Pacific Graphics 2021

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

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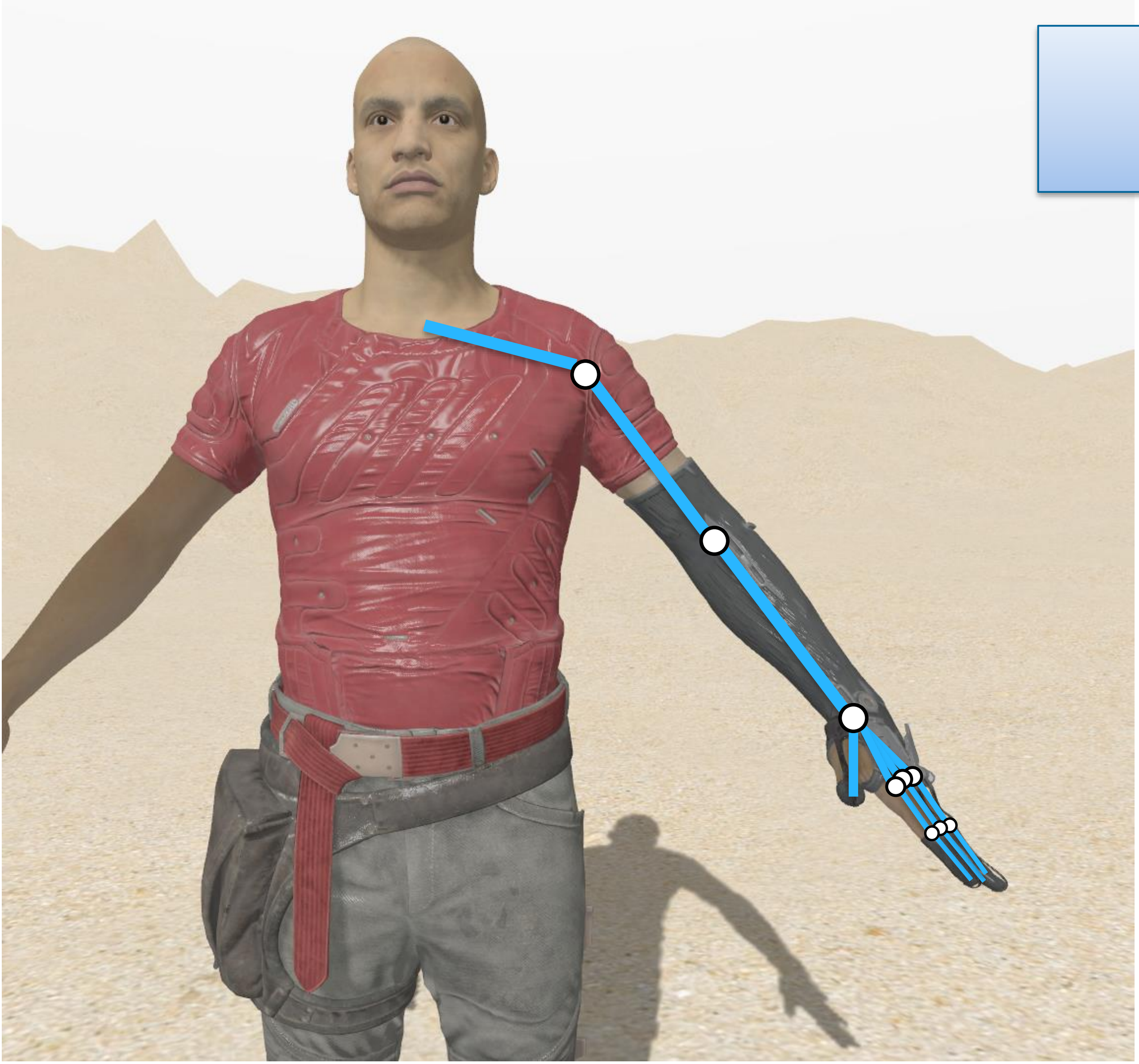
Clusters!

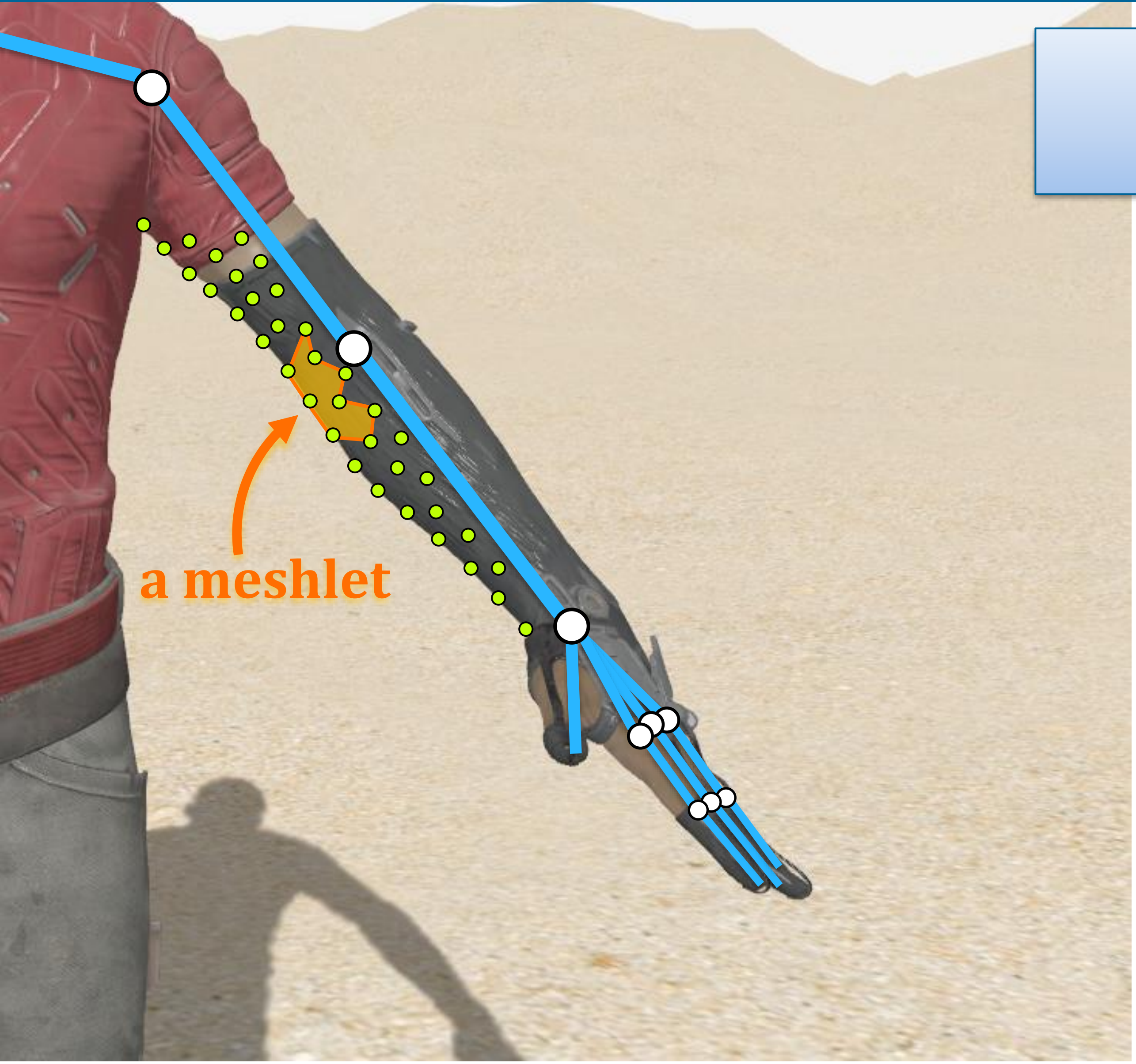
Skinned Meshes



Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

- Skinned, animated models
- Underlying skeleton
  - Bone hierarchy
  - Hierarchical transformation

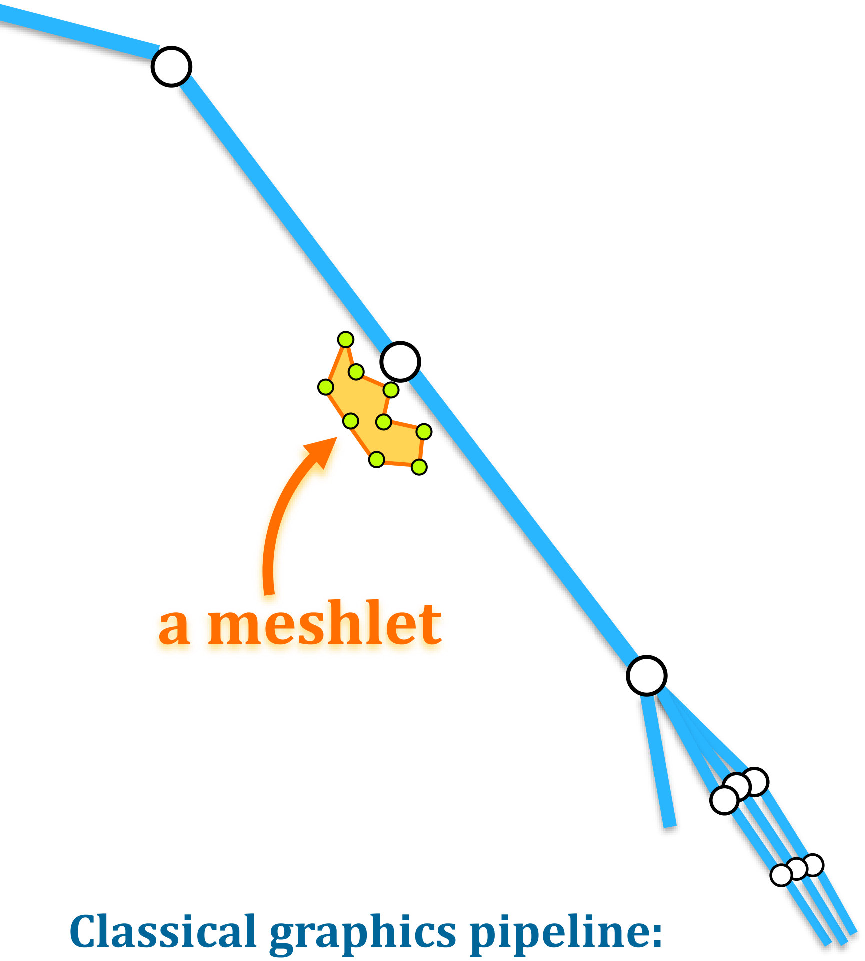
Skinned Mesh…lets



Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

- Skinned, animated models
- Underlying skeleton
  - Bone hierarchy
  - Hierarchical transformation
- Vertices (the skin)
  - Assigned to one or multiple bones
  - Transformed by bones (weighted)

Meshlets!



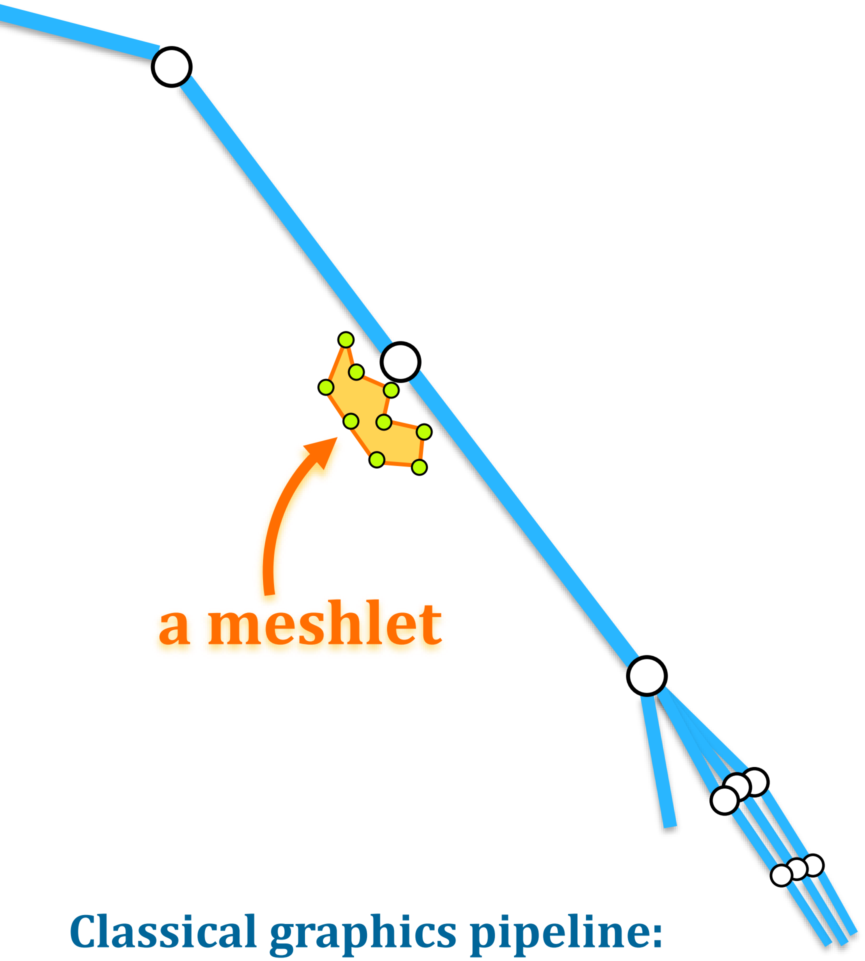
Conservative **Meshlet** Bounds for Robust Culling of Skinned Meshes

- Meshlets
  - Small clusters of geometry
  - E.g., small patch of indexed geometry
- New shader stages (`task` and `mesh`) for efficient processing
  - *within* rasterization pipelines
  - Using Vulkan with Nvidia extension
    - Max. 64 vertices and 126 triangles

Classical graphics pipeline:

Input Assembly → Vertex Shader → Tess.Ctrl. Shader → Tessellator → Tess.Eval. Shader → Geometry Shader → Rasterizer → Fragment Shader

Meshlets!



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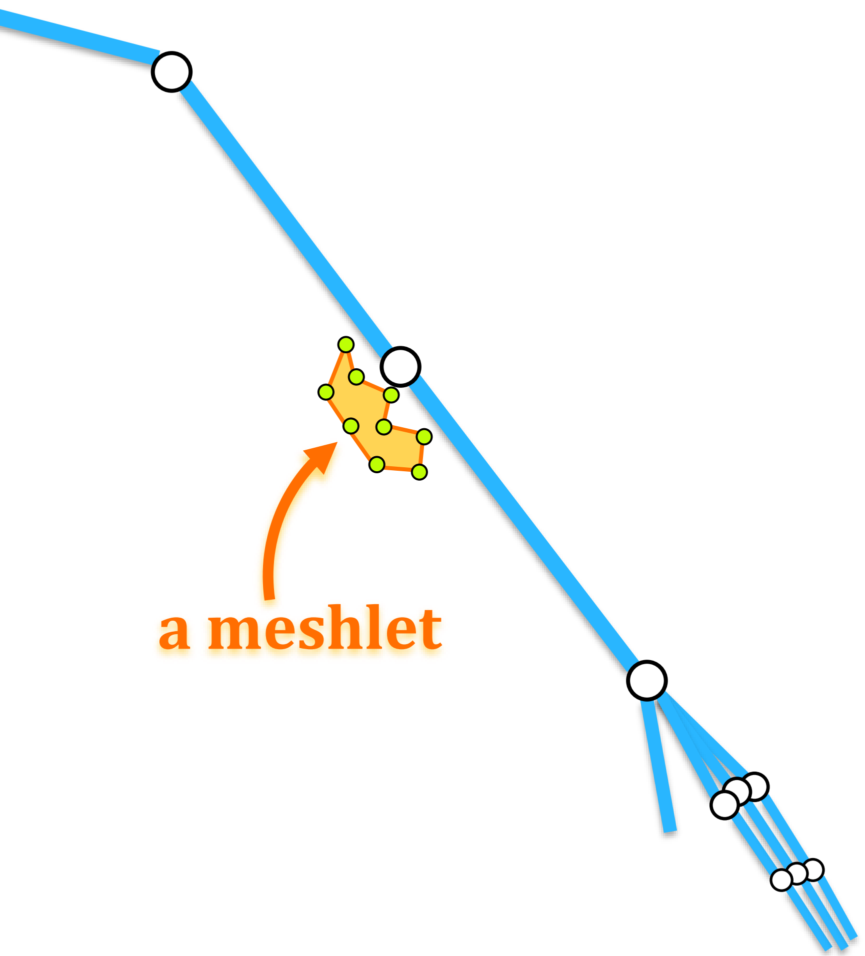
Classical graphics pipeline:

Mesh Shader-Based Graphics Pipeline



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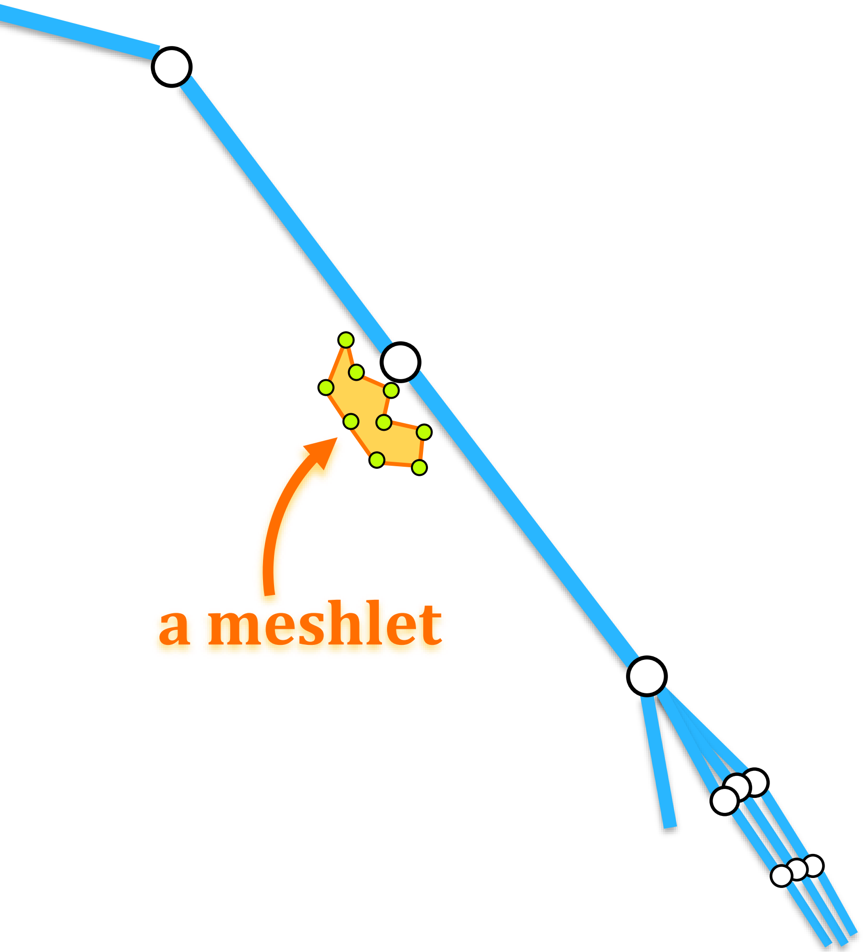
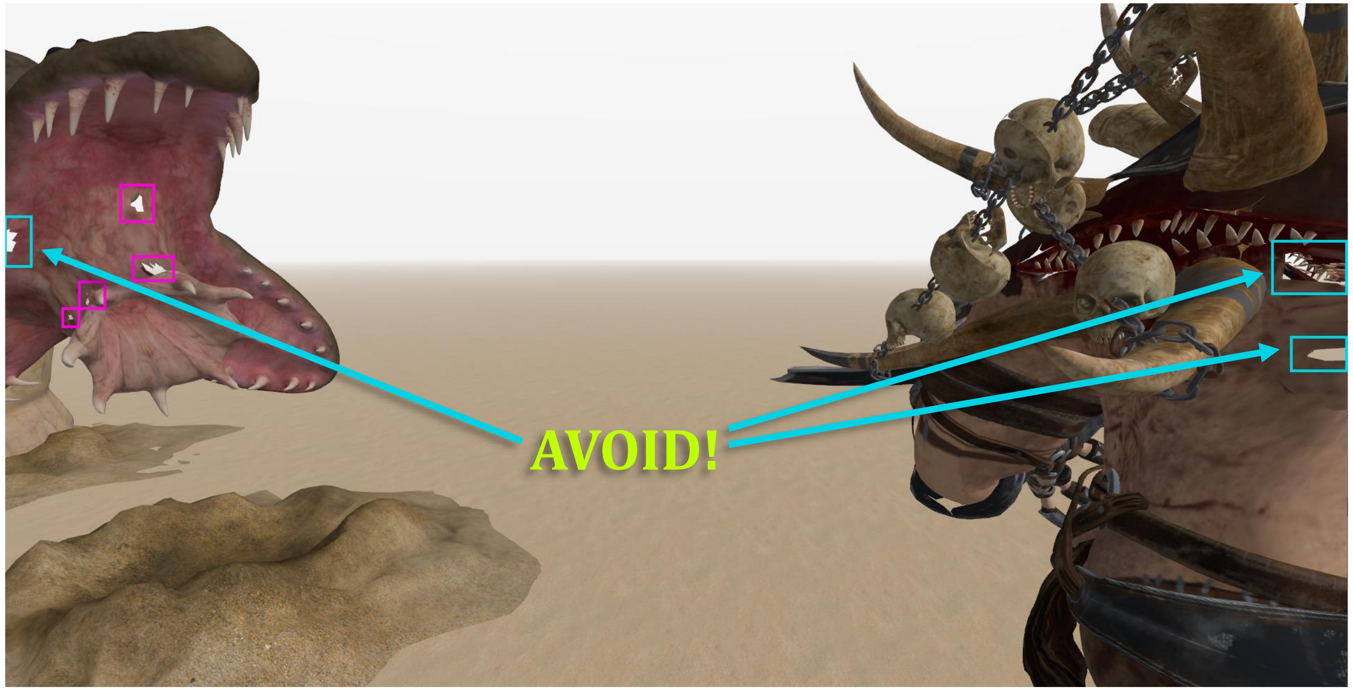
Task and mesh shader pipeline:

- Efficient processing of meshlets
- Culling in `task` shader stage

Rendering Artefacts To Be Avoided





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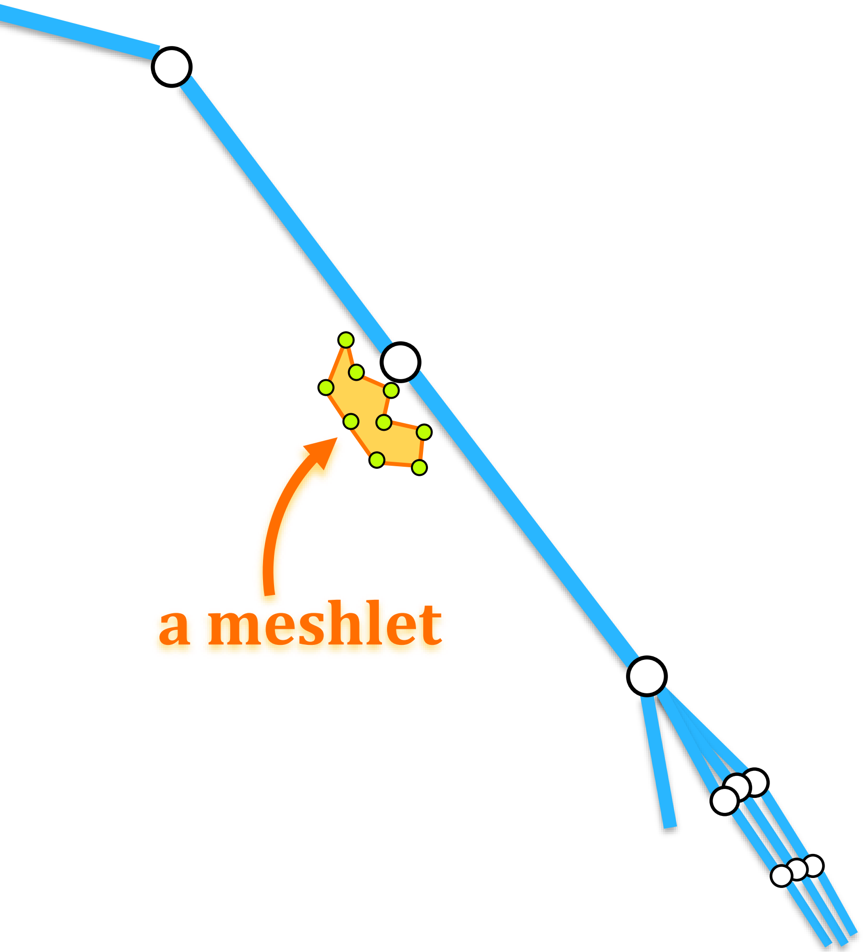

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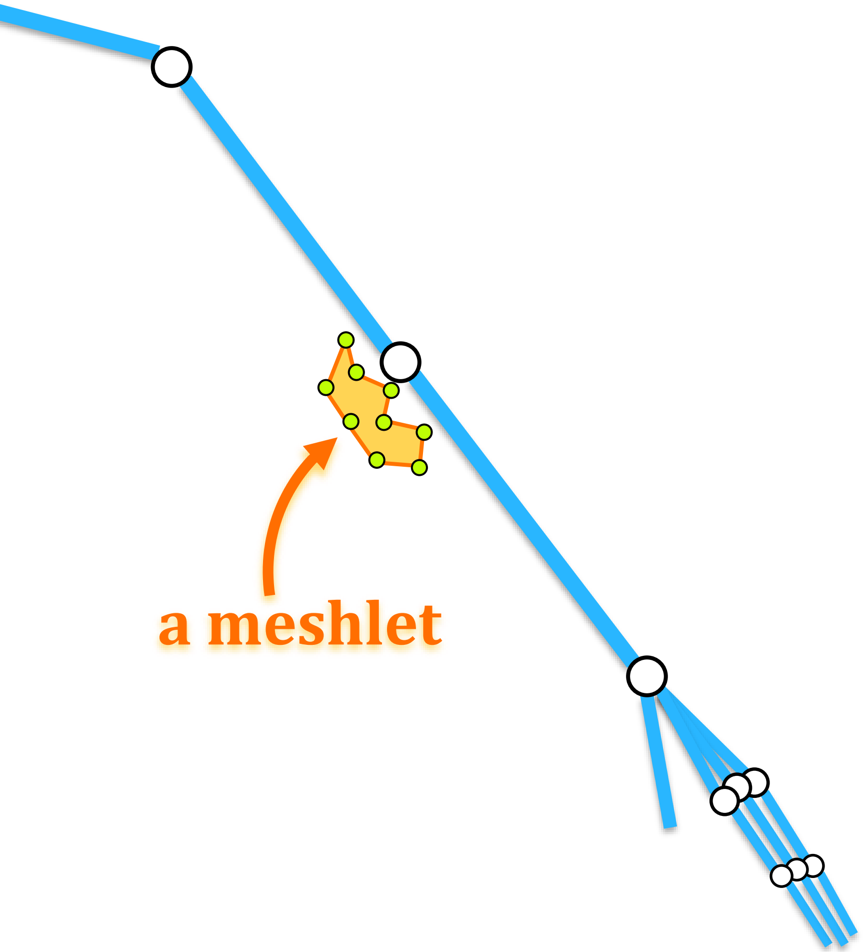

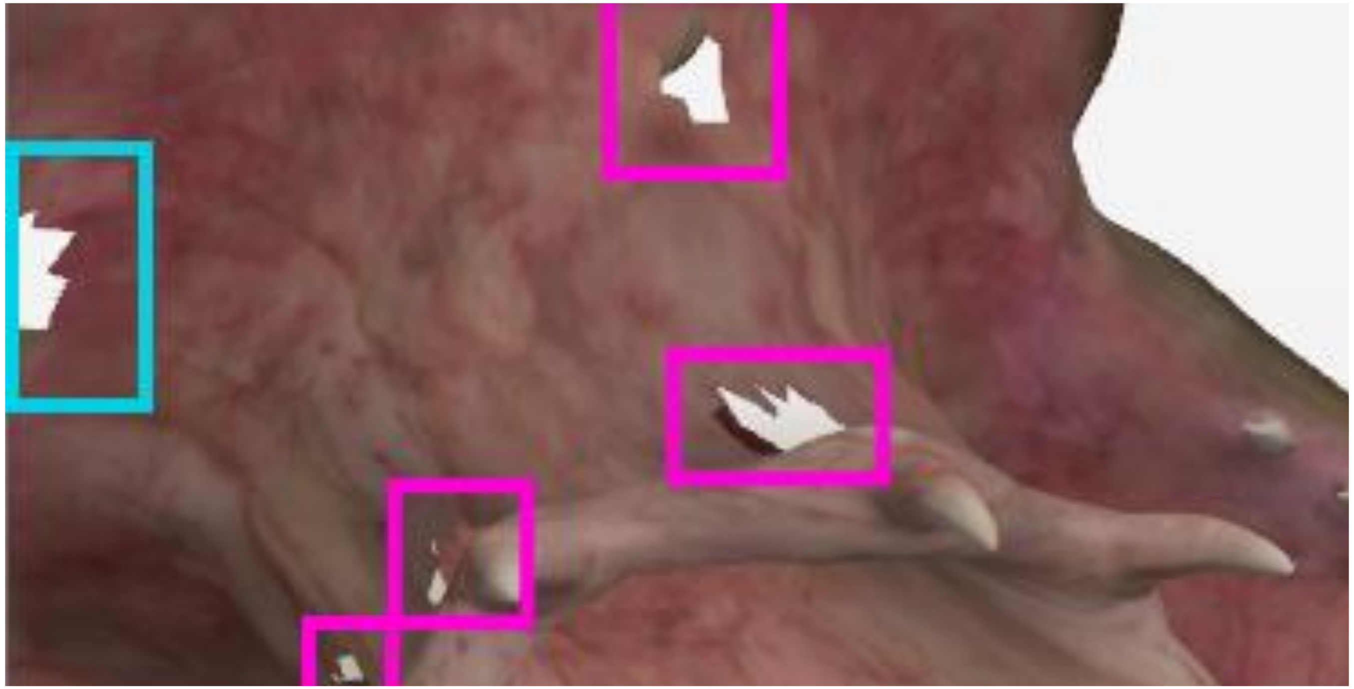

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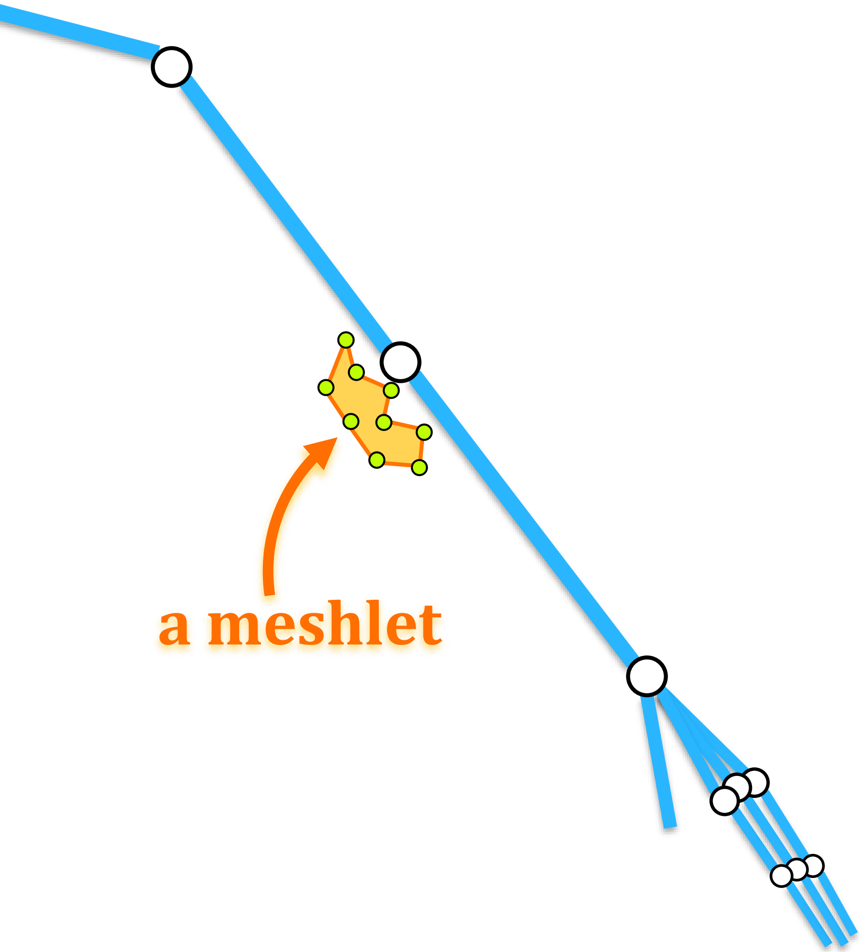

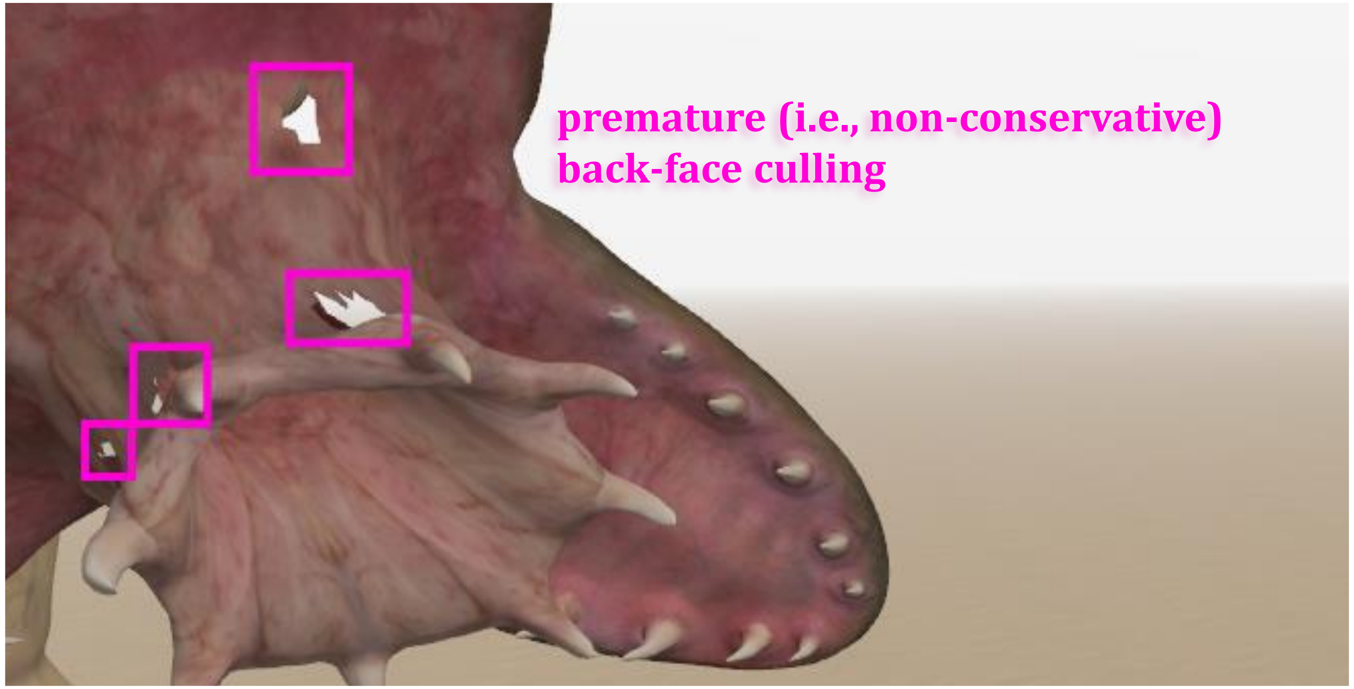

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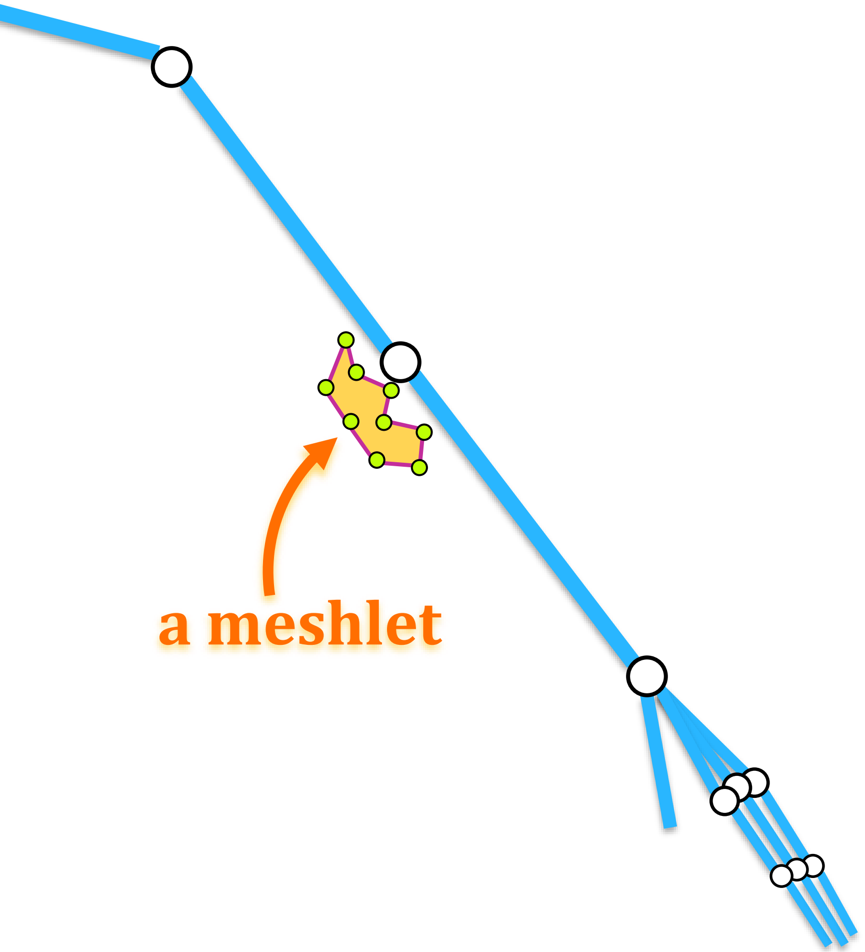
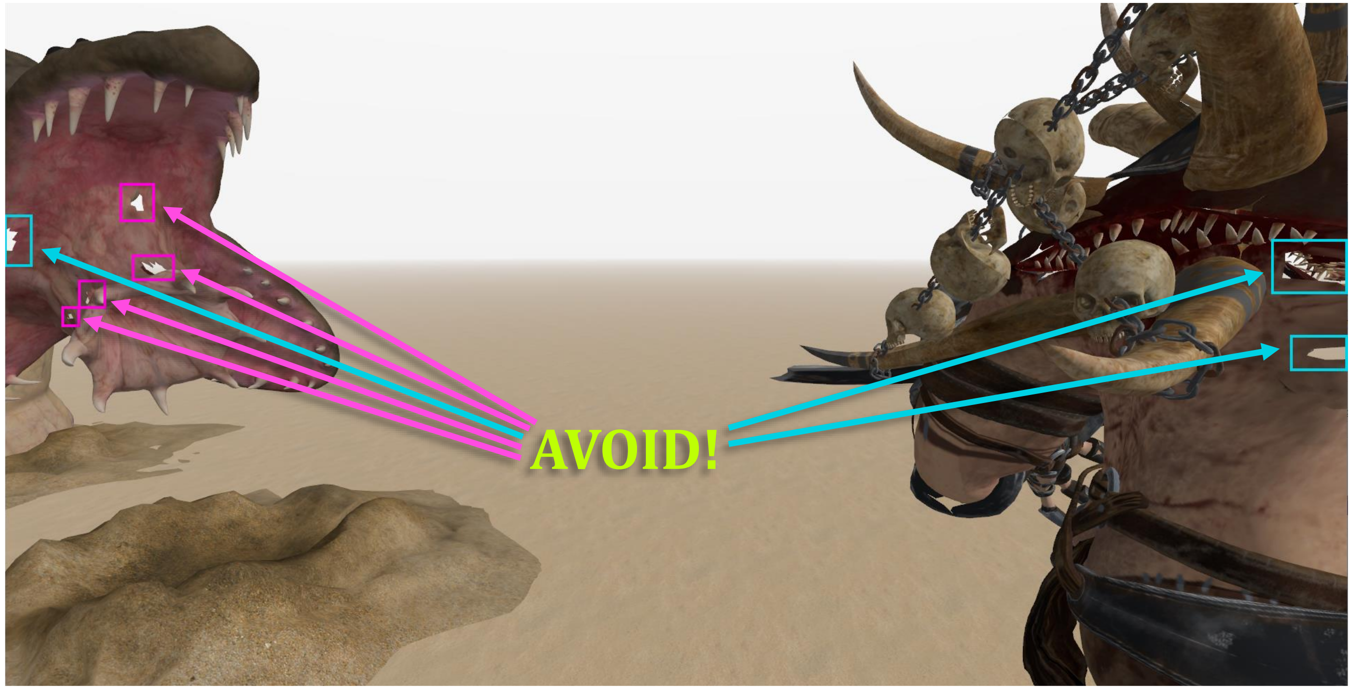


Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes



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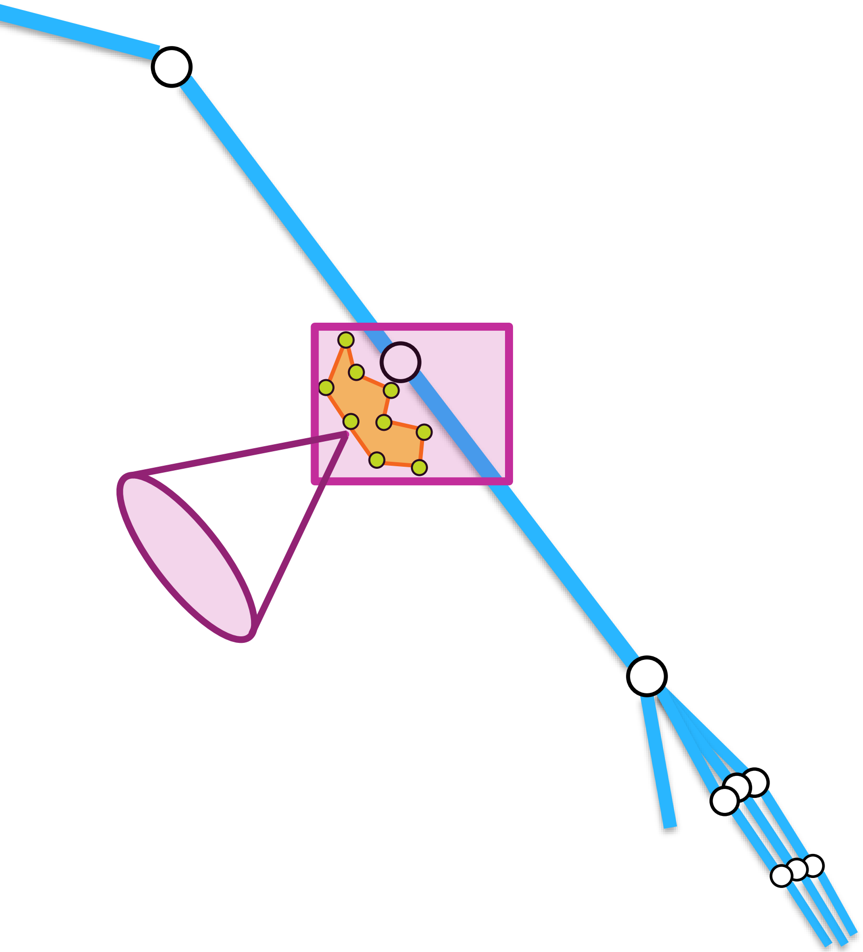

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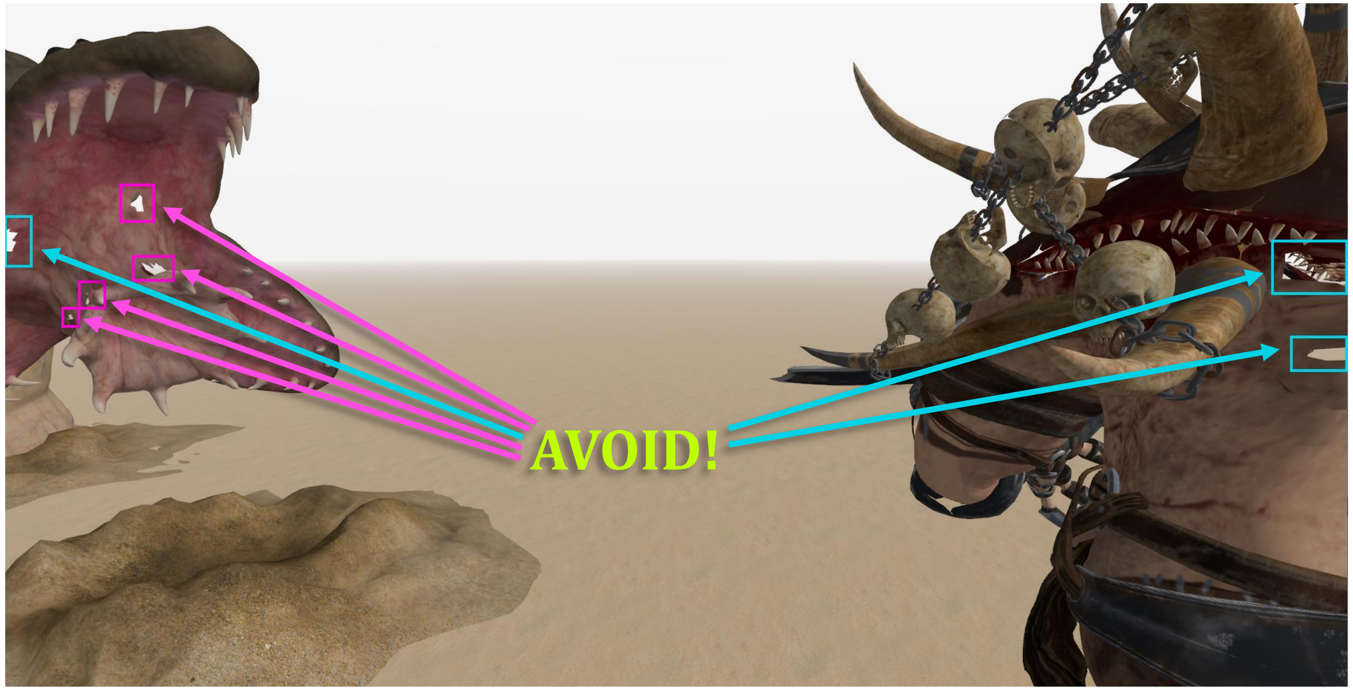
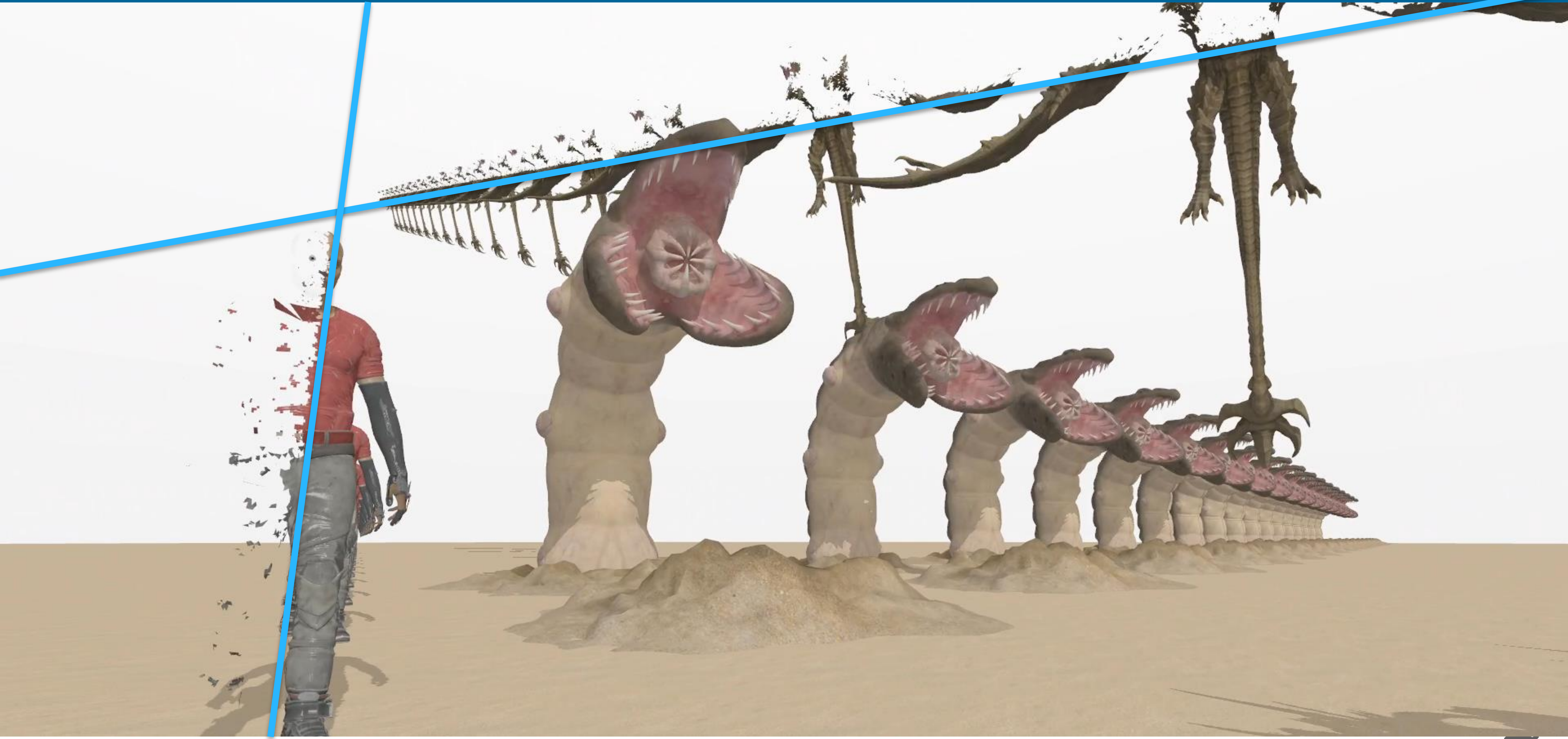


Fine-Grained Culling of Meshlets

Fine-Grained Culling of Meshlets



Rendering Artefacts To Be Avoided

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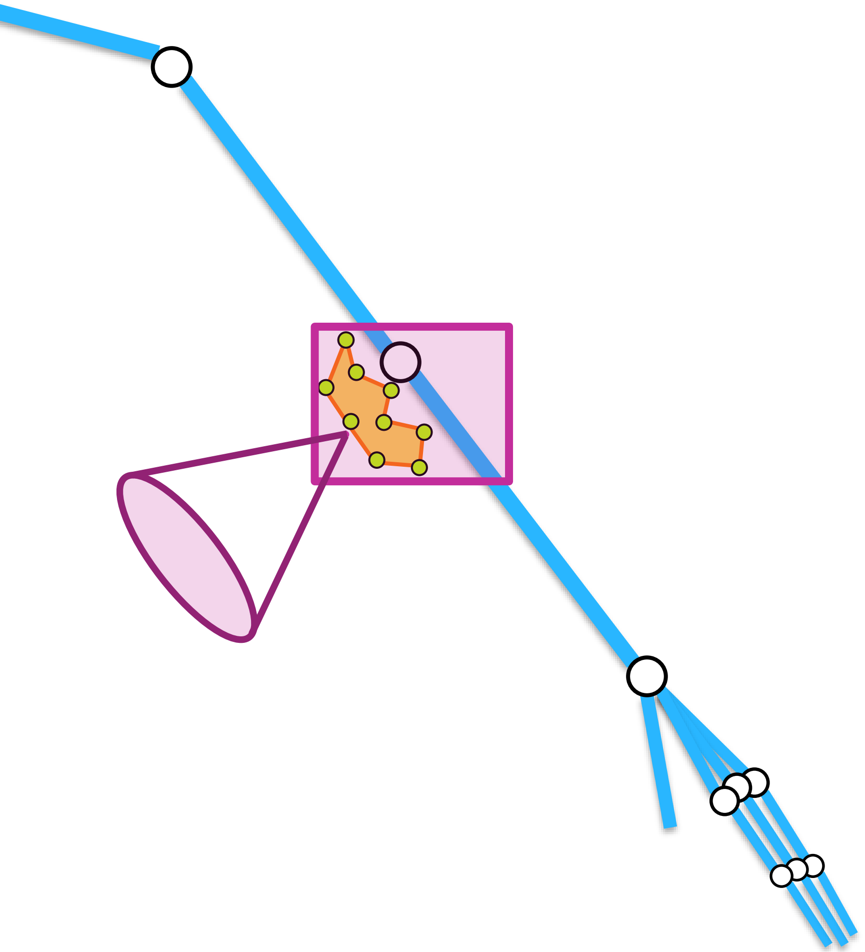
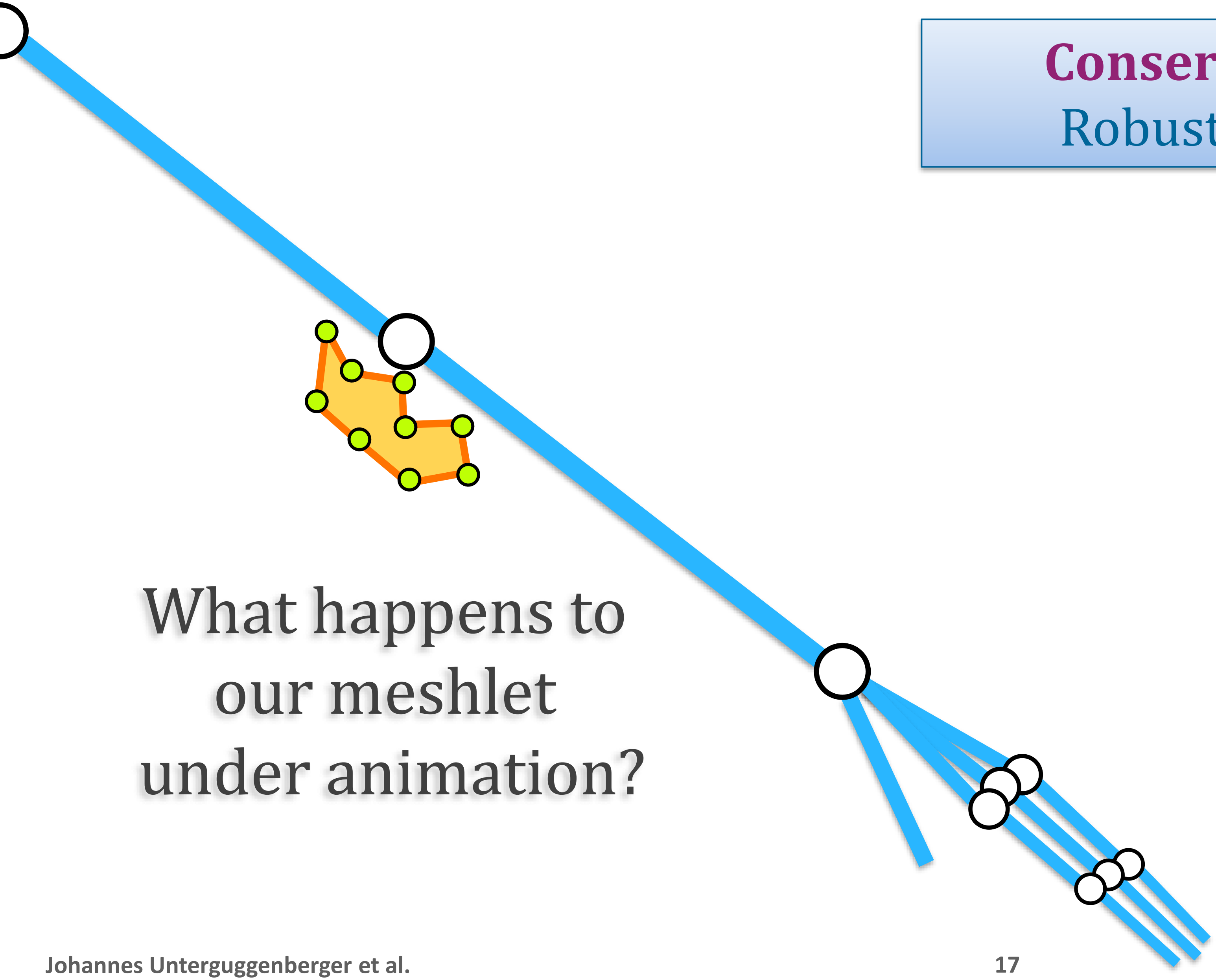
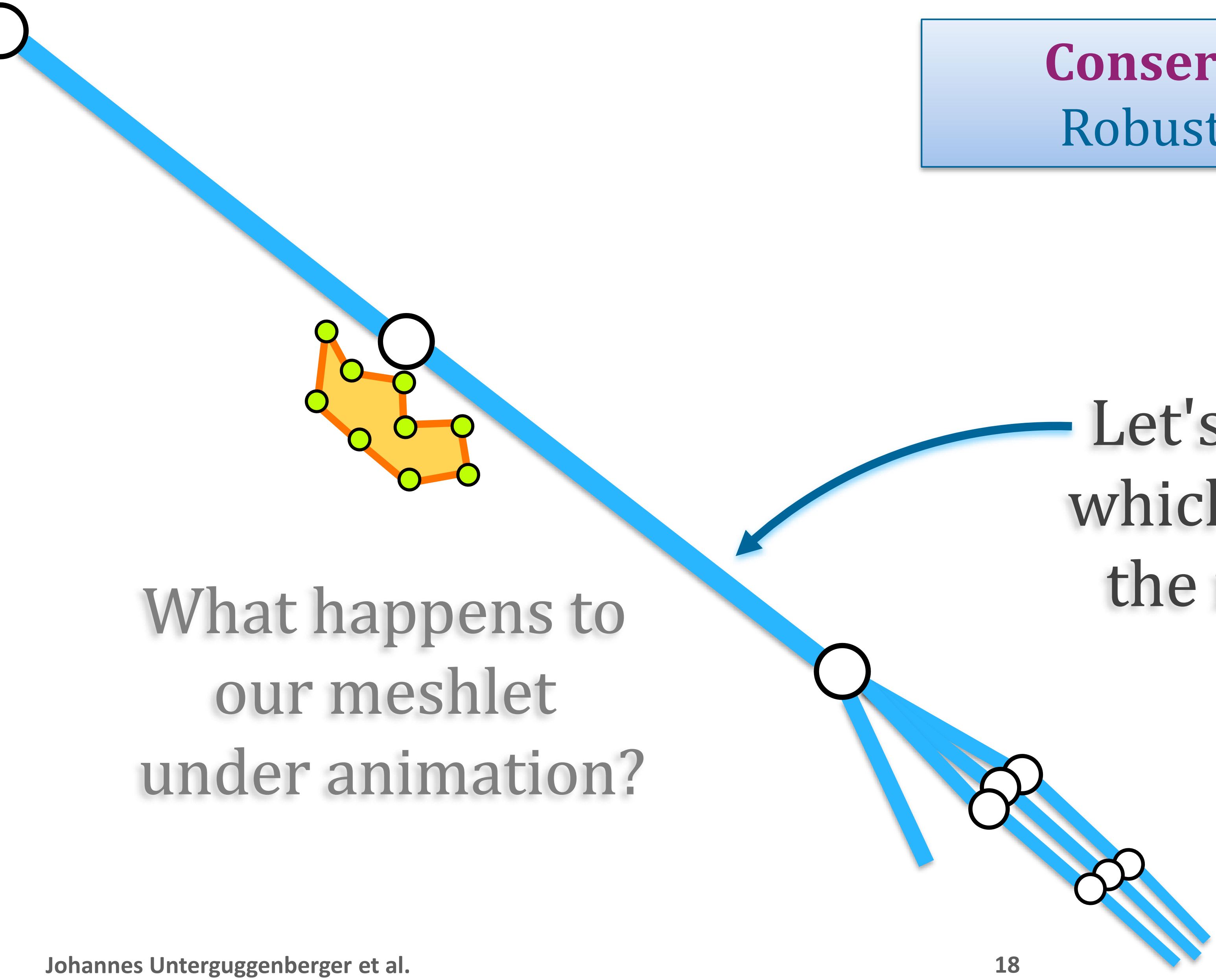




What happens to our meshlet under animation?

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

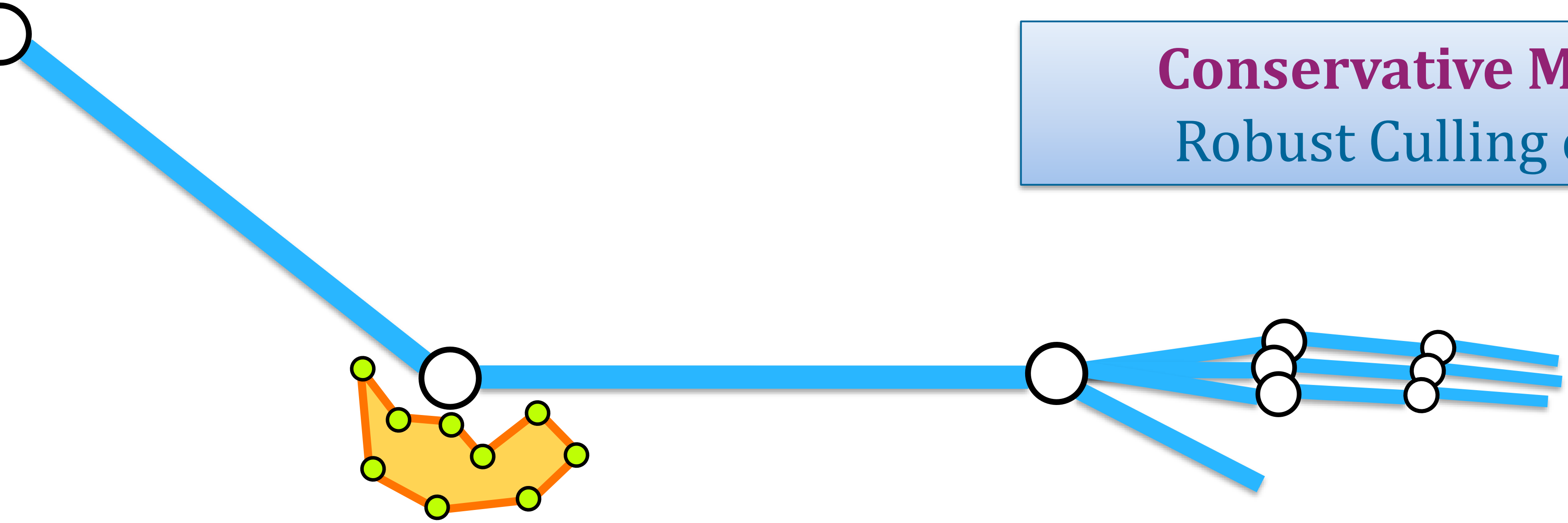


Let's animate that bone,
which in turn transforms
the meshlet's **vertices**.

What happens to
our meshlet
under animation?

Meshlet Under Animation

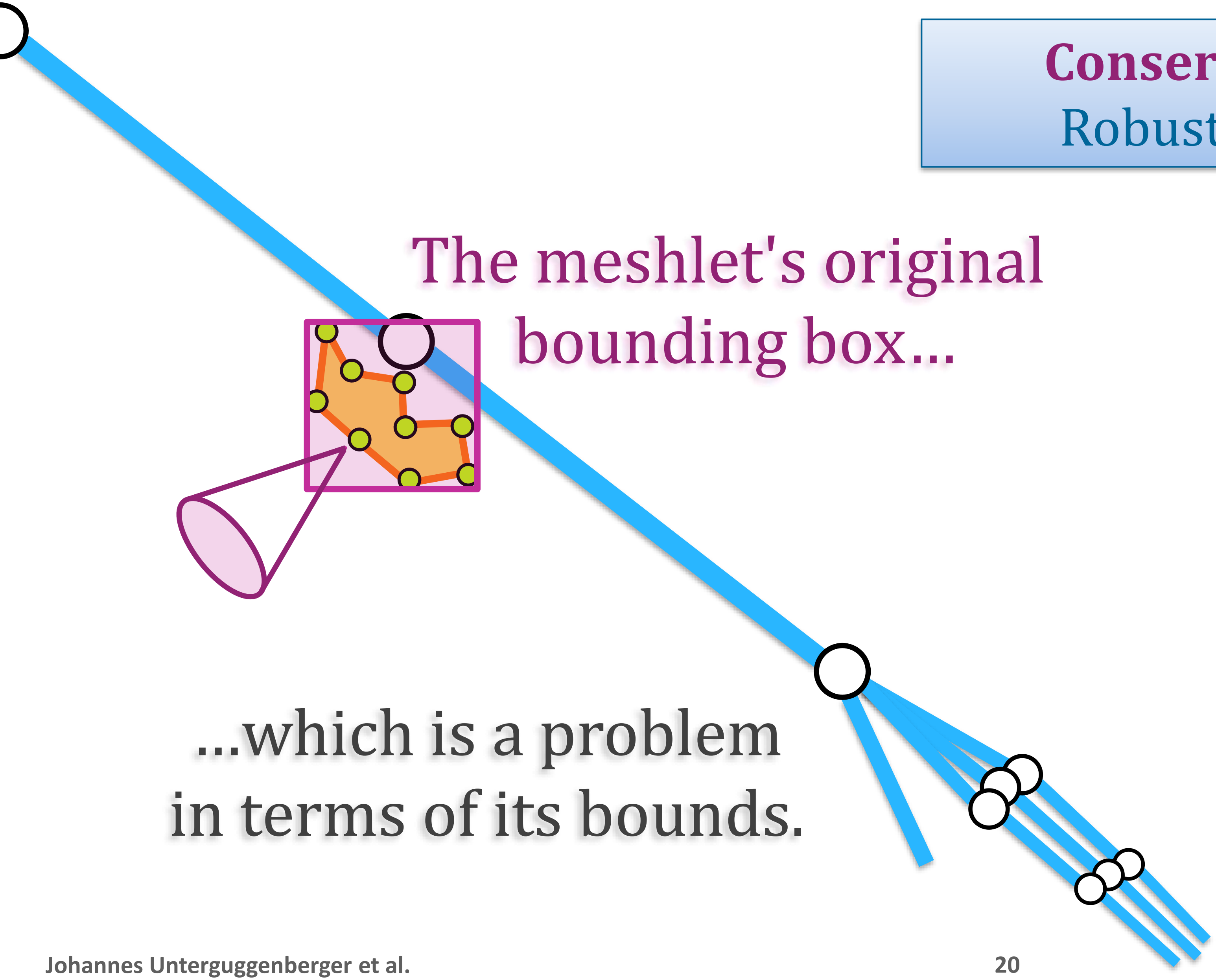
Conservative Meshlet Bounds for Robust Culling of Skinned Meshes



The meshlet's **shape** changed...

Meshlet Bounds

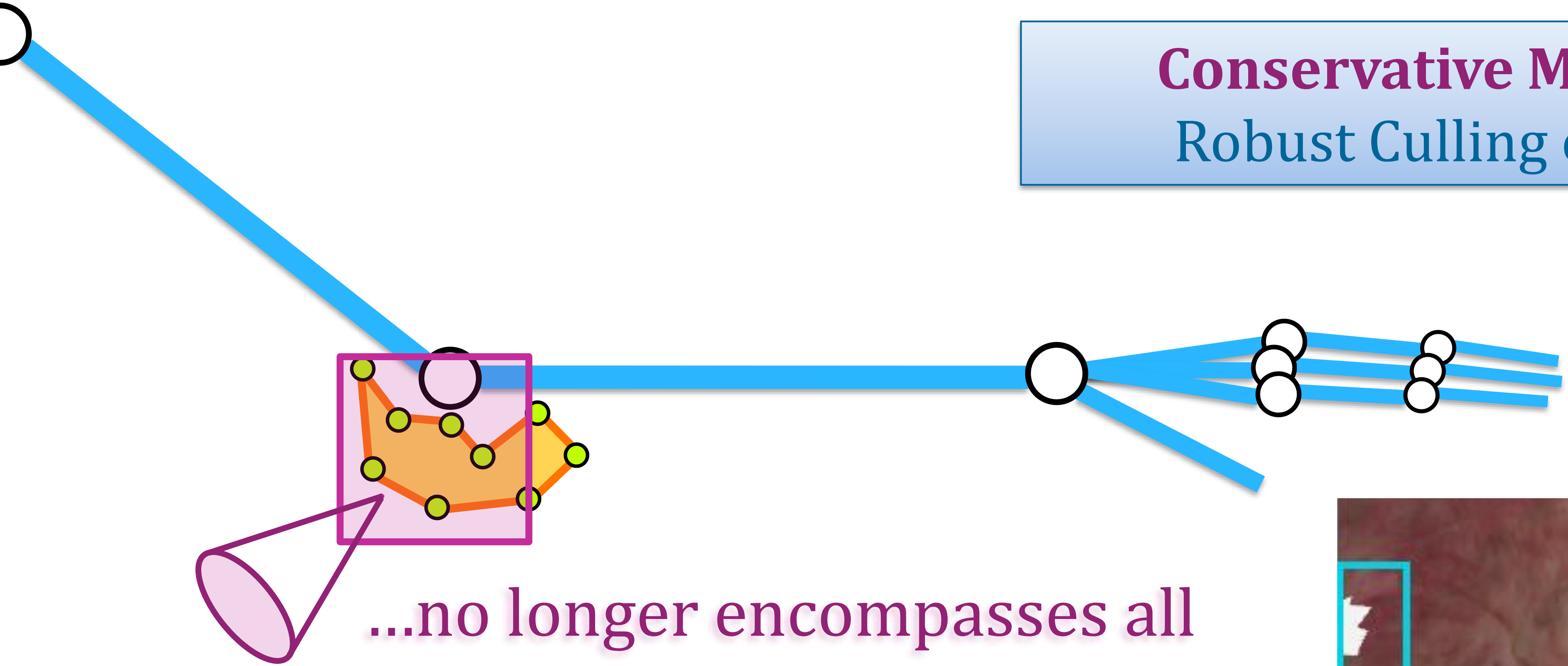
Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes



The meshlet's original bounding box...

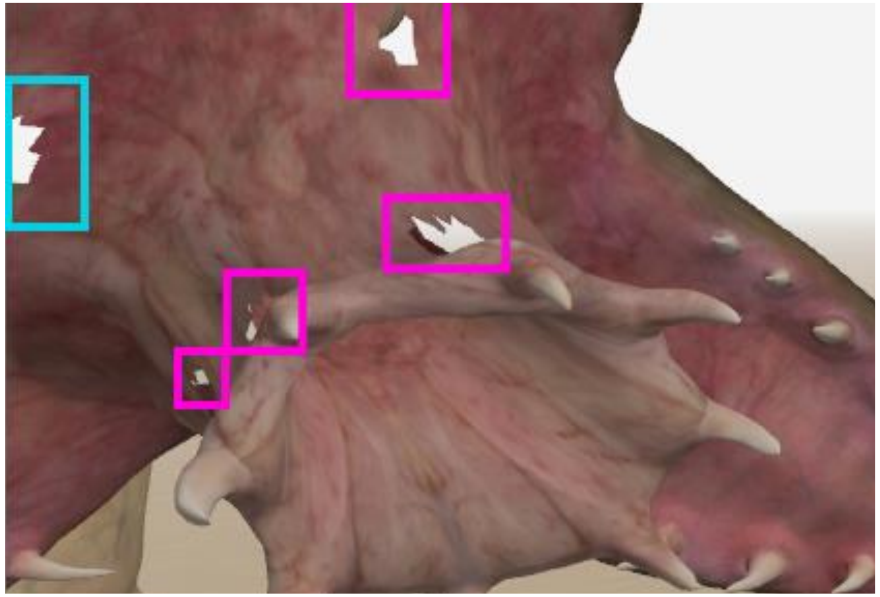
...which is a problem
in terms of its bounds.

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

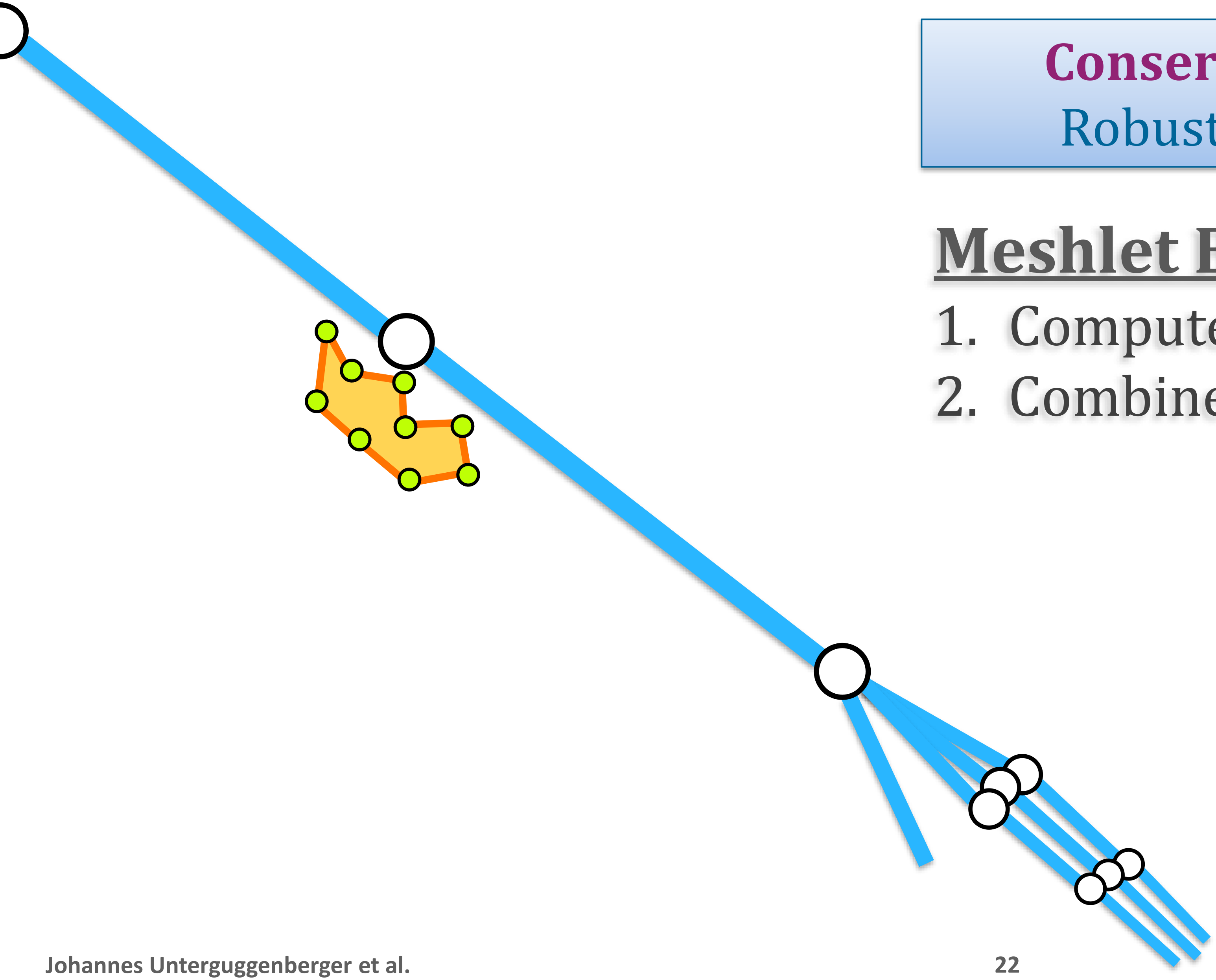


…no longer encompasses all **vertex positions** in the transformed state.

Also, the face normals distribution has changed under animation.



Meshlet Bounds



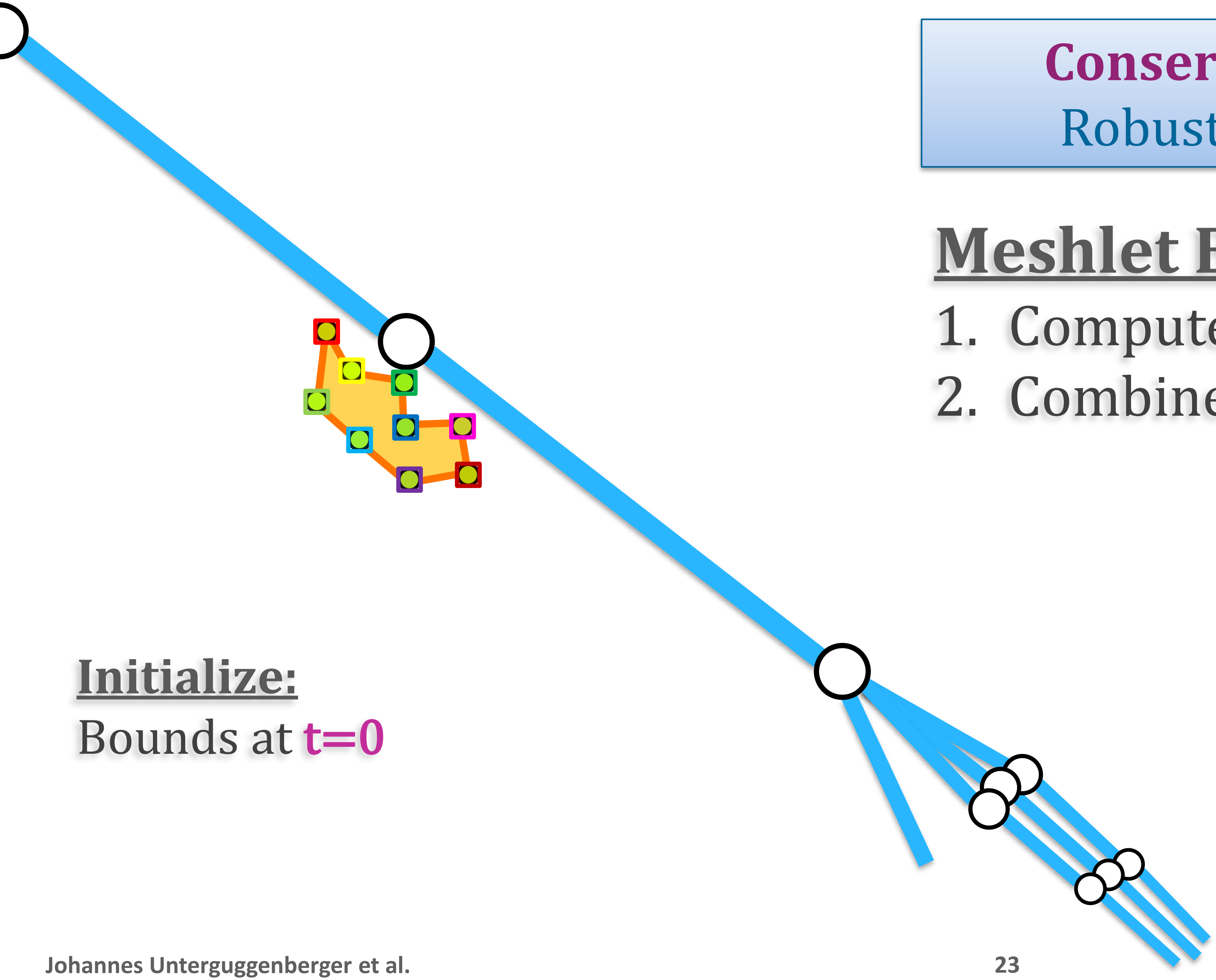
Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

Meshlet Bounds Algorithm:

1. Compute all *vertex bounds*
2. Combine into *meshlet bounds*

Vertex Bounds

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes



Meshlet Bounds Algorithm:

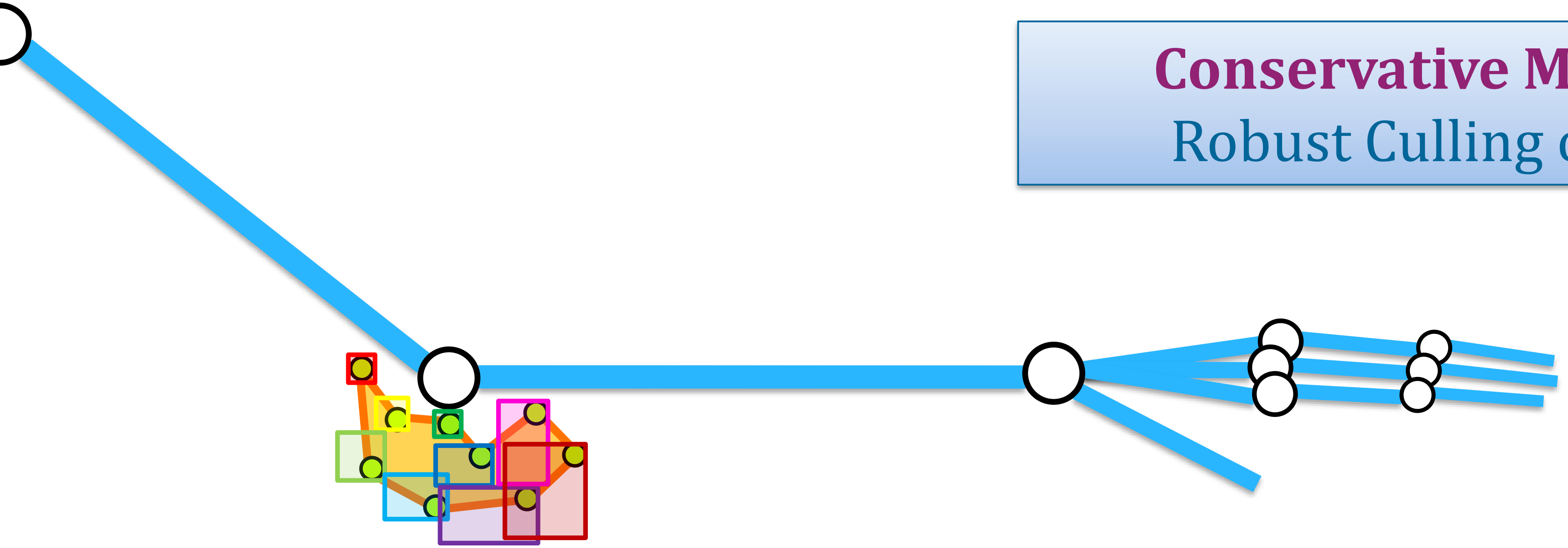
1. Compute all *vertex bounds*
2. Combine into *meshlet bounds*

Initialize:

Bounds at **t=0**

Vertex Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

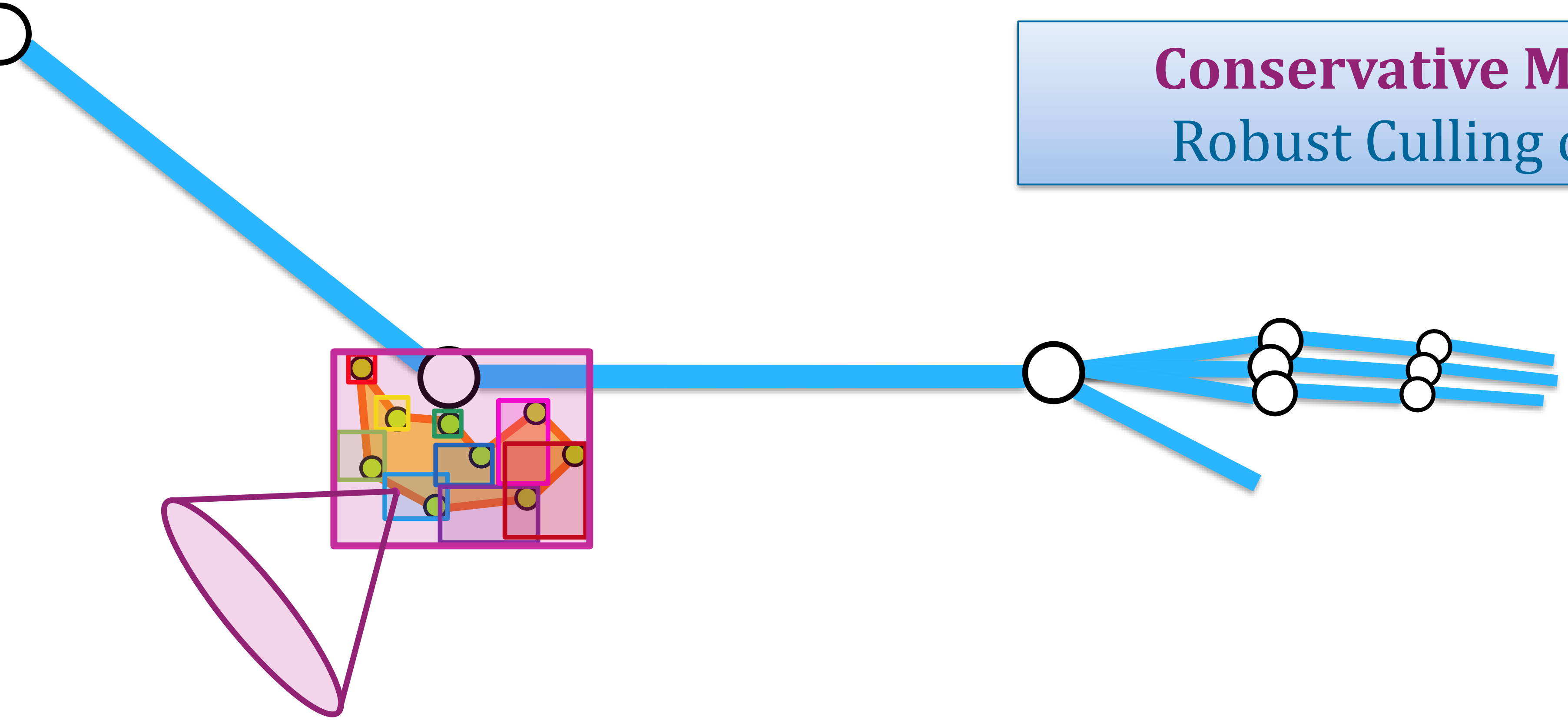


Calculate:

1. Bounds from t=0 to t=1 per vertex

Vertex Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

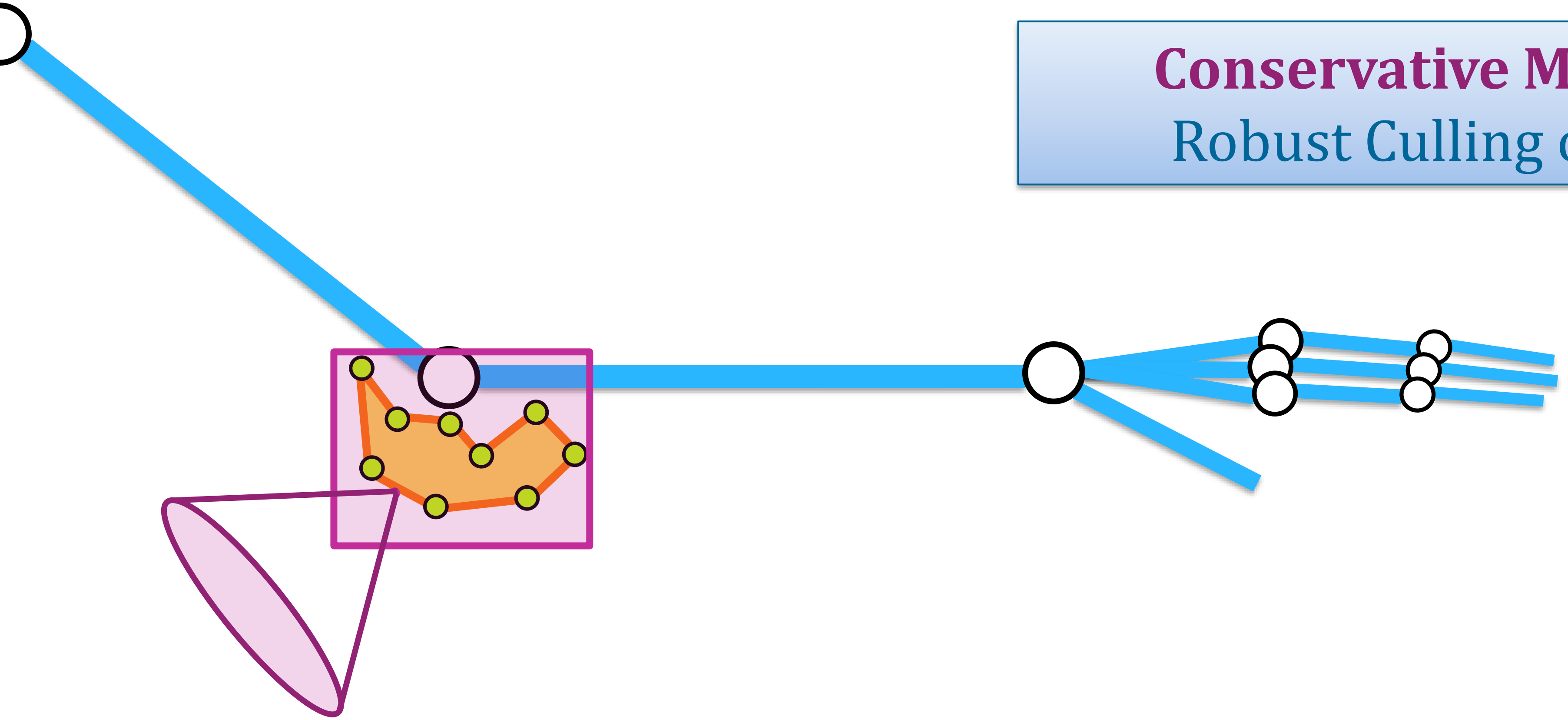


Calculate:

1. Bounds from **t=0** to **t=1** per vertex
2. Meshlet bounds = min and max bounds
   Normals distribution based on vertex bounds, too

Vertex Bounds

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes



Meshlet Bounds

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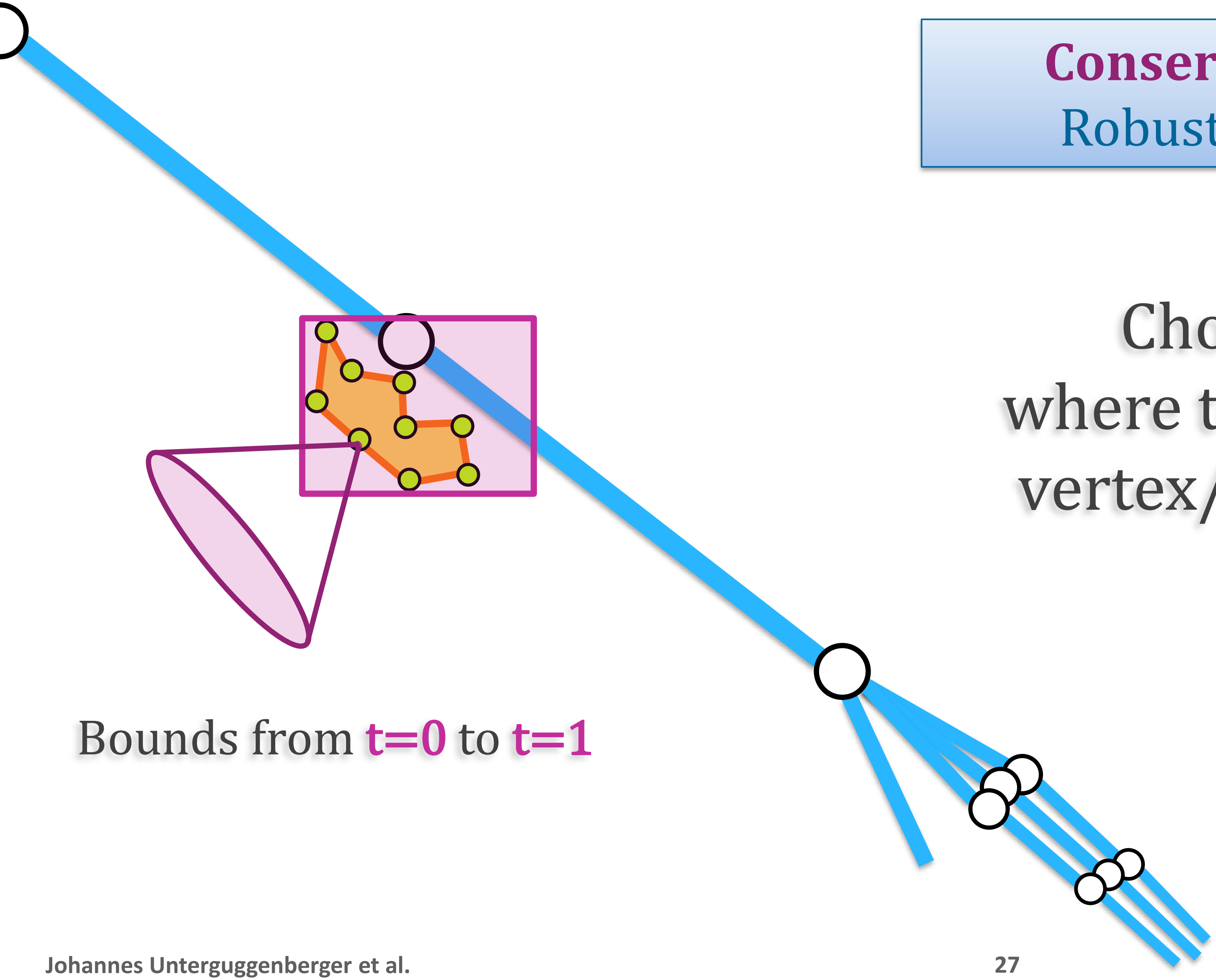
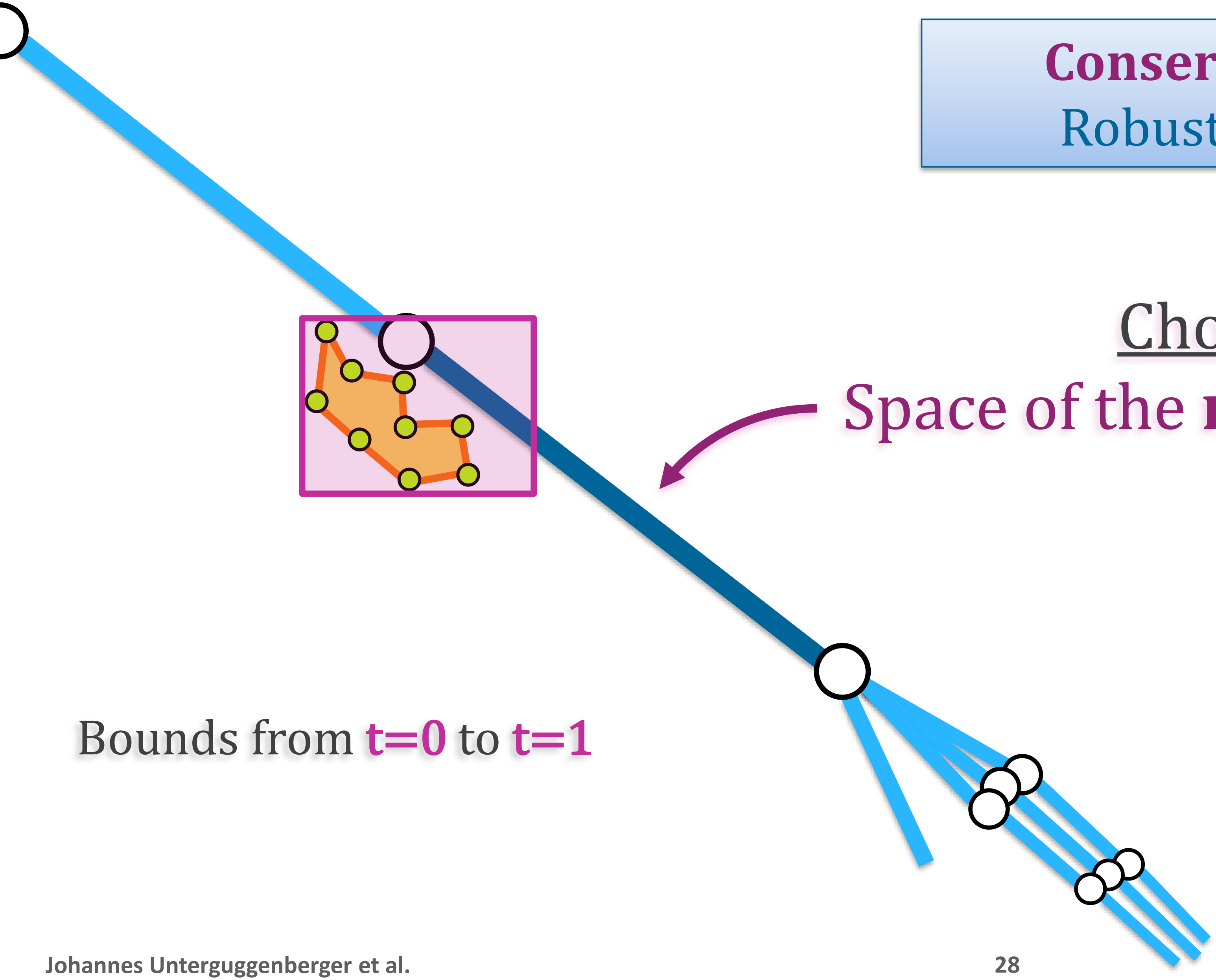


Bounds from **t=0** to **t=1**

Choice of **space**
where to store/calculate
vertex/meshlet bounds

Meshlet Bounds

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes



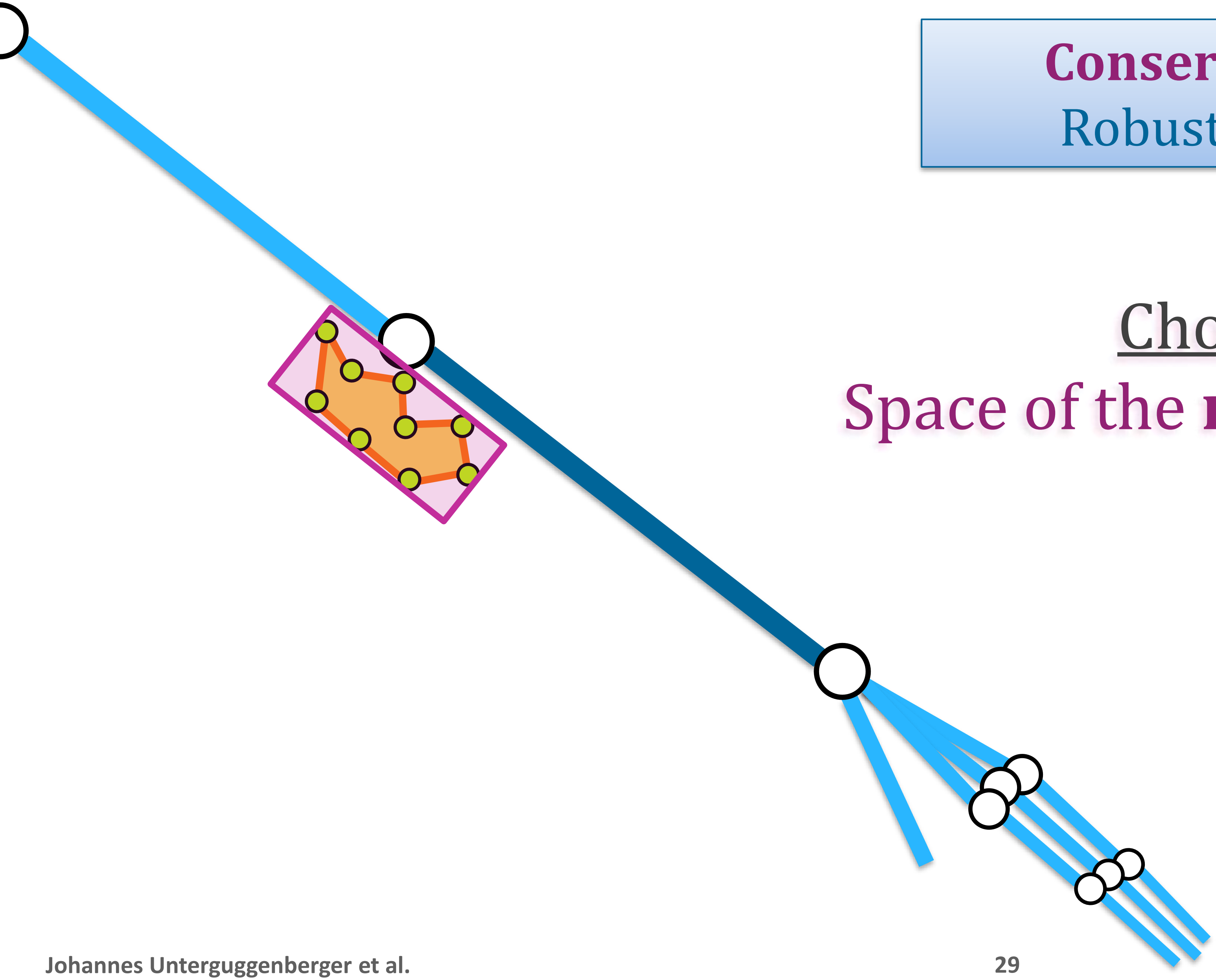
Choice of **space:**

Space of the **most influential bone**

Bounds from t=0 to t=1

Meshlet Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes



Choice of **space:**

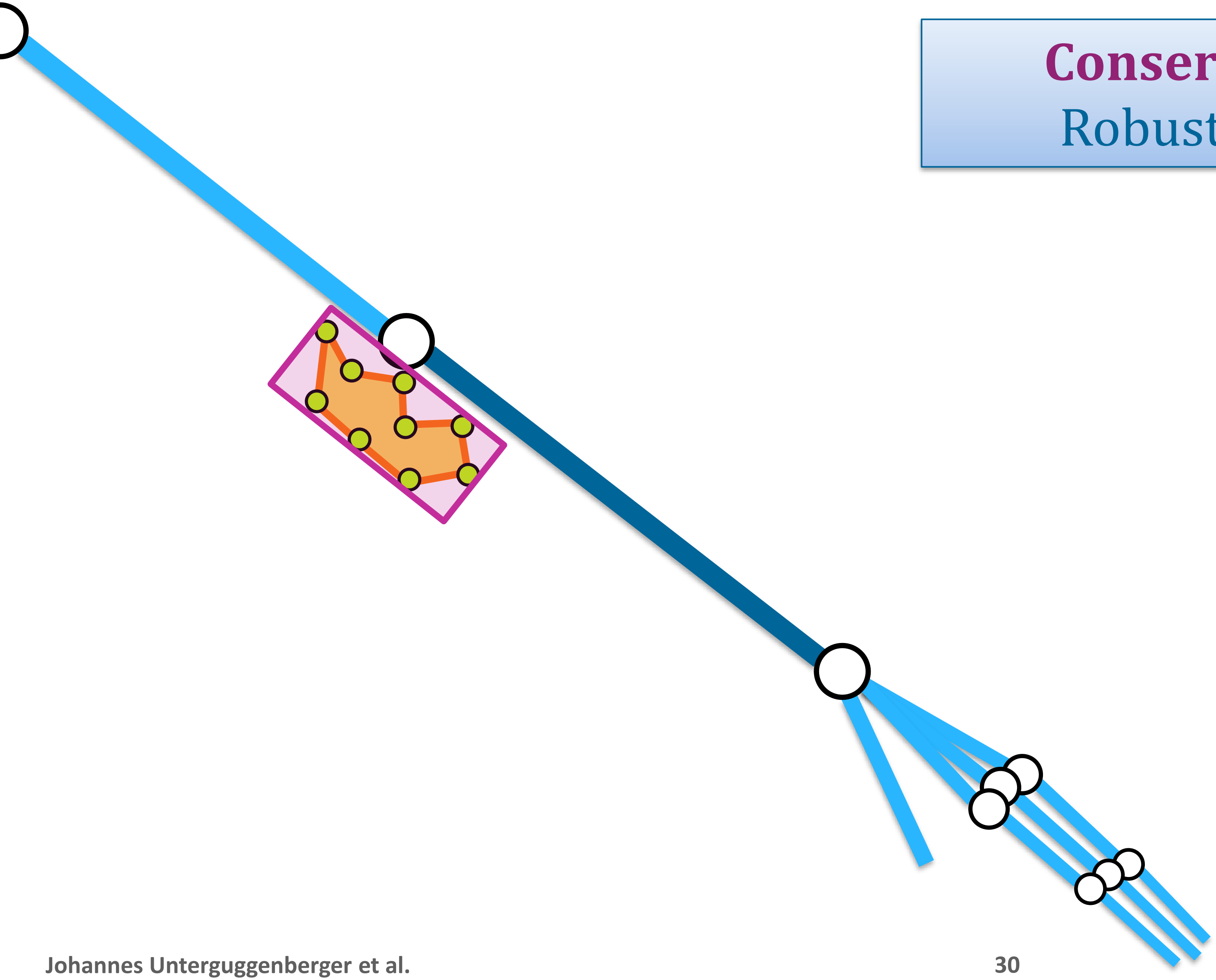
Space of the **most influential bone**

We are going to**:**

- Compute **initial bounds** in that space
- Transform bounds **with** that space

Meshlet Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes



- Transform bounds **with** that space

Meshlet Bounds

Conservative Meshlet Bounds for
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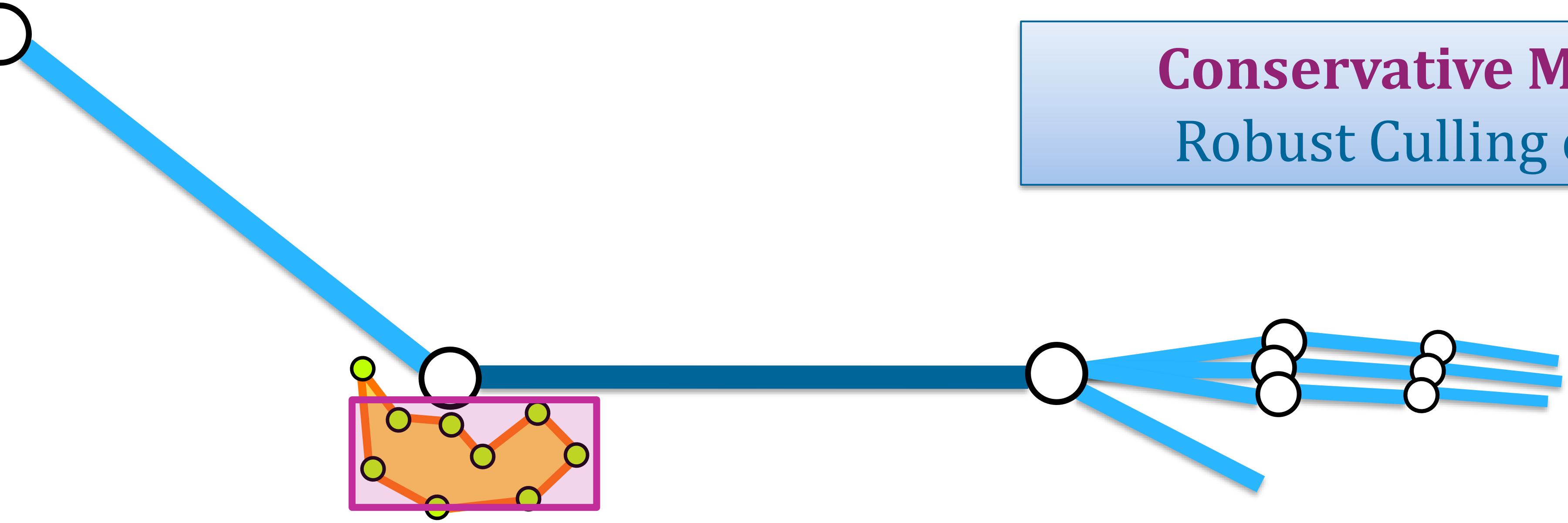
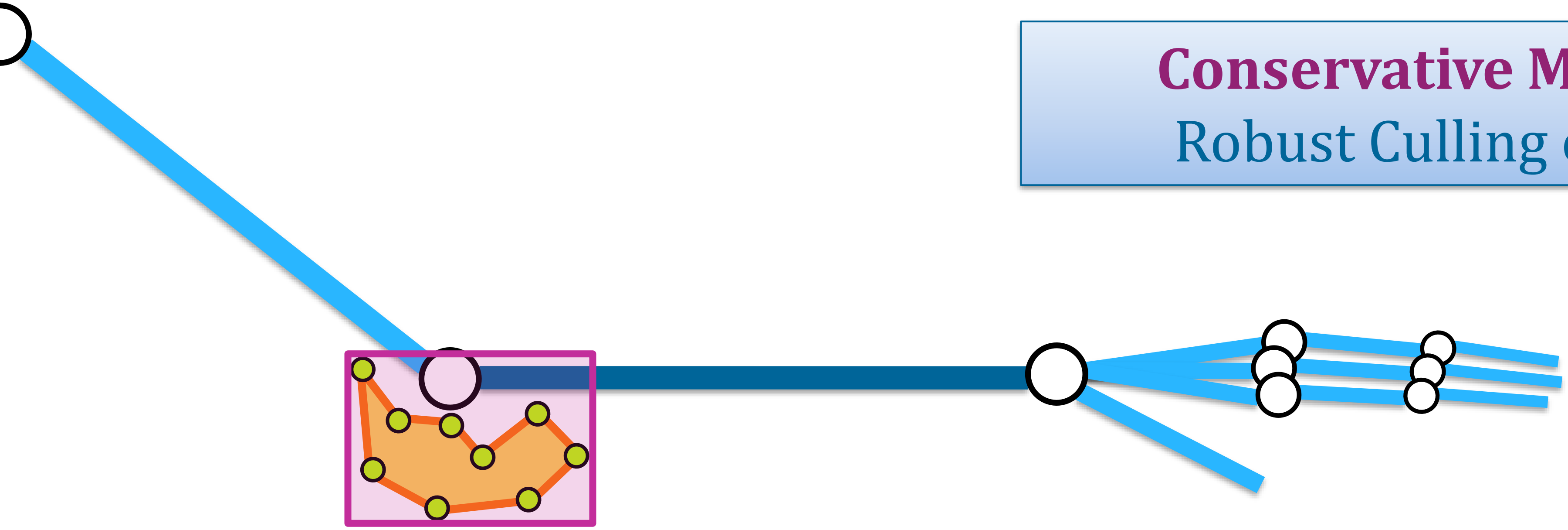


Calculate bounds for all animation intervals of interest!

- Transform bounds **with** that space

Meshlet Bounds



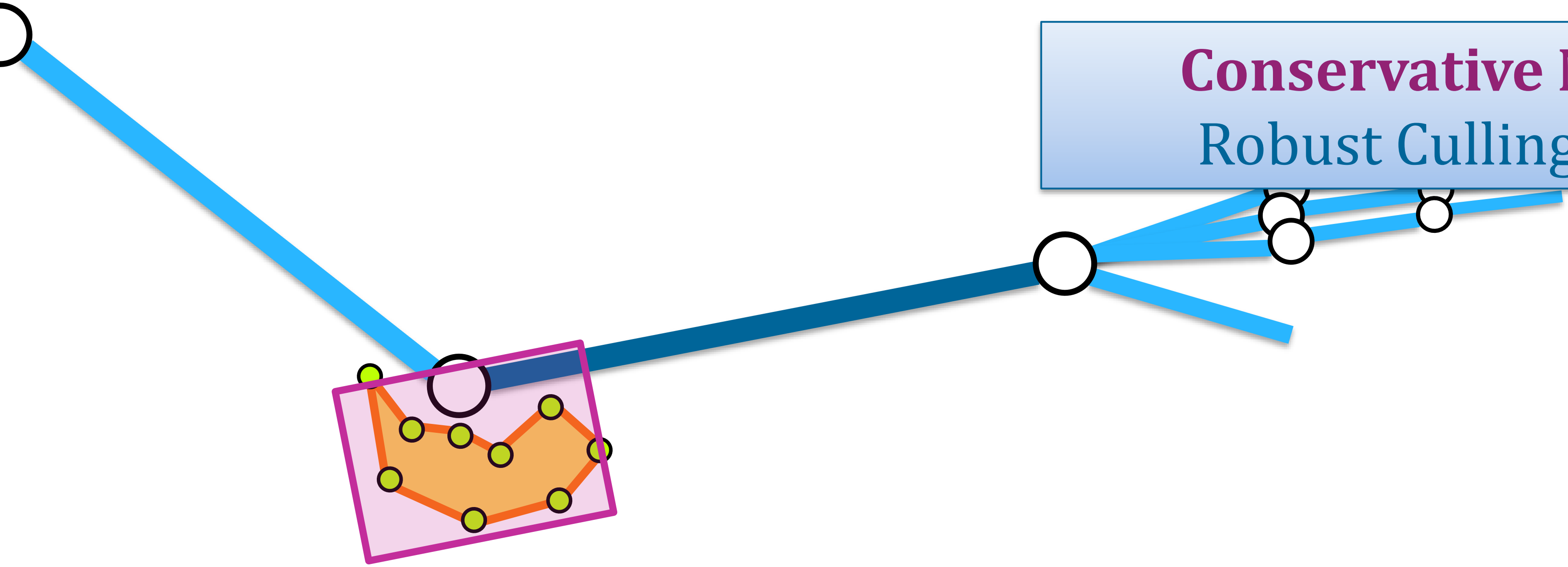
Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

Calculate bounds for all animation intervals of interest!

from **t=0** to **t=1**
from **t=1** to **t=2**

Meshlet Bounds

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes



Calculate bounds for all animation intervals of interest!

from t=0 to t=1

from t=1 to t=2

Meshlet Bounds

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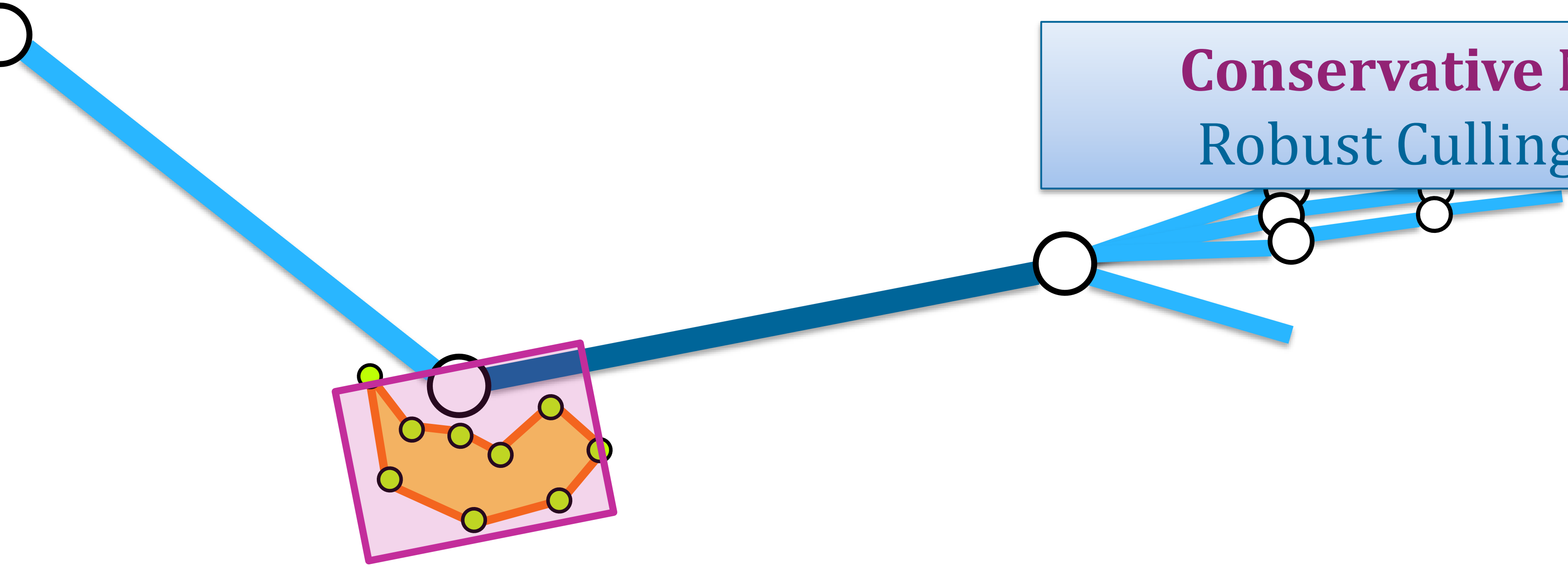
Robust Culling of Skinned Meshes



Calculate bounds for all animation intervals of interest!

from t=0 to t=1
from t=1 to t=2

Meshlet Bounds

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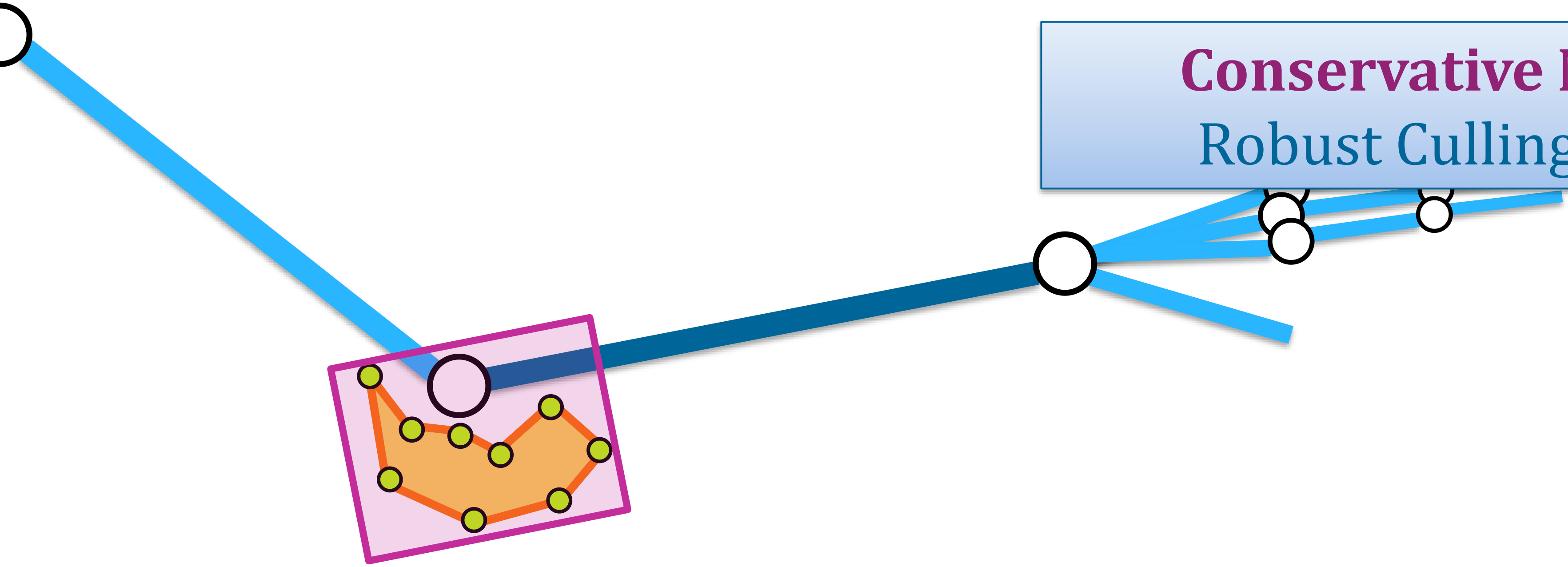

Calculate bounds for all animation intervals of interest!

from t=0 to t=1
from t=1 to t=2

Meshlet Bounds

Conservative Meshlet Bounds for
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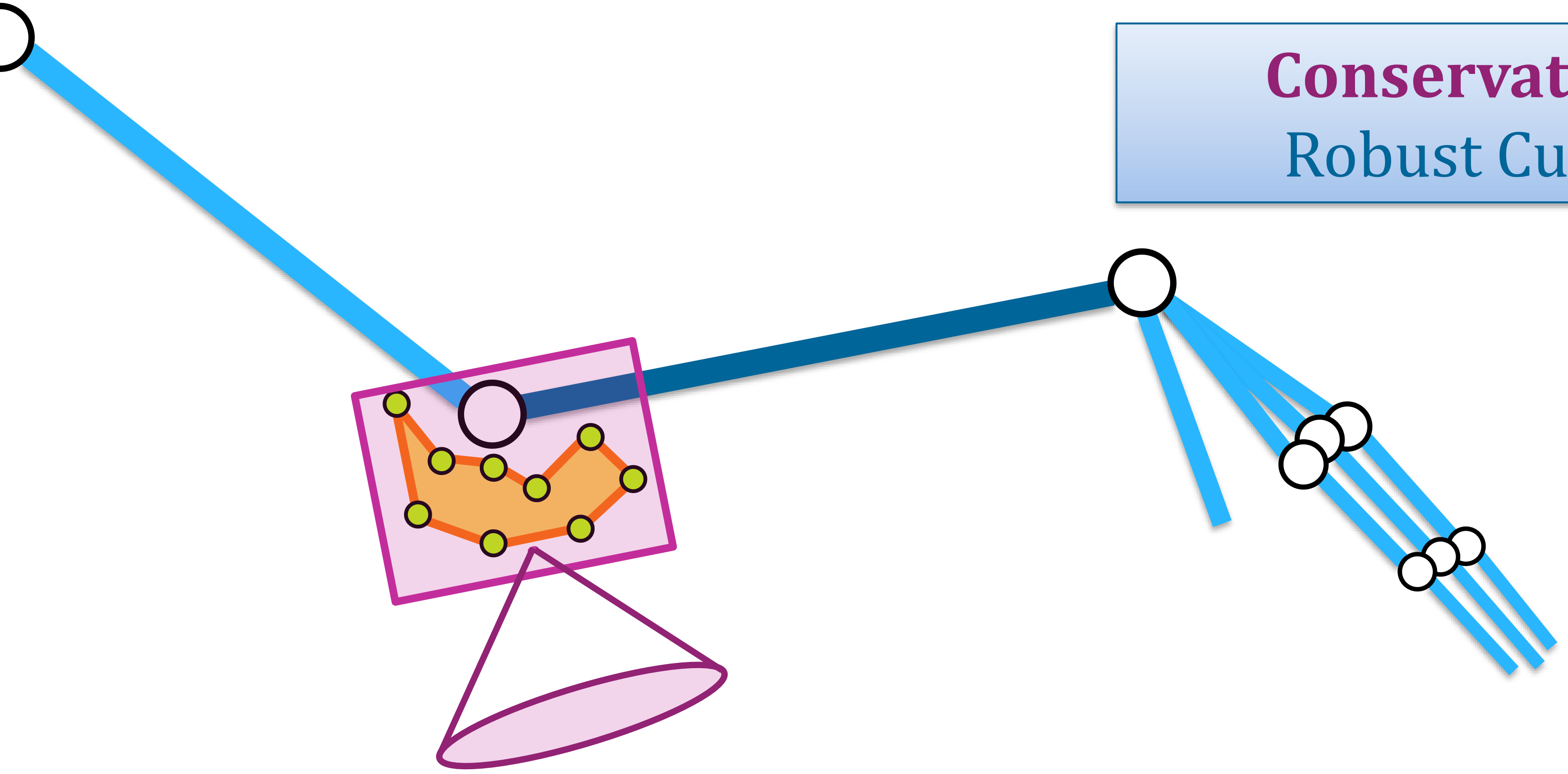


Calculate bounds for all animation intervals of interest!

from **t=0** to **t=1**

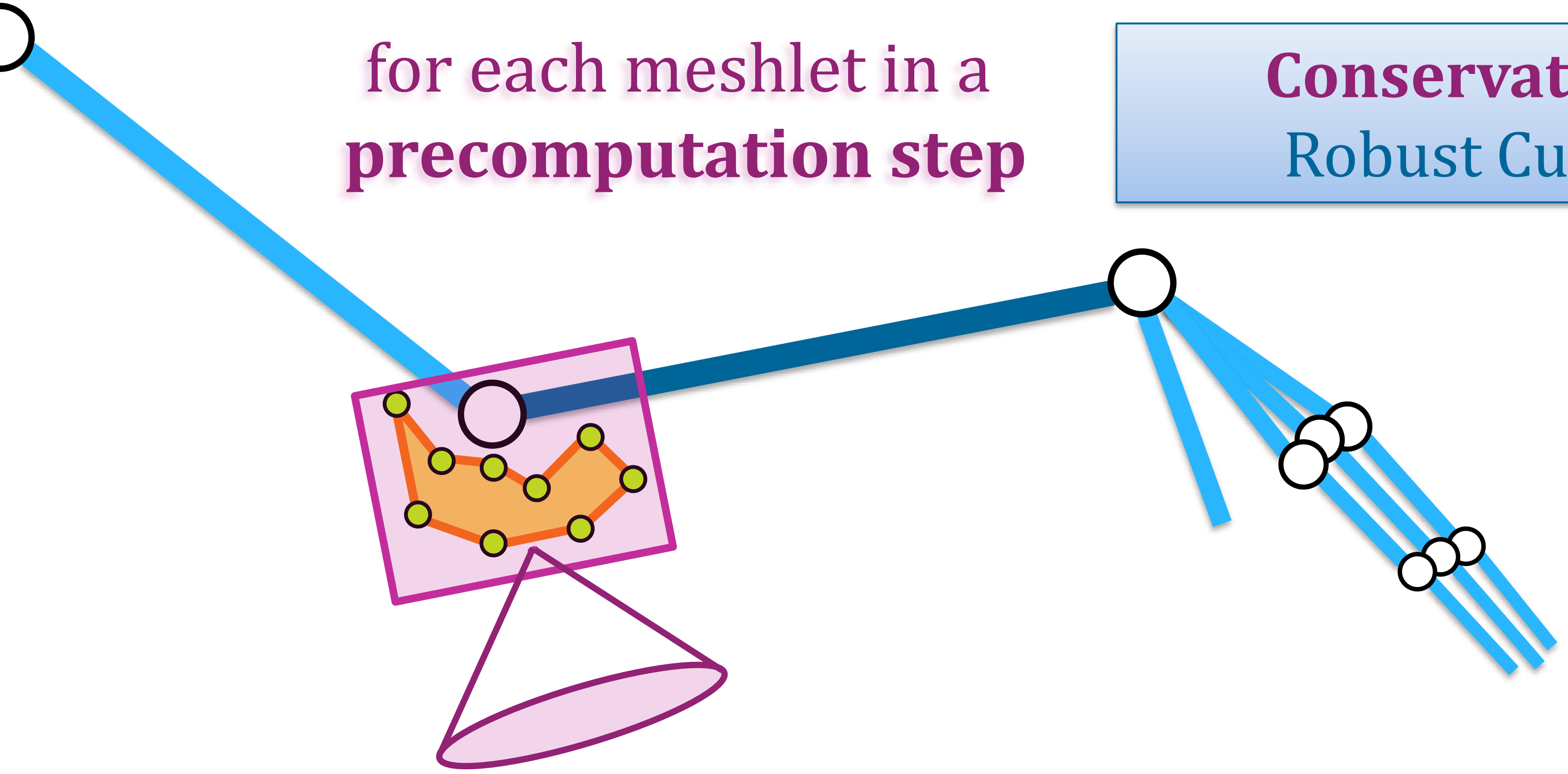
from **t=1** to **t=2**

from **t=2** to **t=3**

Task Shader → Mesh Shader → Rasterizer → Fragment Shader

Meshlet Bounds

for each meshlet in a **precomputation step**

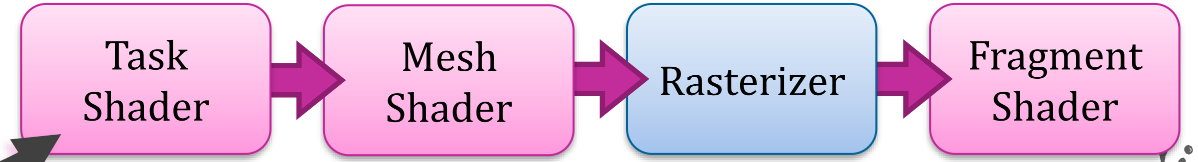


Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

- Low-overhead culling in task shaders
- Low memory consumption
- Low memory bandwidth

from t=0 to t=1
from t=1 to t=2
from t=2 to t=3

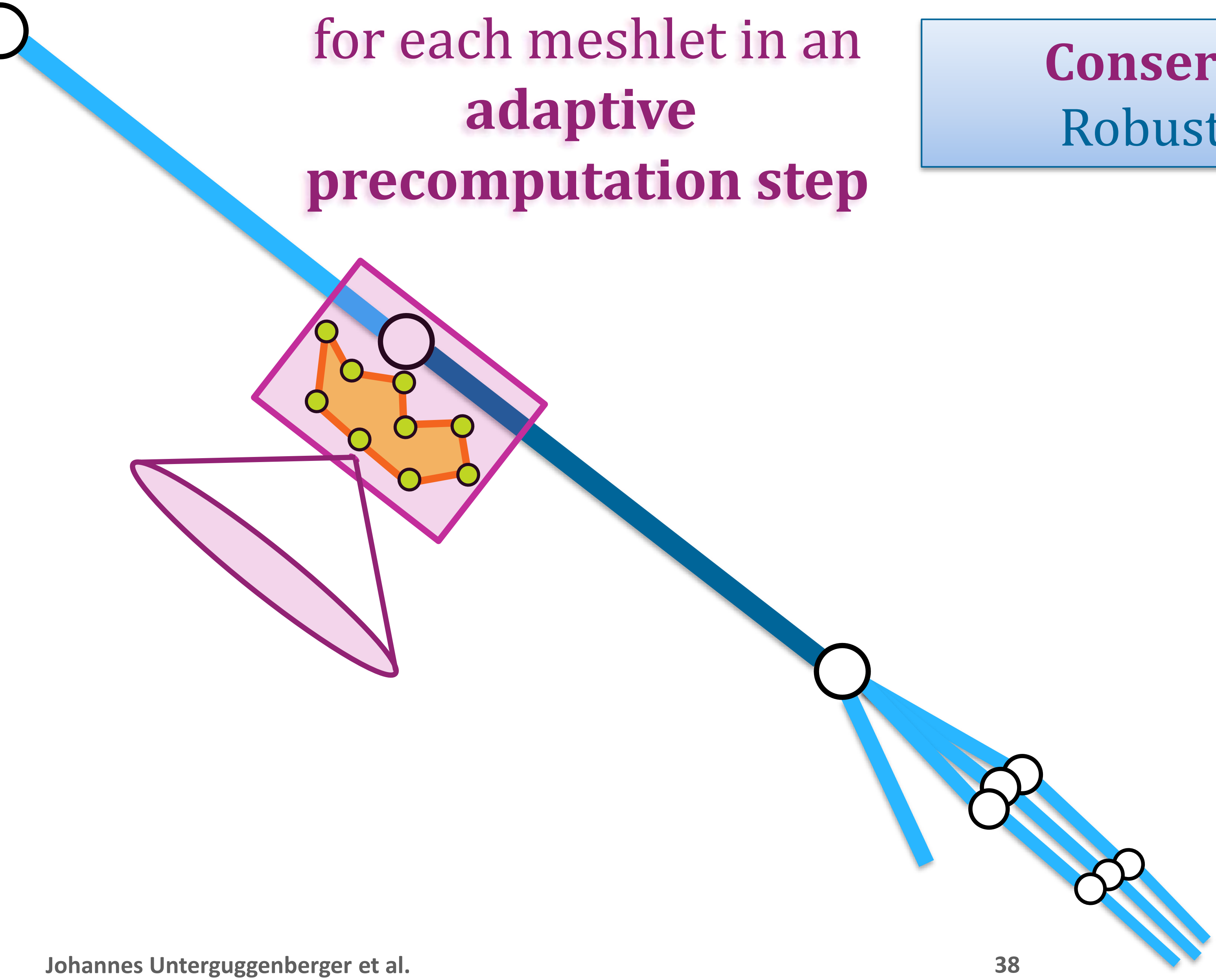
Store 1 bounding box and 1 normals distribution "cone"



Meshlet Bounds

for each meshlet in an **adaptive precomputation step**

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes



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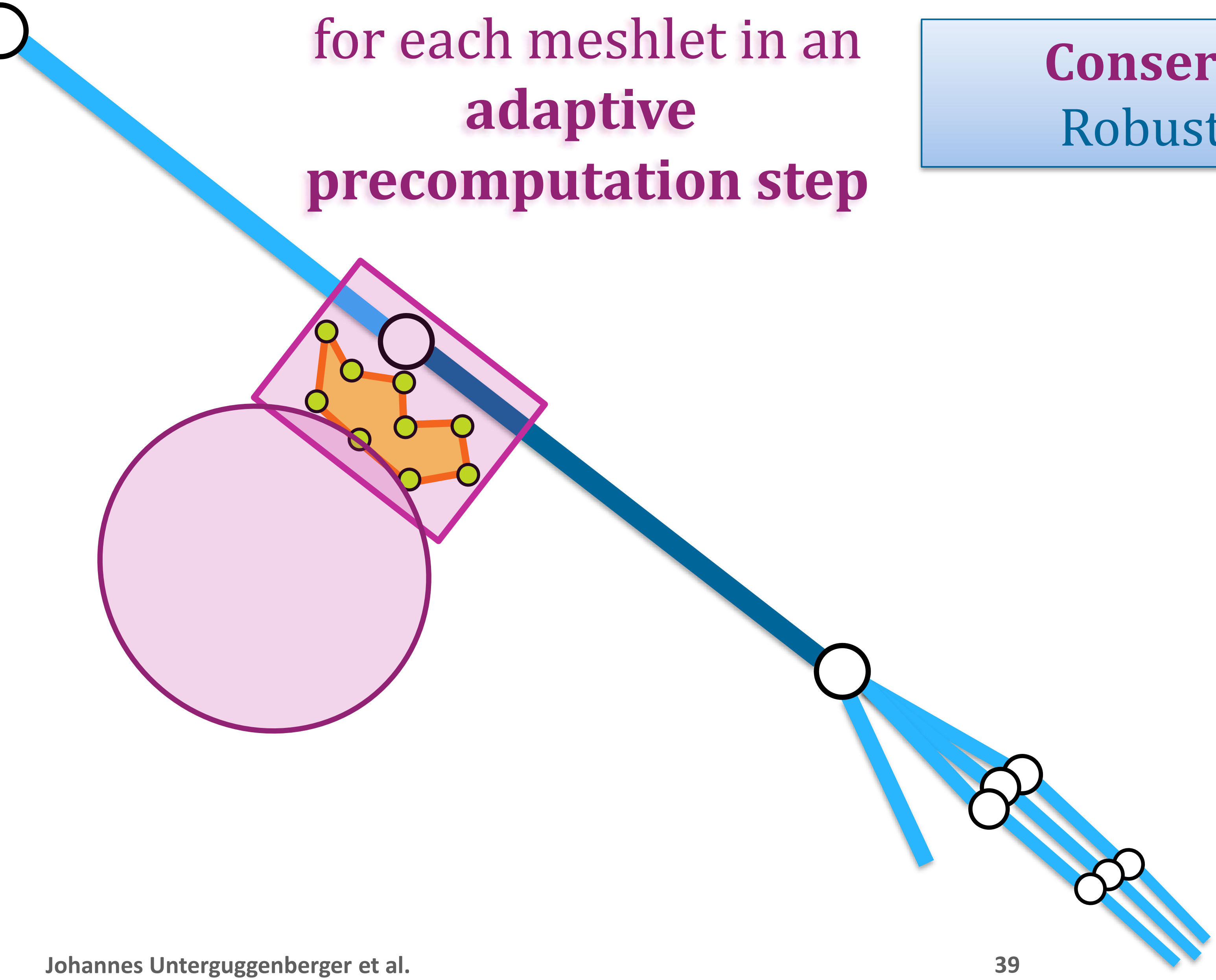
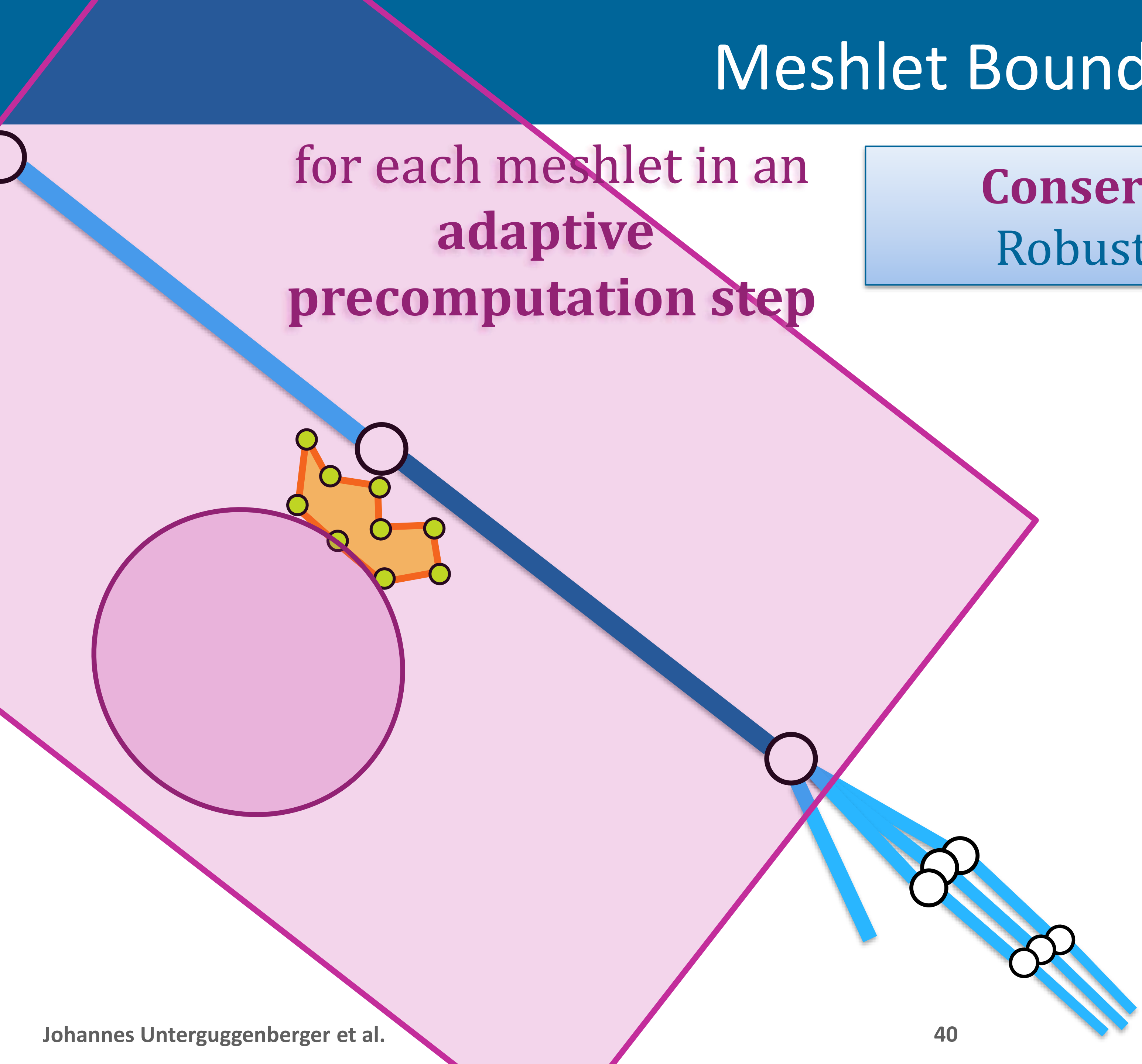




for each meshlet in an **adaptive precomputation step**

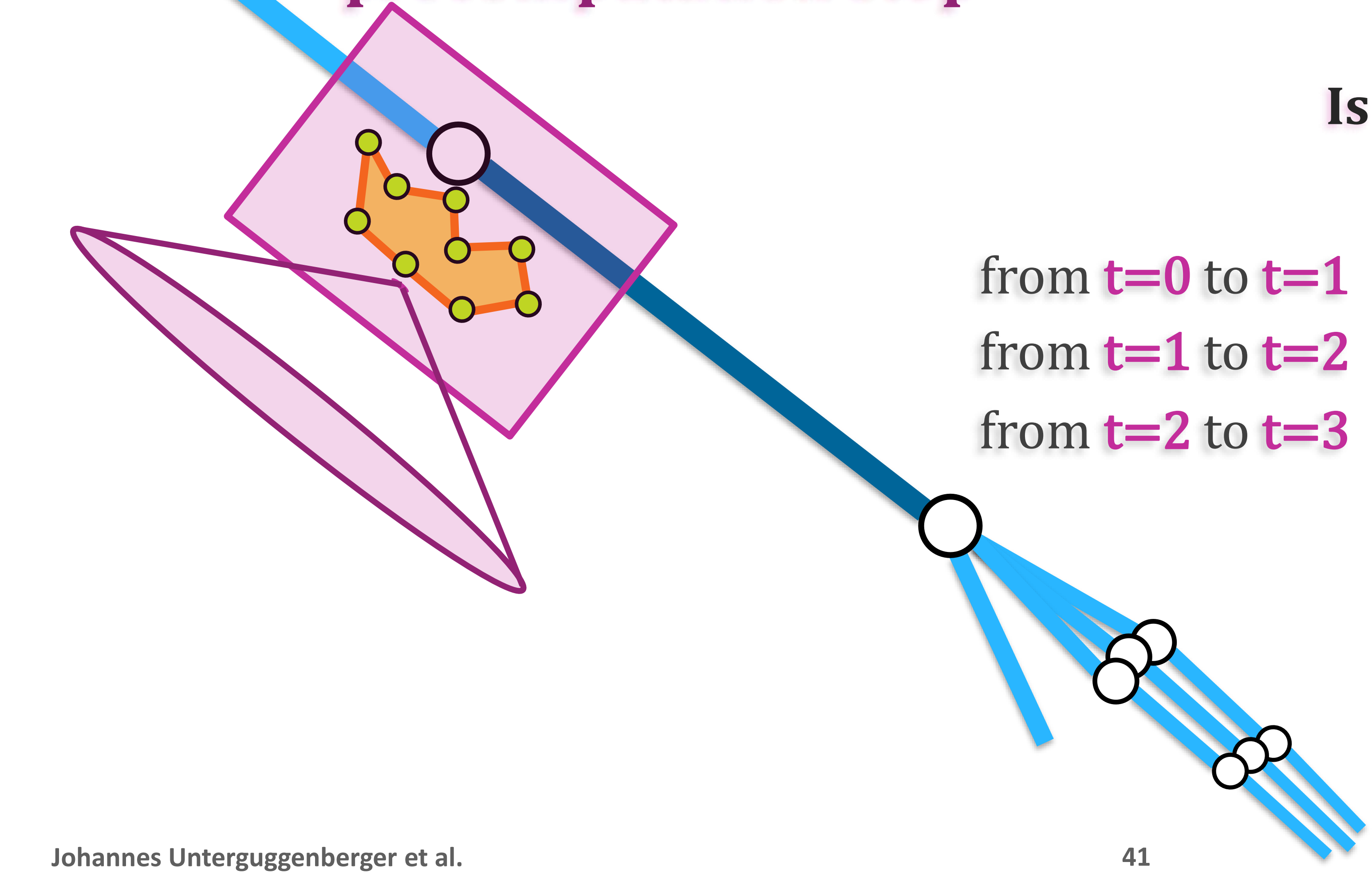
Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

Meshlet Bounds

for each meshlet in an **adaptive precomputation step**

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

Is this a "well-~~b~~ehaved" meshlet?



from t=0 to t=1

from t=1 to t=2

from t=2 to t=3

Meshlet Bounds

for each meshlet in an **adaptive precomputation step**

Conservative Meshlet Bounds for
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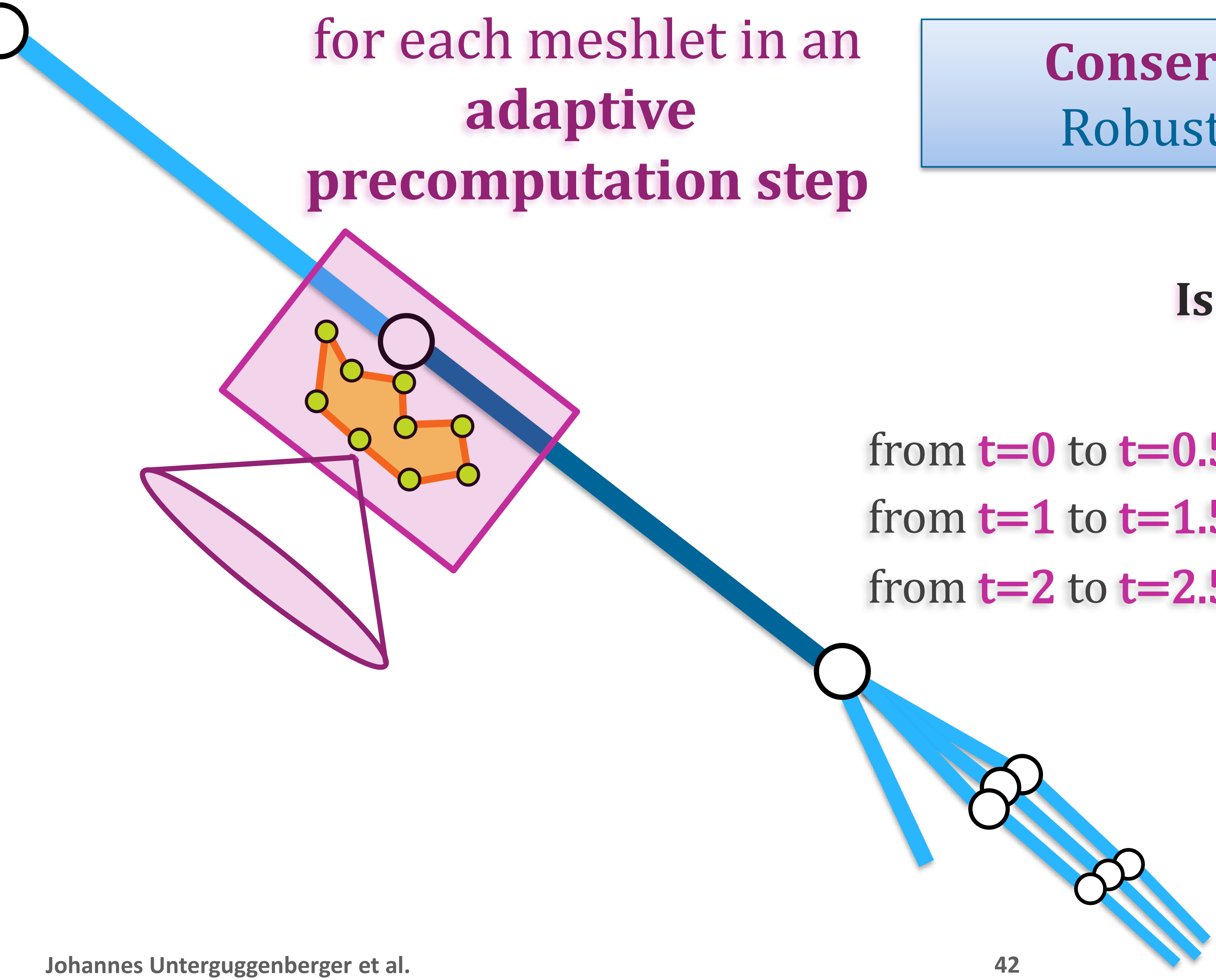
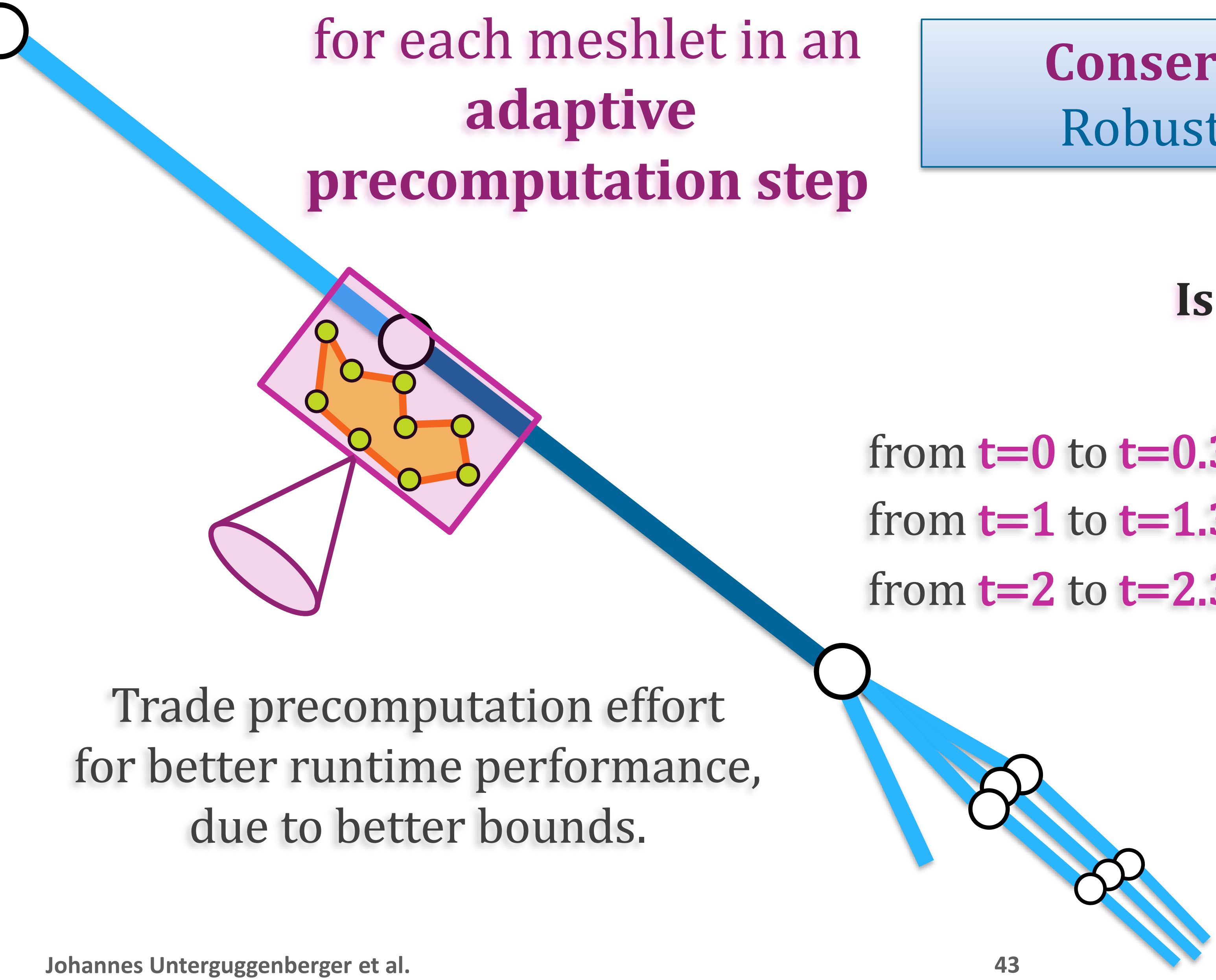


Is this a "well-~~b~~ehaved" meshlet?

from t=0 to t=0.5 and t=0.5 to t=1
from t=1 to t=1.5 and t=1.5 to t=2
from t=2 to t=2.5 and t=2.5 to t=3

Meshlet Bounds



for each meshlet in an **adaptive precomputation step**

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

Is this a "well-~~b~~ehaved" meshlet?

from **$t=0$** to **$t=0.\dot{3}$** and **$t=0.\dot{3}$** to **$t=0.\dot{6}$** and **$t=0.\dot{6}$** to **$t=1$**
from **$t=1$** to **$t=1.\dot{3}$** and **$t=1.\dot{3}$** to **$t=1.\dot{6}$** and **$t=1.\dot{6}$** to **$t=2$**
from **$t=2$** to **$t=2.\dot{3}$** and **$t=2.\dot{3}$** to **$t=2.\dot{6}$** and **$t=2.\dot{6}$** to **$t=3$**

Trade precomputation effort for better runtime performance, due to better bounds.

From our test models:

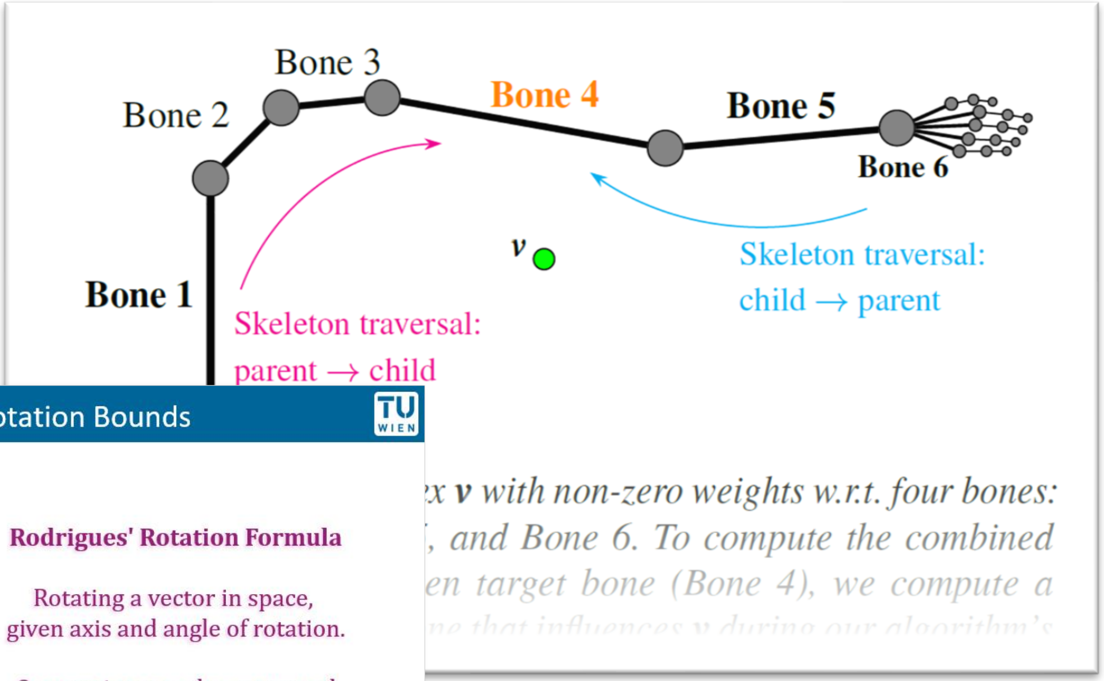
- ≥ 94% view frustum cullable
- ~60%–90% backface cullable

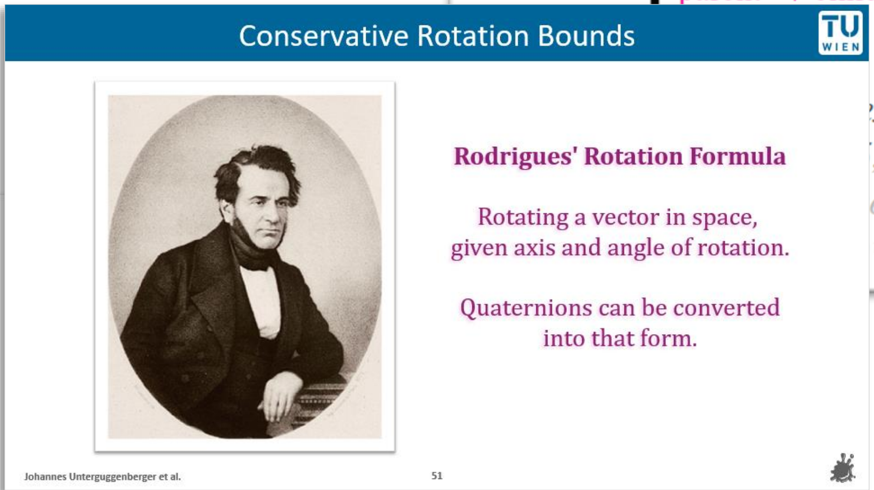
In Our Paper…

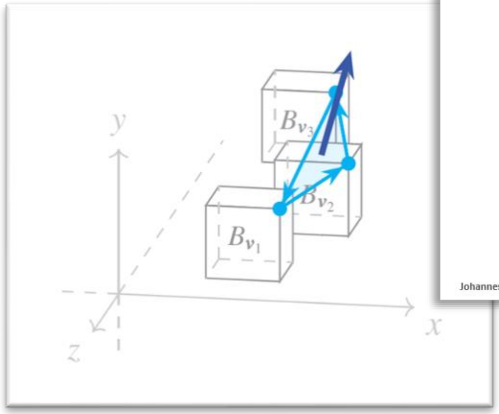
Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

Please consult our paper for:

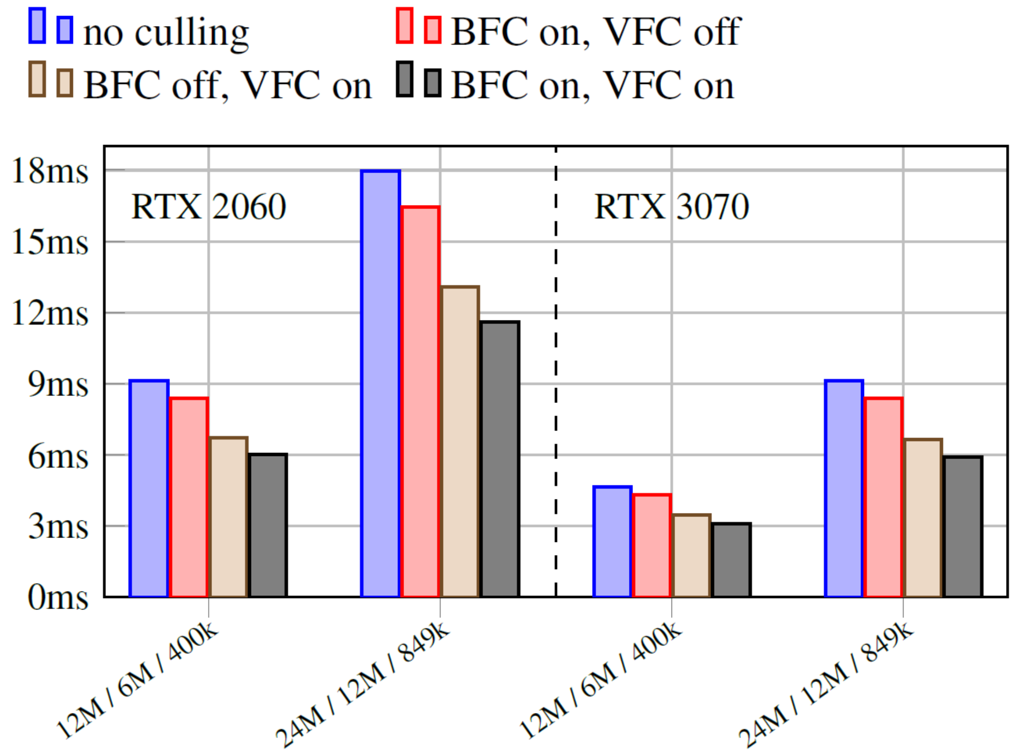
- Vertex bounds **algorithm**
- Conservative rotation bounds extension (Derivative of **Rodrigues' Rotation Formula**)
- Vertex bounds combination for **linear blend skinning**
- Conservative **normal bounds** from vertex bounds
- **Results**, Percentages, …
- Discussion
- Future work





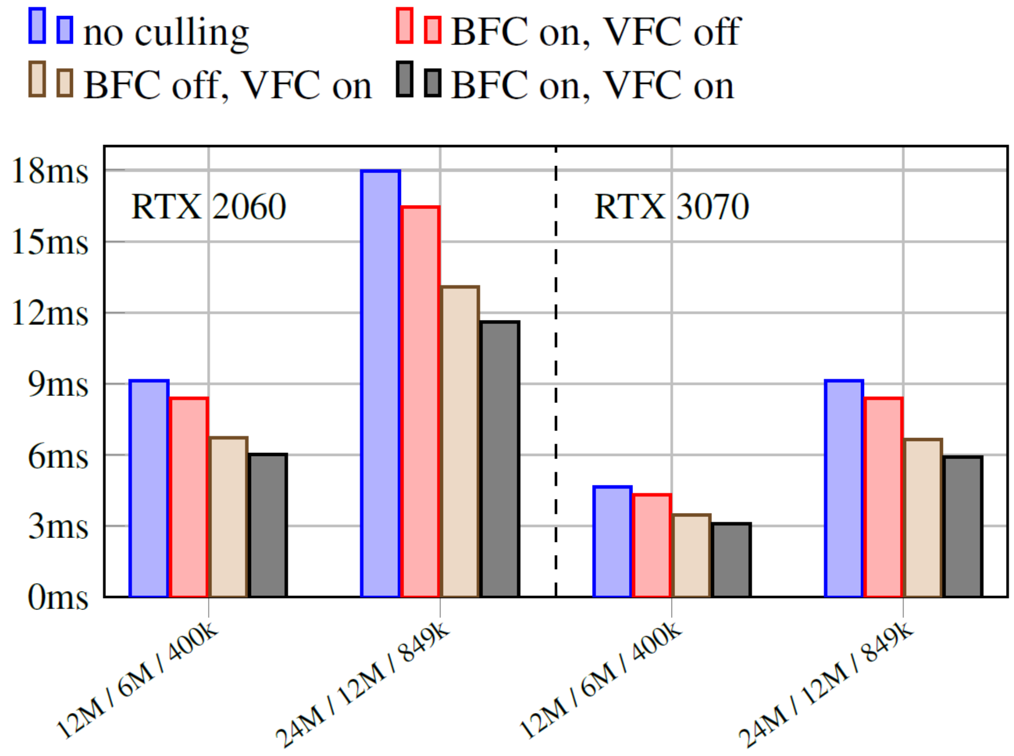


Results



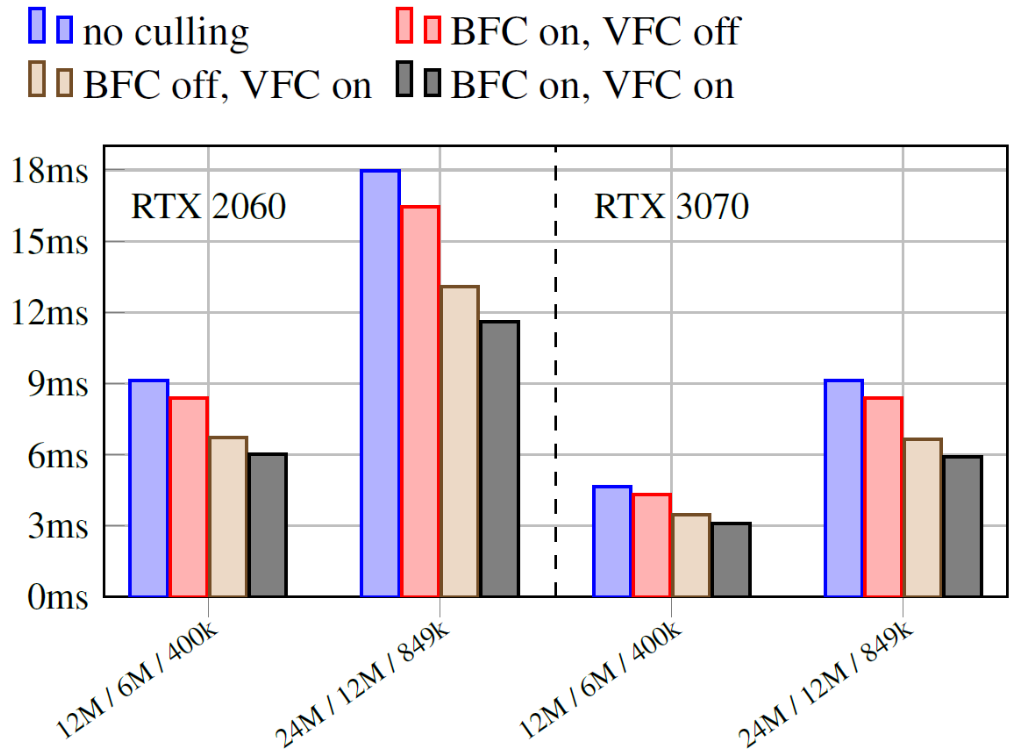
GPU	Scene	BFC only		VFC only		BFC+VFC	
		Culled	Faster	Culled	Faster	Culled	Faster
RTX 2060	400k	11.4%	8.1%	31.3%	26.3%	39.9%	33.8%
	849k	11.5%	8.5%	31.4%	27.1%	39.7%	35.4%
RTX 3070	400k	11.4%	7.8%	31.3%	26.1%	39.9%	34.0%
	849k	11.5%	7.9%	31.4%	27.2%	39.7%	35.4%

Results



GPU	Scene	BFC only		VFC only		BFC+VFC	
		Culled	Faster	Culled	Faster	Culled	Faster
RTX	400k	11.4%	8.1%	31.3%	26.3%	39.9%	33.8%
2060	849k	11.5%	8.5%	31.4%	27.1%	39.7%	35.4%
RTX	400k	11.4%	7.8%	31.3%	26.1%	39.9%	34.0%
3070	849k	11.5%	7.9%	31.4%	27.2%	39.7%	35.4%

Results



GPU	Scene	BFC only		VFC only		BFC+VFC	
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RTX	400k	11.4%	8.1%	31.3%	26.3%	39.9%	33.8%
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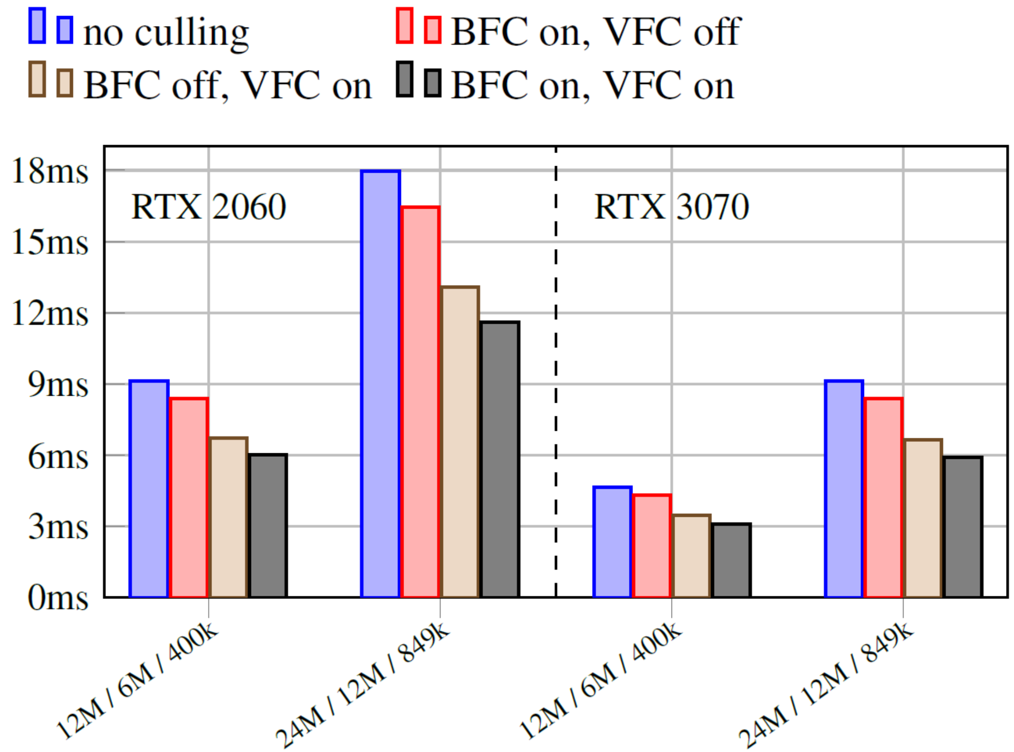
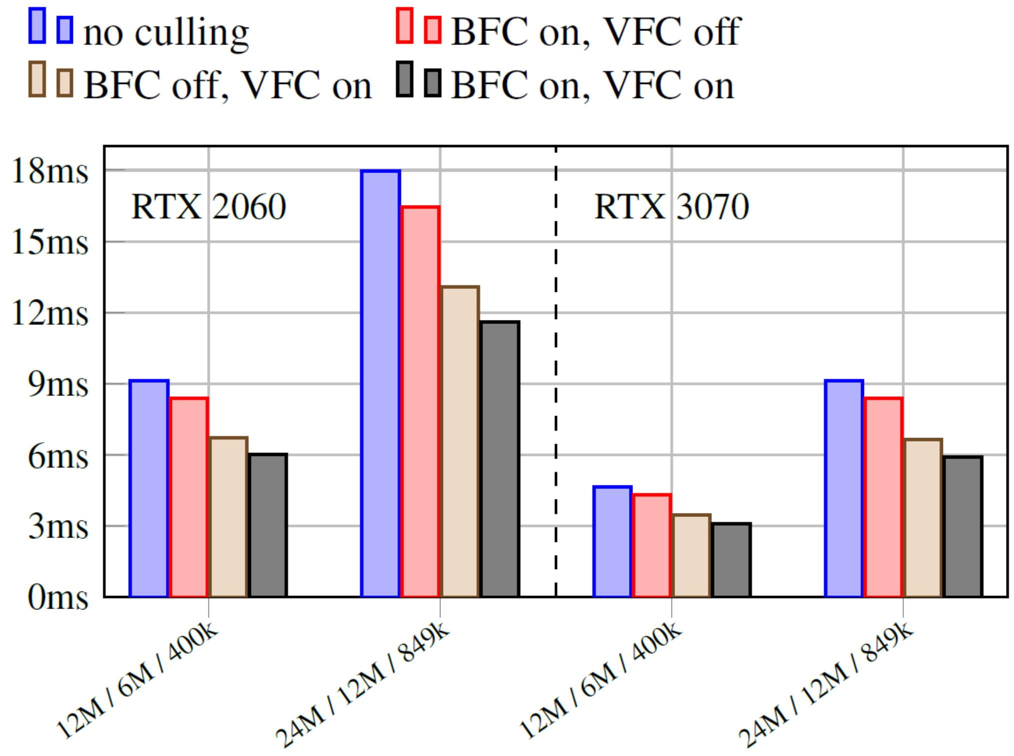
Results



GPU	Scene	BFC only		VFC only		BFC+VFC	
		Culled	Faster	Culled	Faster	Culled	Faster
RTX 2060	400k	11.4%	8.1%	31.3%	26.3%	39.9%	33.8%
	849k	11.5%	8.5%	31.4%	27.1%	39.7%	35.4%
RTX 3070	400k	11.4%	7.8%	31.3%	26.1%	39.9%	34.0%
	849k	11.5%	7.9%	31.4%	27.2%	39.7%	35.4%

Results



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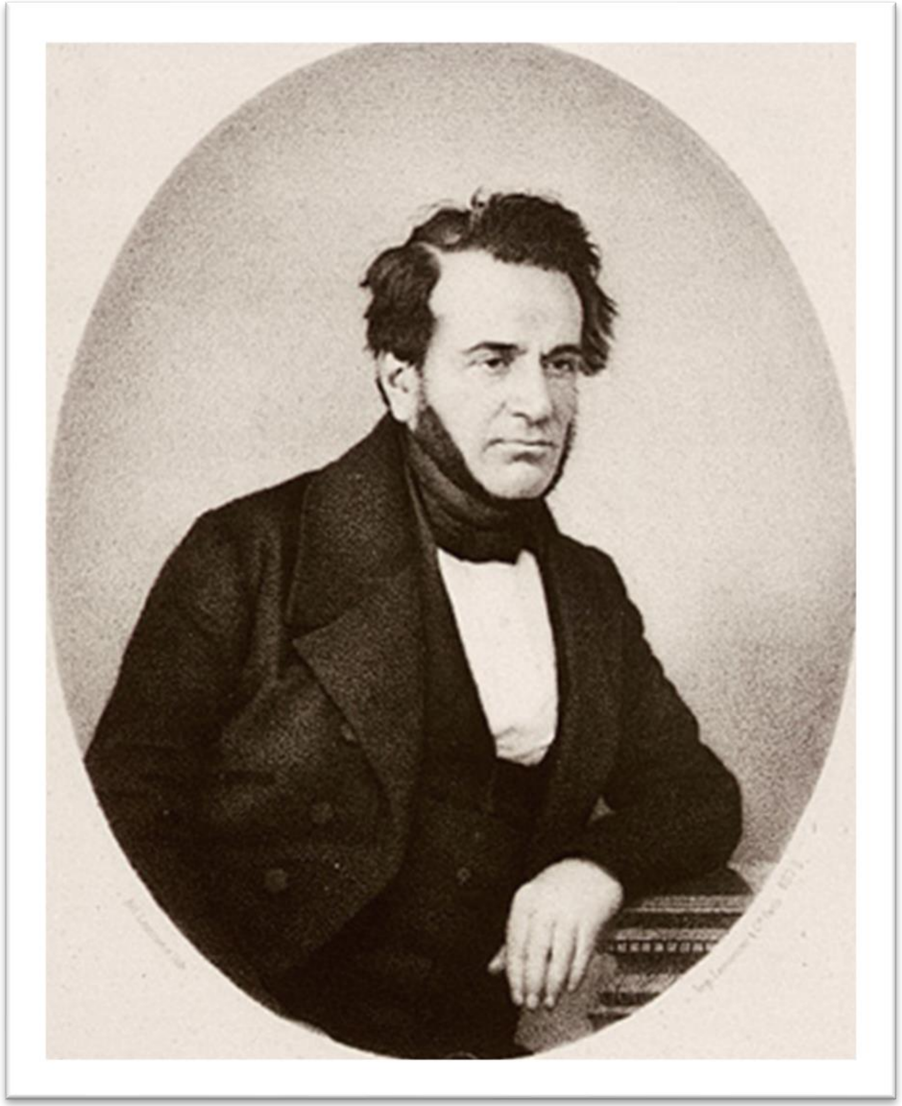
Pacific Graphics 2021

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

"Gawain" model © by Unity Technologies, provided through their "The Heretic: Digital Human" package.

Johannes Unterguggenberger, Bernhard Kerbl, Jakob Pernsteiner, and Michael Wimmer
TU Wien, Institute of Visual Computing & Human-Centered Technology, Austria



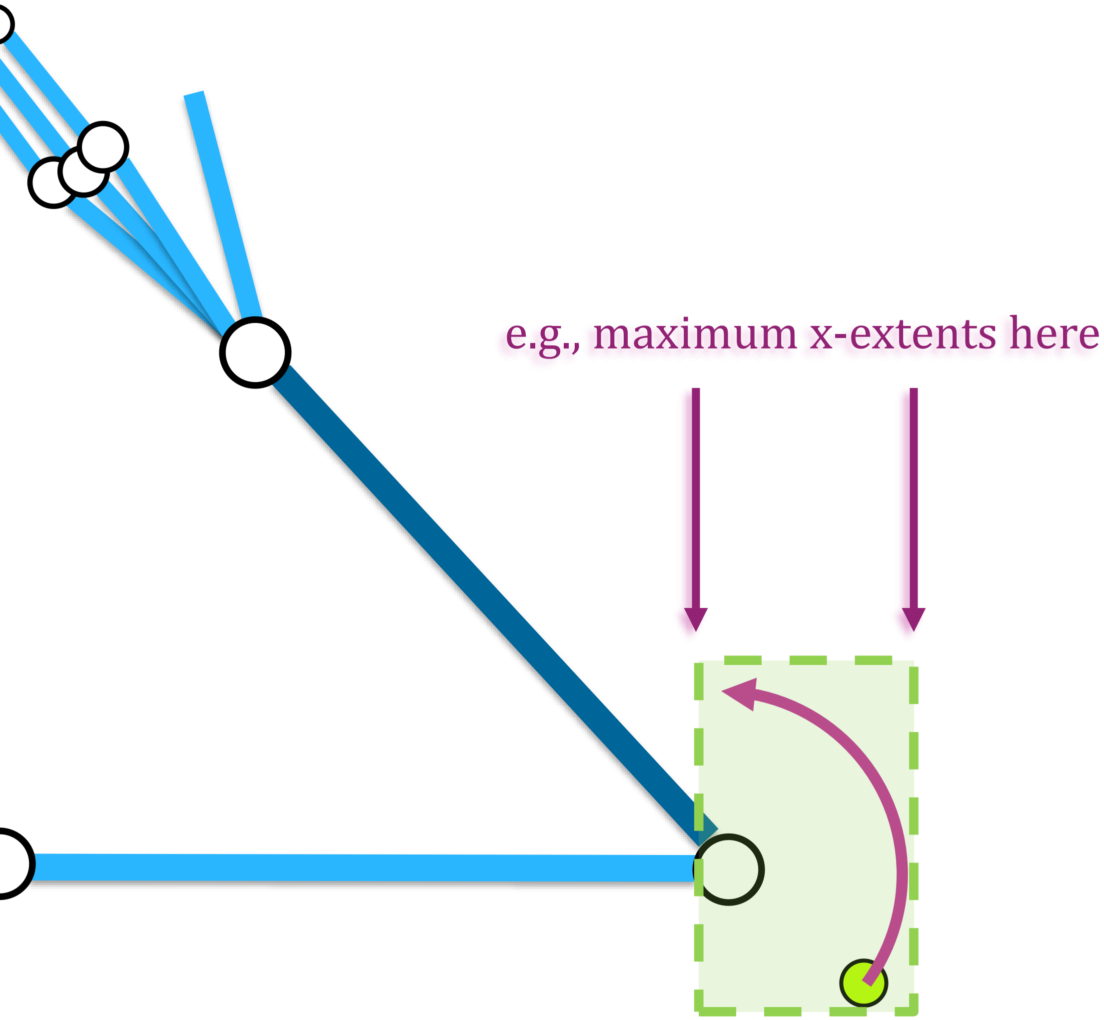
Rodrigues' Rotation Formula

Rotating a vector in space,
given axis and angle of rotation.

Quaternions can be converted
into that form.

Conservative Rotation Bounds

Conservative Rotation Bounds



$$\boldsymbol{v}' = \boldsymbol{v}\cos\theta + (\boldsymbol{n}\times\boldsymbol{v})\sin\theta + \boldsymbol{n}(\boldsymbol{n}\cdot\boldsymbol{v})(1-\cos\theta). \quad (3)$$

We use its first-order derivative by θ to find those angles that lead to maximum extents in each of the principal axes' directions. Setting that first-order derivative of Equation (3) by θ to zero in order to find the extrema results in Equation (4)

$$\boldsymbol{x}_\theta = -\tan^{-1}\frac{\boldsymbol{n}\times\boldsymbol{v}}{\boldsymbol{n}(\boldsymbol{n}\cdot\boldsymbol{v})-\boldsymbol{v}}, \quad (4)$$

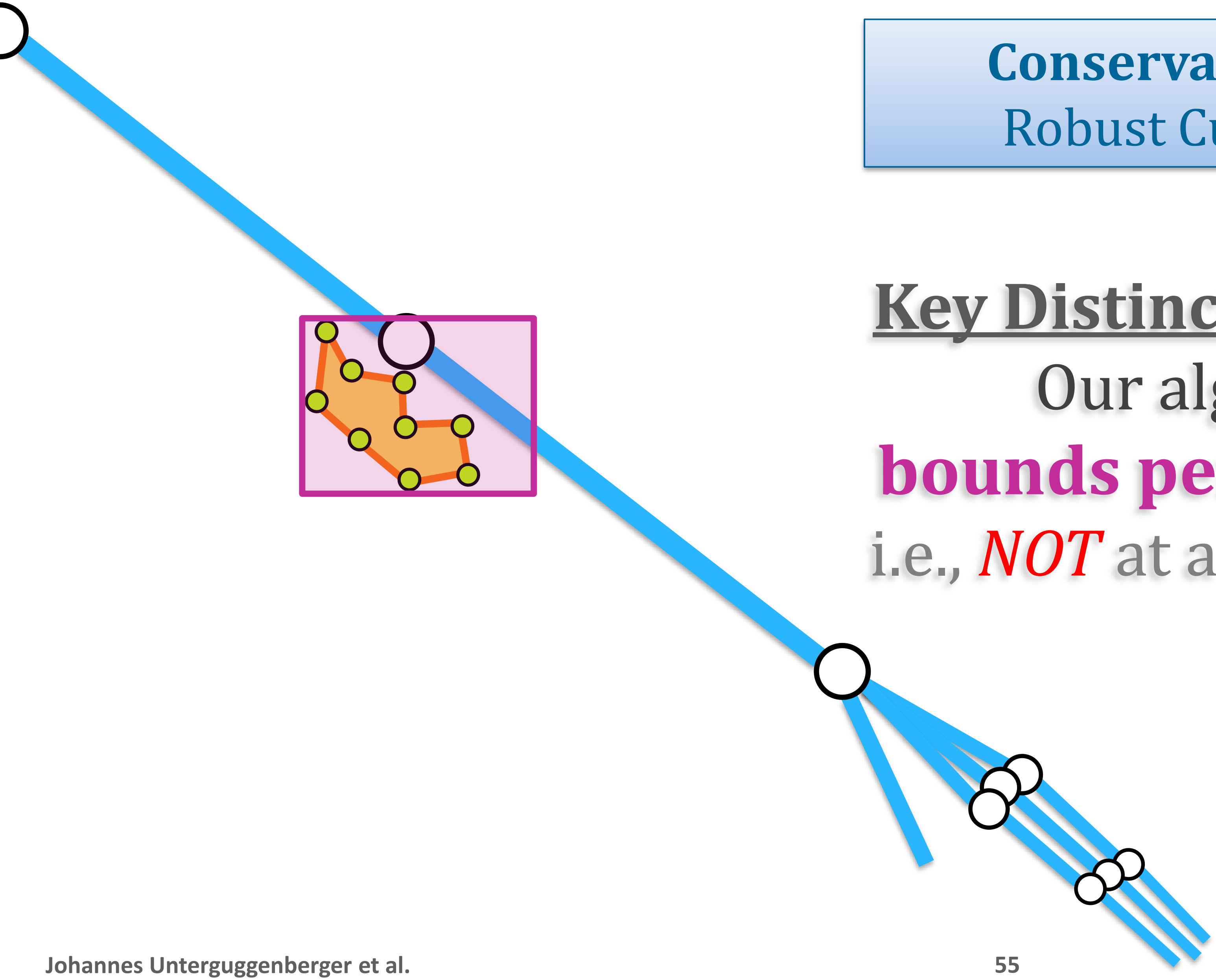
which yields a vector of angles $\boldsymbol{x}_\theta$ in radians that represents the rotation angles which lead to maximum extents in each principal axis direction. Please note that the operations in Equation (4) mean component-wise application of the division and $\tan^{-1}$.

Appendix

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

Johannes Unterguggenberger, Bernhard Kerbl, Jakob Pernsteiner, and Michael Wimmer
TU Wien, Institute of Visual Computing & Human-Centered Technology, Austria

Vertex Bounds

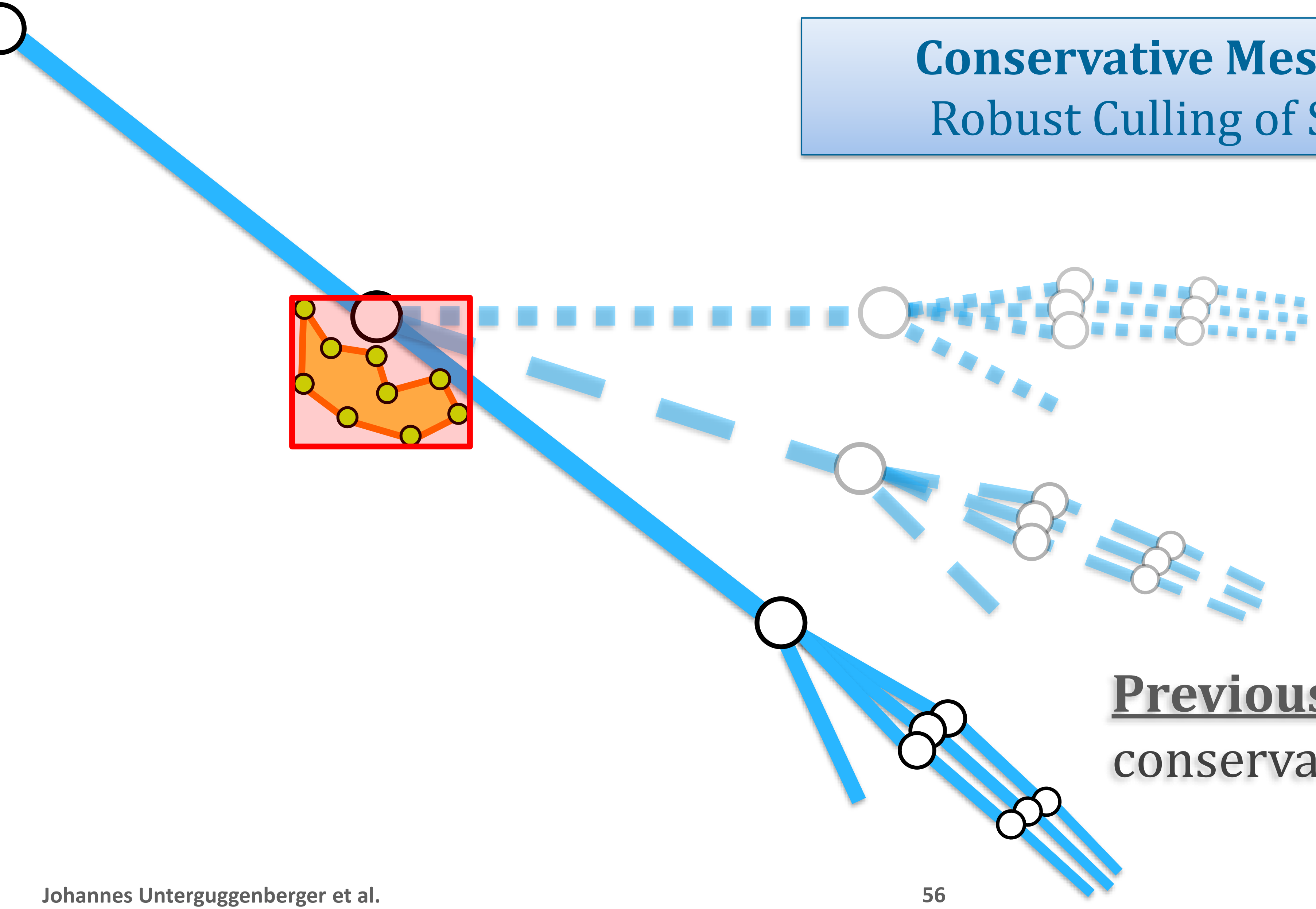


Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

Key Distinction to Previous Work:

Our algorithm computes
bounds per animation interval,
i.e., *NOT* at a specific animation time.

Meshlet Bounds



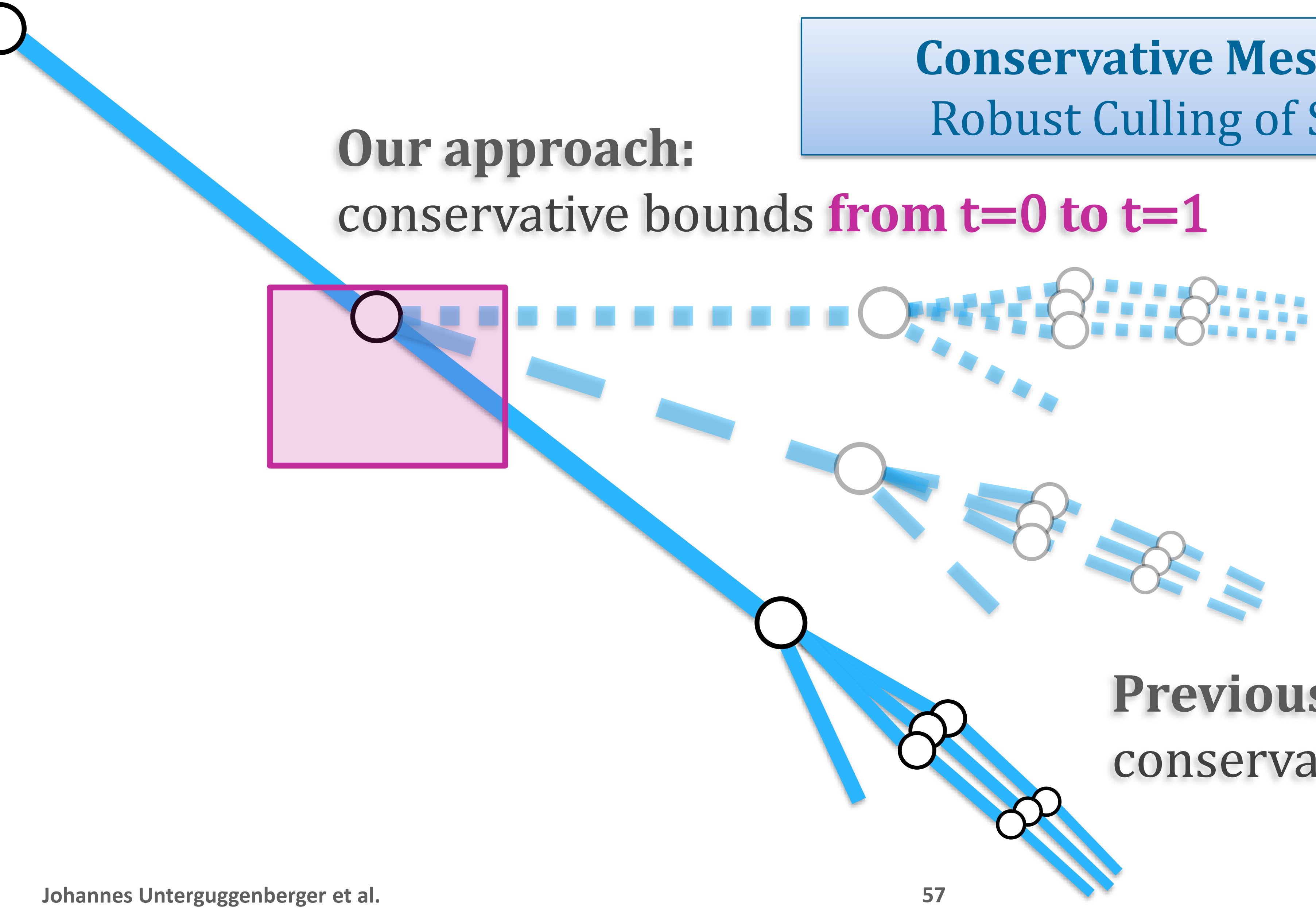
Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

Previous approaches:
conservative bounds **at** t=0.5

Meshlet Bounds

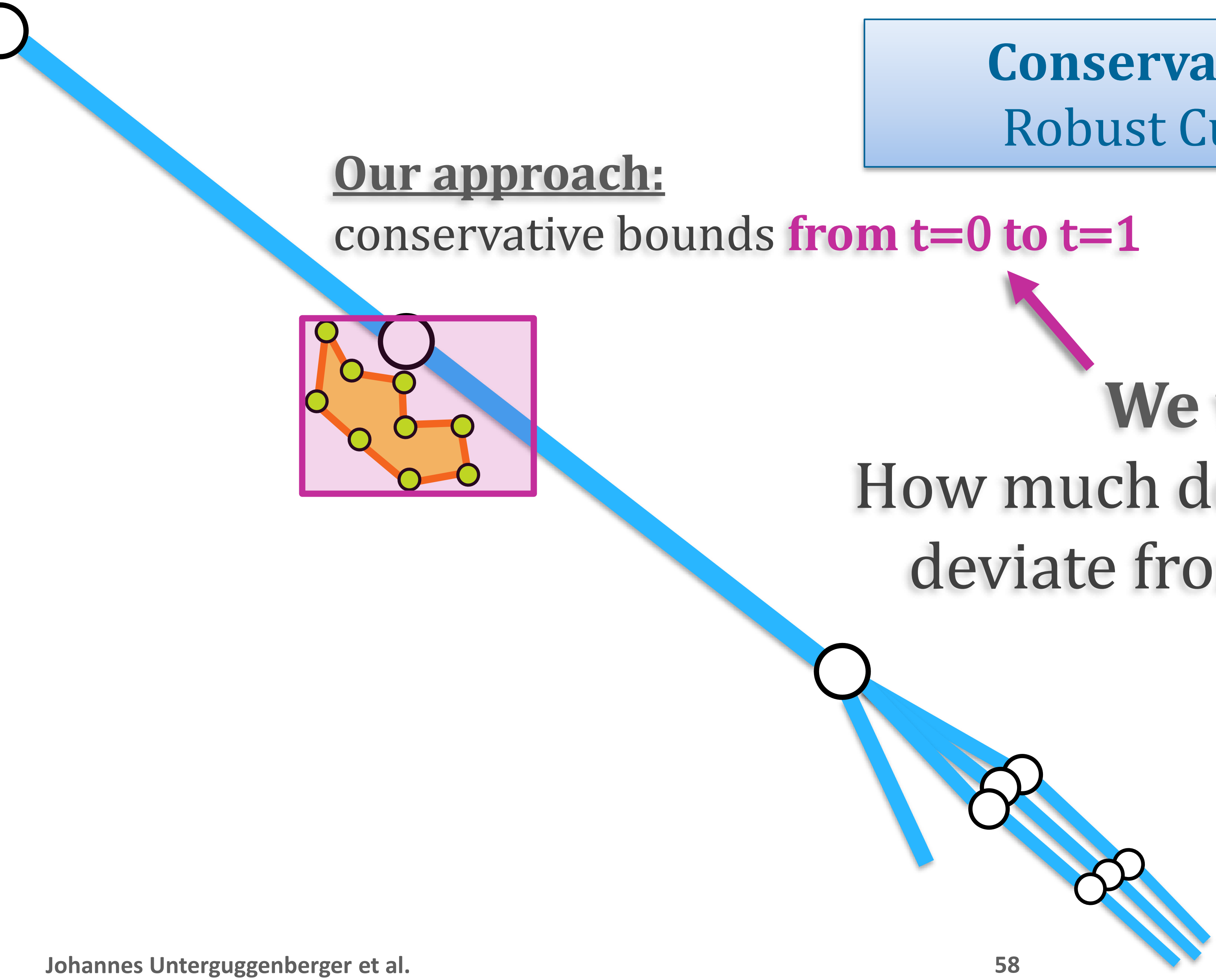
Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

Our approach:
conservative bounds **from t=0 to t=1**



Previous approaches:
conservative bounds **at t=0.5**

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes



Our approach:
conservative bounds **from t=0 to t=1**

We want to know:
How much do **any** animated bounds deviate from an initial position?

Previous approaches:
conservative bounds **at t=0.5**

Meshlet Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

Our approach:
conservative bounds **from t=0 to t=1**

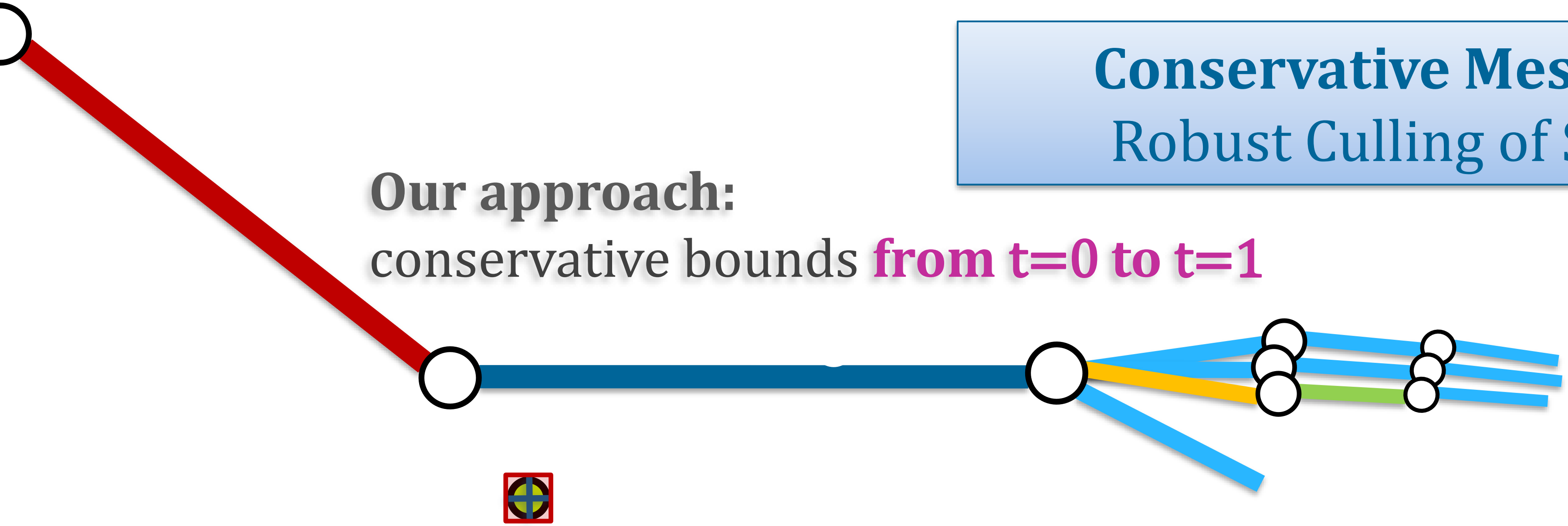
We want to know:
How much do **any** animated bounds deviate from an initial position?

Because if we know
across all animation states
=> very efficient culling in task shader
no computation/memory fetch for different animation states per meshlet with **constant scaling factor**

Meshlet Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

Our approach:
conservative bounds **from t=0 to t=1**



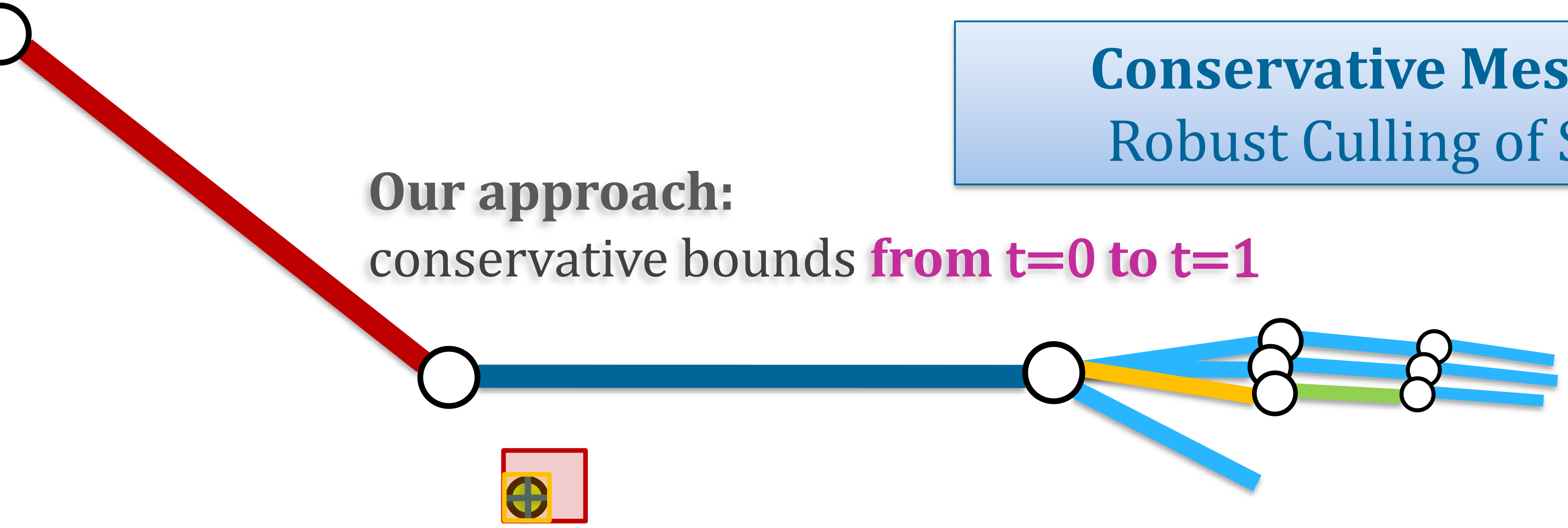
Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

Our approach:
conservative bounds **from t=0 to t=1**

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

Our approach:

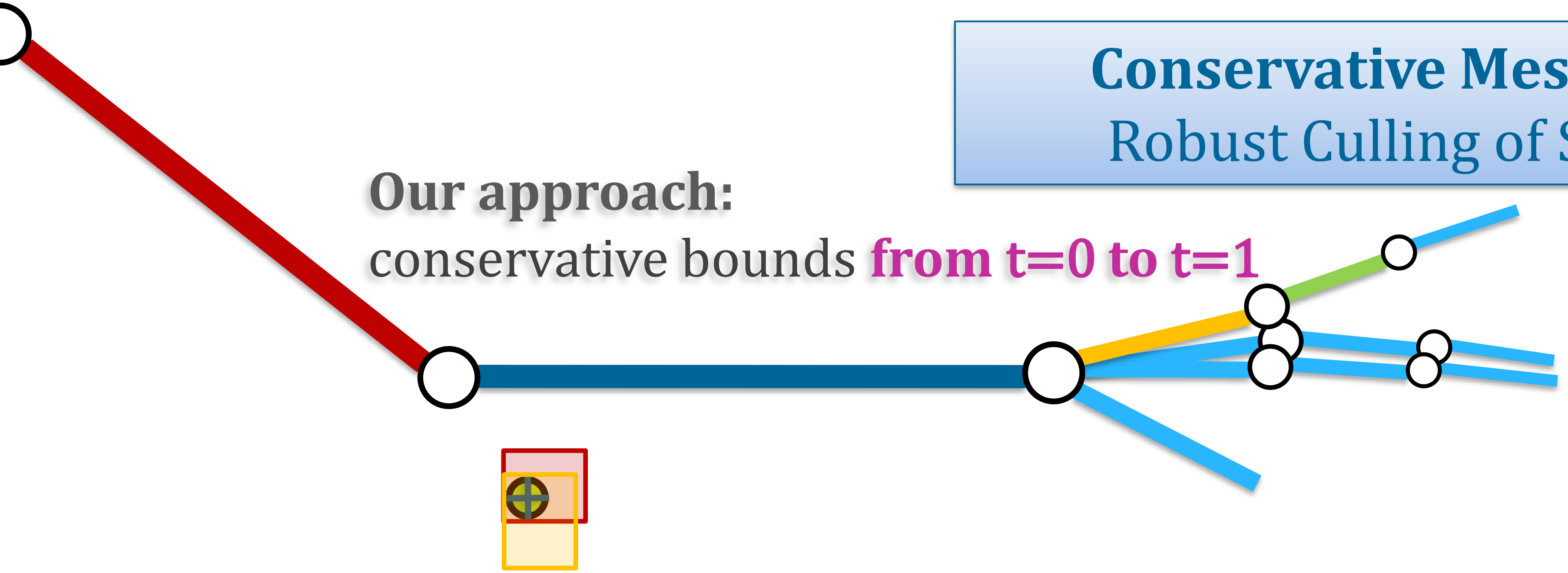
conservative bounds **from t=0 to t=1**



Meshlet Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

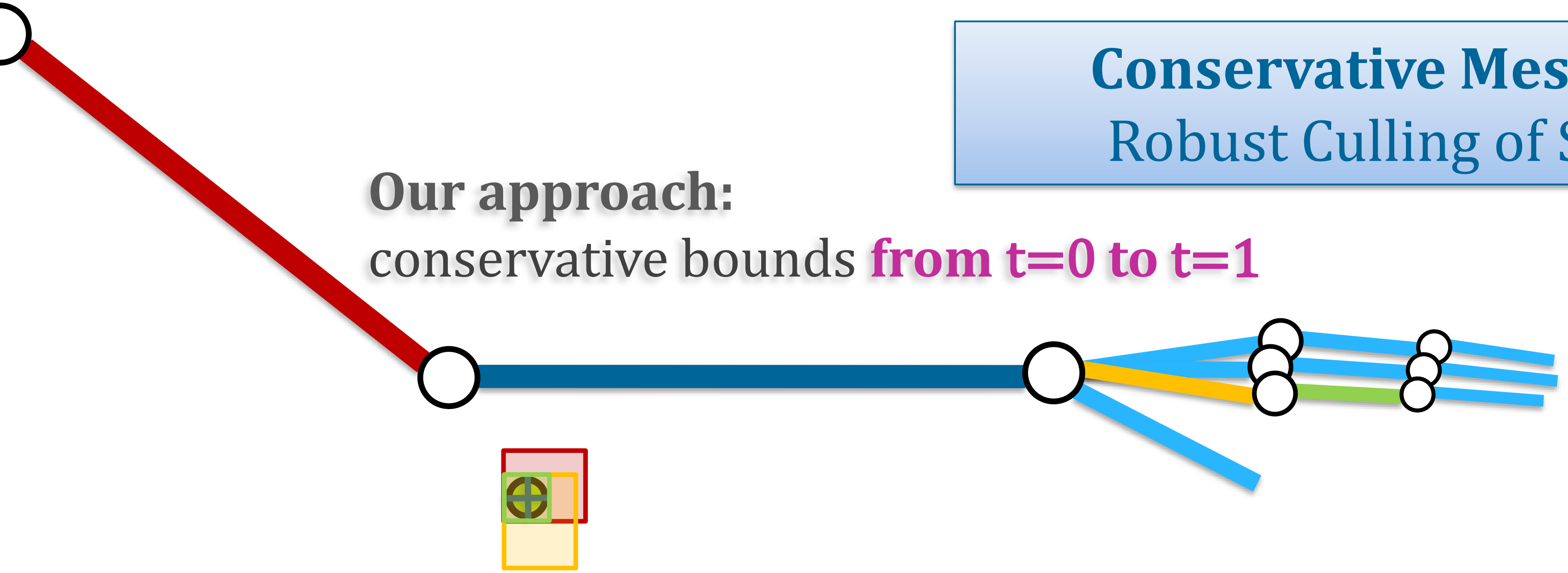
Our approach:
conservative bounds **from t=0 to t=1**



Meshlet Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

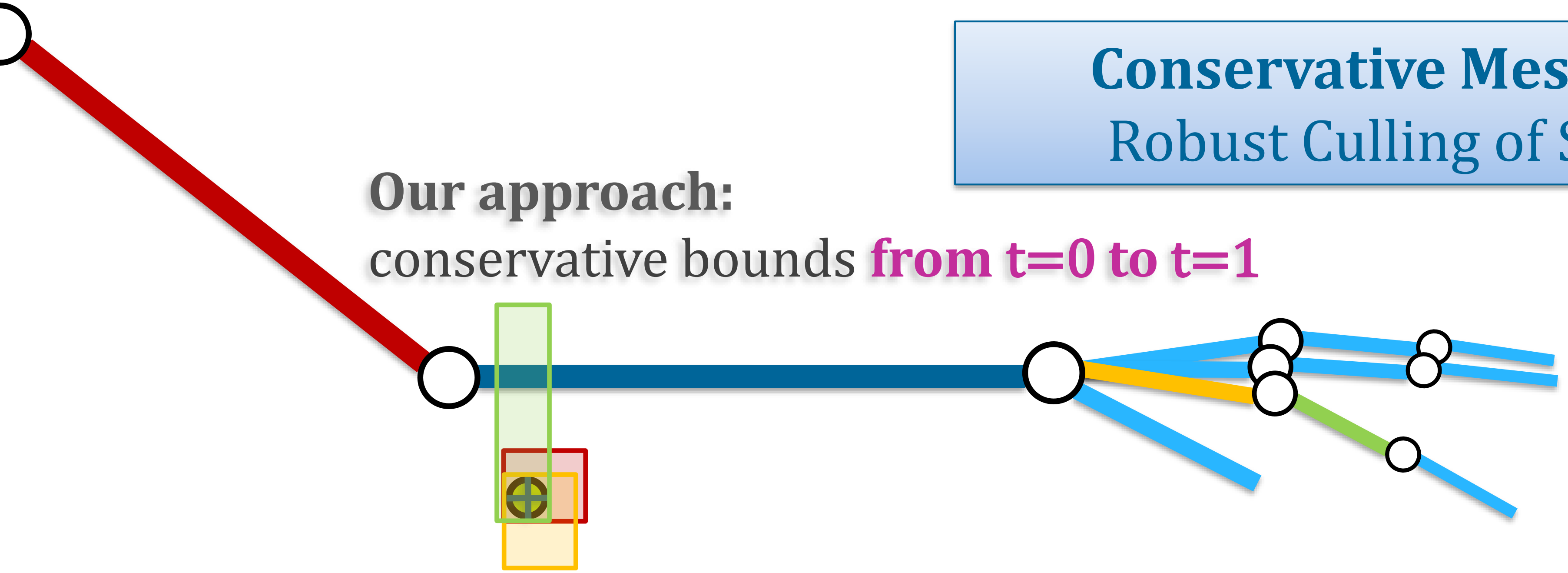
Our approach:
conservative bounds **from t=0 to t=1**



Meshlet Bounds

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

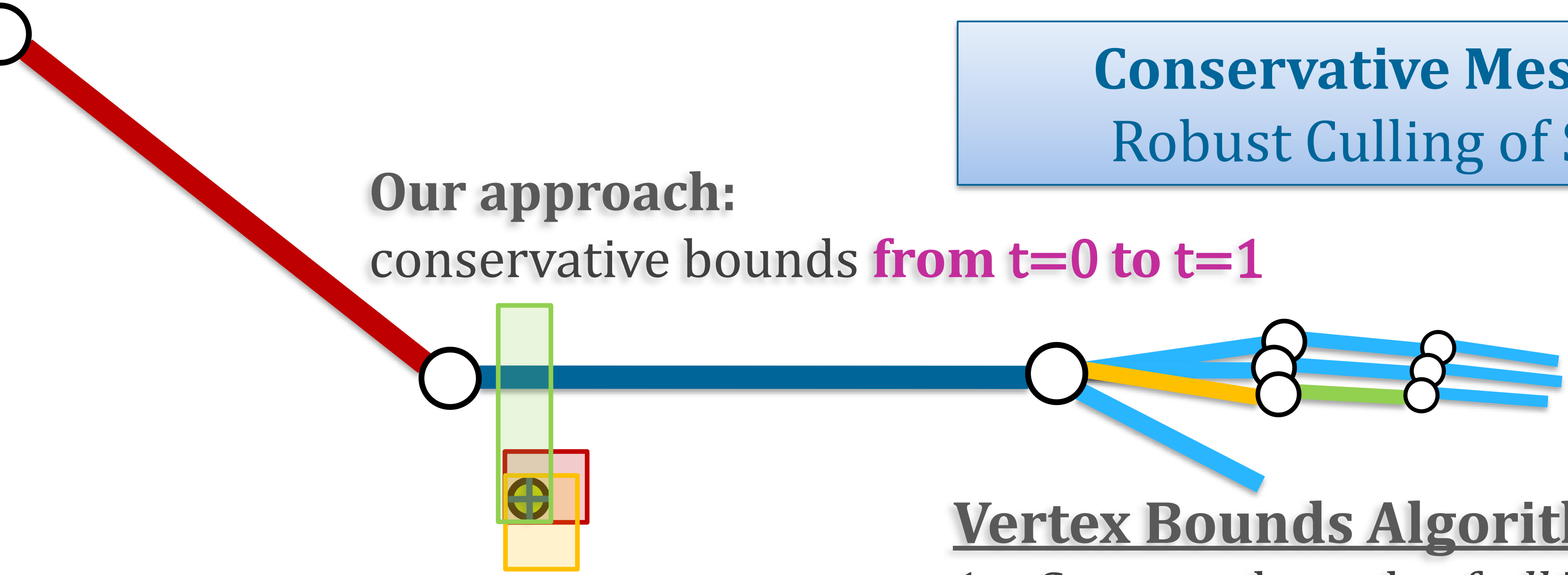
Our approach:
conservative bounds **from t=0 to t=1**



Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

Our approach:

conservative bounds **from t=0 to t=1**



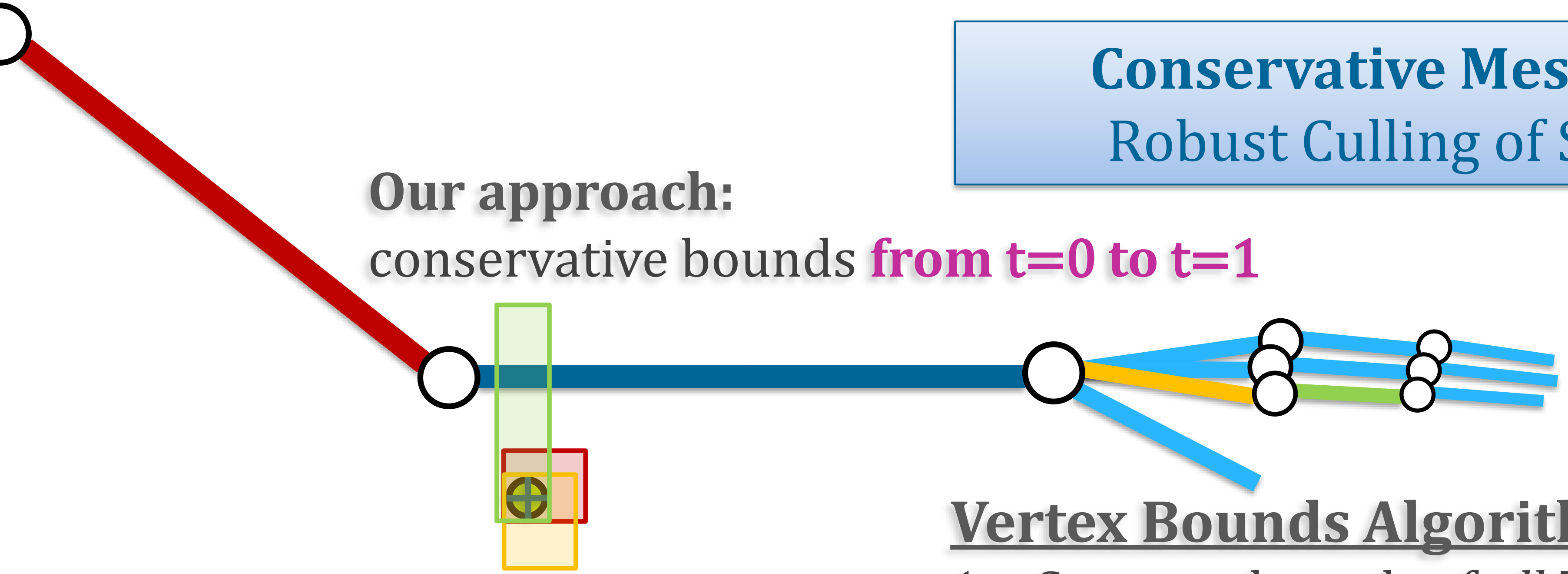
Vertex Bounds Algorithm:

1. Compute bounds of *all* **individual bones** of influence (weight != 0) as if they had weight 1
   a) Initial bounds
   b) Step-wise towards target bone
   c) Conservatively extend
2. Combine weighted into **vertex bounds** according to the skinning method used (LBS)

Meshlet Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

Our approach:
conservative bounds **from t=0 to t=1**



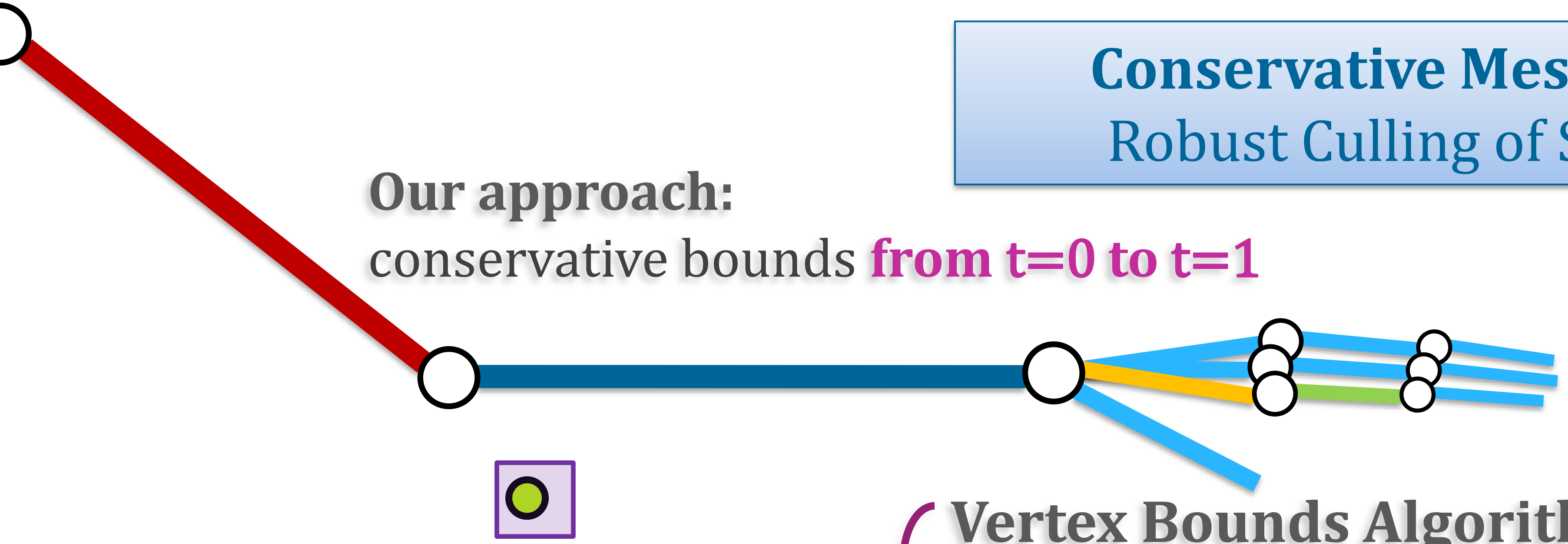
Contribution:
Conservative extension by maximum rotations in x, y, z through a derivative of Rodrigues' Rotation Formula

Vertex Bounds Algorithm:

1. Compute bounds of *all* **individual bones** of influence (weight != 0) as if they had weight 1
   a) Initial bounds
   b) Step-wise towards target bone
   c) Conservatively extend
2. Combine weighted into **vertex bounds** according to the skinning method used (LBS)

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

Our approach:
conservative bounds **from t=0 to t=1**



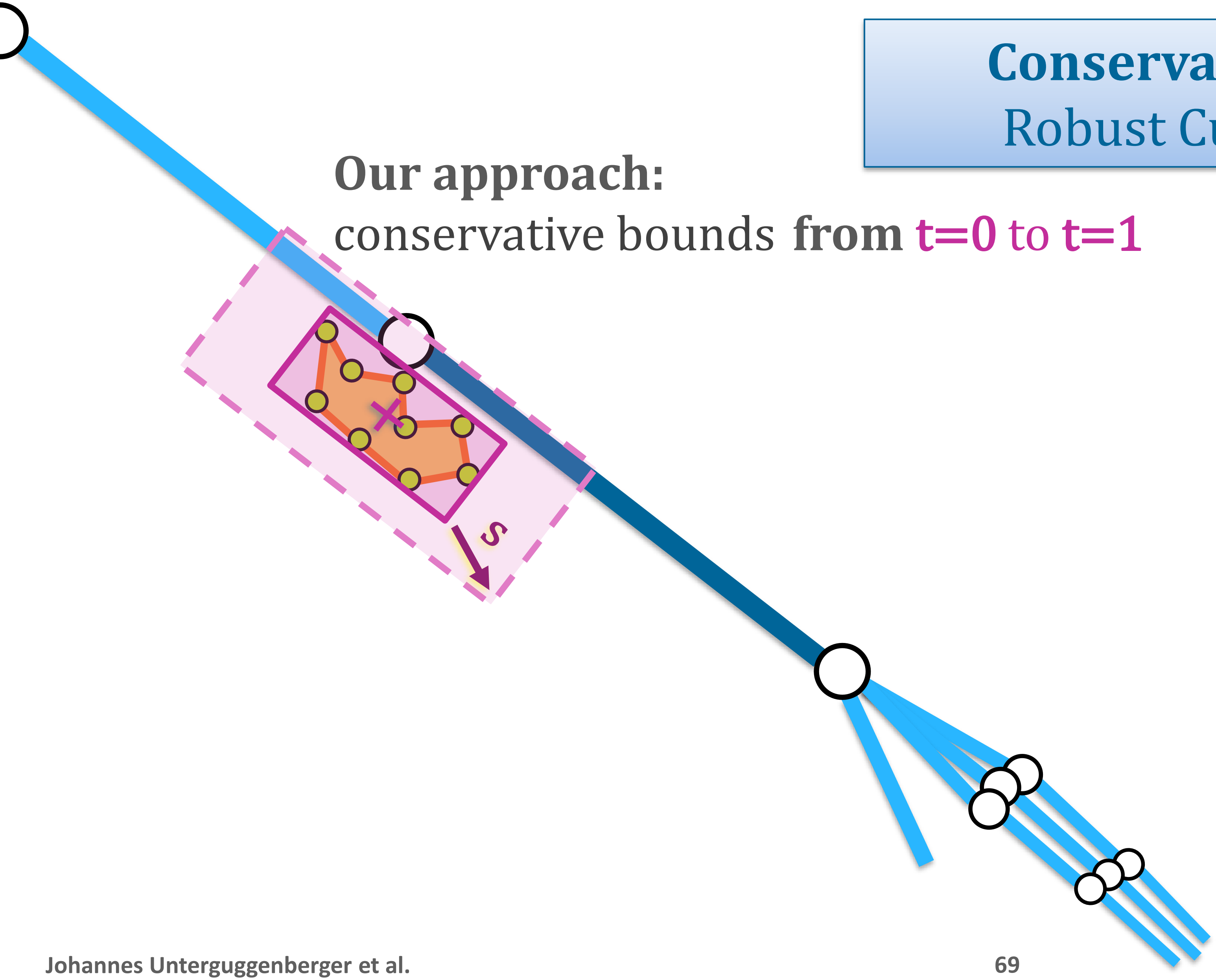
as precomputation step

Vertex Bounds Algorithm:

1. Compute bounds of *all* **individual bones** of influence (weight != 0) as if they had weight 1
   a) Initial bounds
   b) Step-wise towards target bone
   c) Conservatively extend
2. Combine weighted into **vertex bounds** according to the skinning method used (LBS)

Conservative Meshlet Bounds for Robust Culling of Skinned Meshes

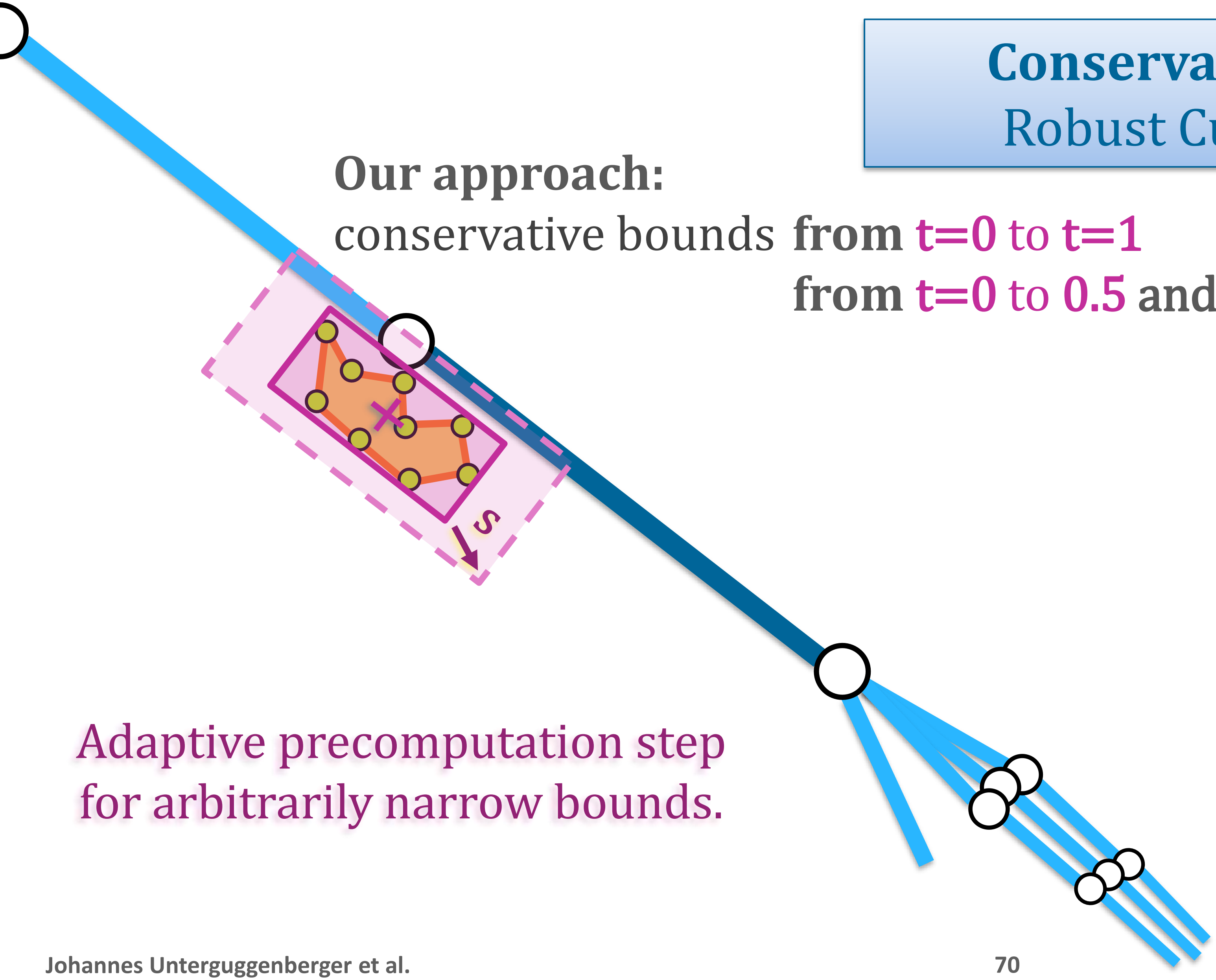
Our approach:
conservative bounds **from t=0** to **t=1**



Meshlet Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes

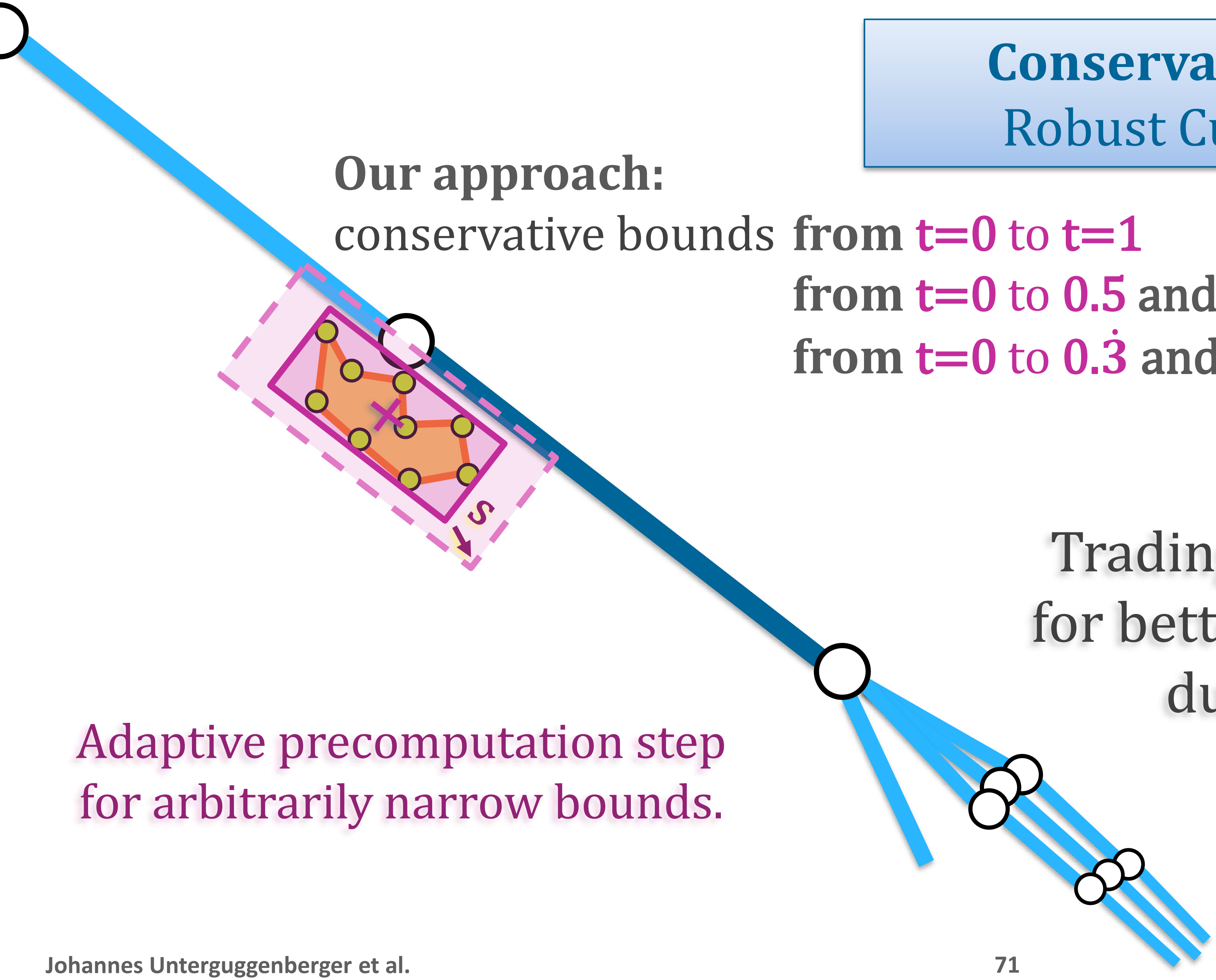
Our approach:
conservative bounds **from t=0 to t=1**
from t=0 to 0.5 and t=0.5 to 1



Adaptive precomputation step
for arbitrarily narrow bounds.

Meshlet Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes



Our approach:

conservative bounds **from** t=0 to t=1

from t=0 to 0.5 **and** t=0.5 to 1

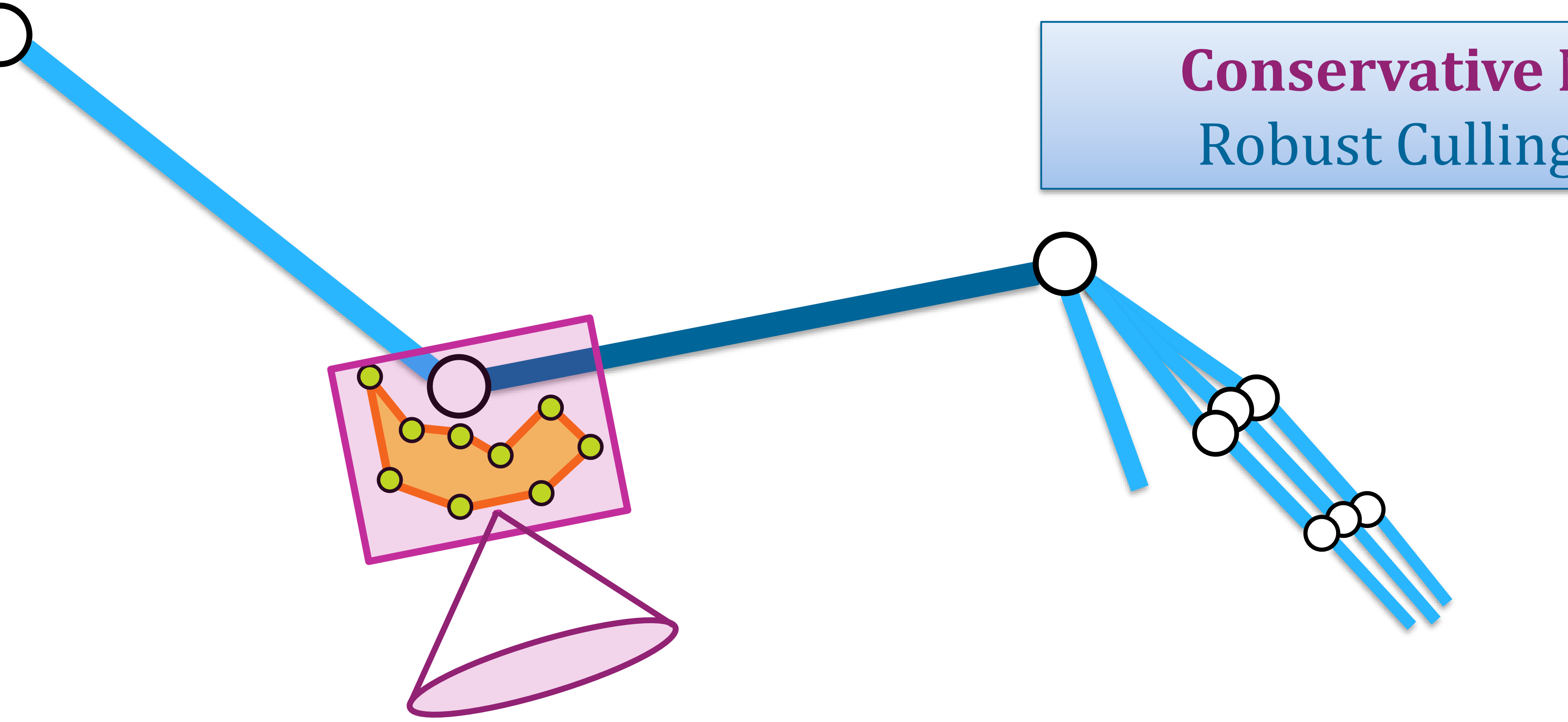
from t=0 to $0.\dot{3}$ **and** t=$0.\dot{3}$ to $0.\dot{6}$ **and and** t=$0.\dot{6}$ to 1

Trading precomputation effort
for better runtime performance,
due to better bounds.

Adaptive precomputation step
for arbitrarily narrow bounds.

Meshlet Bounds

Conservative Meshlet Bounds for
Robust Culling of Skinned Meshes



- High memory consumption
- Increased memory bandwidth
- More cache misses

Calculate bounds for all animation intervals of interest!

from t=0 to t=1
from t=1 to t=2
from t=2 to t=3

~~Store one bounding box per interval?~~