Physics-Inspired Adaptive Fracture Refinement

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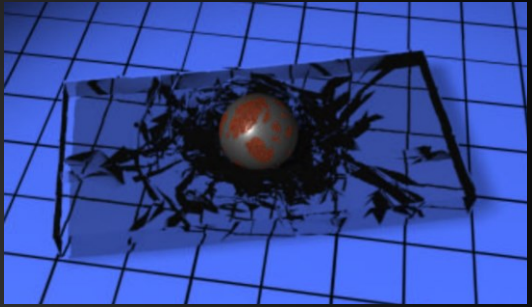
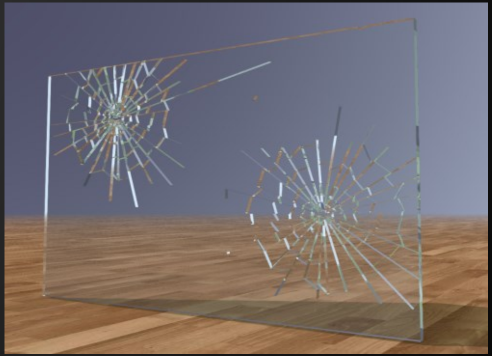
Fracture Animation

- Physically simulated fracture
  - ✓ Physically accurate
  - X Stability issue
  - X Slow in high resolution
- Pre-defined fracture pattern
  - ✓ Easier artistic control
  - ✓ Fast and robust
  - X Difficult to create physically plausible detail



O’brien, et.al. 1999

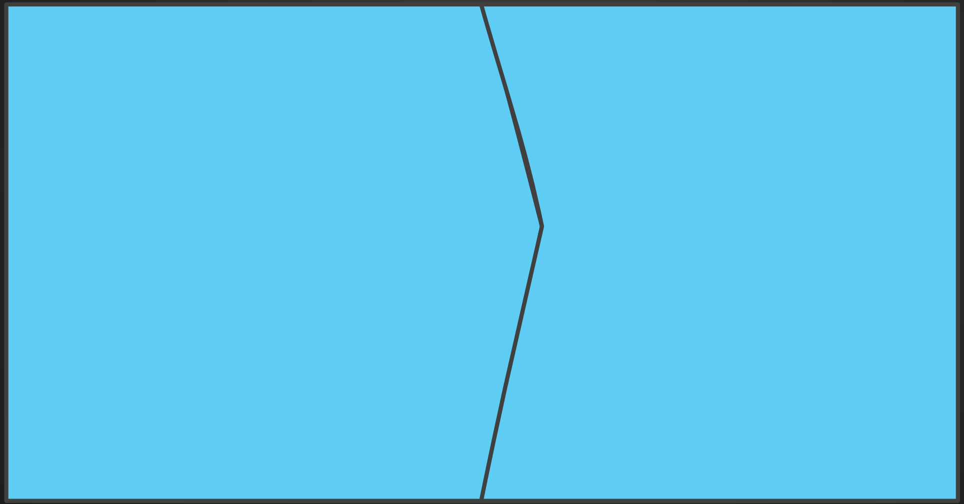


Müller, et.al. 2013

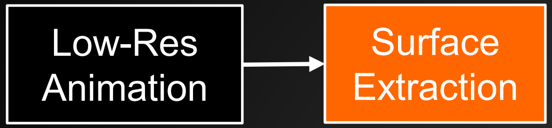
Physics-Inspired Fracture Refinement

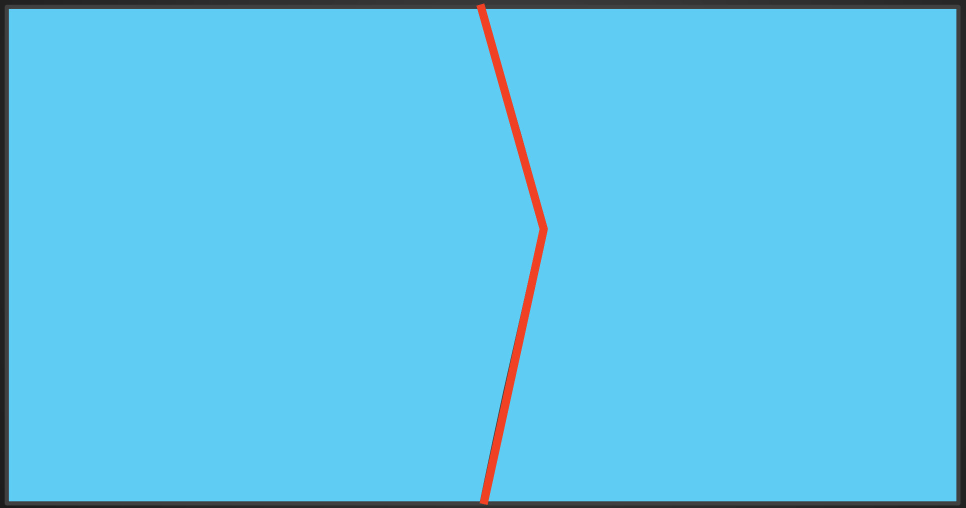
- Physically plausible
  - Material property and stress variation
- Fast and stable
  - Generate refined result in seconds
- Easy artistic control
  - Can use low-resolution animation as preview

Low-Res Animation

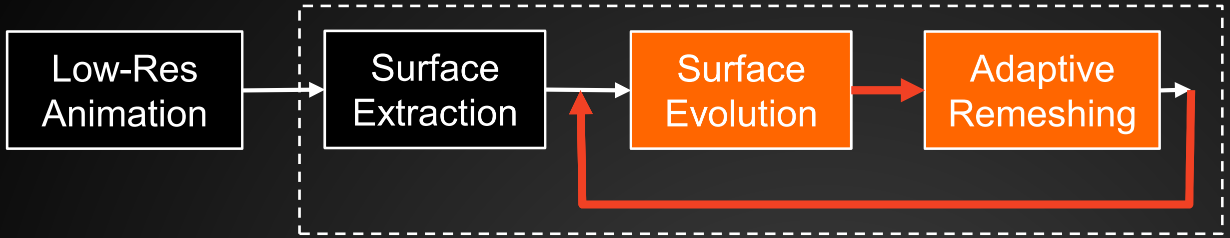


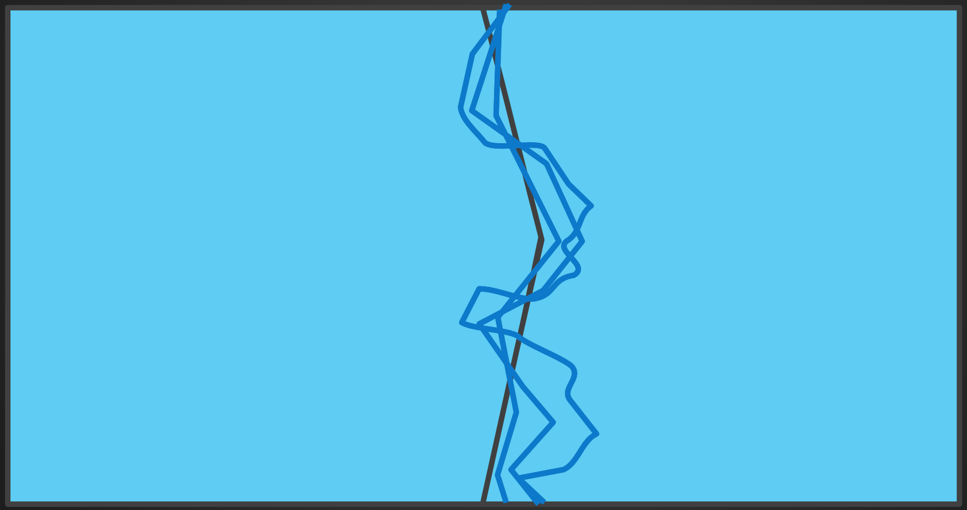
Input animation in low resolution



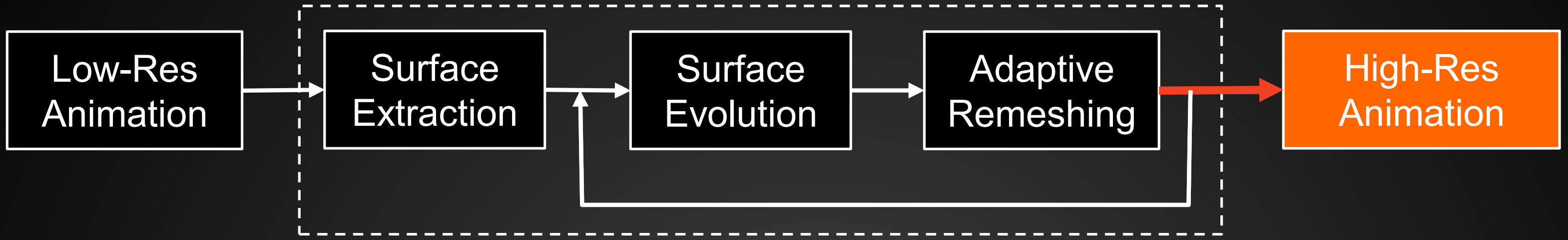


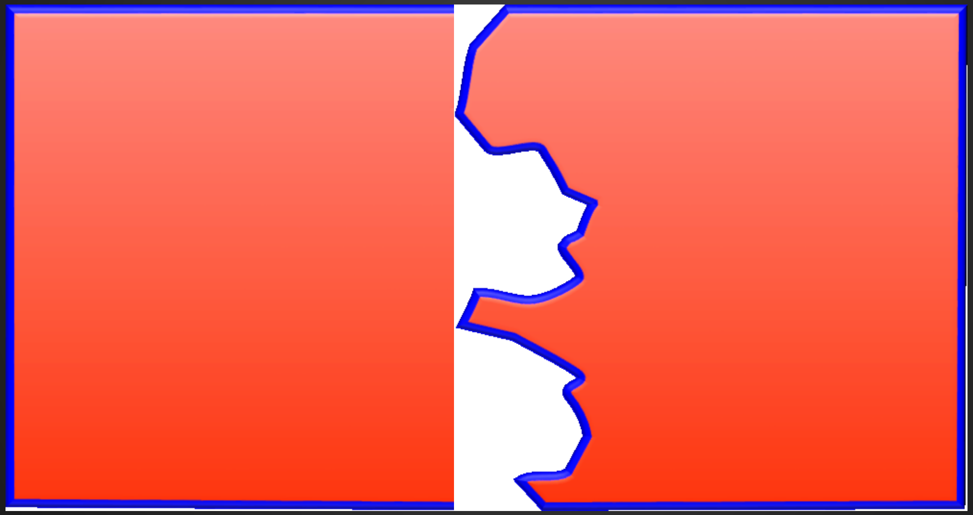
Low-resolution fracture surface





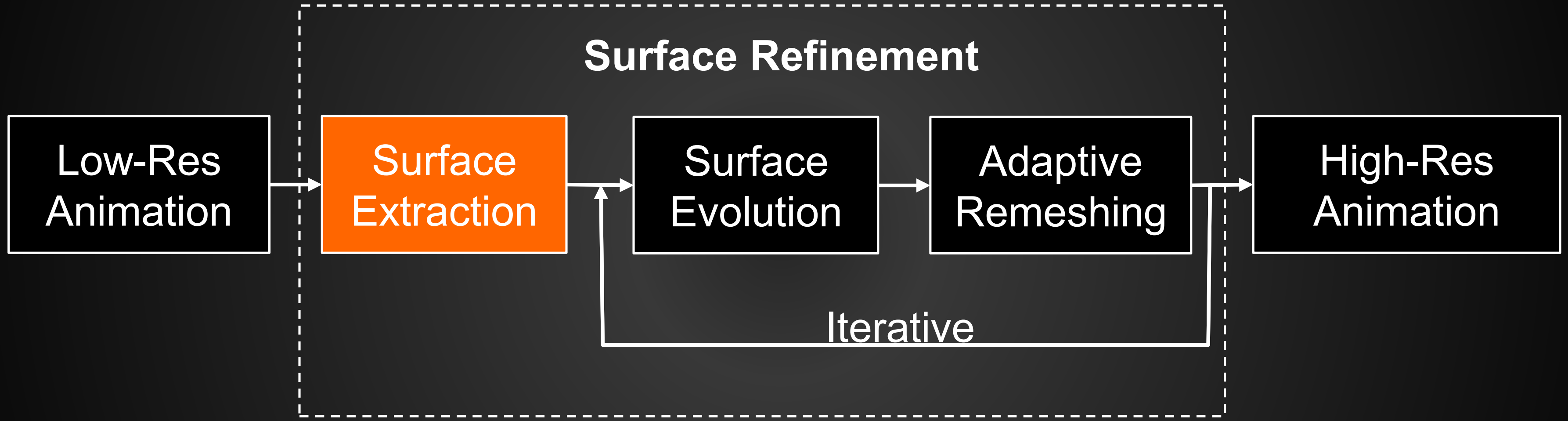
Evolve fracture surface to higher resolution



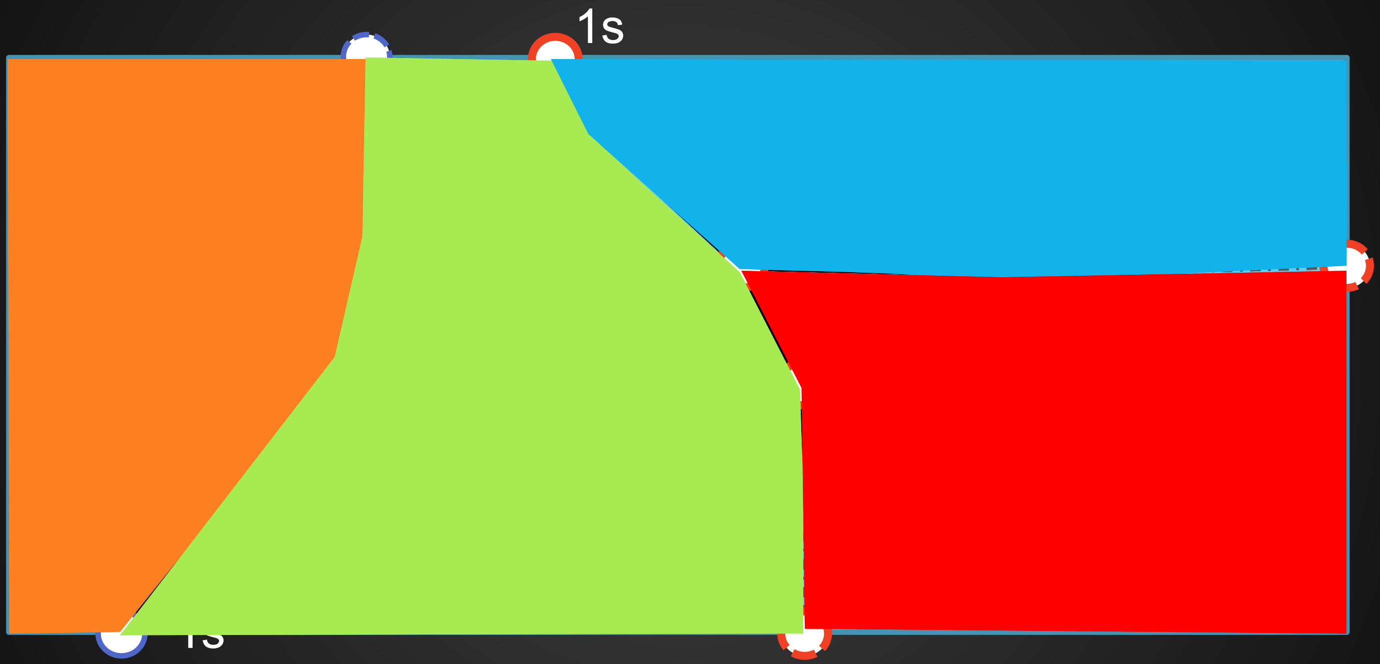


Transfer deformation to high-resolution fracture surface

Physics-Inspired Fracture Refinement

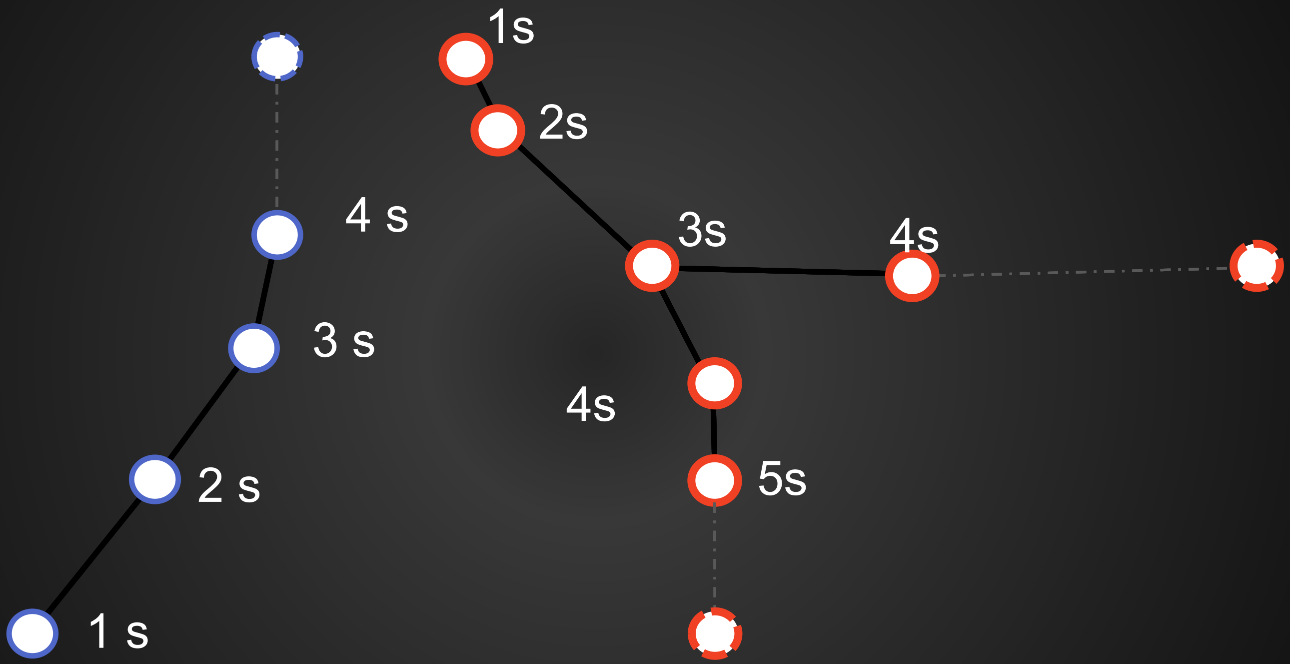


Fracture Surface Extraction



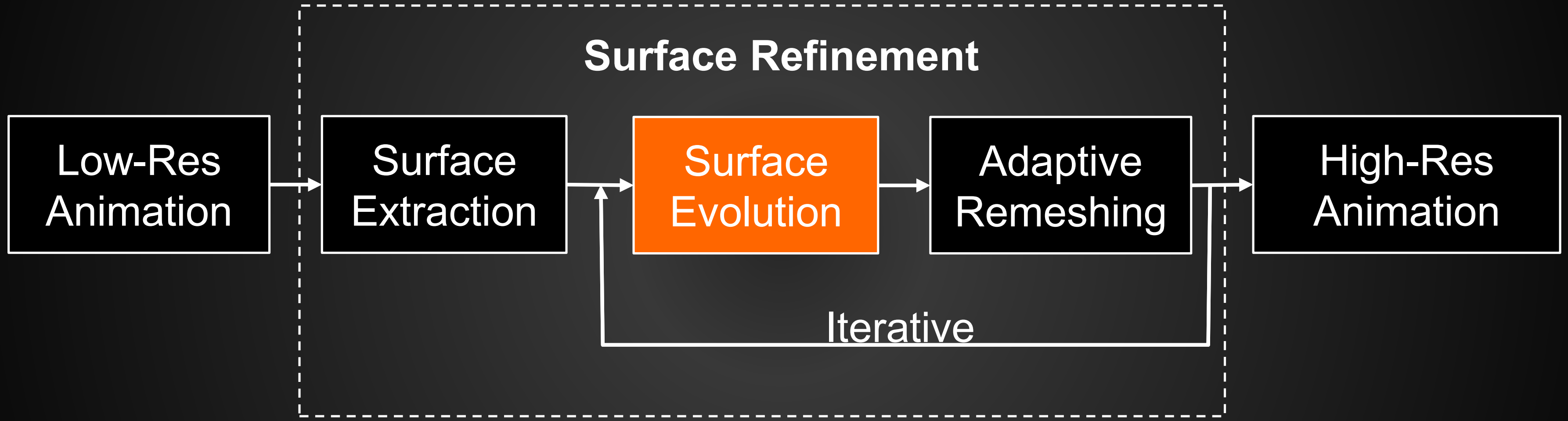
Material space in final frame

Fracture Surface Extraction



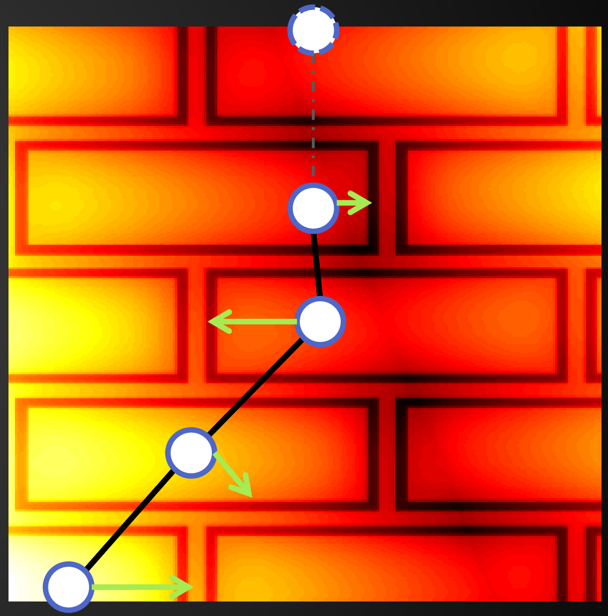
Material space in final frame

Physics-Inspired Fracture Refinement



Fracture Surface Evolution

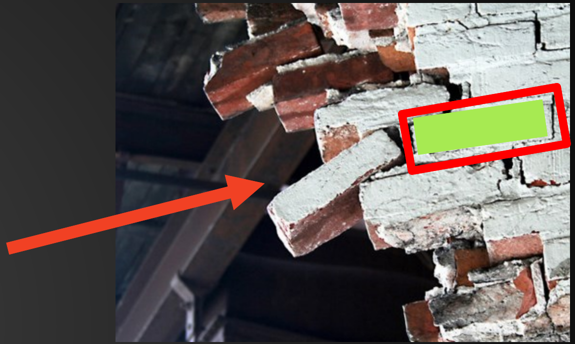
- How to advect vertices?
  - Towards where the material most likely breaks
  - Define Separation Field in high resolution
  - Vertices advect in separation field



Separation Field

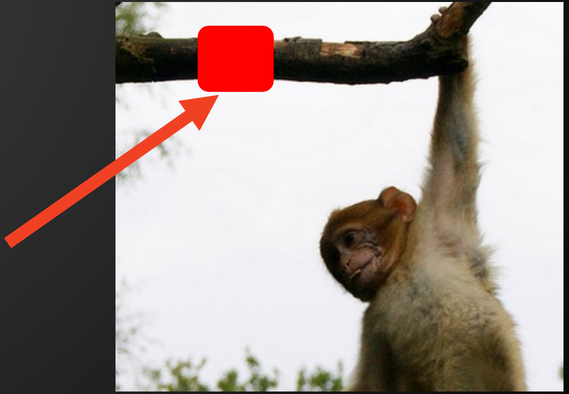
Material Strength Field

Some locations within the object are more likely to break due to material property/structure

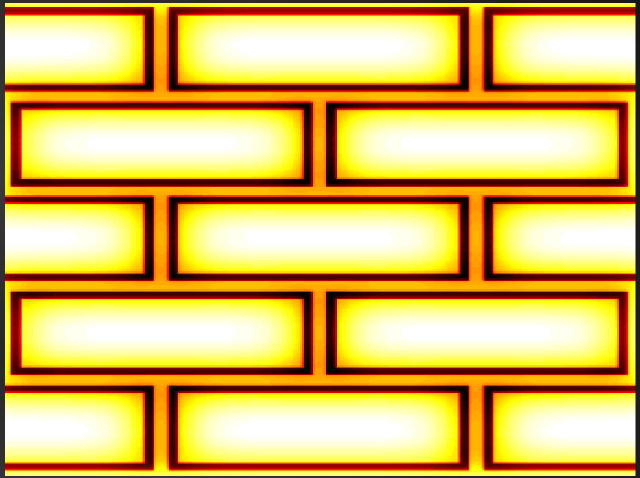


Stress Field

The object is more likely to break at where the stress is large



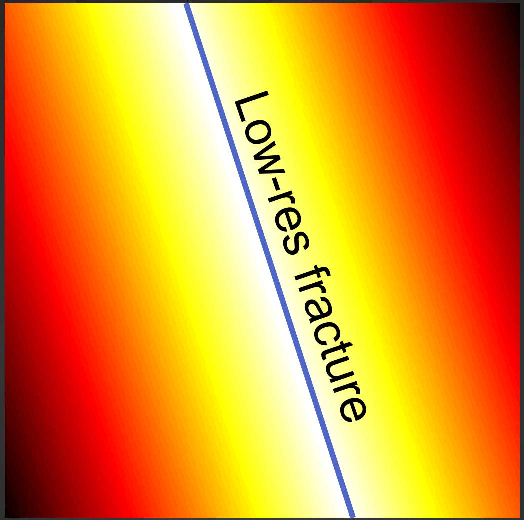
Material Strength Field



Darker –> Easier to break

– Volumetric field as user input
  - Procedurally generated solid texture
  - Volumetric data from CT scan, etc.
  - Voxelization of 3D mesh

Stress Field

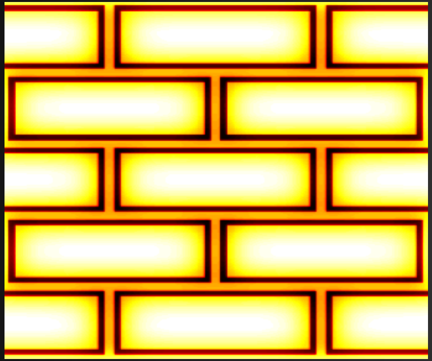
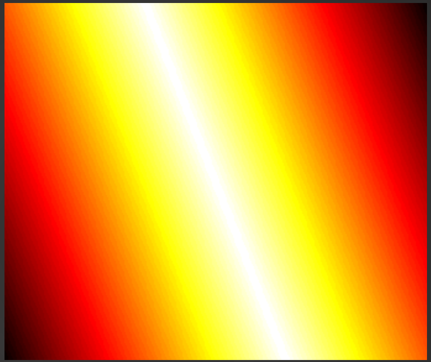
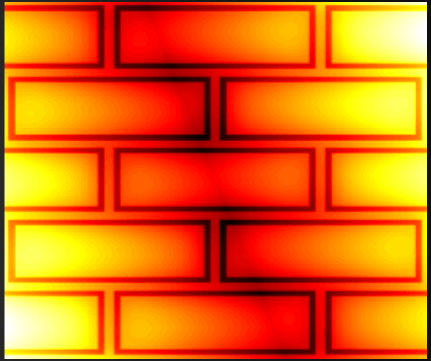


Brighter –> Higher stress

Approximation:

- The closer to low-res fracture surface, the higher the stress

Separation Field

W1*  - W2*  = 

Material Strength Field

Stress Field

Separation Field

Discrete Gradient Descent Flow

Evolve surface $\mathbf{S}$ to minimize

$$\mathcal{E}(\mathbf{S}) = \int_{\mathbf{S}} \psi(x)\, ds \qquad (\psi(x)) \text{ separation field}$$

Gradient descent for each vertex

$$\frac{d\mathbf{x}_i}{dt} = -\frac{1}{A_i} \sum_{j \in N_i} \left(\int_{\mathbf{S}_j} \nabla_{\mathbf{x}_i} \psi(\mathbf{x}) \phi_i(\mathbf{x})\, ds - \frac{\mathbf{e}_j^i \times \mathbf{n}_j}{2A_j} \int_{\mathbf{S}_j} \psi(\mathbf{x})\, ds \right)$$

Delaunoy, A., and Prados, E. 2011.

Discrete Gradient Descent Flow

Evolve surface $\mathbf{S}$ to minimize

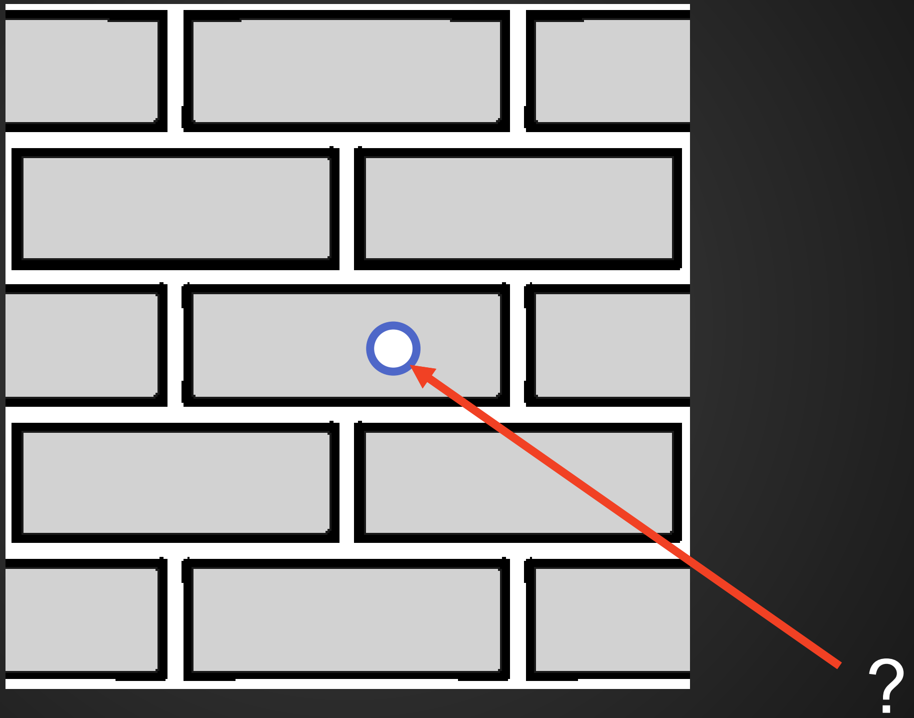
$$\mathcal{E}(\mathbf{S}) = \int_{\mathbf{S}} \psi(x)\, ds \qquad (\psi(x)) \text{ separation field}$$

Gradient descent for each vertex

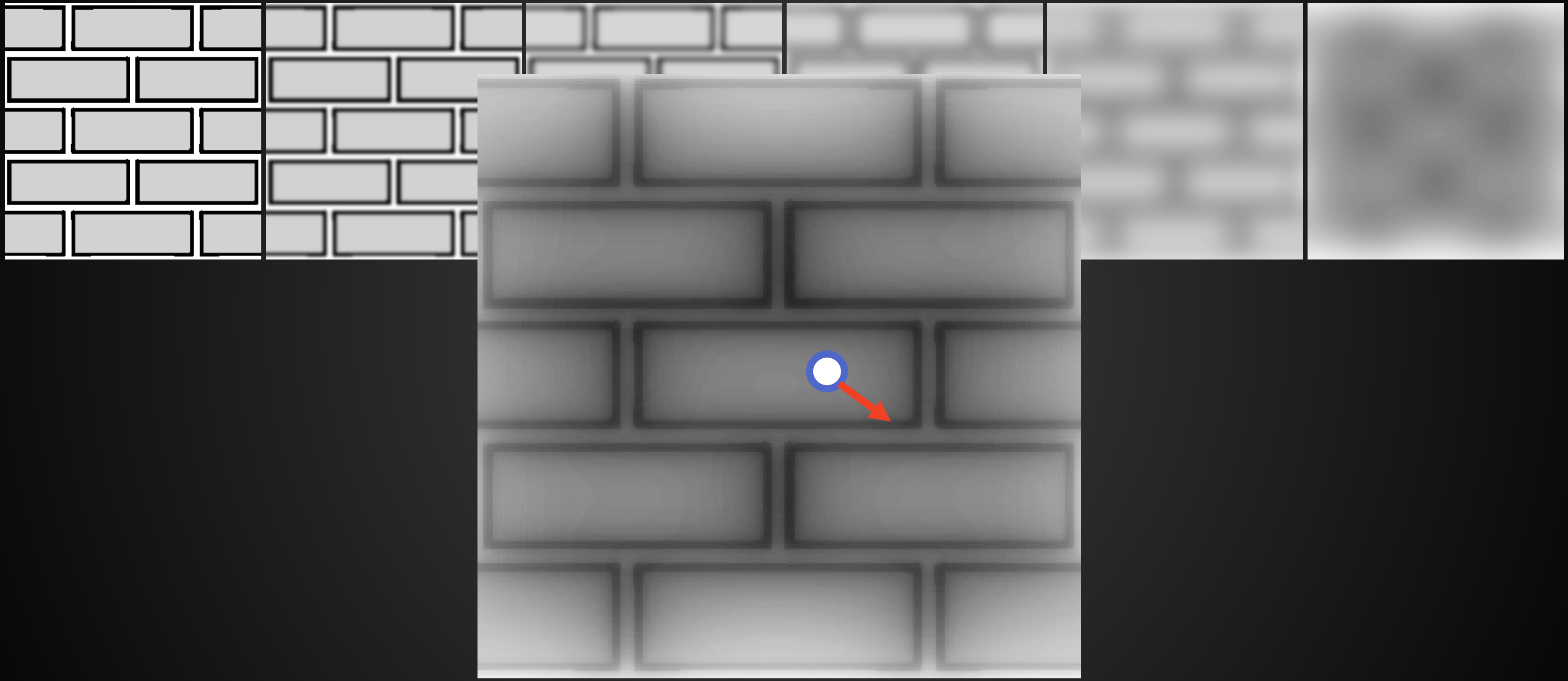
$$\frac{d\mathbf{x}_i}{dt} = -\frac{1}{A_i} \sum_{j \in N_i} \left(\frac{1}{3} A_j \nabla \psi(\mathbf{x}_i) - \frac{\mathbf{e}_j^i \times \mathbf{n}_j}{2A_j} \sum_{k \in T_j} \psi(\mathbf{x}_k) \right)$$

Approximation: $\psi(x)$ varies linearly within triangle plane

Gradient Computation

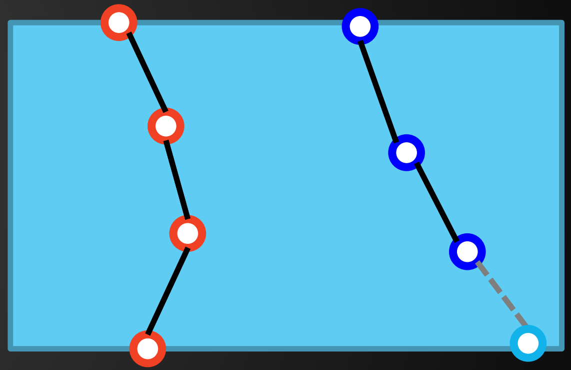


Gradient Computation



Constraints

- Fracture boundary
  - Vertices on exterior surface only move on exterior surface



Constraints

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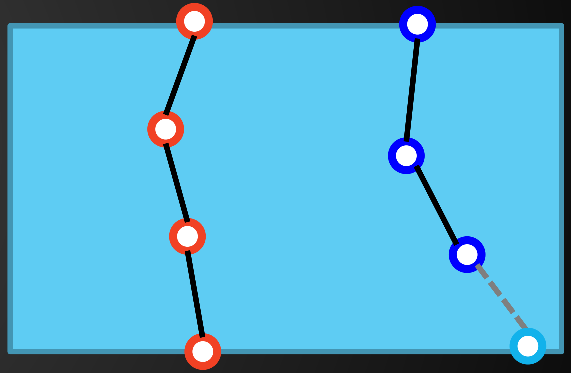
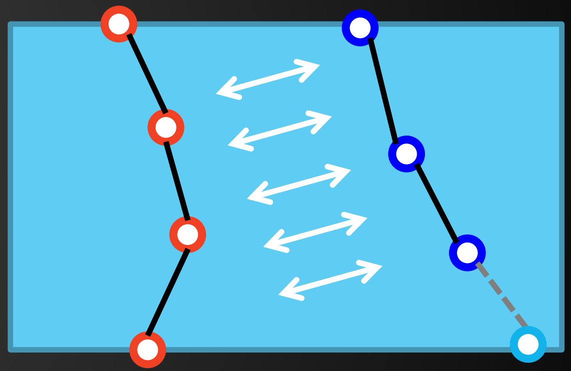
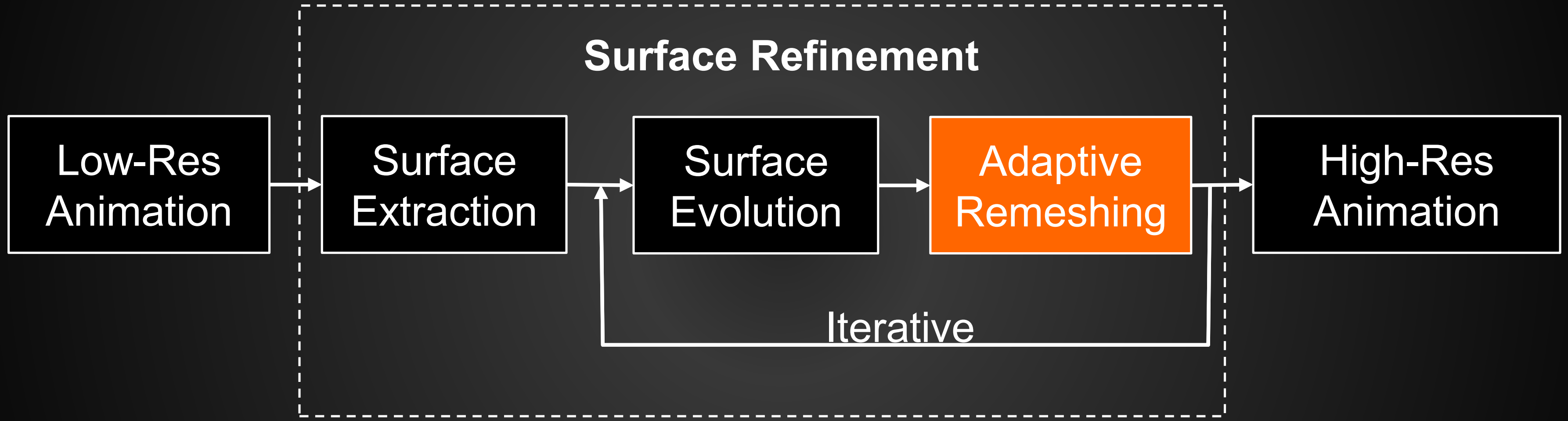


Constraints

- Fracture boundary
  - Vertices on exterior surface only move on exterior surface
- Intersection free
  - Fracture surfaces do not intersect with each other or themselves

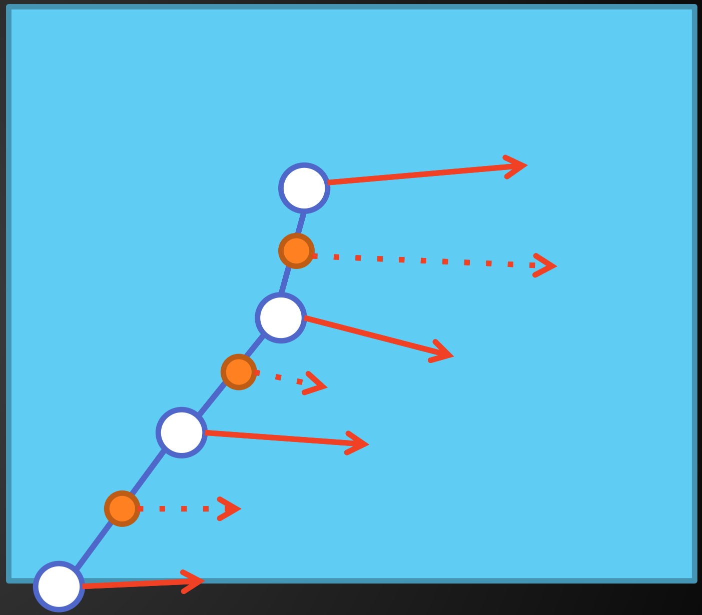


Physics-Inspired Fracture Refinement



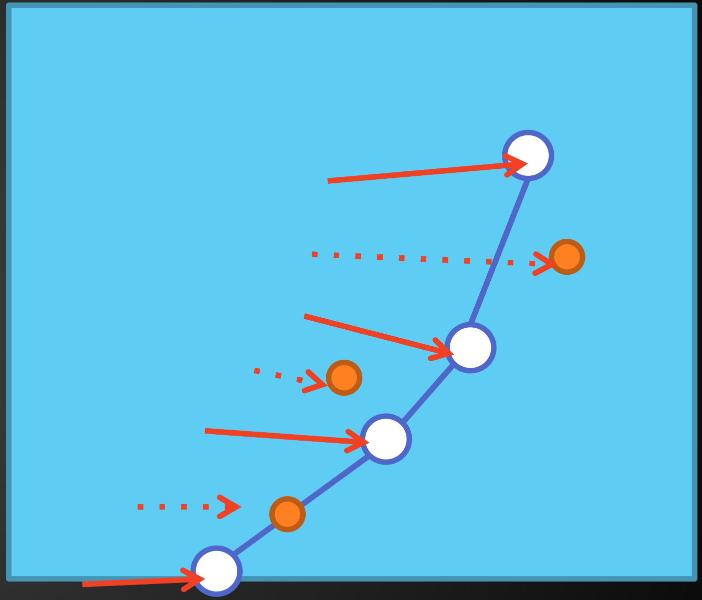
Adaptive Remeshing

- Random candidate vertices



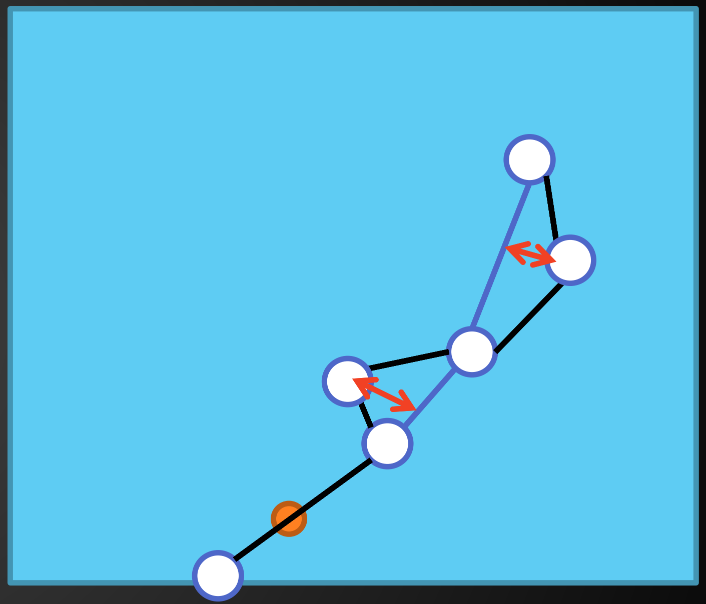
Adaptive Remeshing

- Random candidate vertices

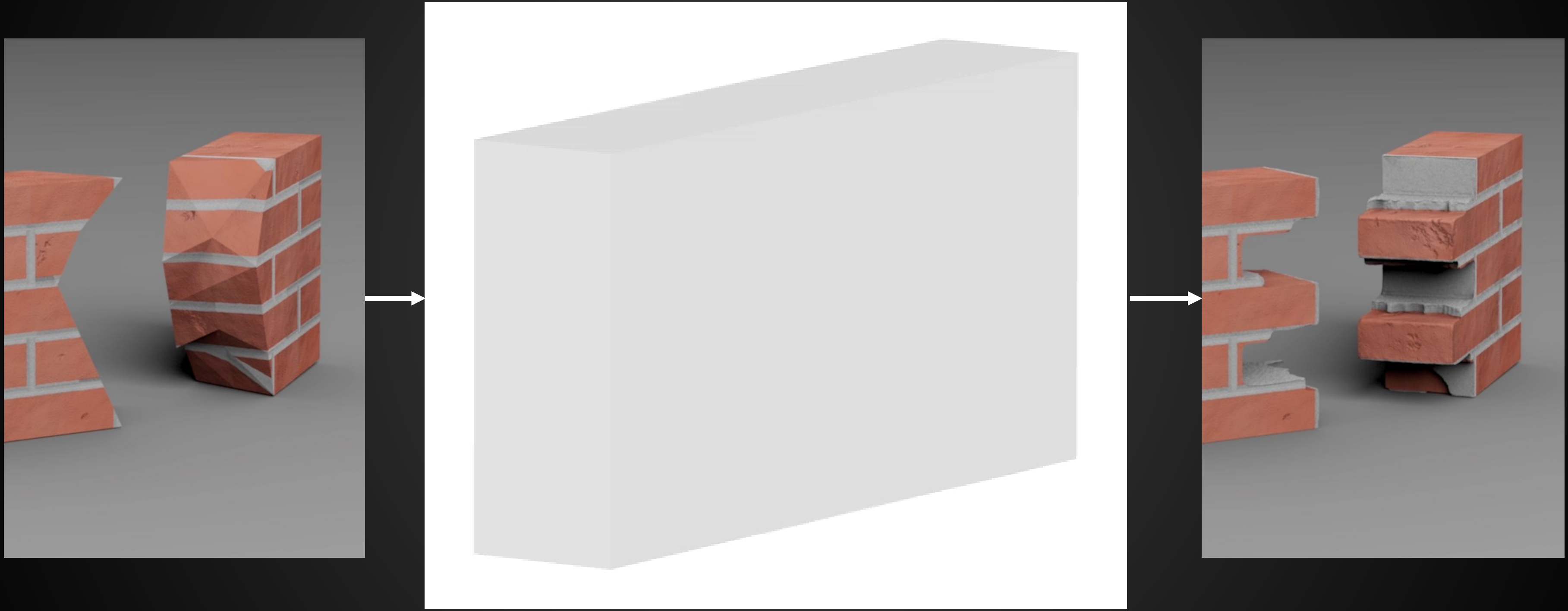


Adaptive Remeshing

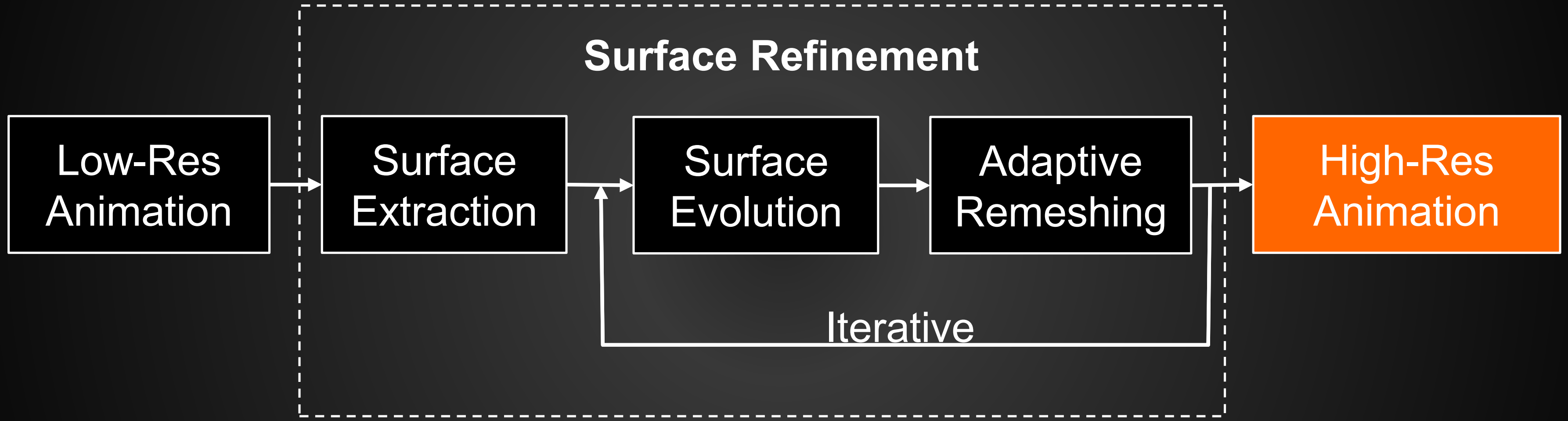
- Random candidate vertices
- Select and insert candidates
- Edge flipping optimization



Fracture Surface Refinement



Physics-Inspired Fracture Refinement

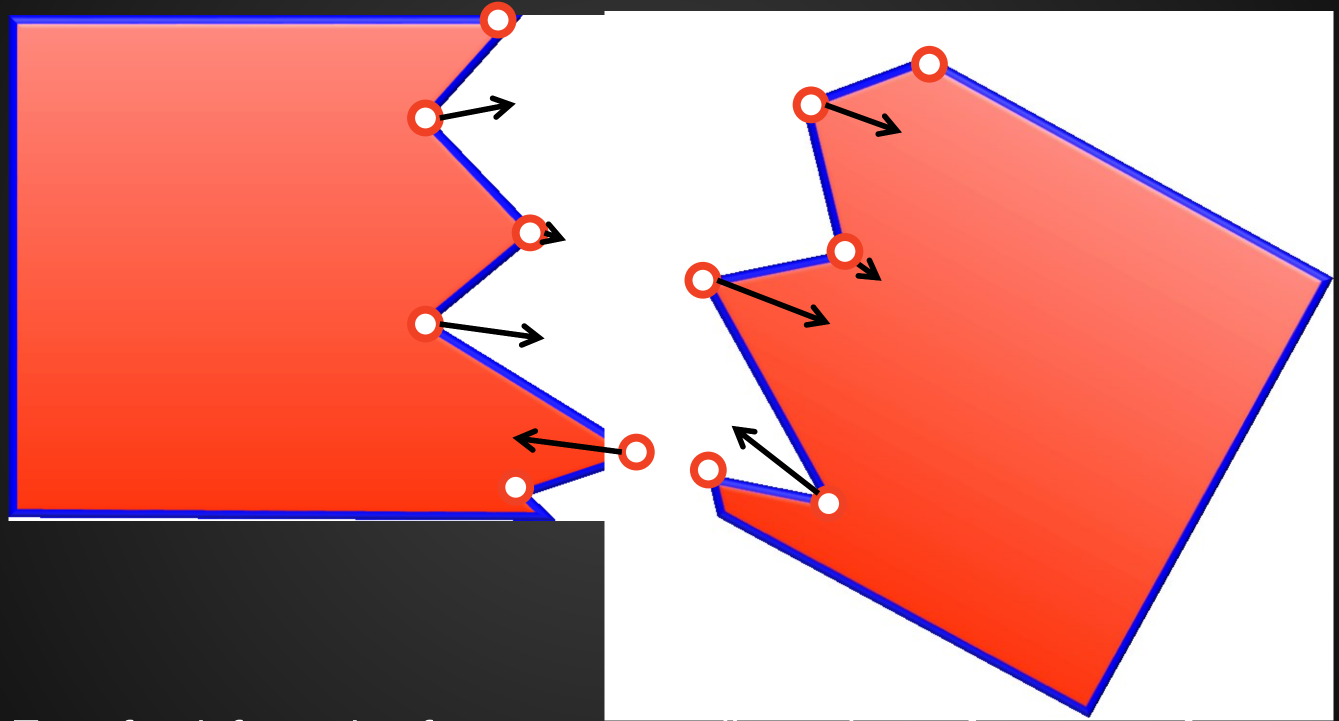


High-resolution Animation Generation

- Transfer { Deformation / Fracture time } from low-res to high-res

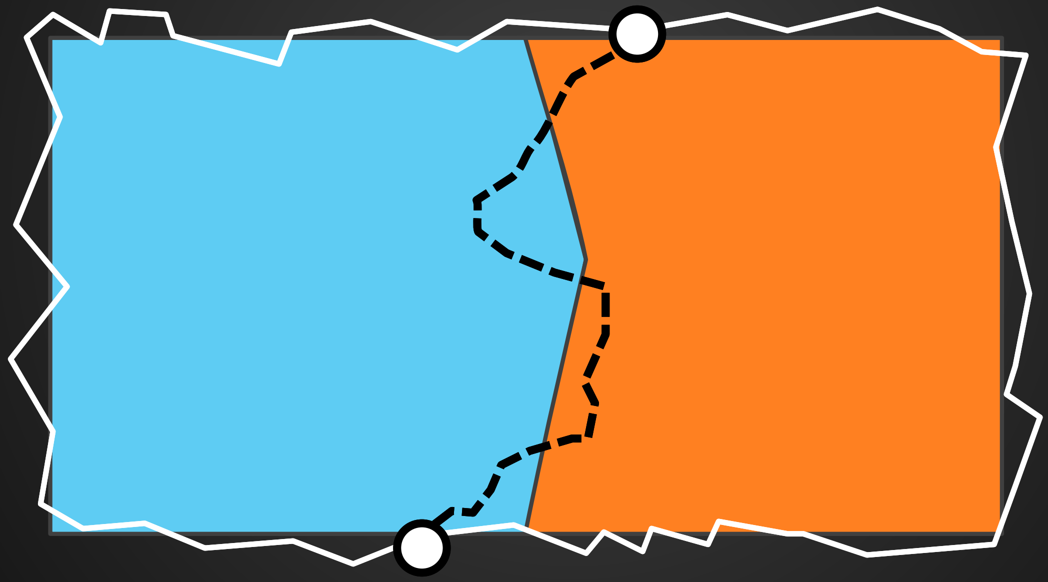
(Different for Fracture surface and Exterior surface)

Fracture Surface Generation

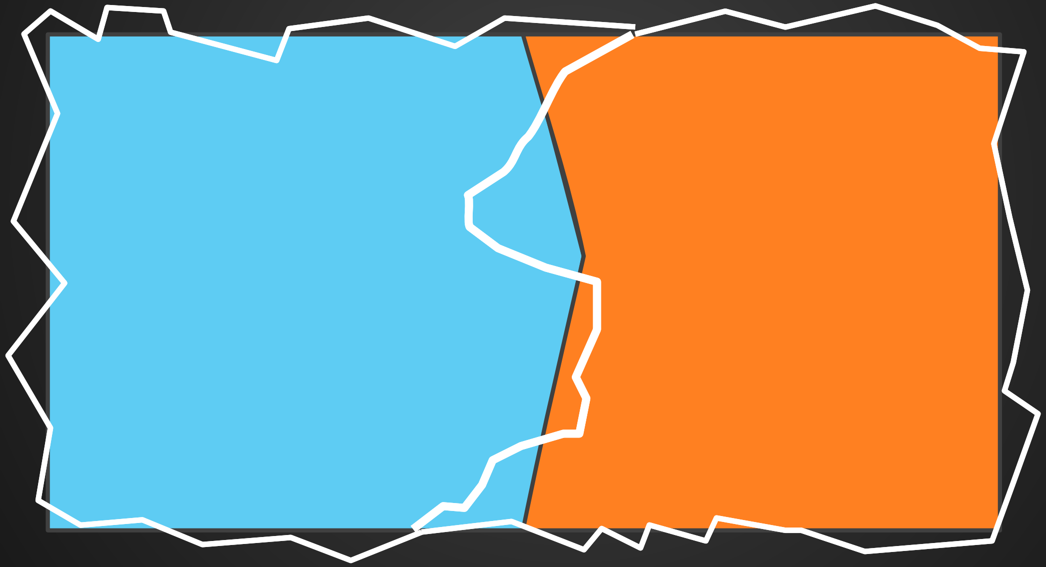


Transfer deformation from corresponding point on fracture surface

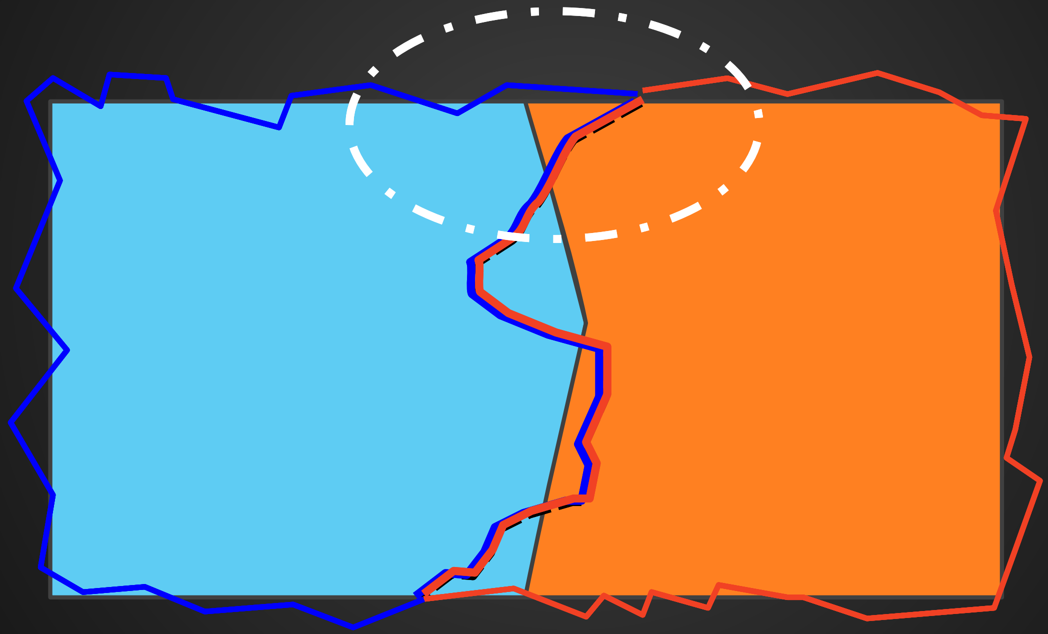
Exterior Surface Generation



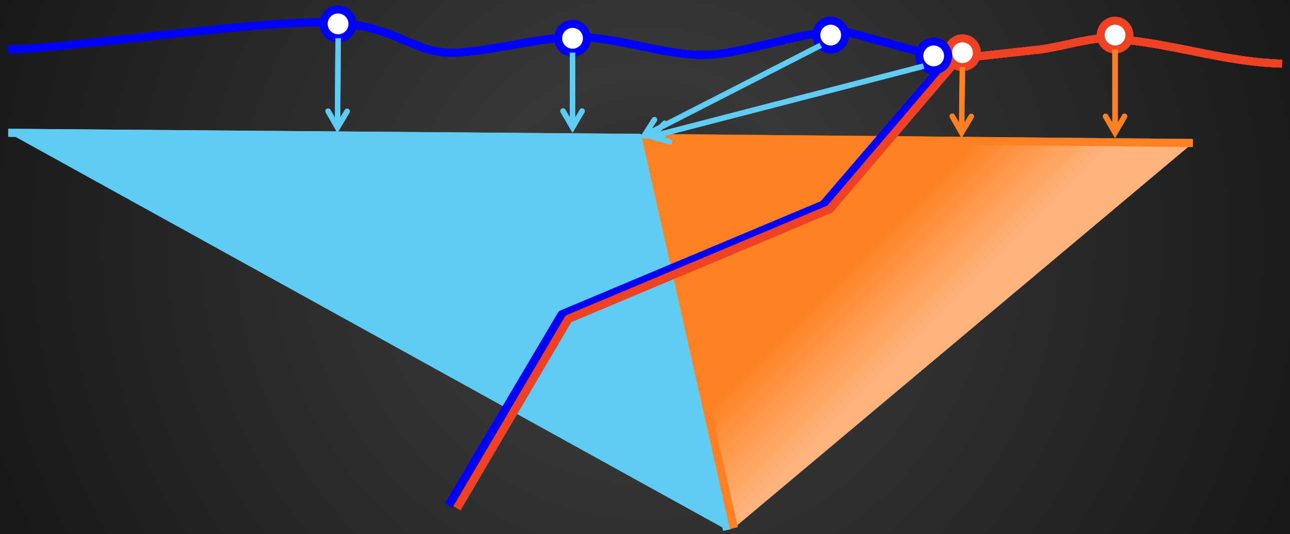
Exterior Surface Generation



Exterior Surface Generation

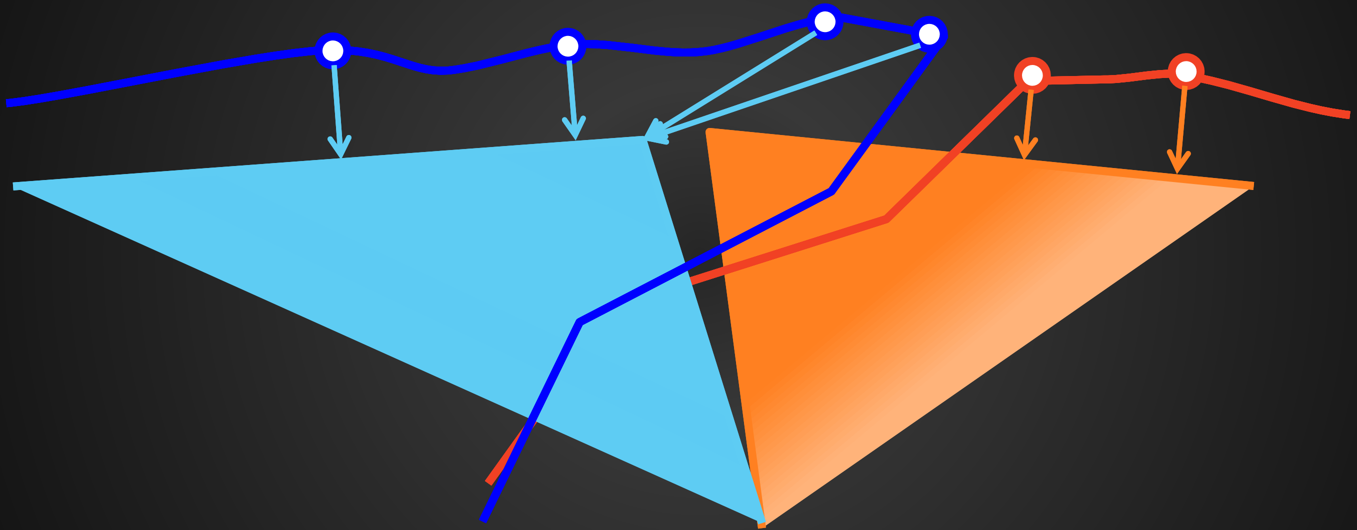


Exterior Surface Generation



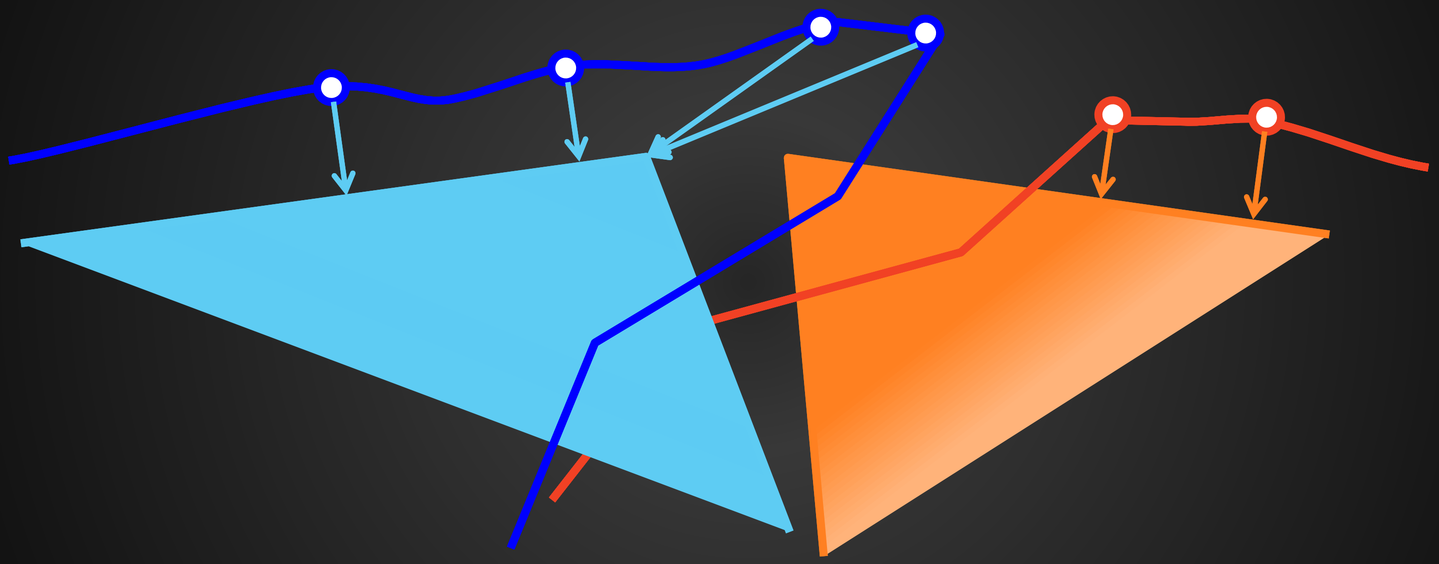
Transfer deformation from closet point that belongs to the same partition

Exterior Surface Generation



Transfer deformation from closet point that belongs to the same partition

Exterior Surface Generation



Transfer deformation from closet point that belongs to the same partition

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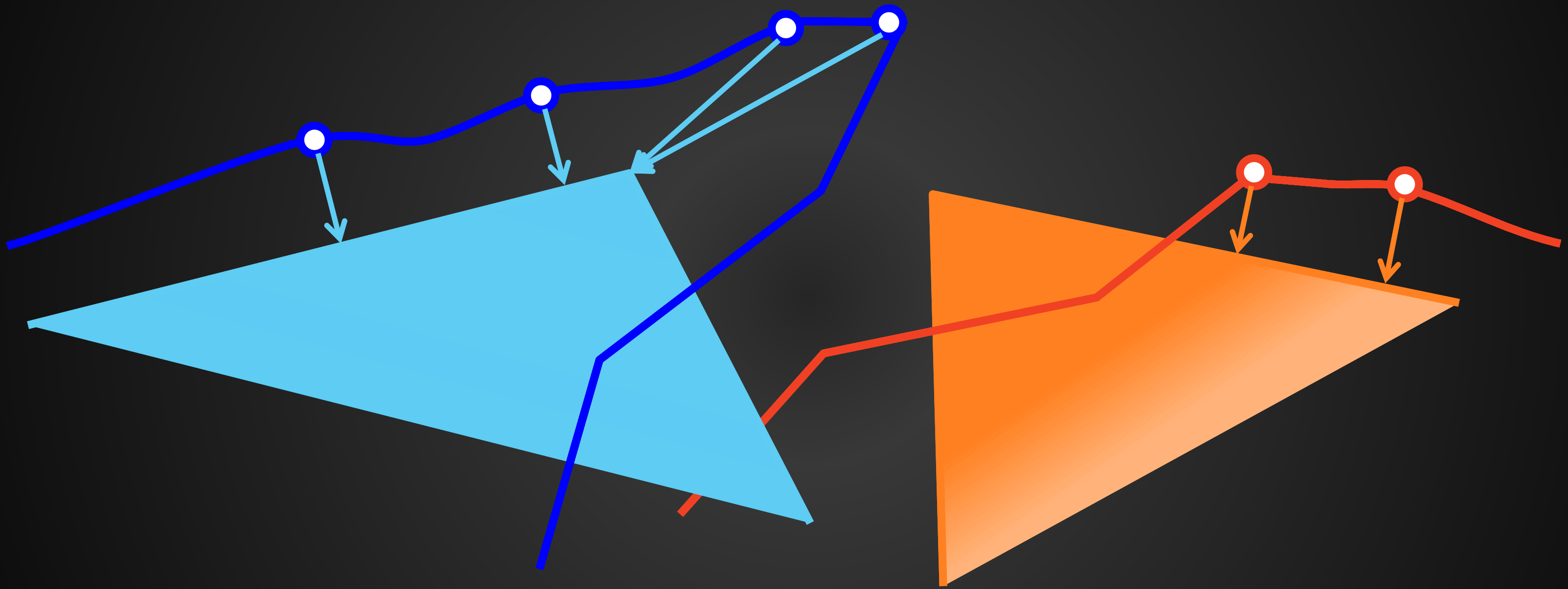
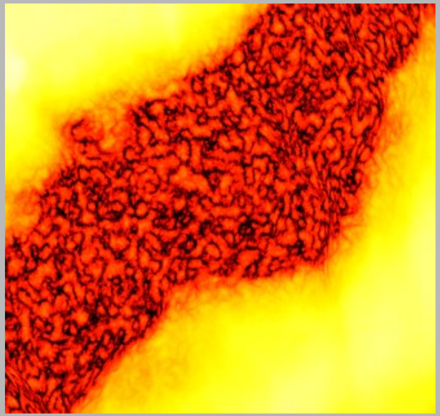


Transfer deformation from closet point that belongs to the same partition

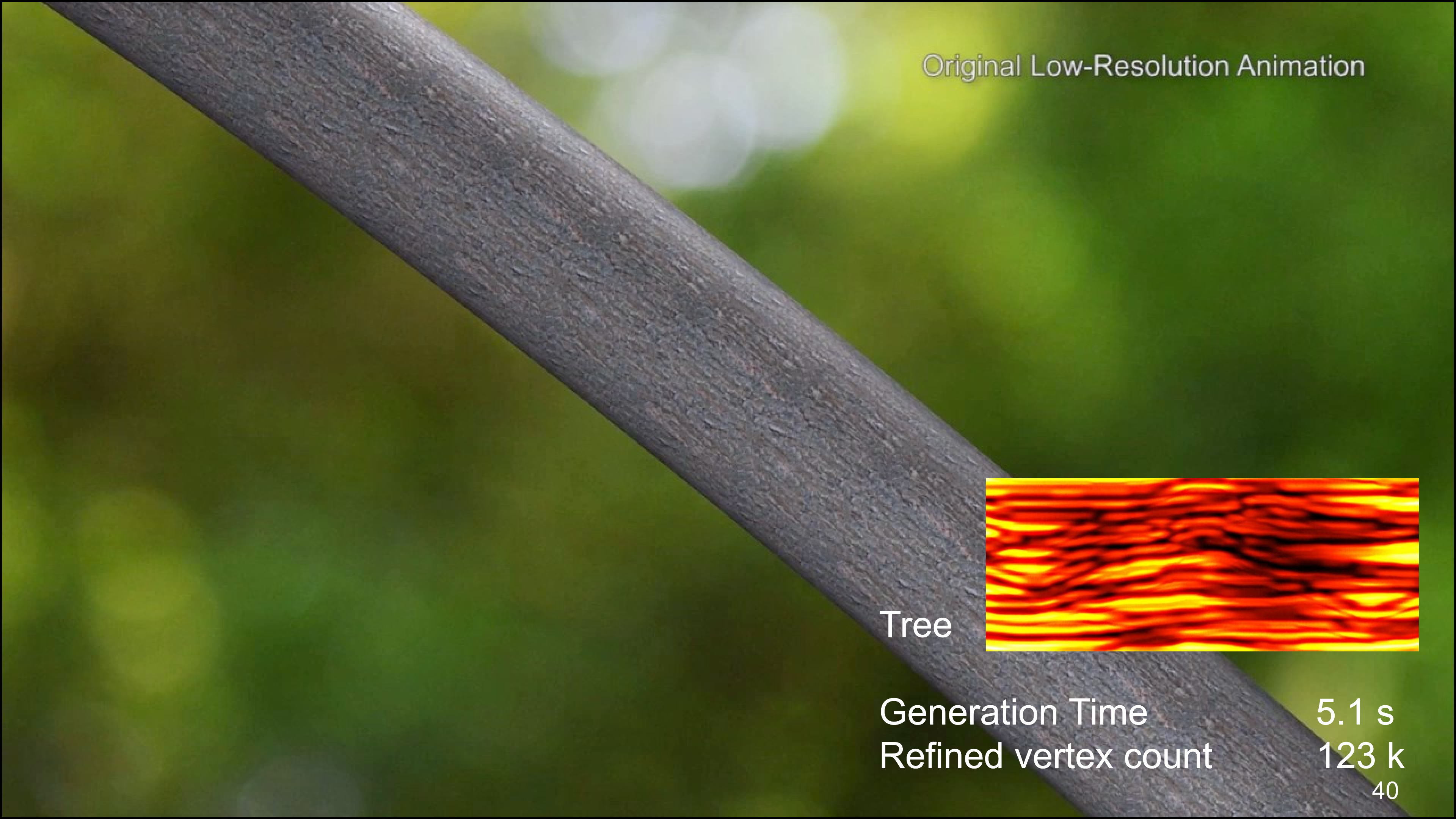
Examples

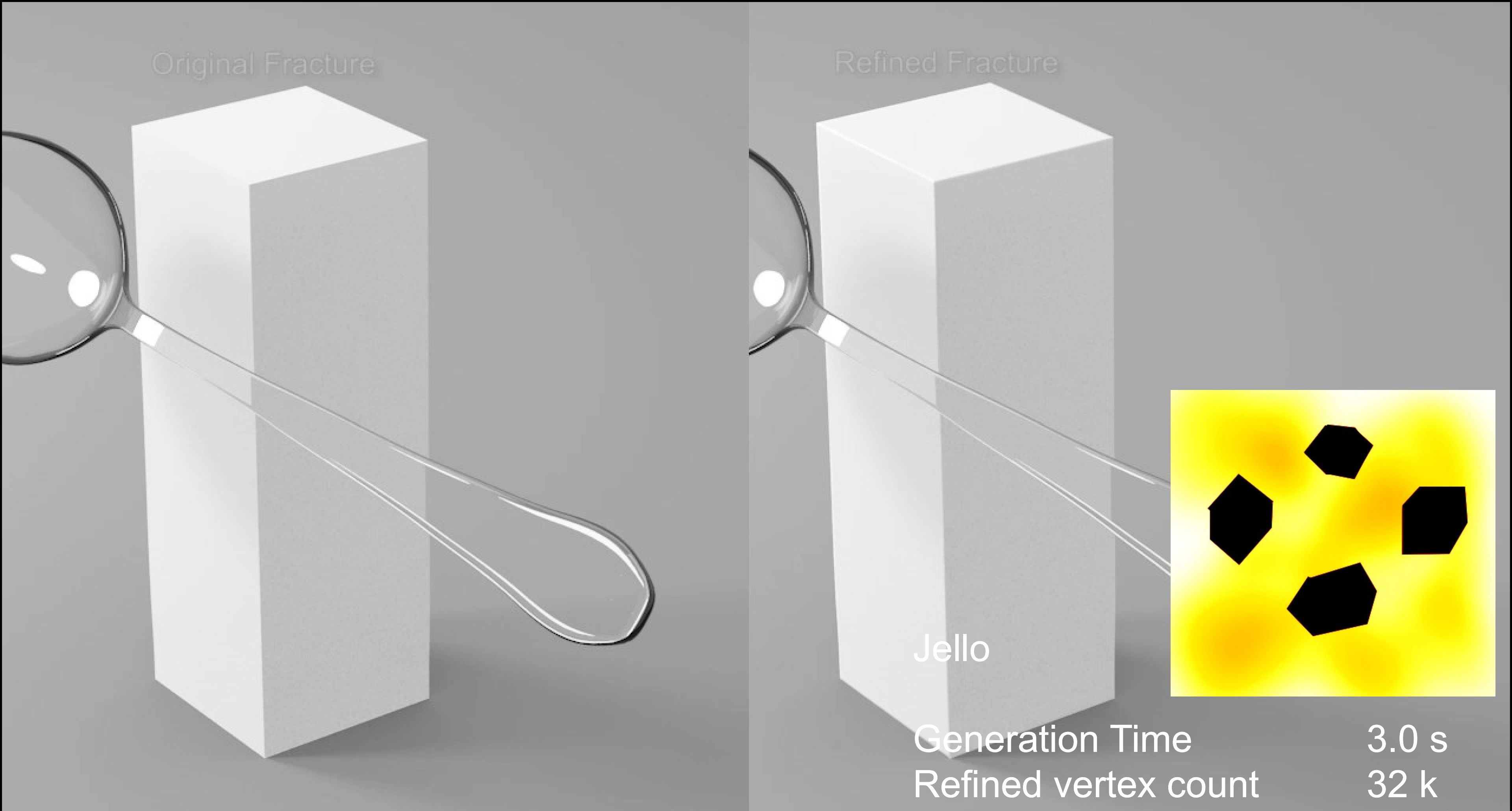
(Slow motion) Fracture Refinement

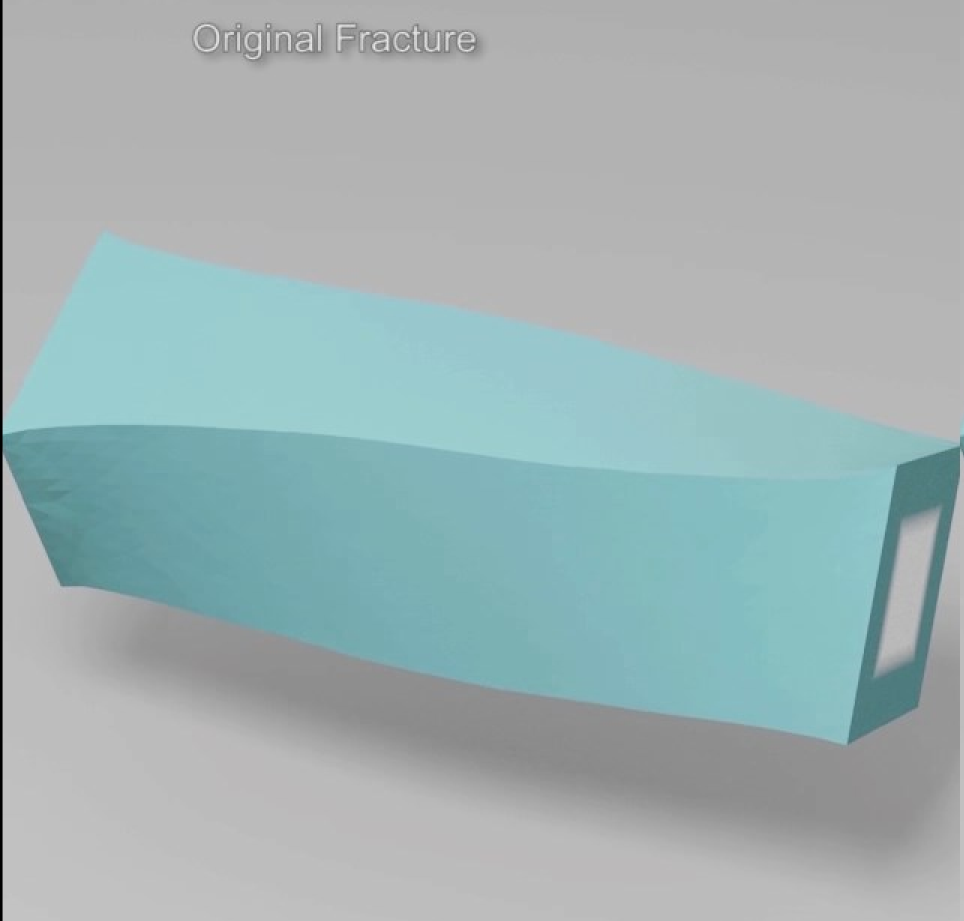
Bunny

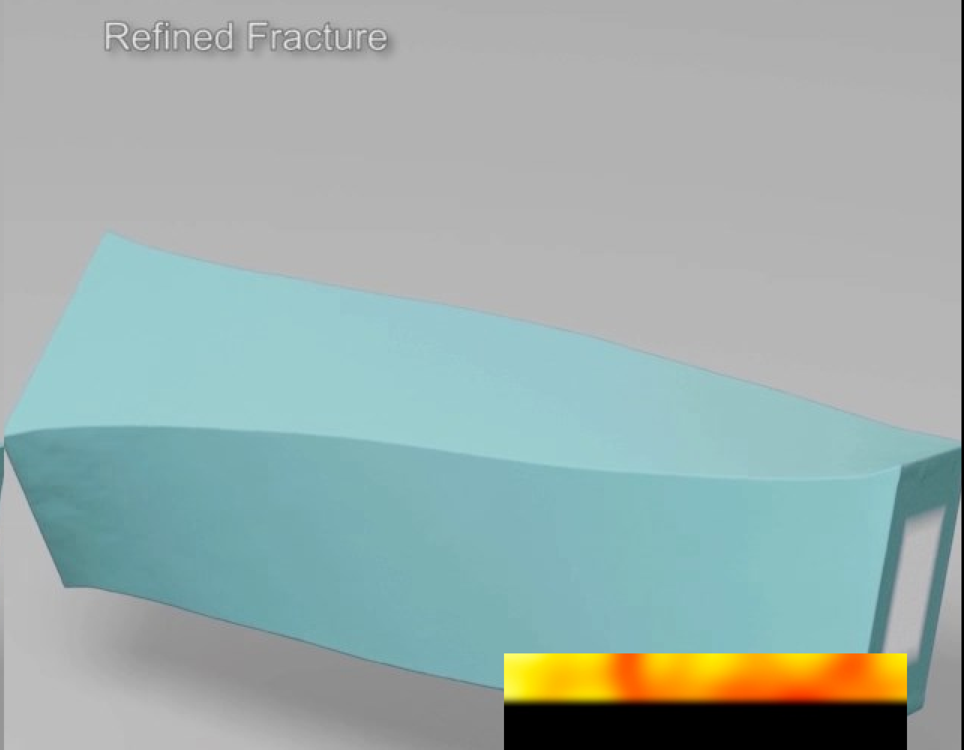


Generation Time	11.7 s
Refined vertex count	174 k


Original Low-Resolution Animation
Tree
Generation Time 5.1 s
Refined vertex count 123 k


Original Fracture
Refined Fracture
Jello
Generation Time 3.0 s
Refined vertex count 32 k





Plastic clay

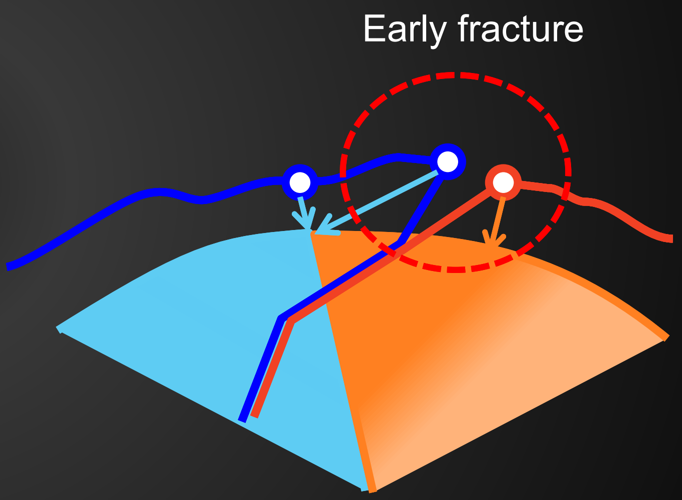
Generation Time 3.0 s
Refined vertex count 40 k

Summary

- PRO
  - Physically plausible
  - Fast and stable
  - Easy artistic control

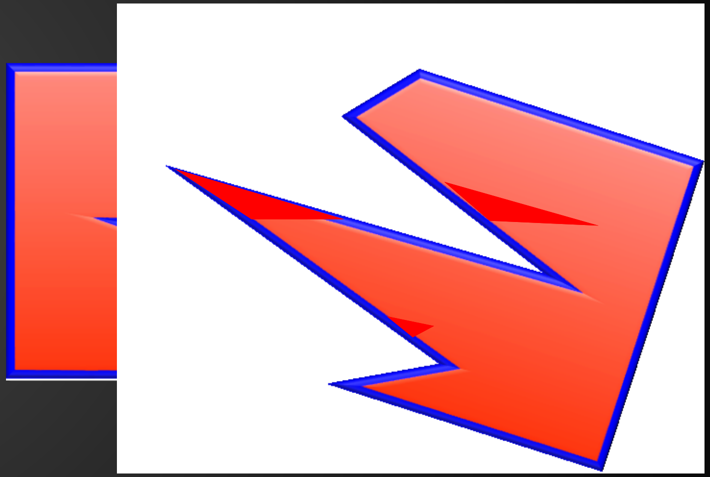
Summary

- PRO
  - Physically plausible
  - Fast and stable
  - Easy artistic control
- CON
  - Issue with nonlinear deformation near fracture boundary



Limitations

- PRO
  - Physically plausible
  - Fast and stable
  - Easy artistic control
- CON
  - Issue with nonlinear deformation near fracture boundary
  - New collisions from refined surface not resolved



Limitations

- PRO
  - Physically plausible
  - Fast and stable
  - Easy artistic control
- CON
  - Issue with nonlinear deformation near fracture boundary
  - New collisions from refined surface not resolved
  - Does not create new fracture pieces

Acknowledgement

Thank you!