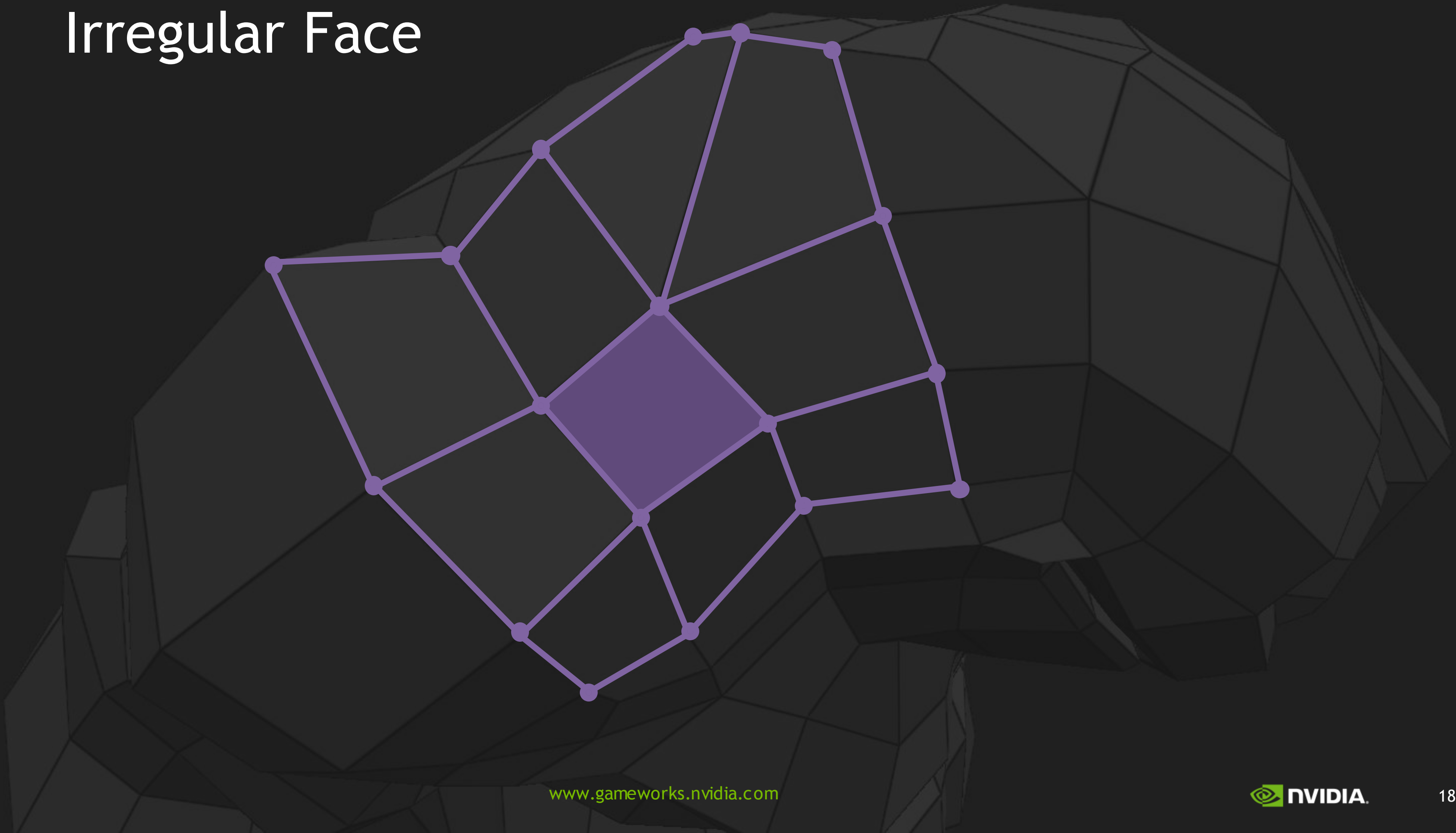


Regular faces are easy to evaluate

Limit surface equivalent to bicubic B-spline patch

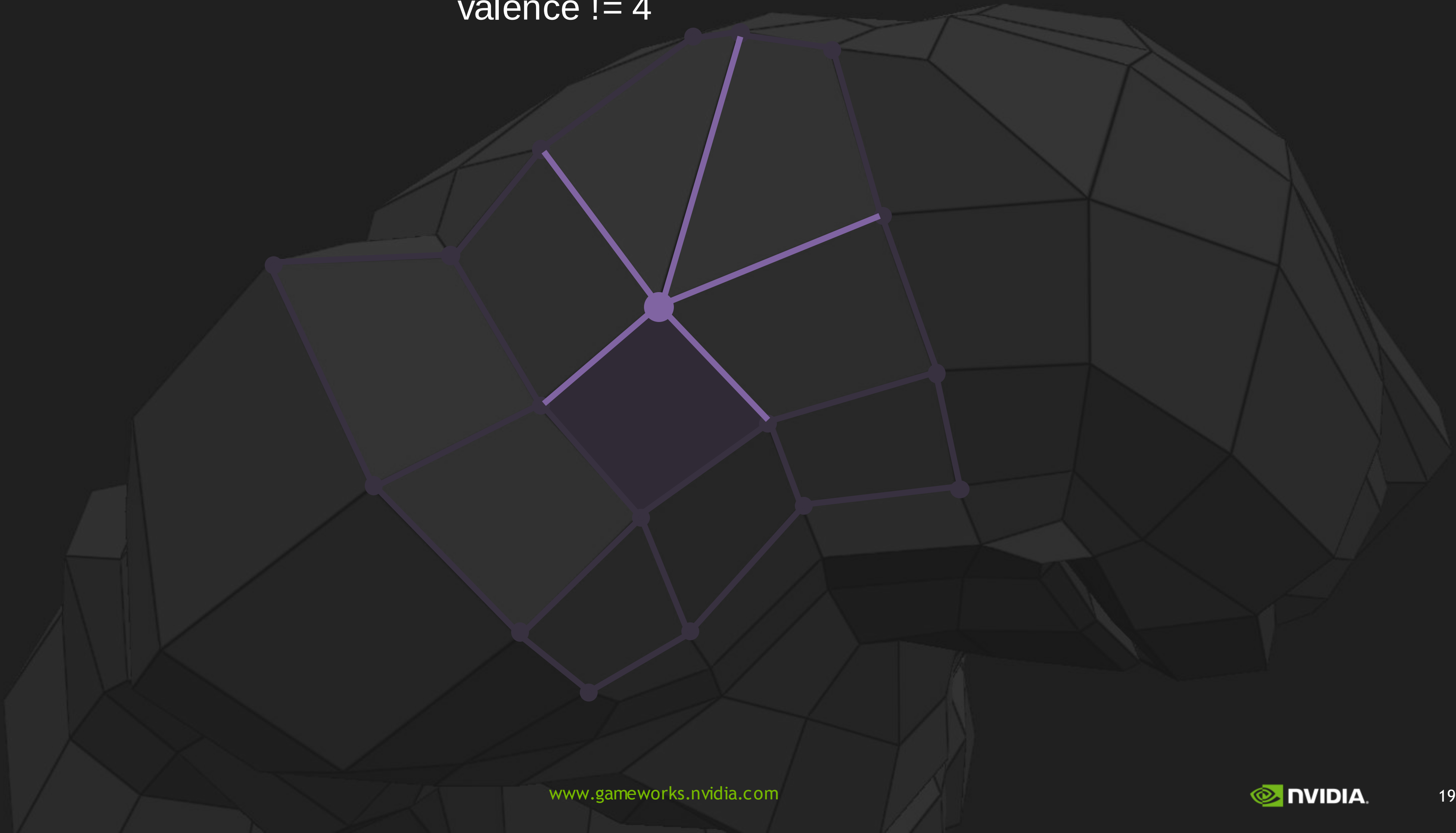


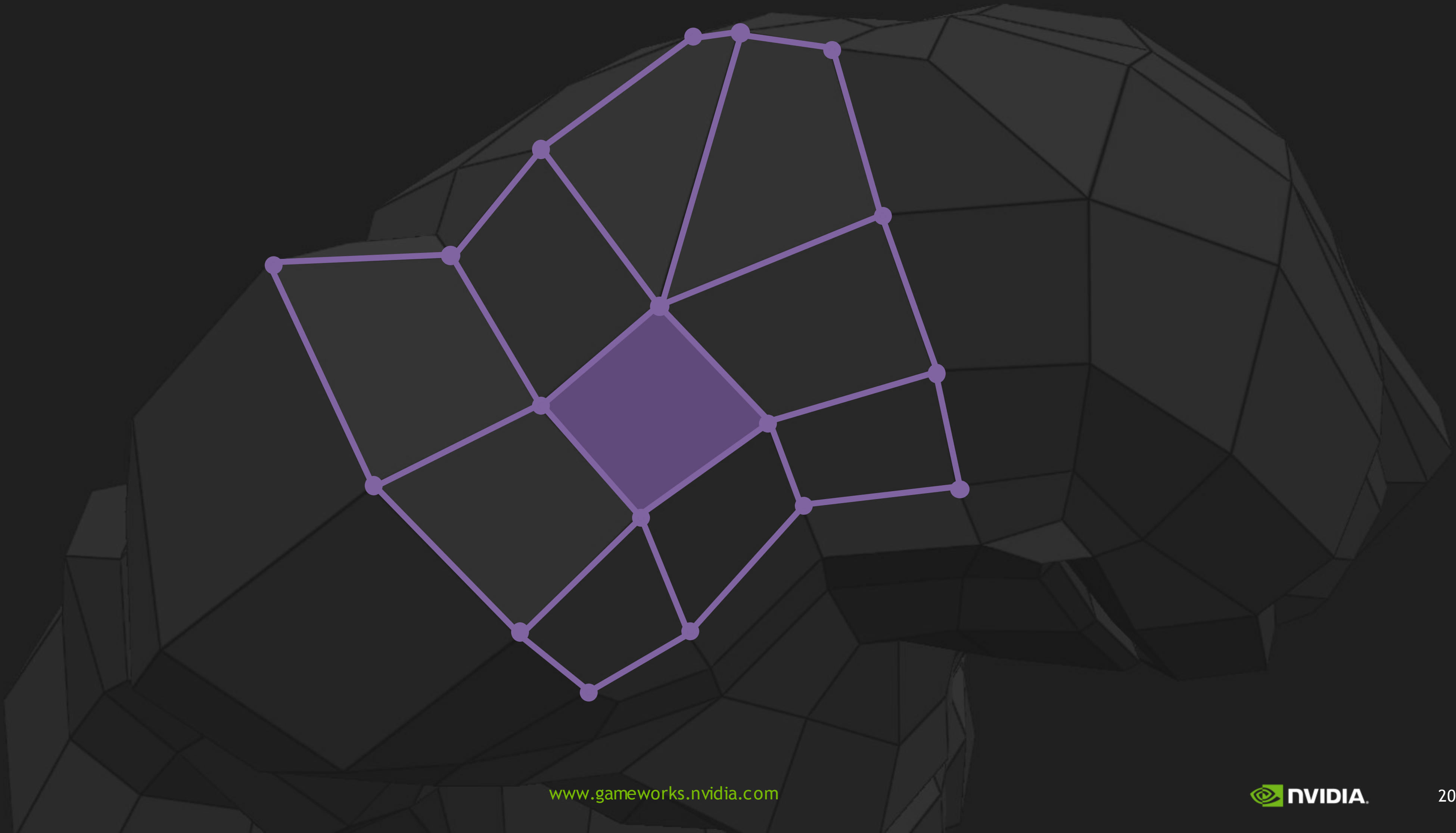
Irregular Face

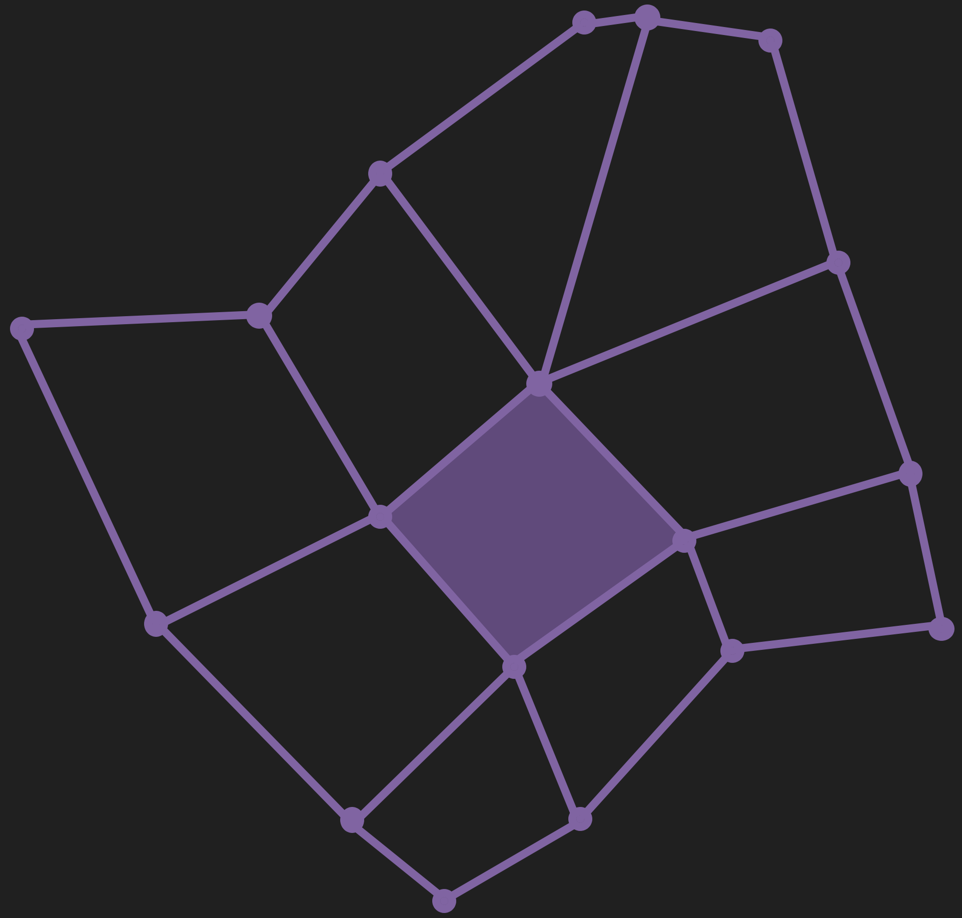


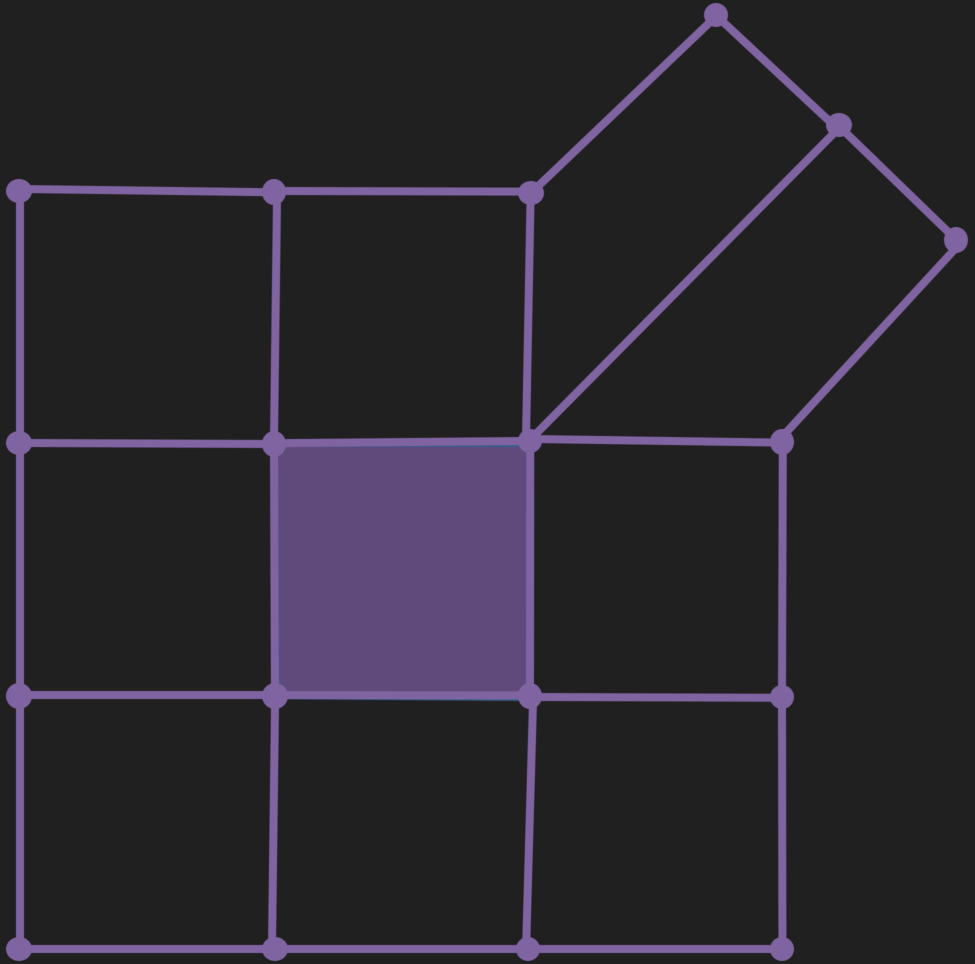
Extraordinary Vertex

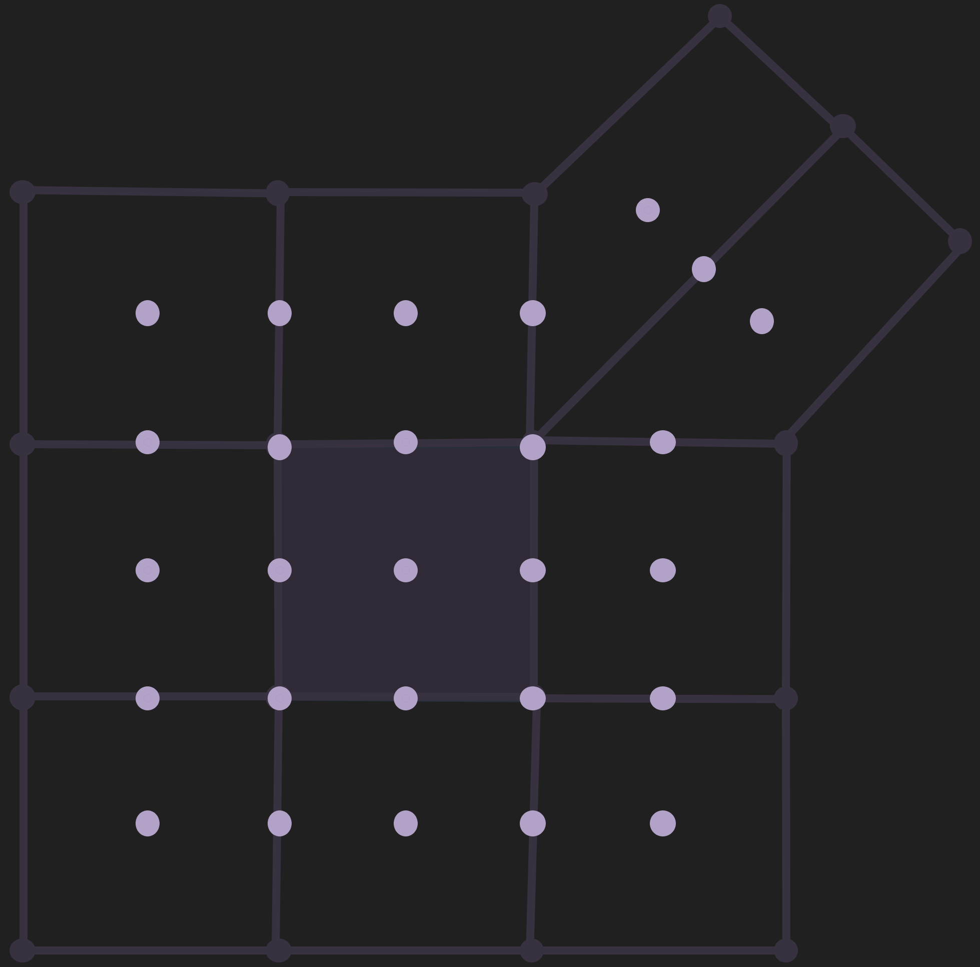
valence != 4

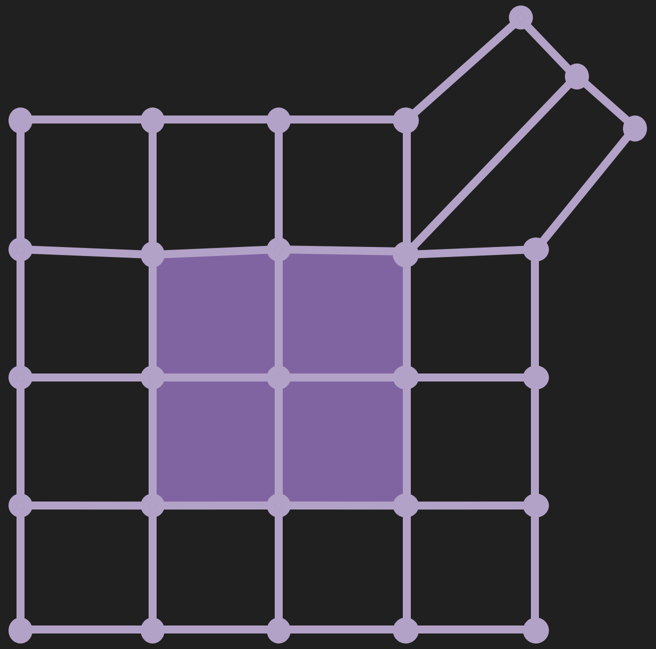




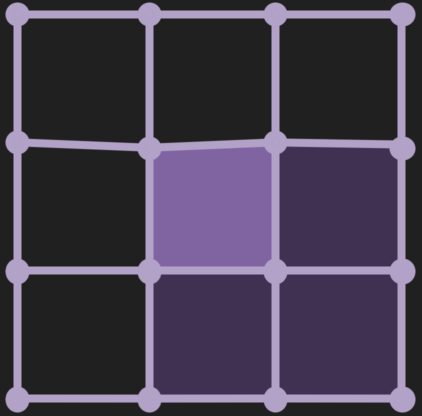


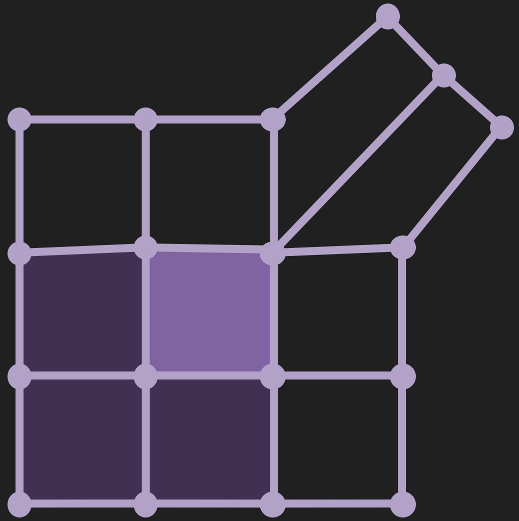






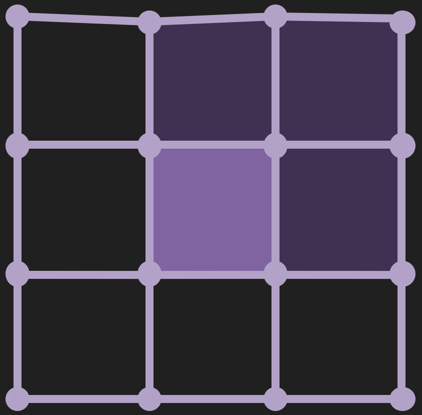
regular

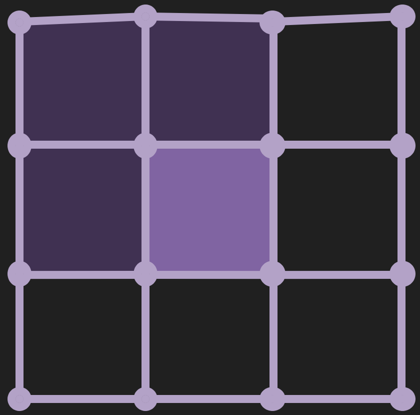




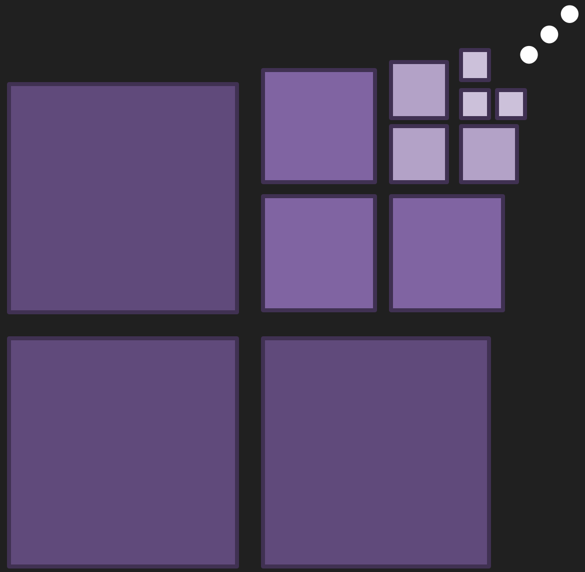
irregular

regular





regular



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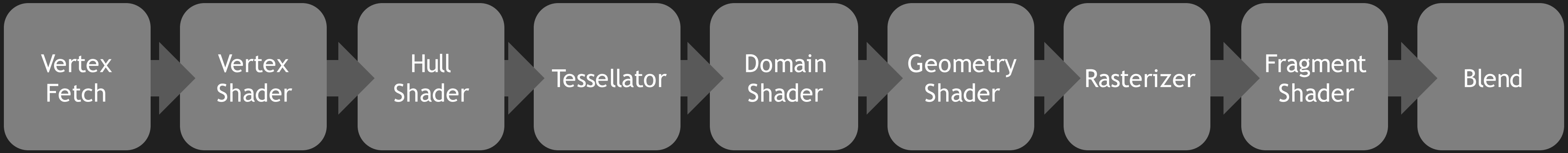
GPU Rasterization Pipeline


Vertex Fetch

Vertex Shader

Hull Shader

Tessellator

Domain Shader

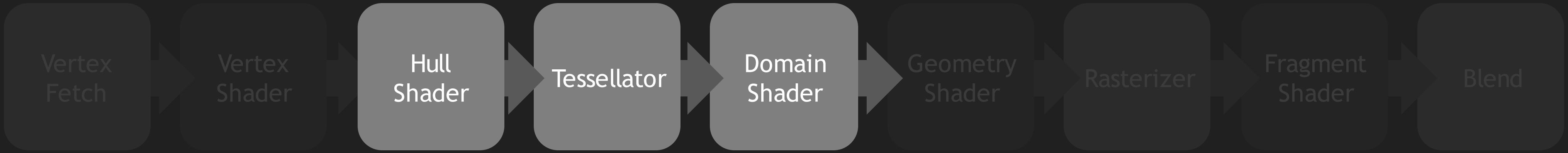
Geometry Shader

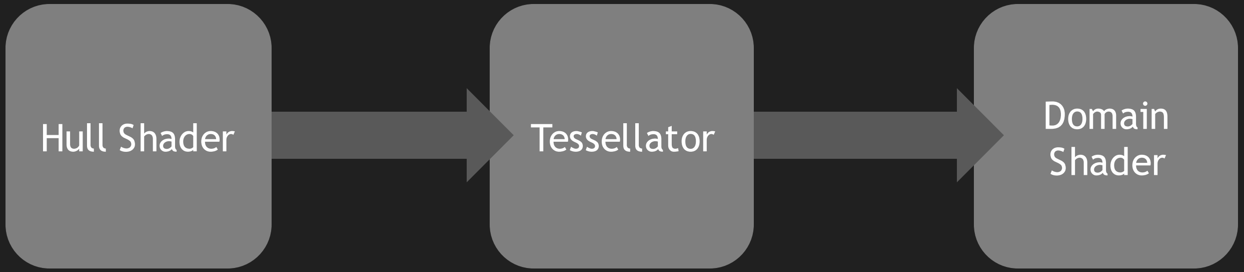
Rasterizer

Fragment Shader

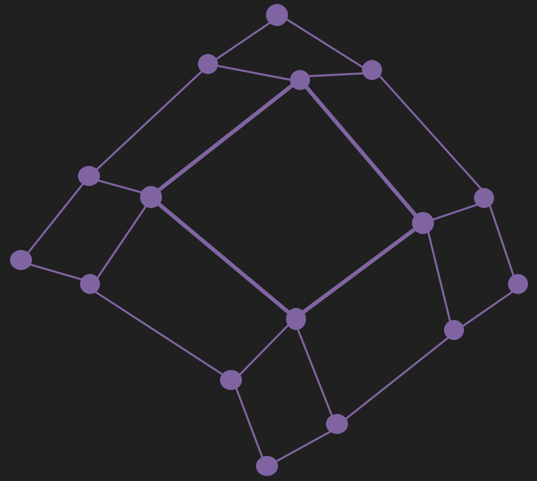
Blend

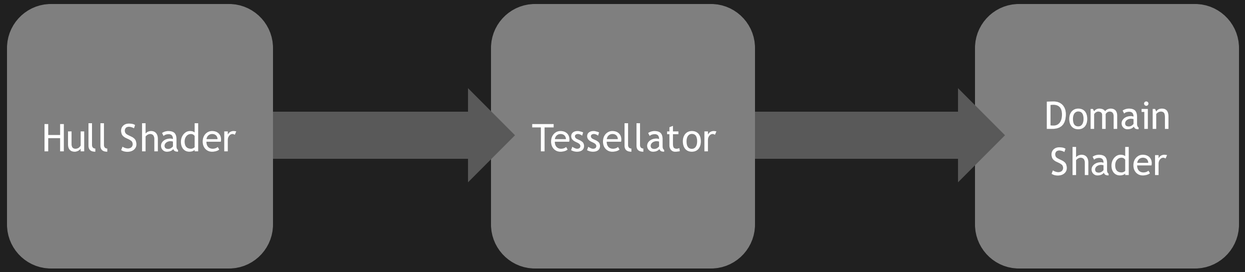
Tessellation Stages

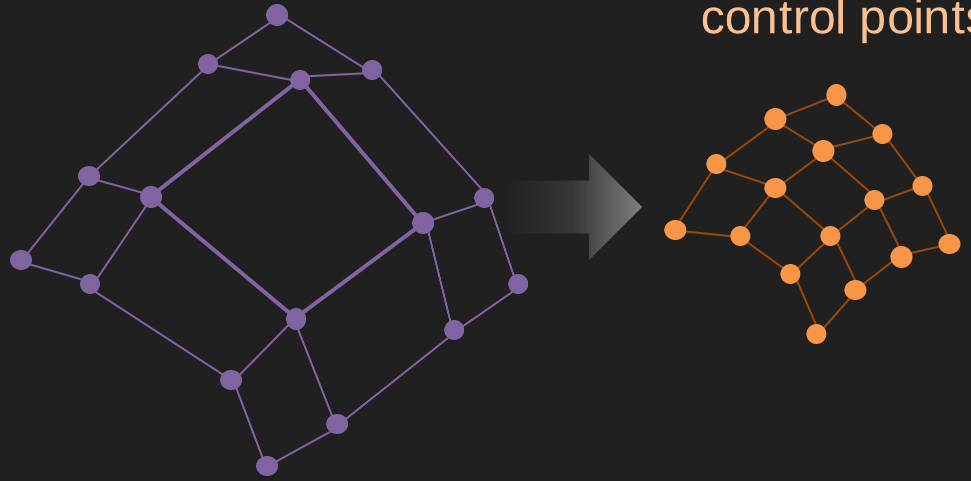



Hull Shader
Tessellator
Domain Shader

primitive
base vertices

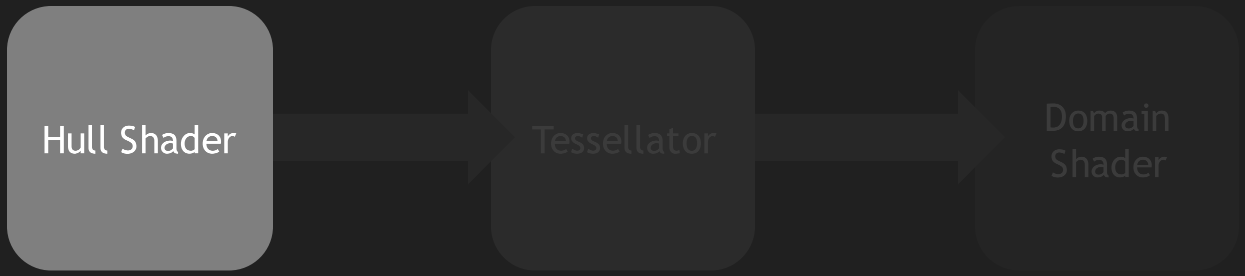






primitive
base vertices

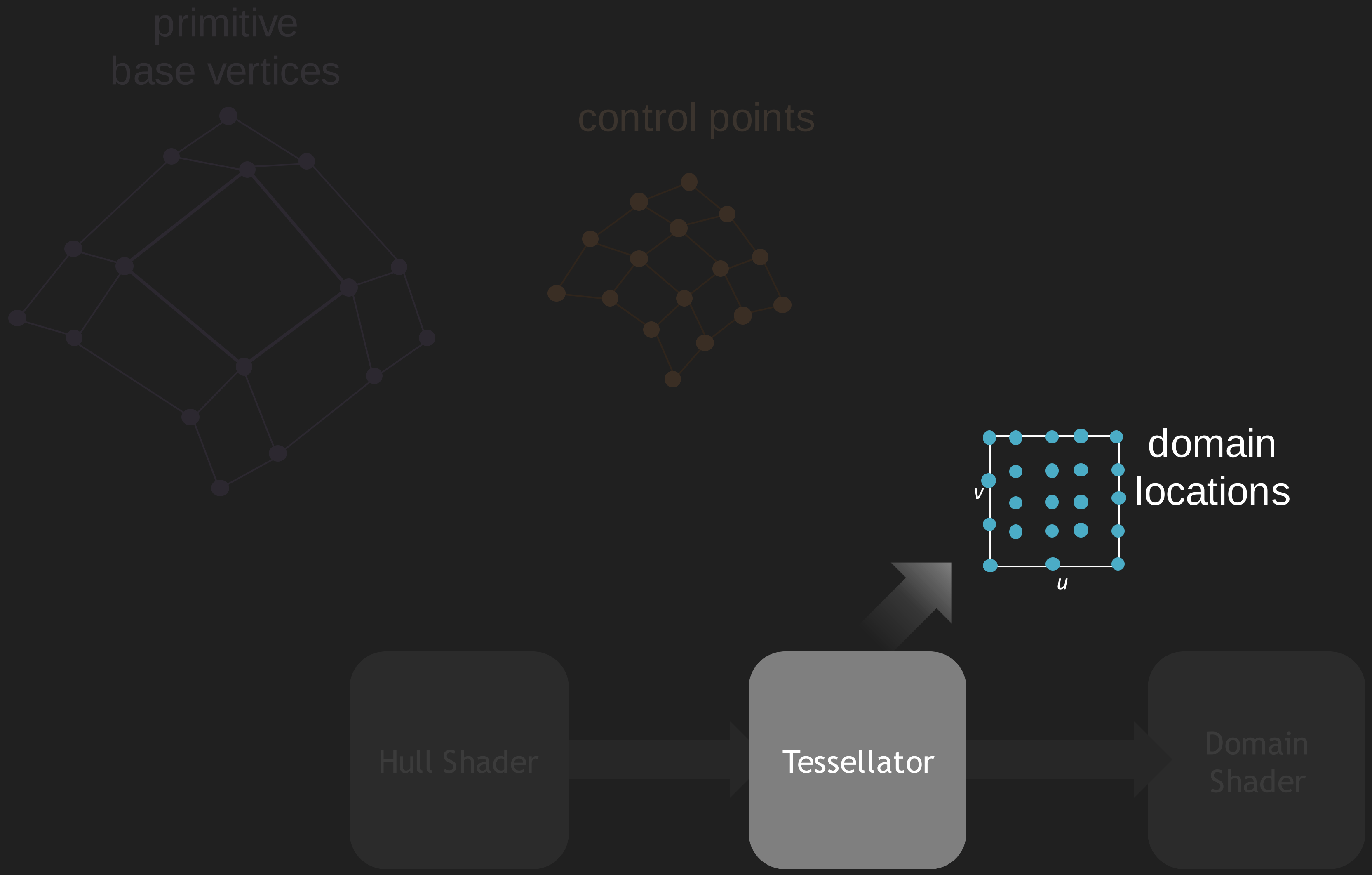
control points



Hull Shader

Tessellator

Domain Shader



primitive
base vertices

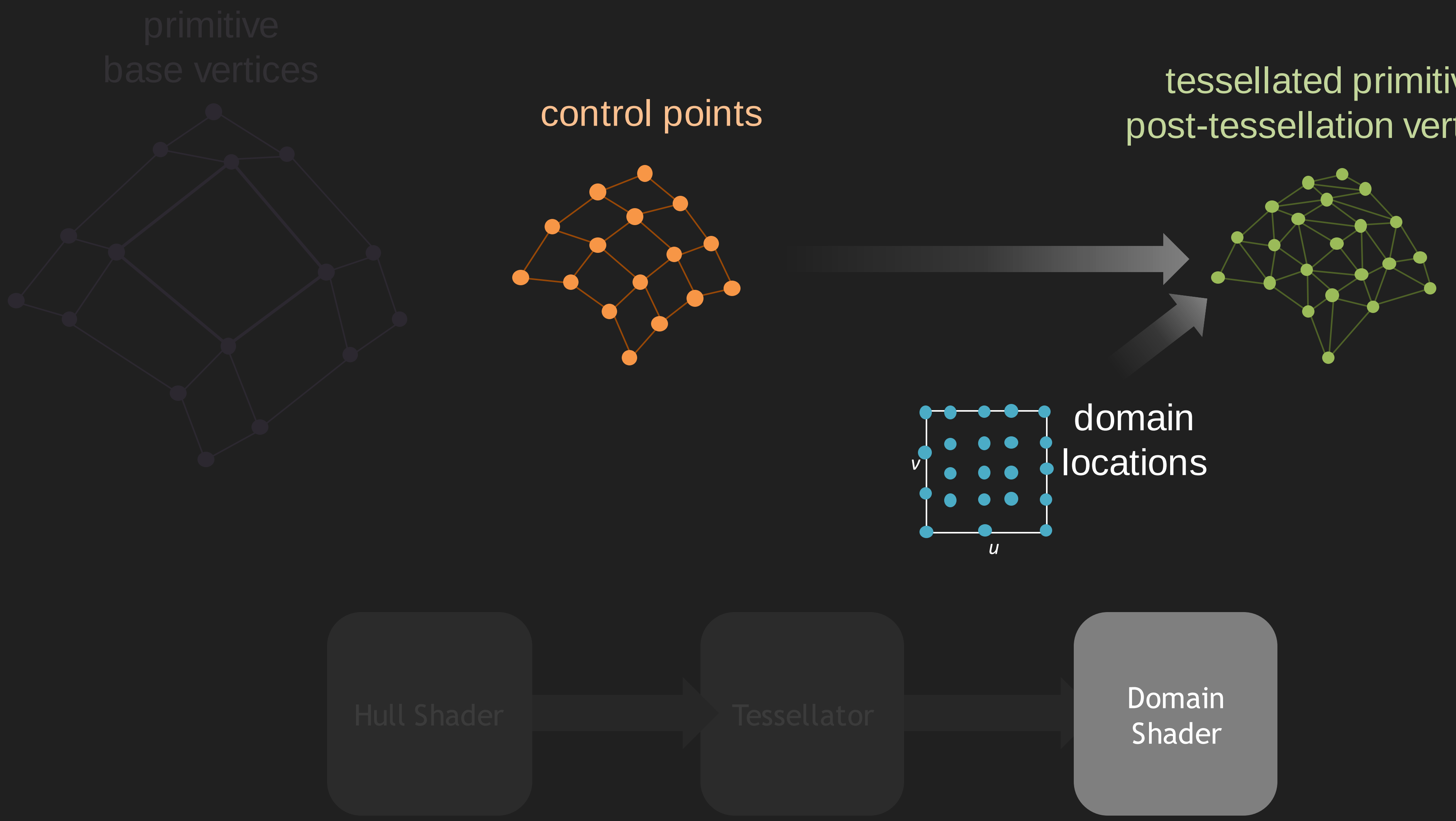
control points

domain
locations

Hull Shader

Tessellator

Domain
Shader



primitive
base vertices

control points

tessellated primitive
post-tessellation vertices

domain
locations

Hull Shader

Tessellator

Domain
Shader

Crux of the Challenge

Limit surface of irregular face defined by recursive subdivision

Expands to many faces with many control points

Variable: depends on subdivision depth

Tessellation hardware wants fixed # of control points per face

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Submit one primitive for each irregular face

Use a fixed # of control points

Submit many primitives for an irregular face

Each of which is simple to evaluate

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Submit many primitives for an irregular face

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Exact Evaluation

[Stam 1998]

- Perform Eigen analysis on subdivision matrix
  - Offline process for each topological configuration
- Project base vertices into Eigen space
  - Yields a fixed # of control points
- Matrix exponentiation in domain shader
  - Many floating-point operations

Approximate irregular faces with simpler patch

- Bicubic Bezier
- Bicubic Gregory (20 control points)

[Loop and Schaefer 2008]

[Loop et al. 2009]

- Fast evaluation

- No support for semi-sharp features (creases)
- Approximation affects tangents, parameterization

Submit one primitive for each irregular face

Use a fixed # of control points

Submit many primitives for an irregular face

Each of which is simple to evaluate

Subdivide and submit many primitives per face

- Feature adaptive subdivision (FAS)
  - Generate sub-face control points using compute kernels
  - Many submit many primitives, depending on subdivision level
  - Need to address T-junctions between sub-faces

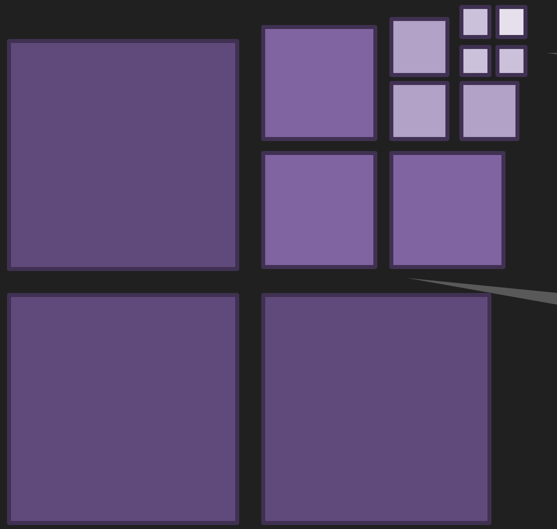
[Nießner et al. 2012]

- Dynamic feature adaptive subdivision (DFAS)
  - Enables non-uniform subdivision levels

[Schäfer et al. 2012]

Open
Subdiv

Issues with Feature-Adaptive Subdivision



many primitives

T-junctions

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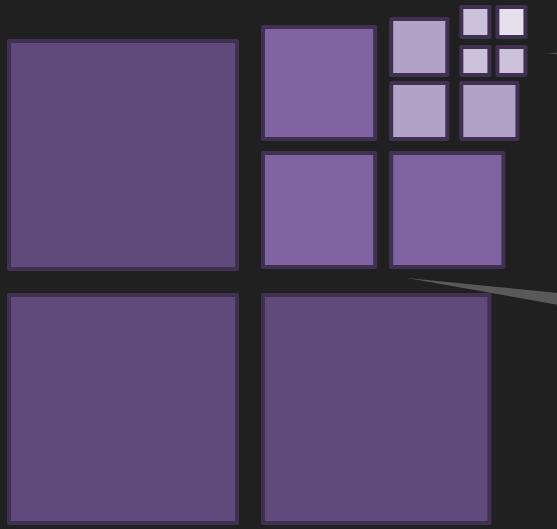
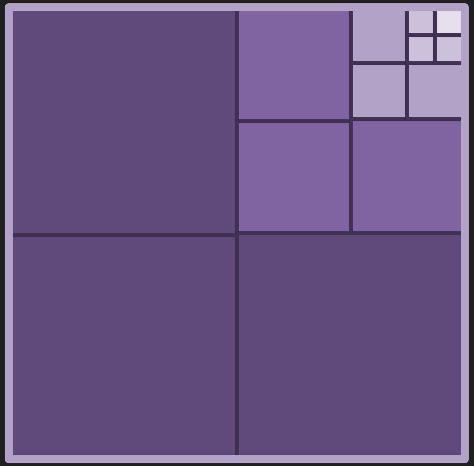
Take recursive subdivision hierarchy…



many primitives

T-junctions

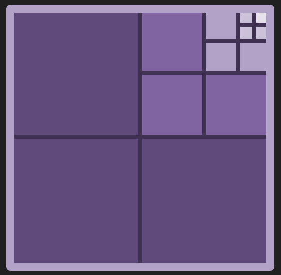
Summarize using a single primitive



one primitive

no T-junctions

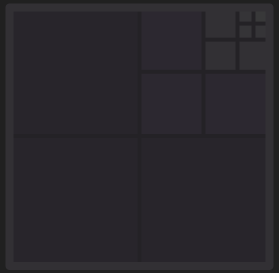
Two key ideas



Use a quadtree to map domain locations to sub-faces

Output a variable # of control points from a Hull Shader

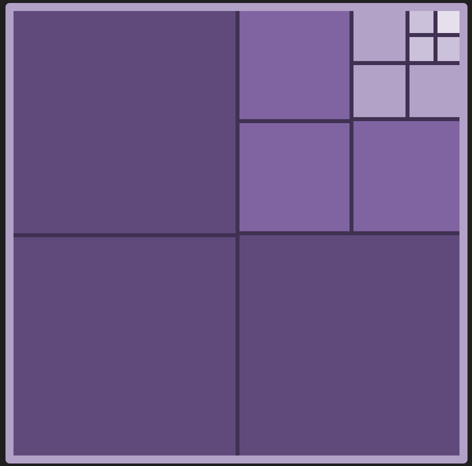
Two key ideas



Use a quadtree to map domain locations to sub-faces

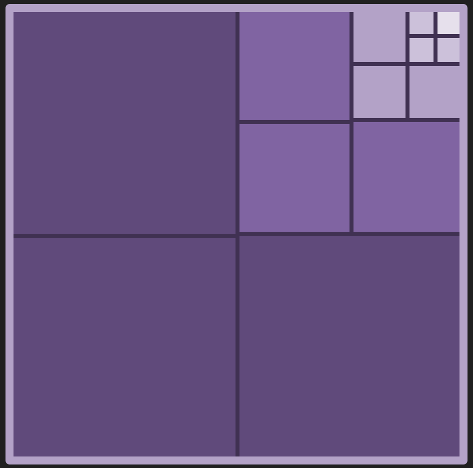
Output a variable # of control points from a Hull Shader

Submit one primitive per base face to tessellator

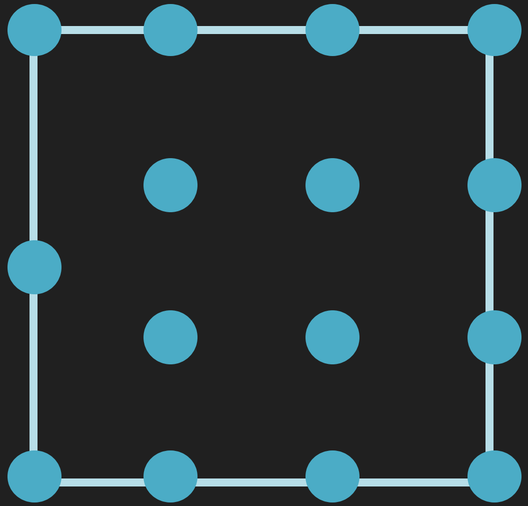


base subdivision face

Tessellator produces domain locations for evaluation

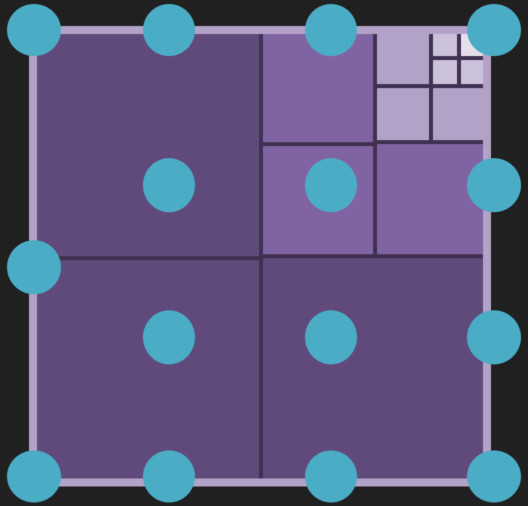


base subdivision face



domain locations

Map domain location to correct sub-face



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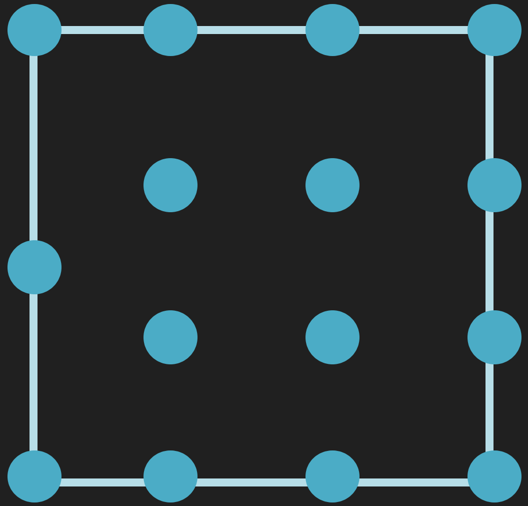

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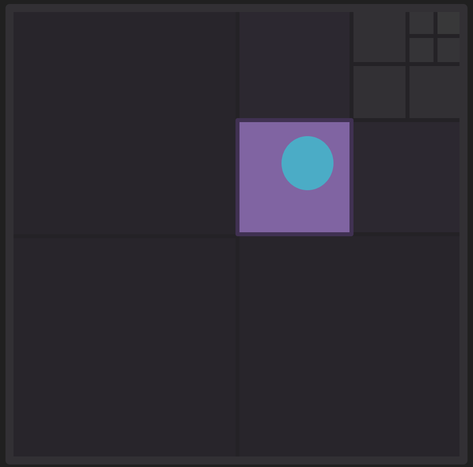
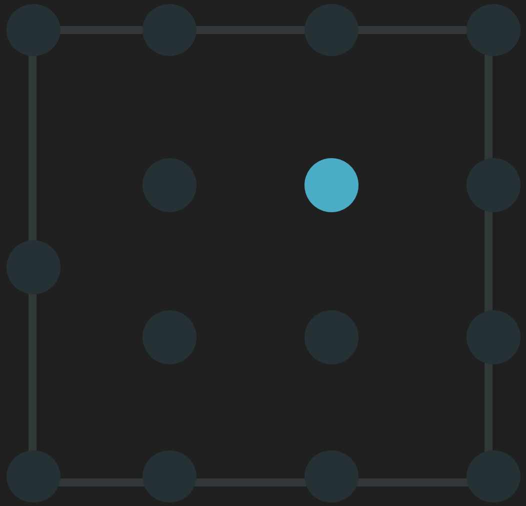


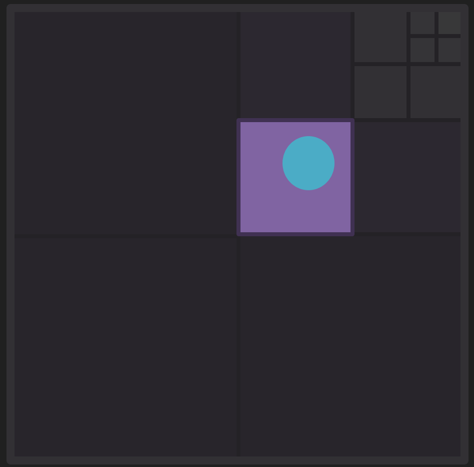
base subdivision face



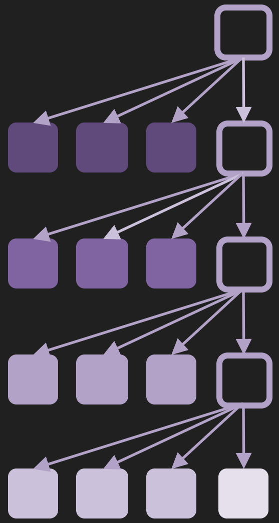
domain locations

Map domain location to correct sub-face

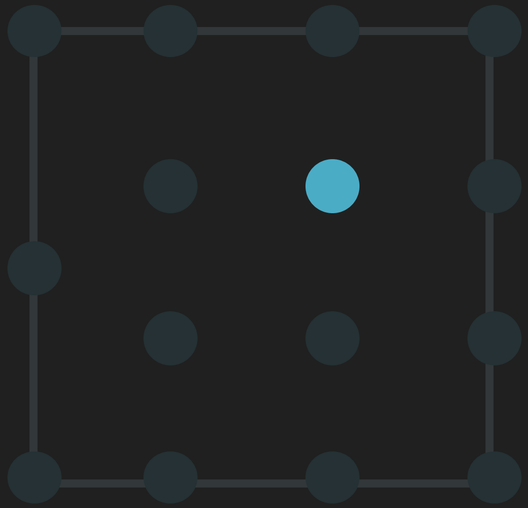
using a quadtree data structure



base subdivision face



quadtree



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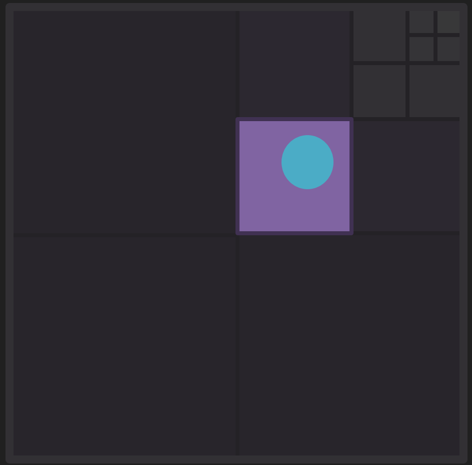

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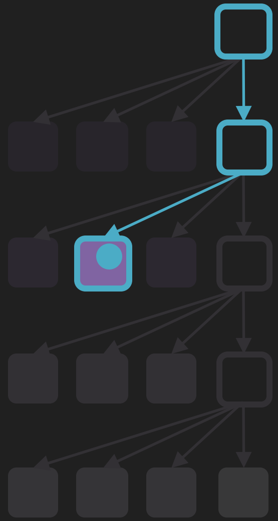

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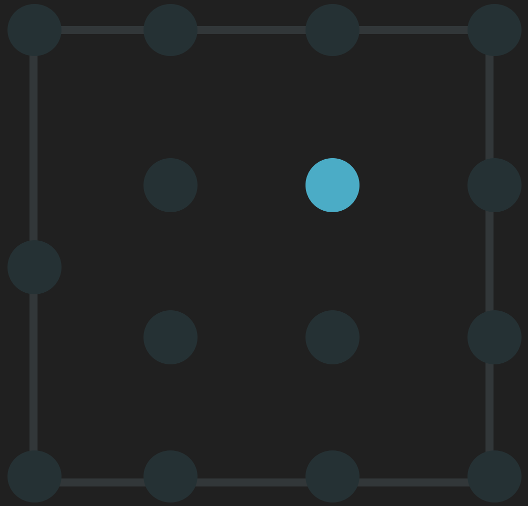
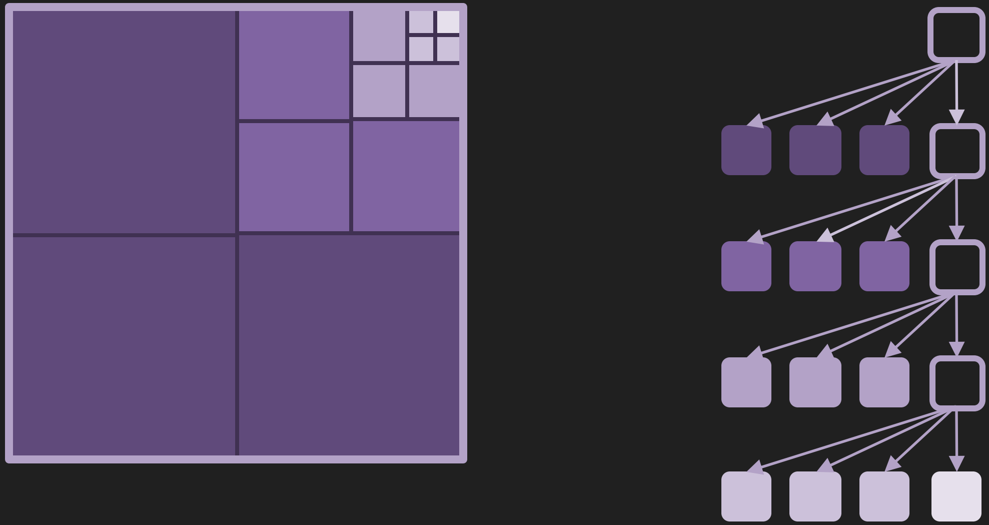


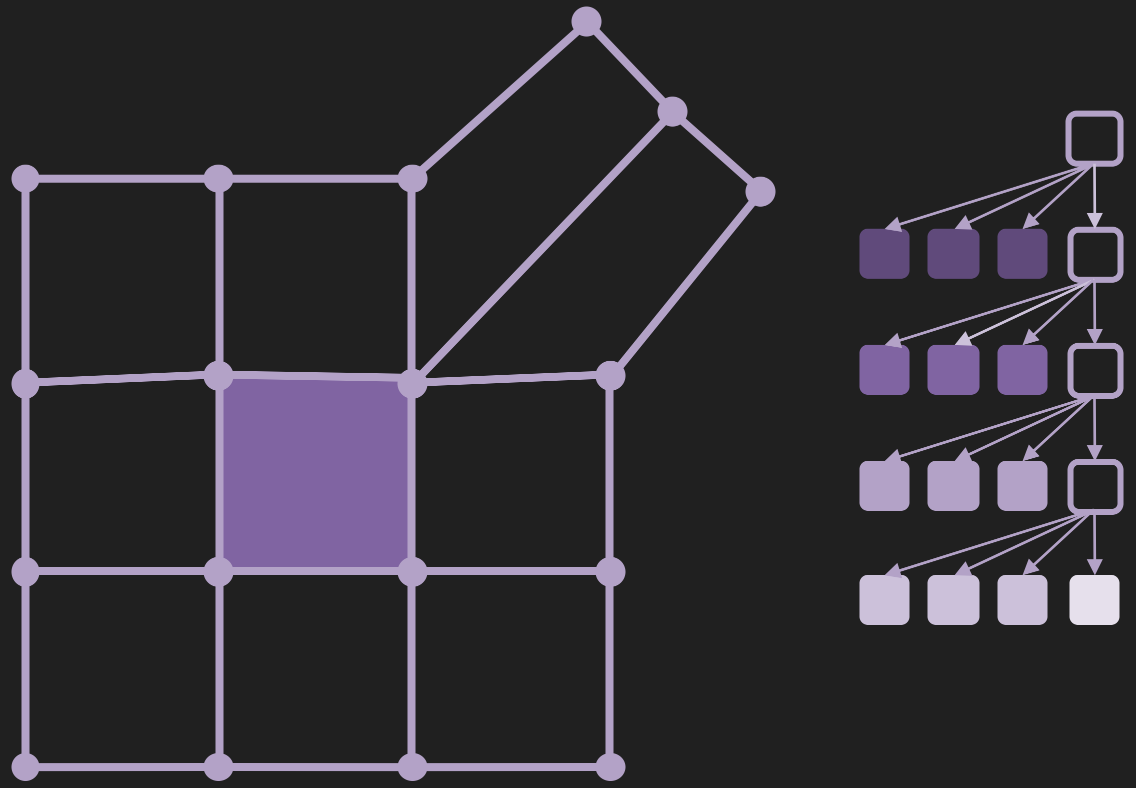
domain locations

Quadtrees can be built ahead of time, and shared

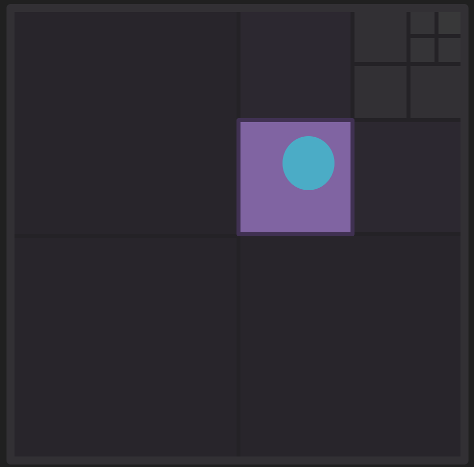


Quadtrees can be built ahead of time, and shared

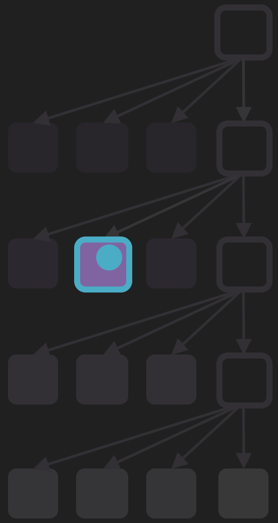
depend only on 1-ring topology



Quadtree leaf node tells us which control points to use



base subdivision face



quadtree

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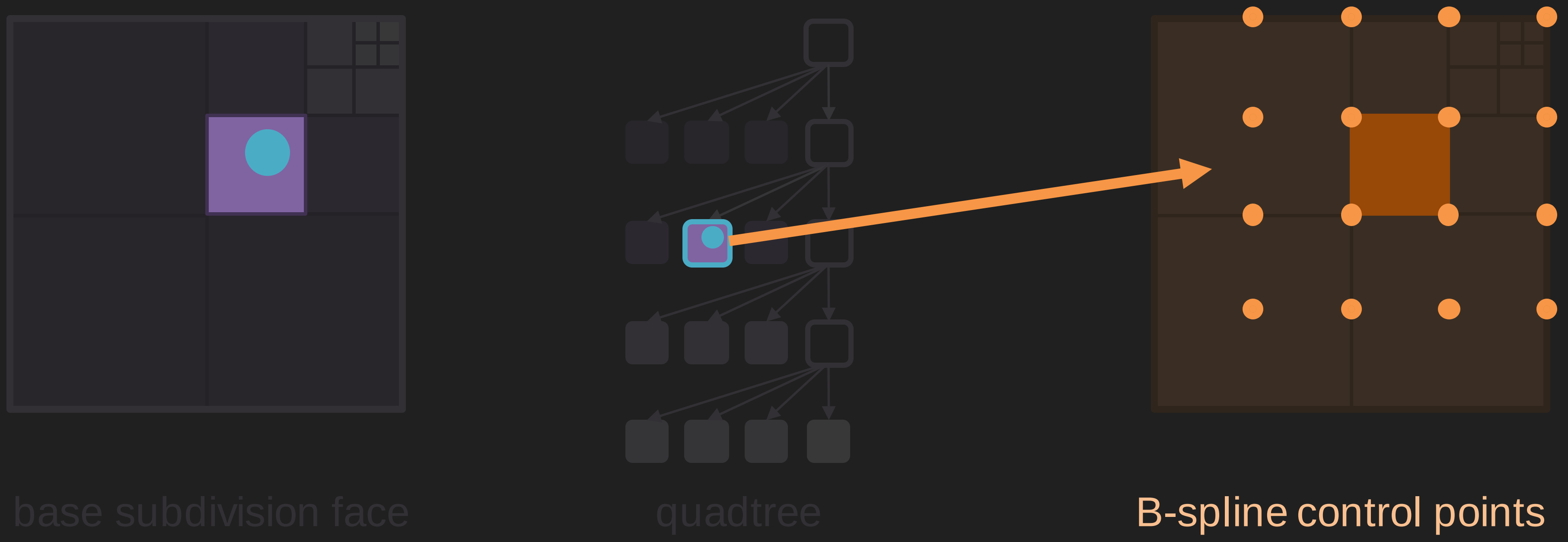

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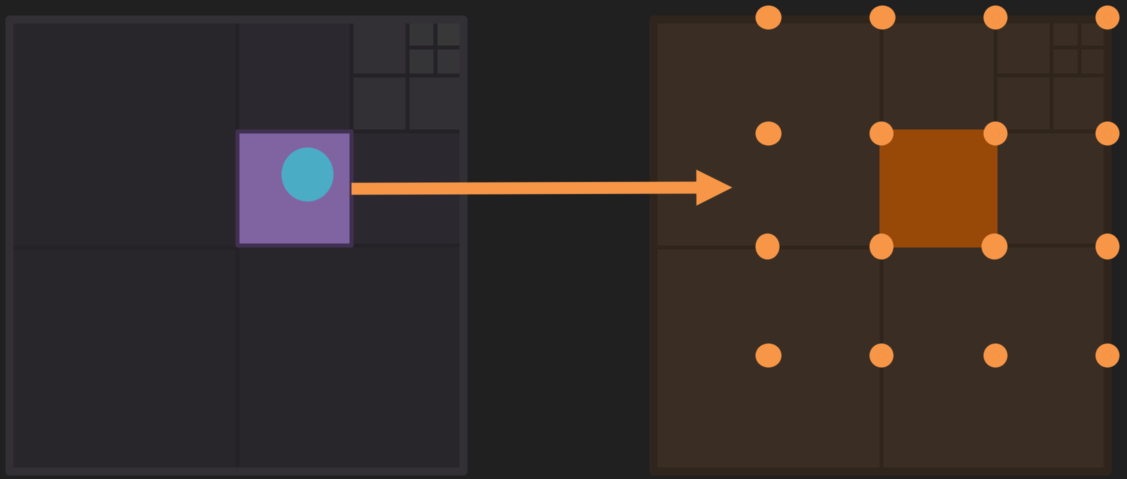
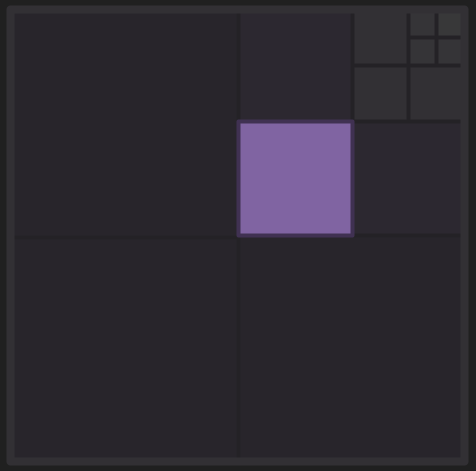


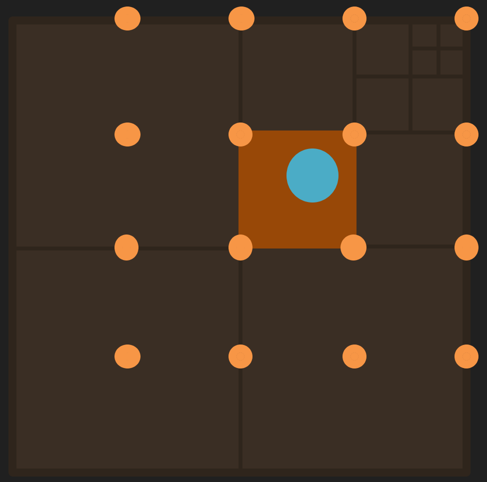
base subdivision face

B-spline control points

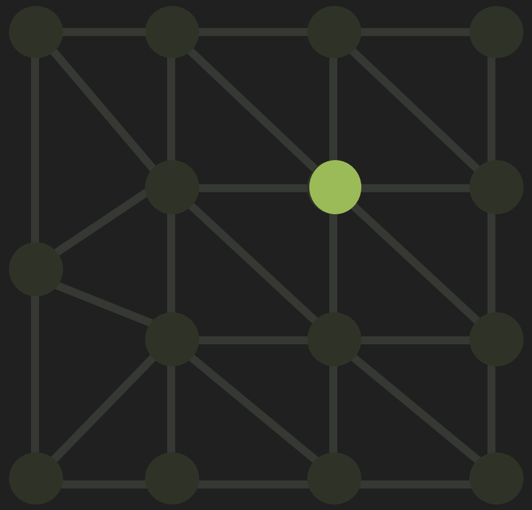
Evaluate sub-face using its control points



base subdivision face

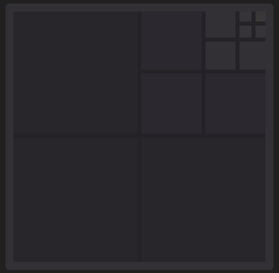


B-spline control points



tessellated primitive

Two key ideas



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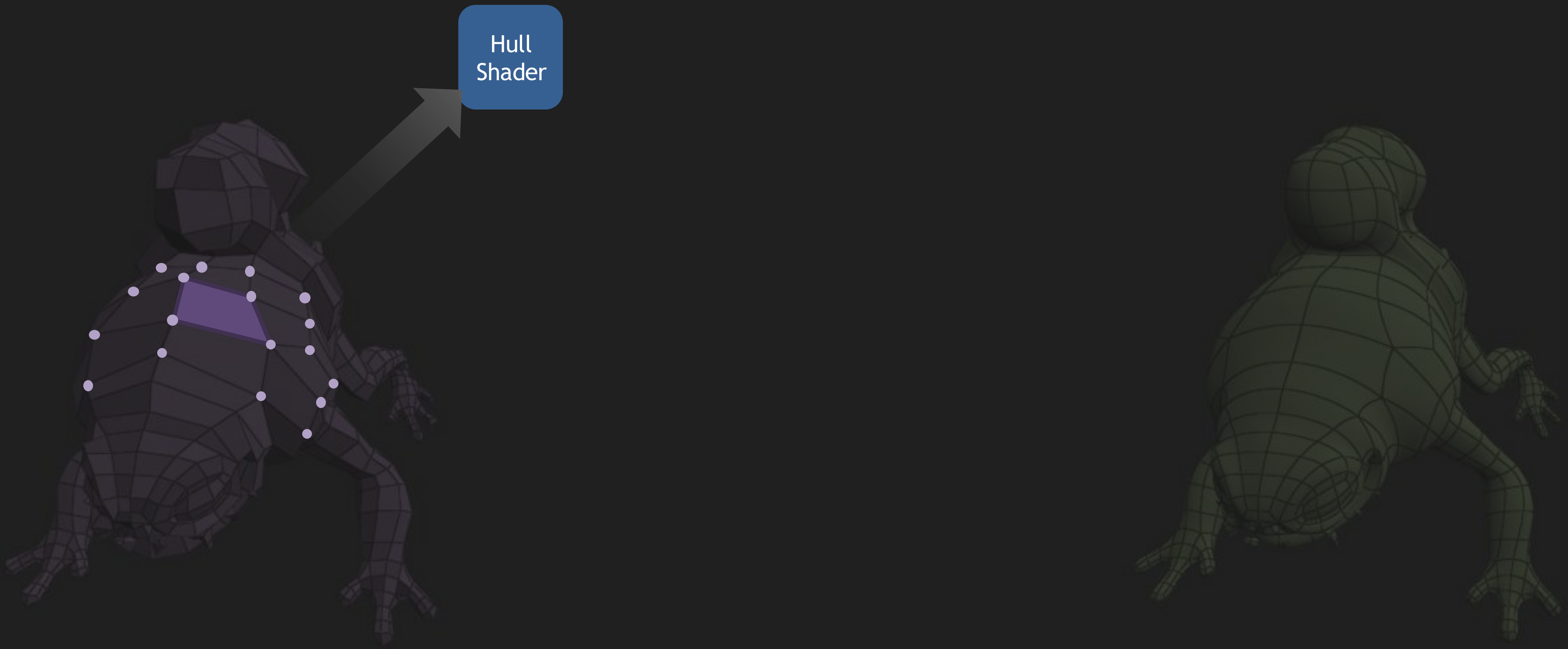
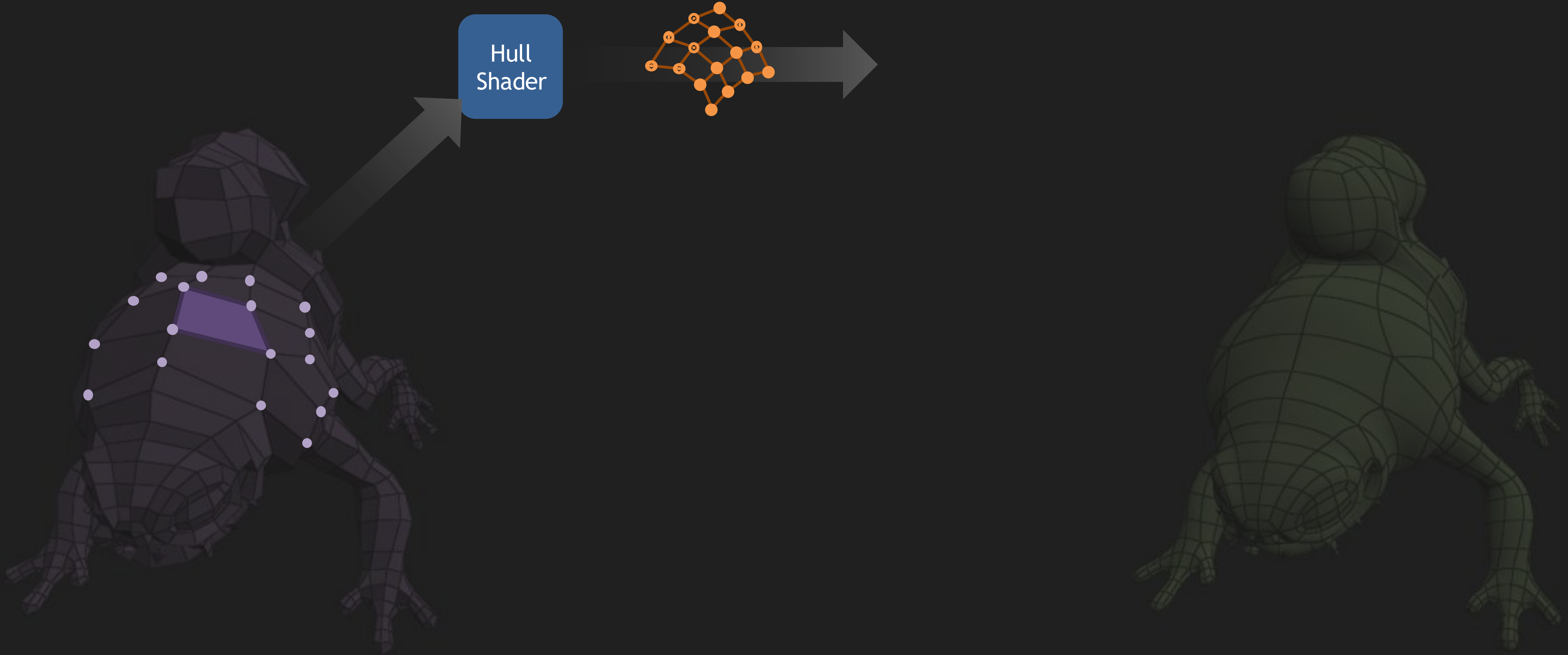
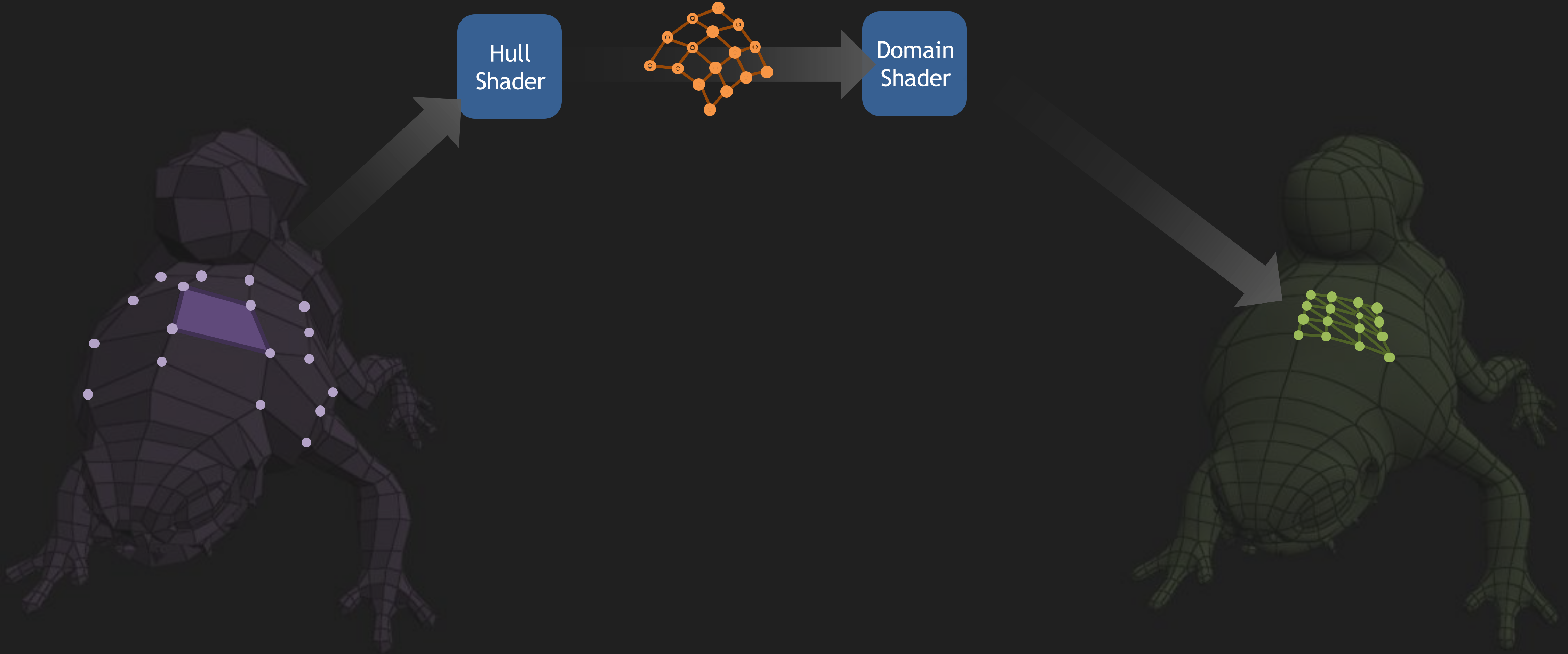
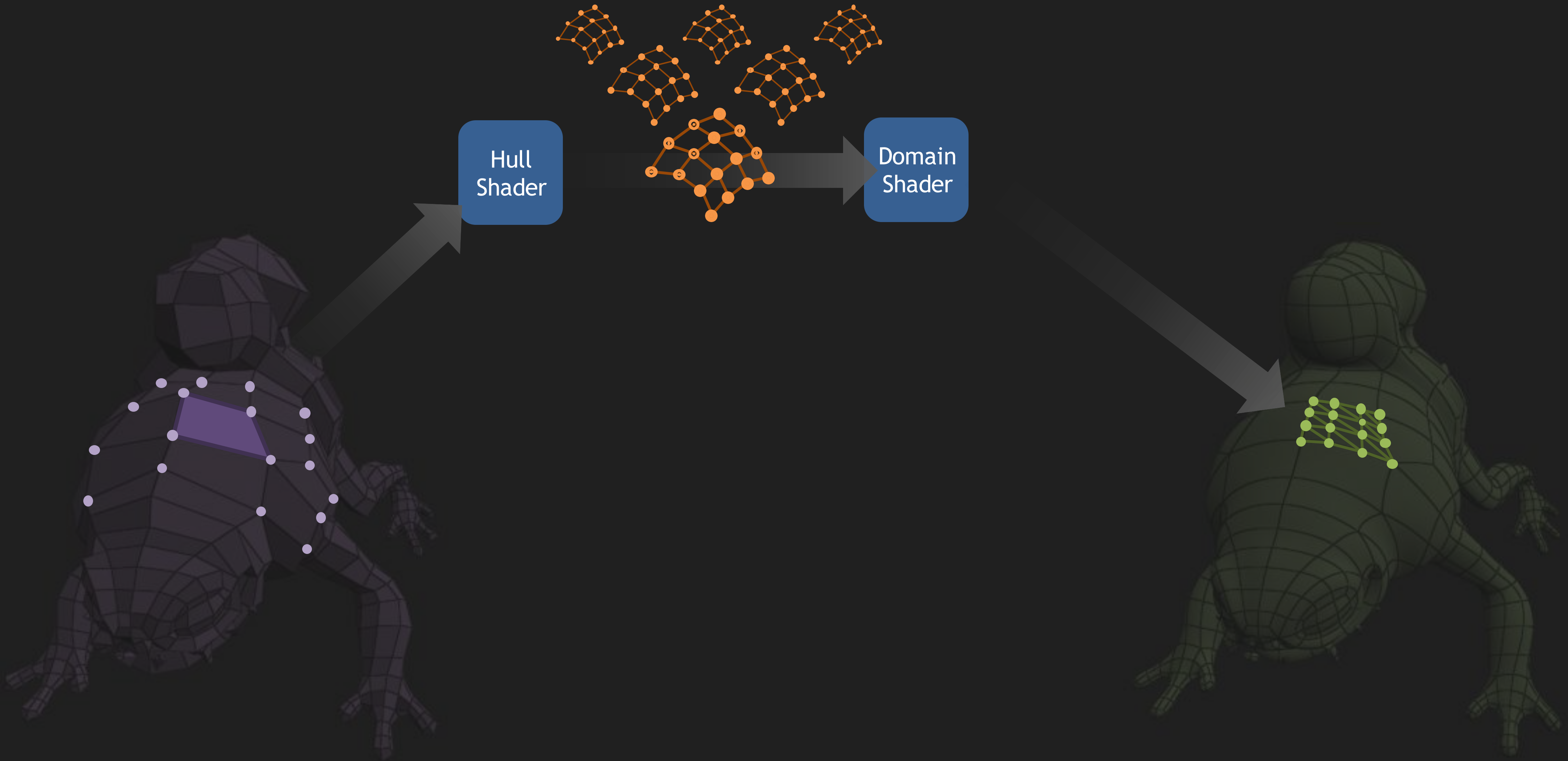
Output a variable # of control points from a Hull Shader

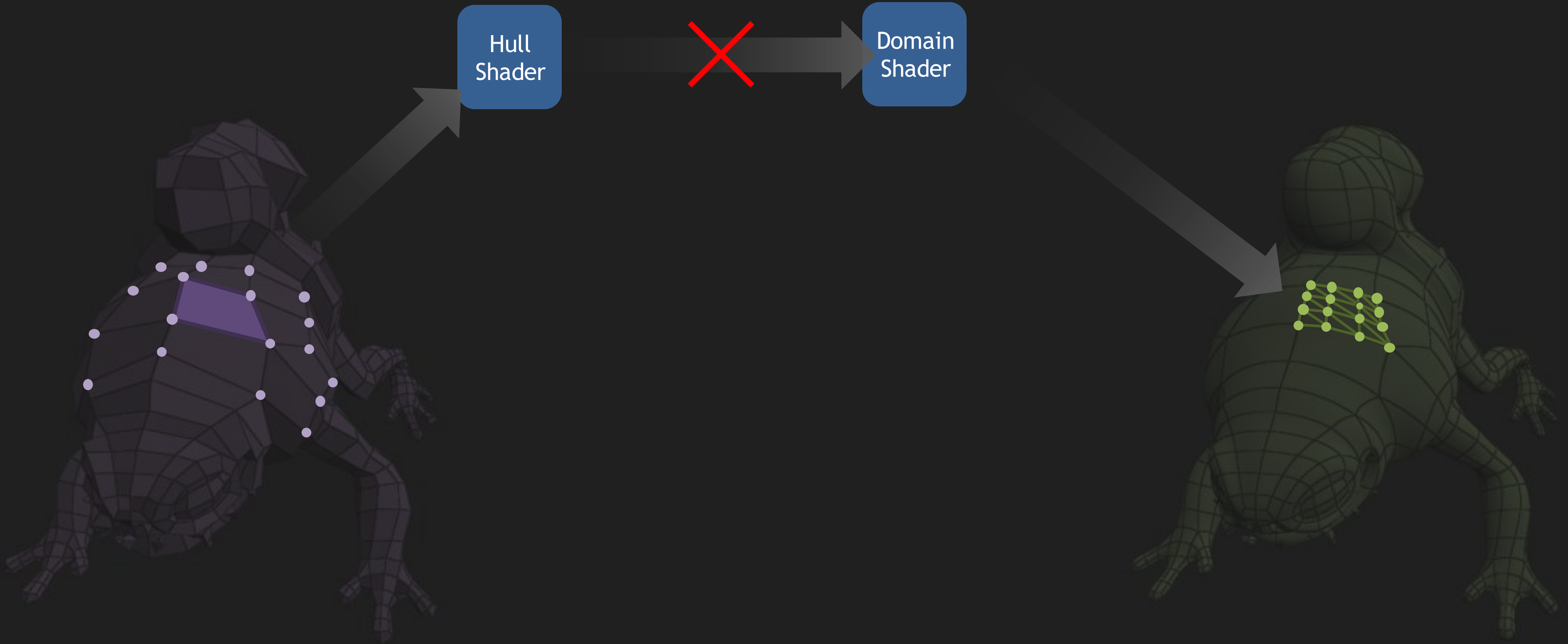


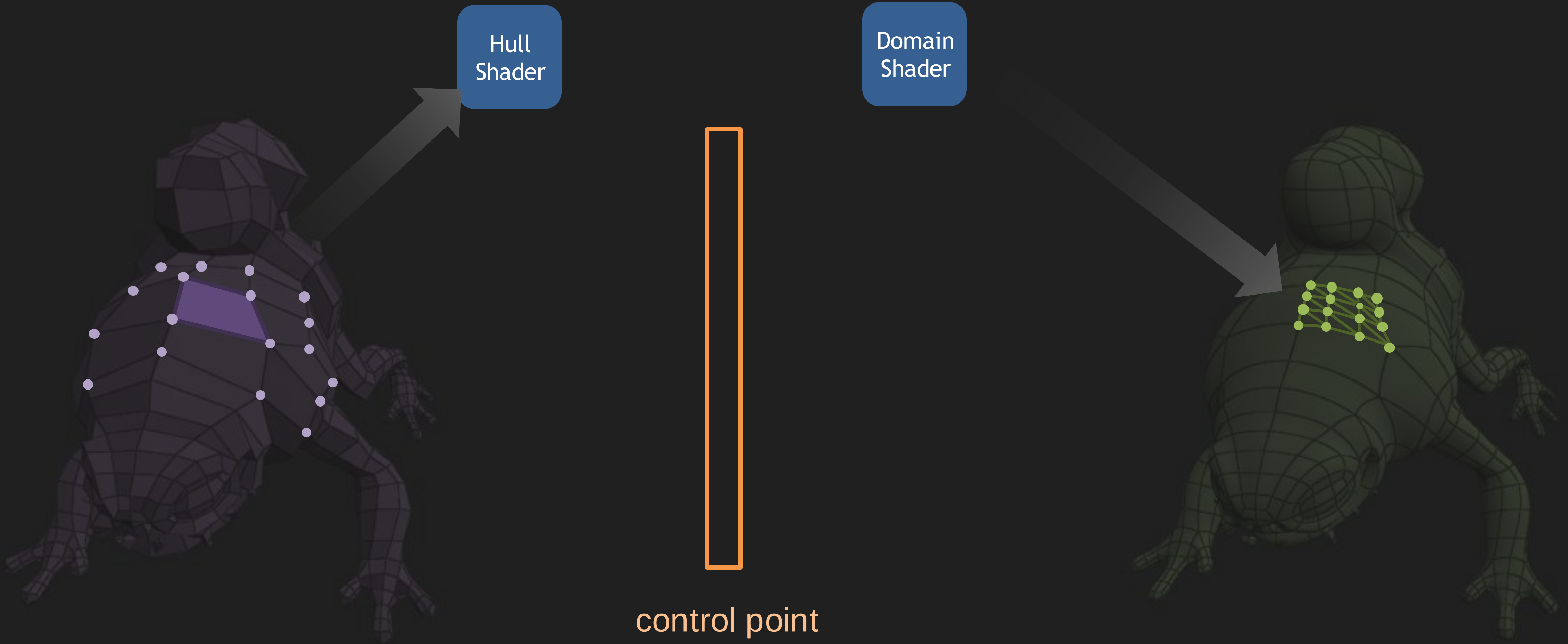
Hull Shader

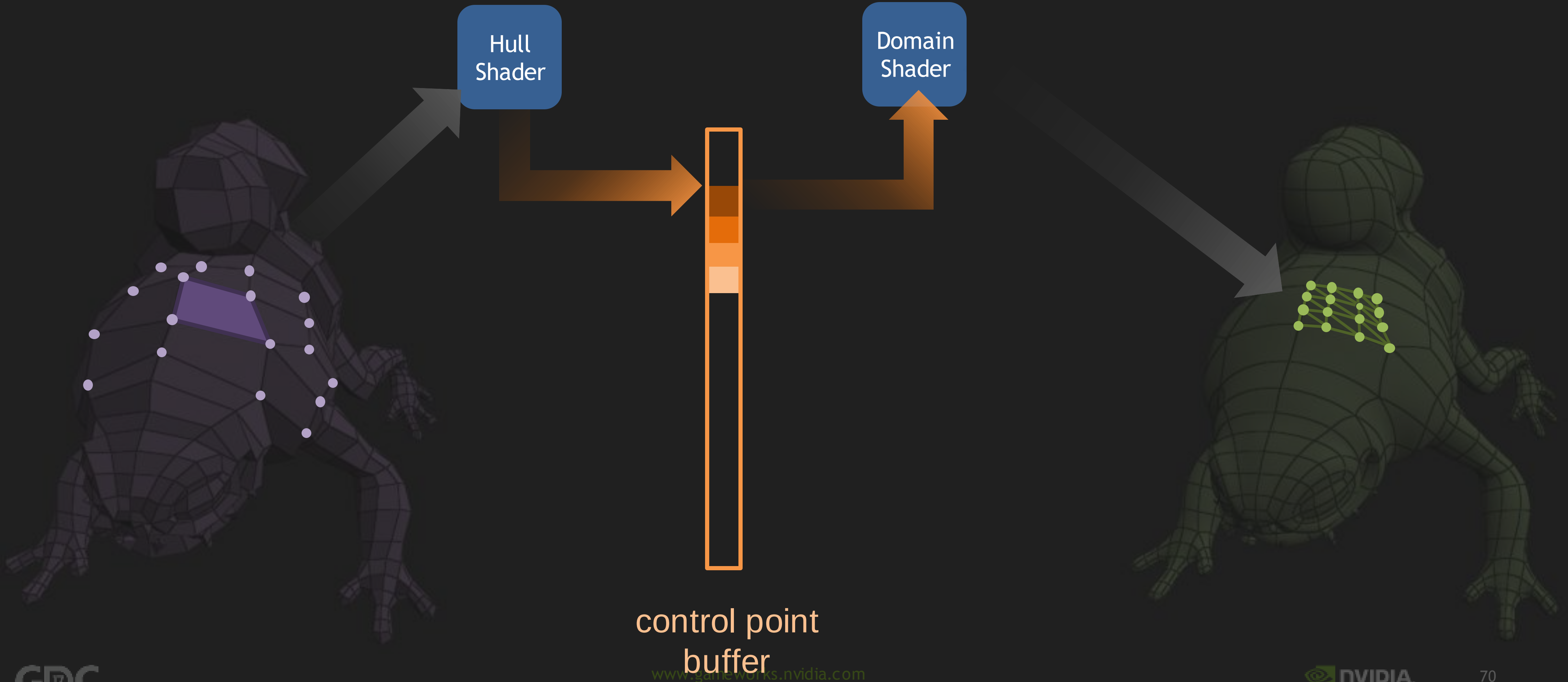

Hull
Shader

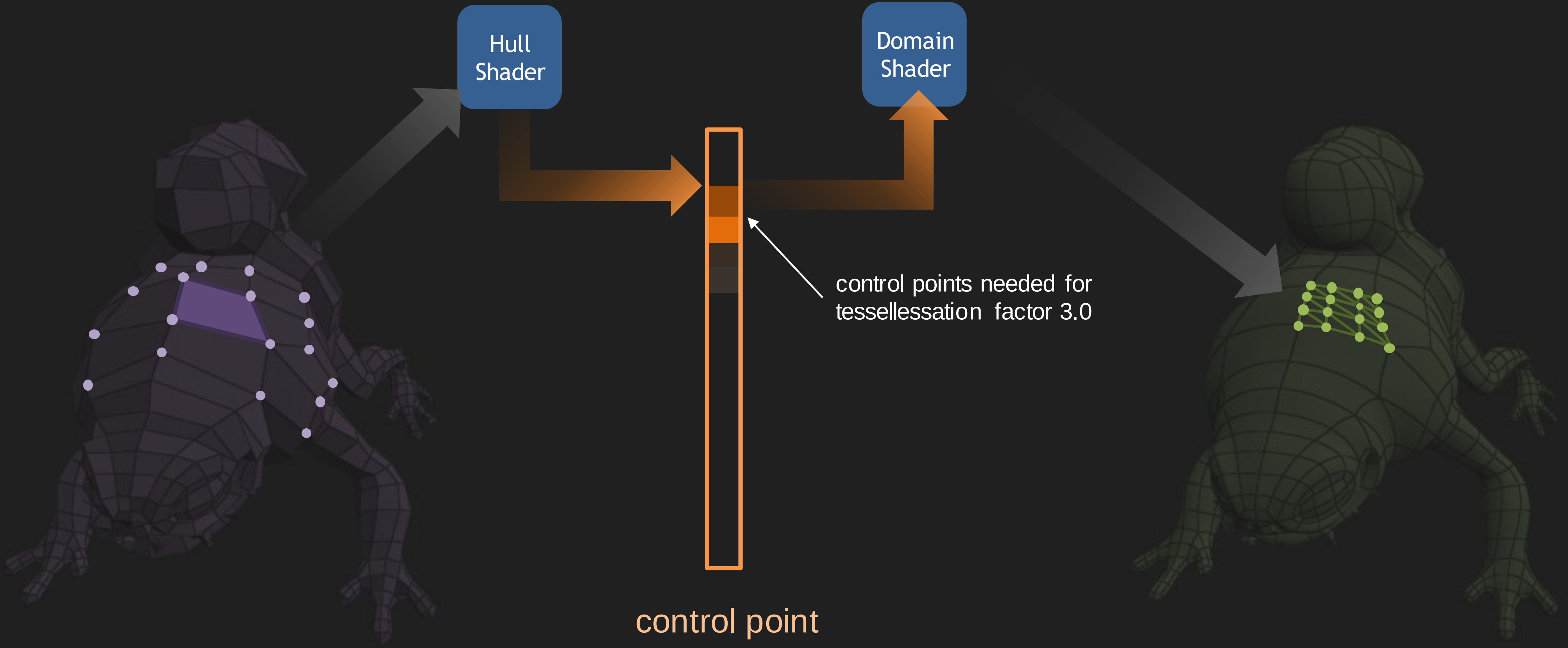

Hull Shader
Domain Shader


Hull Shader
Domain Shader

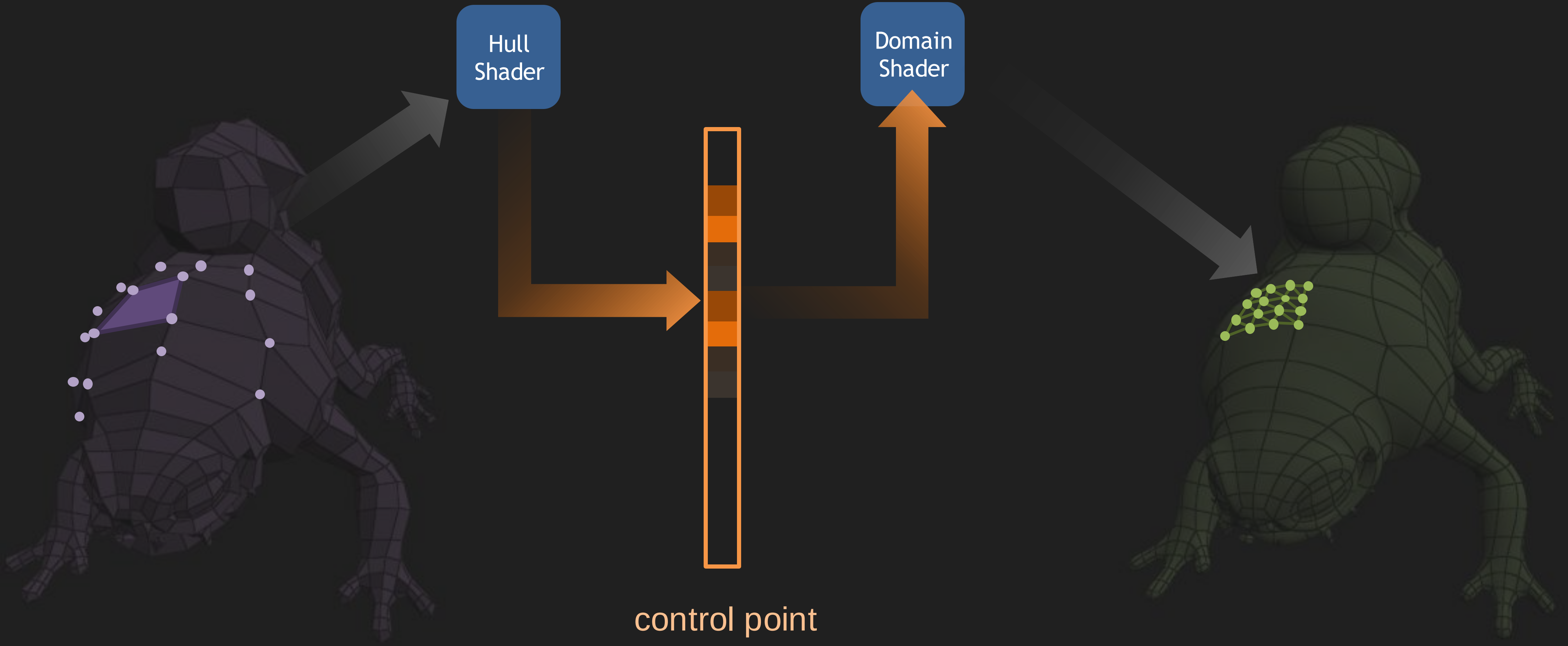

Hull Shader
Domain Shader


Hull Shader
Domain Shader
control point buffer


Hull
Shader
Domain
Shader
control point
buffer



Hull Shader
Domain Shader
control points needed for tessellessation factor 3.0
control point buffer


Hull
Shader
Domain
Shader
control point
buffer

More details in paper

- Collapsing repeated structure in quadtrees
  - Most faces need only one tree traversal step!
- Sorting control point stencils for efficient evaluation
  - Minimize number of control points needed for given tessellation factors
  - Arrange control points for efficient SIMD computation

Outline

- Background
  - Subdivision surfaces
  - GPU tessellation hardware
- Prior work
- Overview of our approach
- Performance evaluation
- Conclusion

Big Guy

Monster Frog

Armor Guy

Sterling

Big Guy

Monster Frog

Armor Guy

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Sterling

(© Disney/Pixar)

low complexity
no crease tags

higher complexity
semi-sharp crease tags

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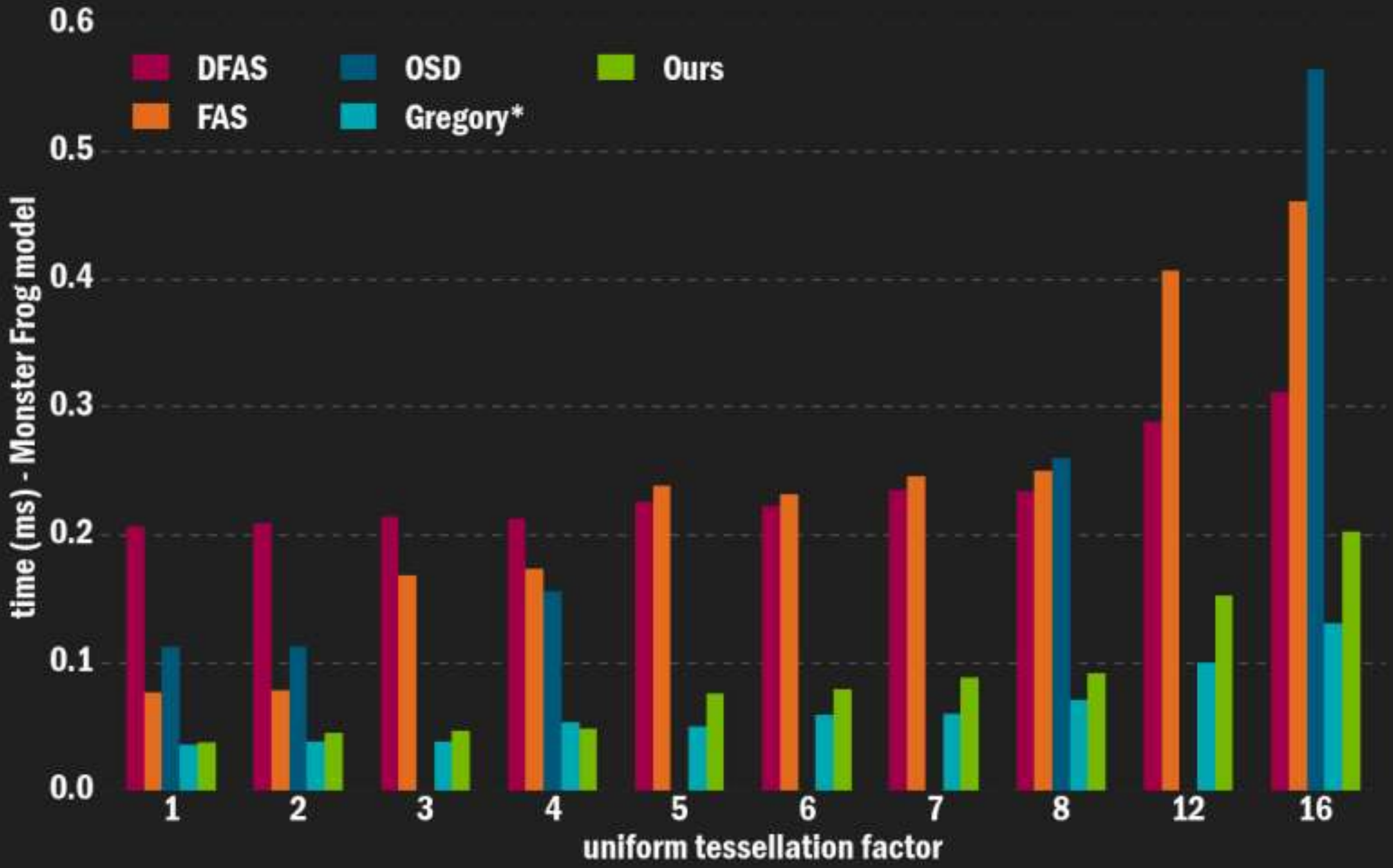
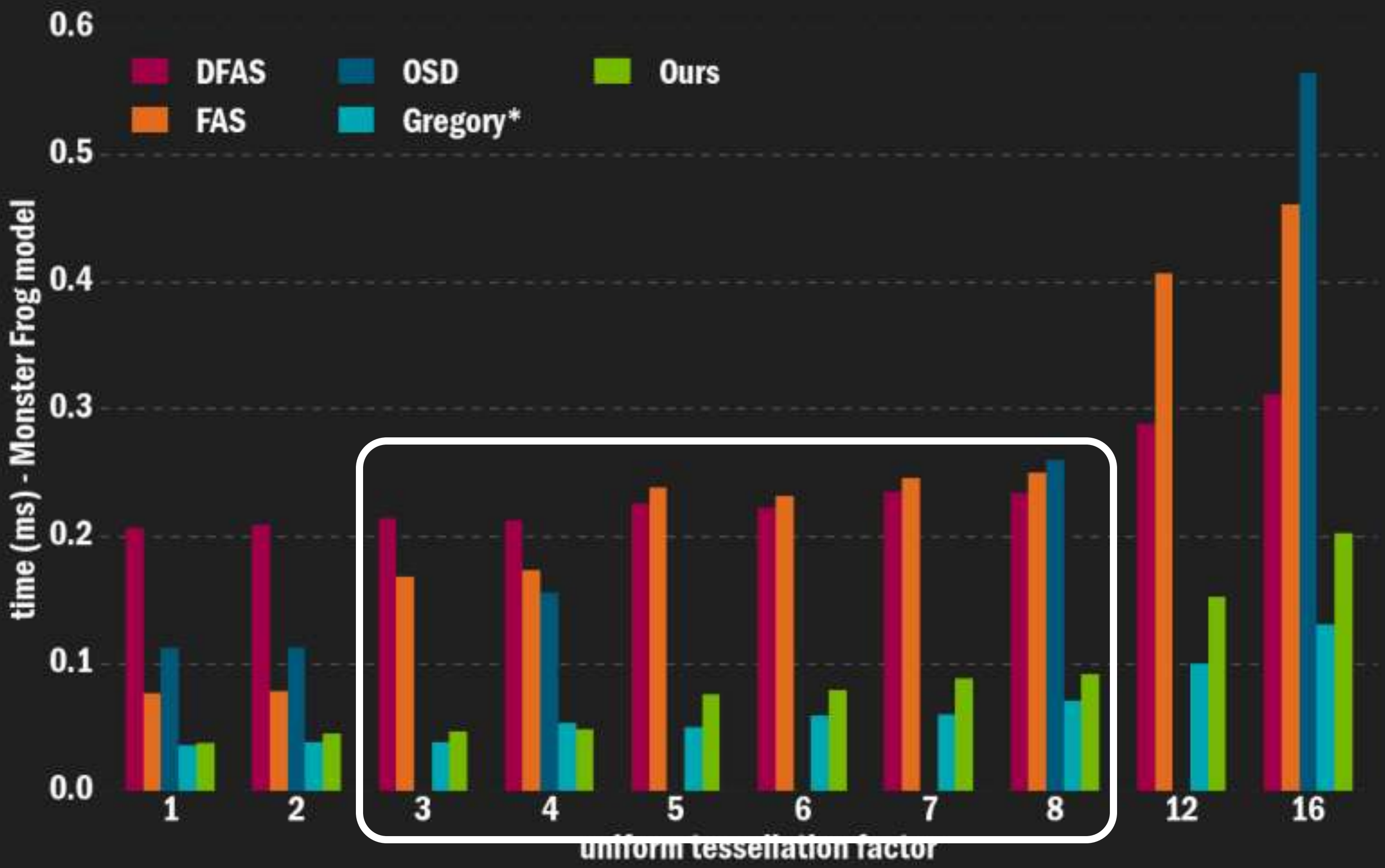
Up to 3x faster than Adaptive Subdivision



*non-exact

Up to 3x faster than Adaptive Subdivision



*non-exact

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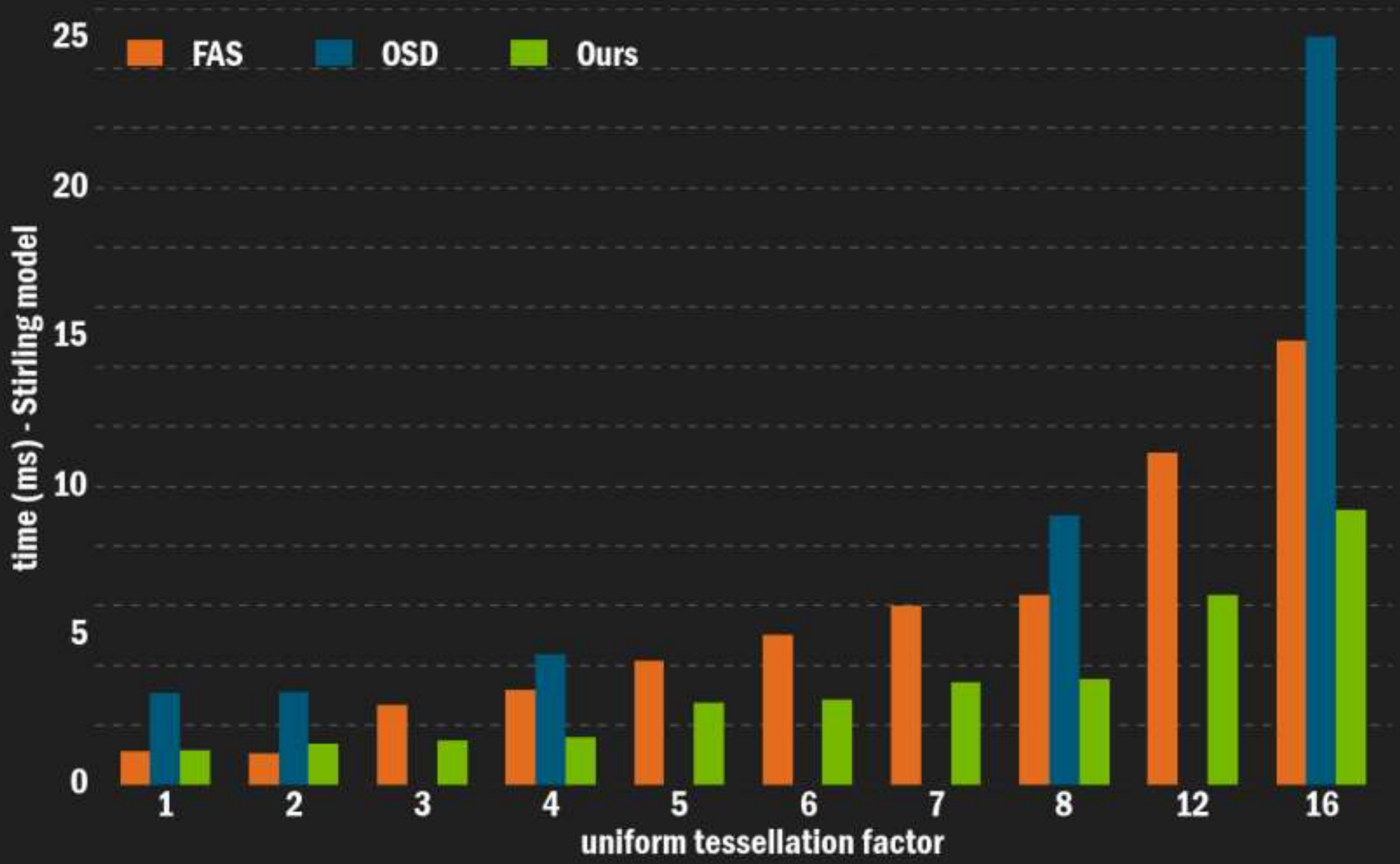
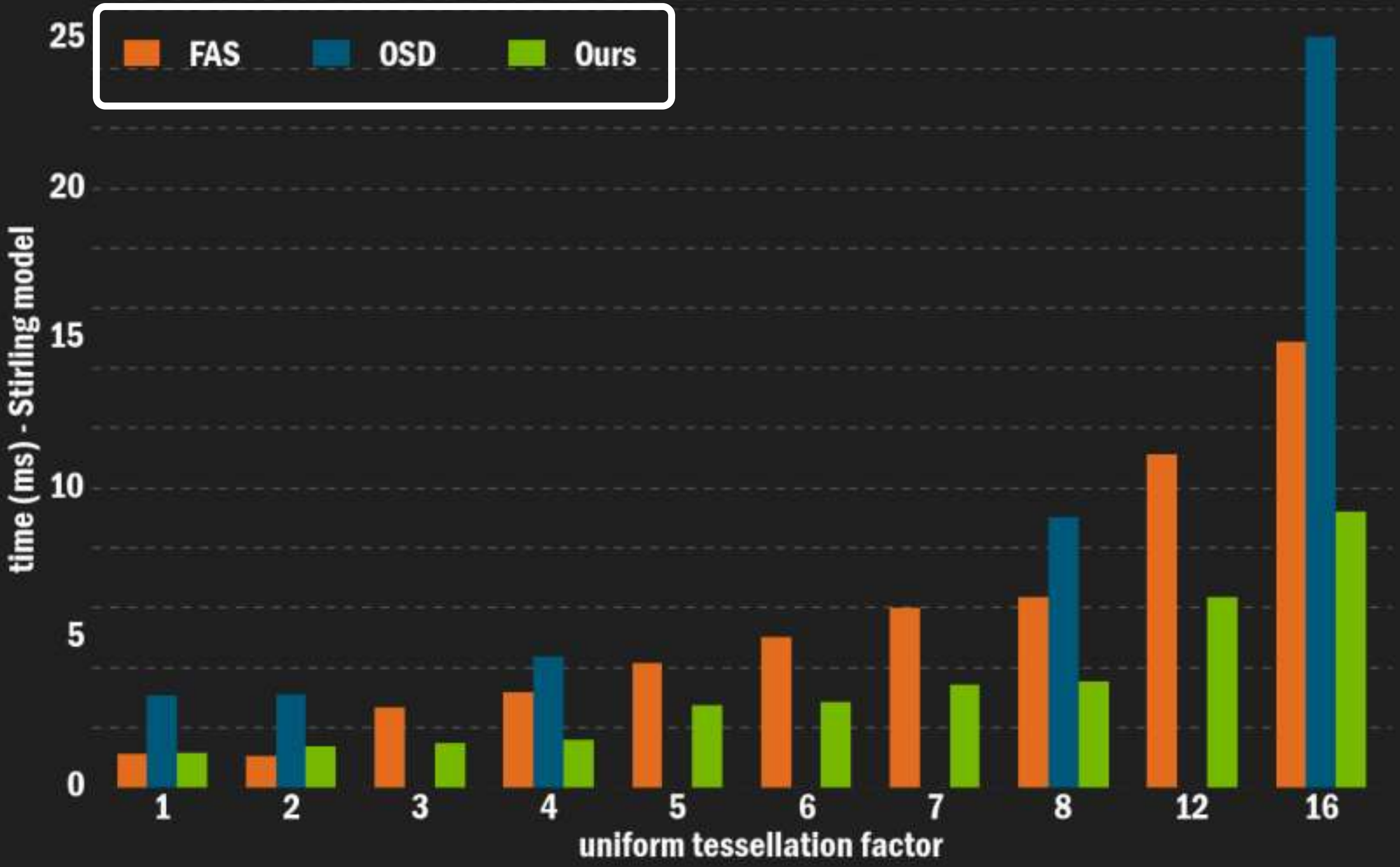
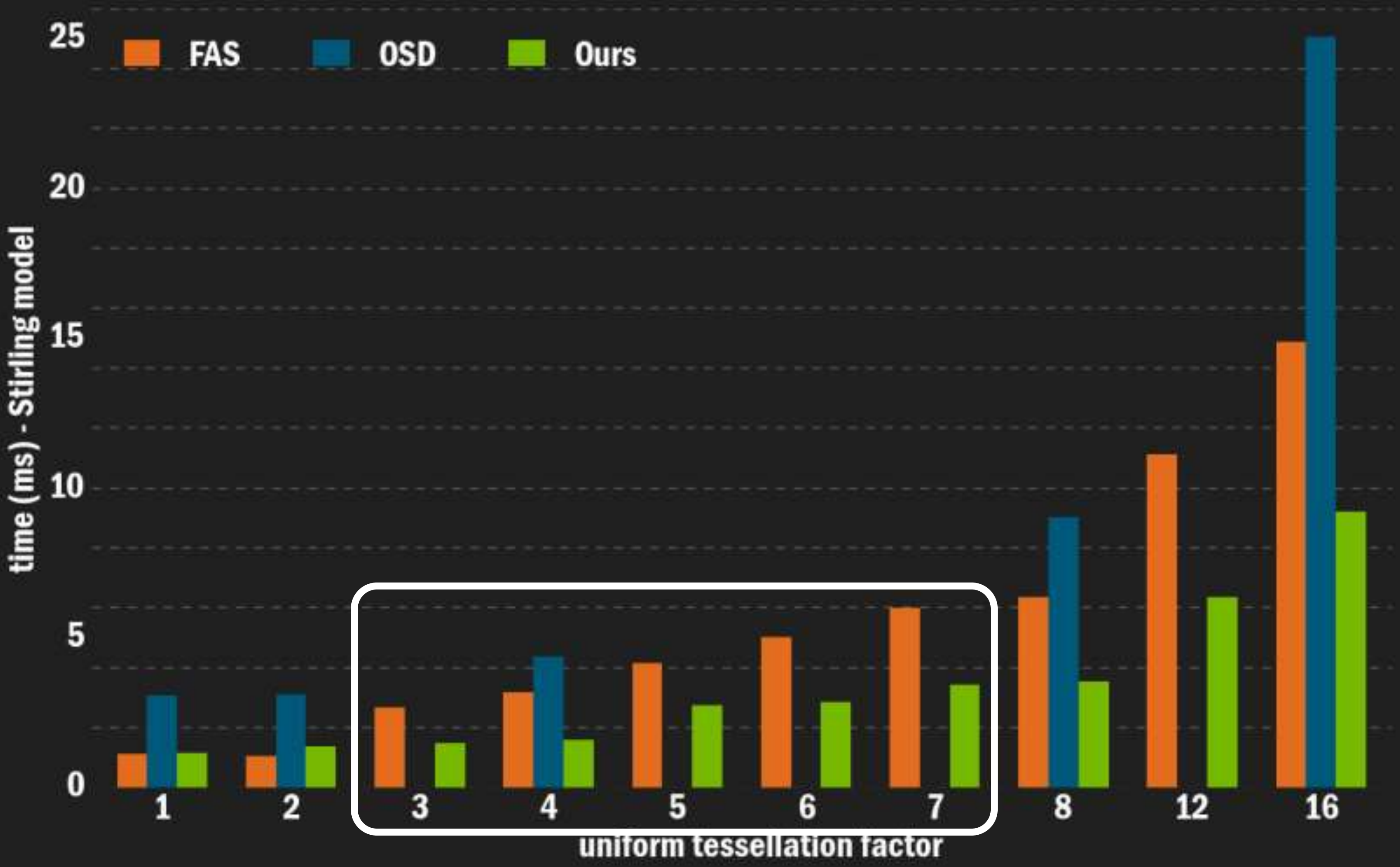
Benefit decreases as fraction of regular faces increases



Only some methods can handle semi-sharp creases



Benefit decreases as fraction of regular faces increases



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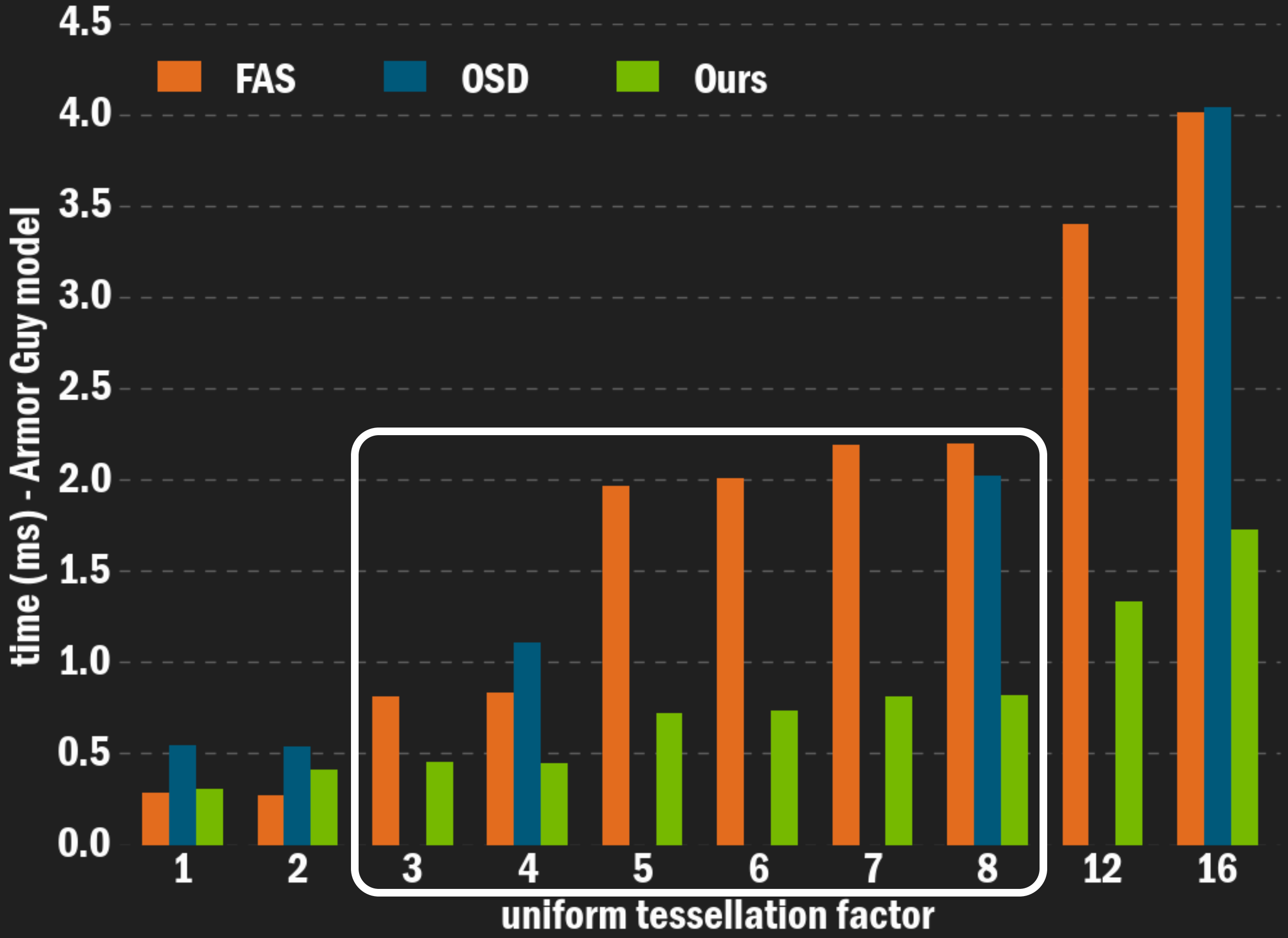
low complexity
no crease tags

higher complexity
semi-sharp crease tags

Armor Guy has a greater fraction of irregular faces



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Conclusion

- A simpler and faster way to render subdivision surfaces
  - Up to 3x faster than state-of-the-art methods
  - Single draw pass
  - Can use existing shaders for animation

- Integration in open-source OpenSubdiv library is in progress
- Interested engine developers should contact NVIDIA

Thank You