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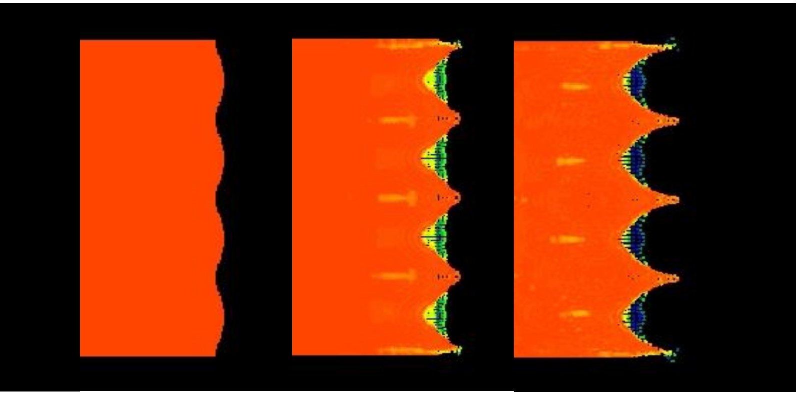

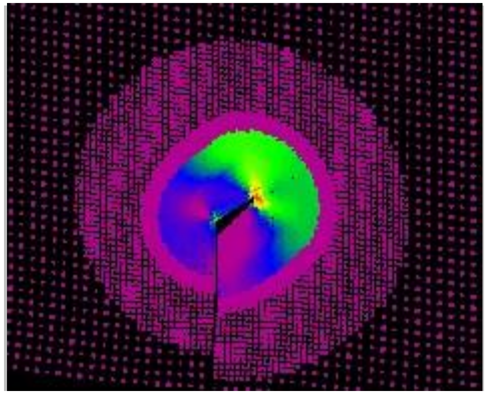

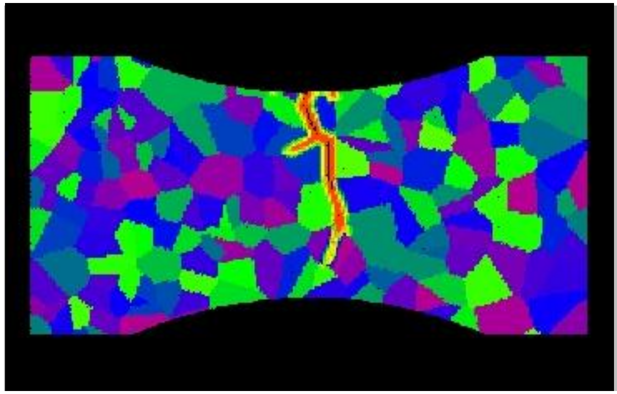

Peridynamics progress update

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Presentation for: Corning Inc., October 14, 2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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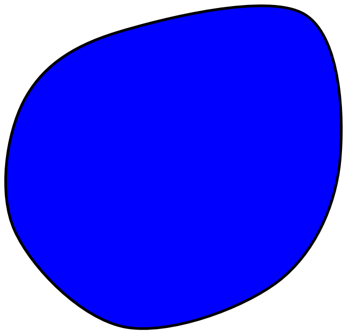
Outline

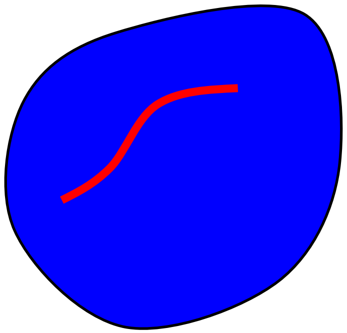
- Peridynamics for impact modeling
- Multiscale method for heterogeneous material damage modeling
  - Damage accumulation due to multiple hits

Purpose of peridynamics

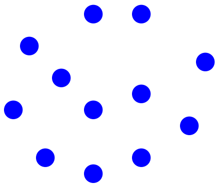
- To unify the mechanics of continuous and discontinuous media within a single, consistent set of equations.



Continuous body



Continuous body
with a defect



Discrete particles

- Why do this?
  - Avoid coupling dissimilar mathematical systems.
  - Model complex fracture patterns.
  - Communicate across length scales.

(b) Complex crack path in a composite

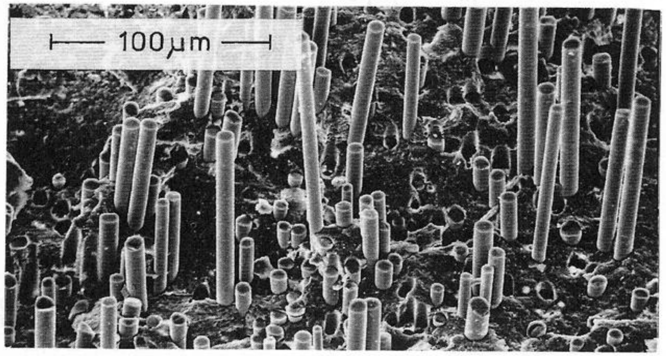
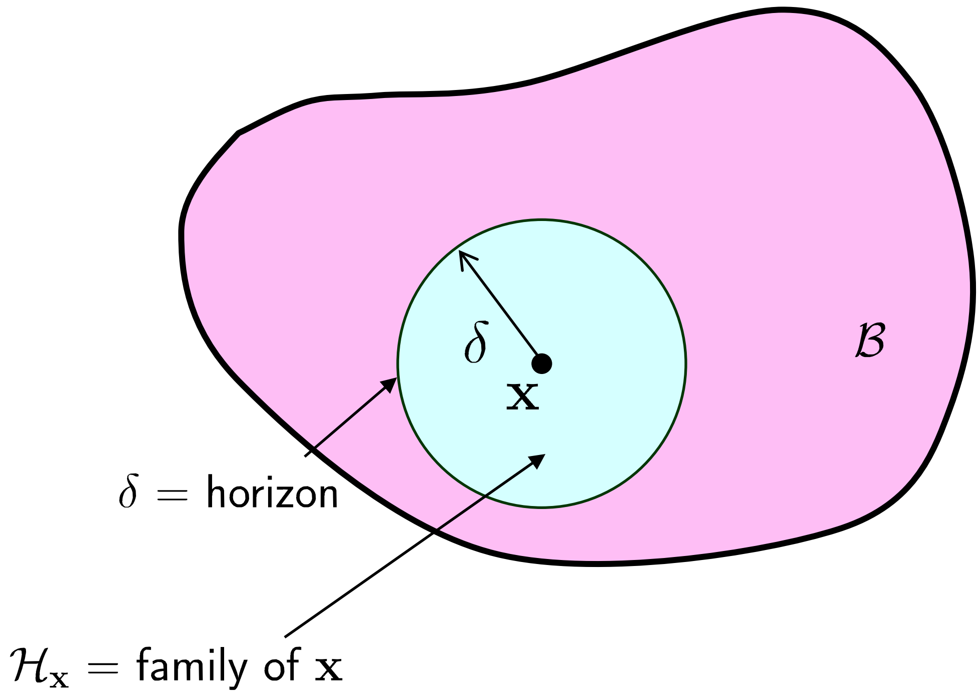


Figure 11.20 Pull-out: (a) schematic diagram; (b) fracture surface of 'Silceram' glass-ceramic reinforced with SiC fibres. (Courtesy H. S. Kim, P. S. Rogers and R. D. Rawlings.)

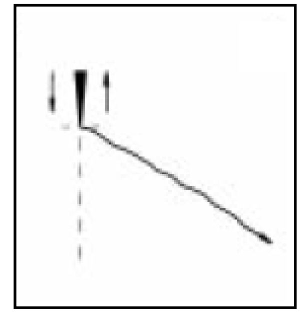
Peridynamics basics: Horizon and family

- Any point $\mathbf{x}$ interacts directly with other points within a distance δ called the "horizon."
- The material within a distance δ of $\mathbf{x}$ is called the "family" of $\mathbf{x}$, $\mathcal{H}_\mathbf{x}$.

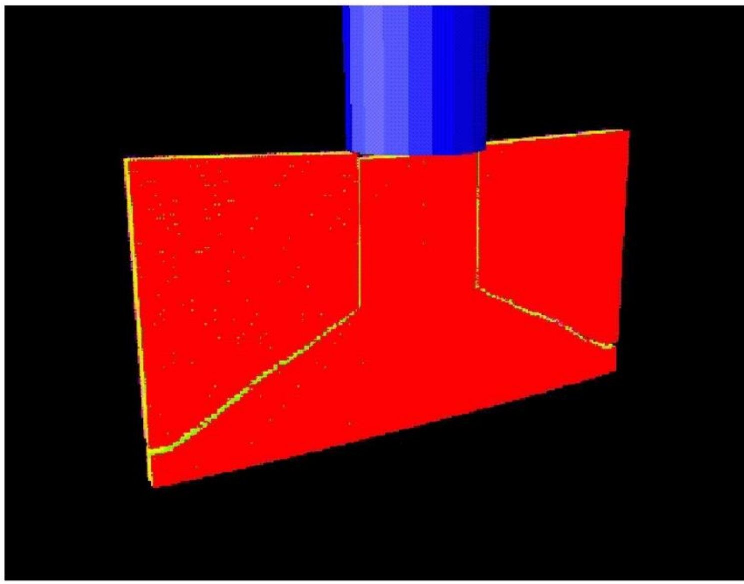


Dynamics of a single crack

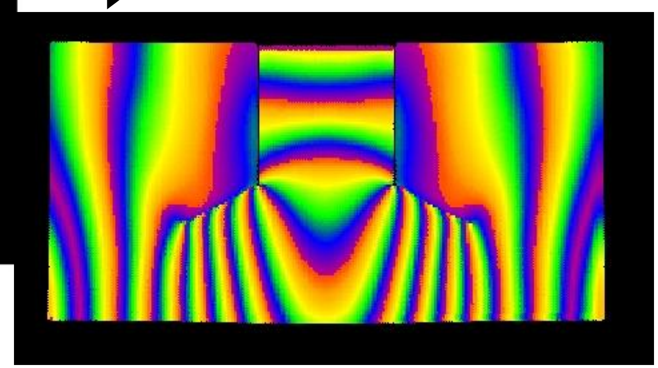
- Dynamic fracture in maraging steel (Kalthoff & Winkler, 1988)
- Mode-II loading at notch tips results in mode-I cracks at 70deg angle.
- 3D EMU model reproduces the crack angle.



Experiment



EMU*

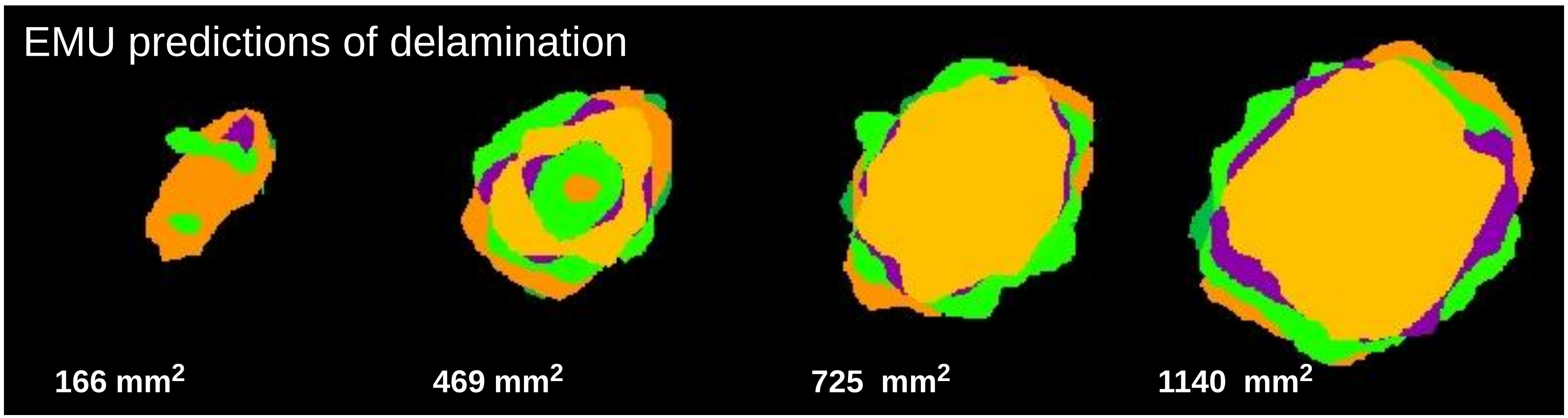


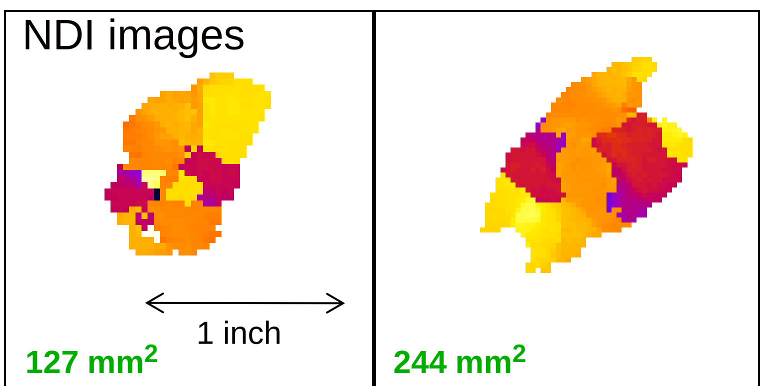
S. A. Silling, Dynamic fracture modeling with a meshfree peridynamic code, in *Computational Fluid and Solid Mechanics 2003*, K.J. Bathe, ed., Elsevier, pp. 641–644.

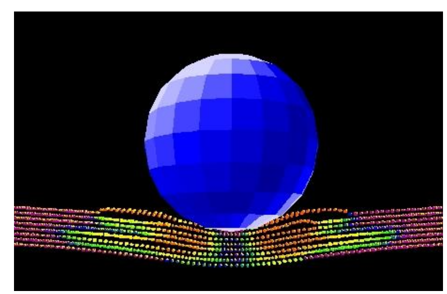
Impact damage in a laminate

- Method reproduces delaminated area through the thickness of an aerospace composite.

Impact energy = 100 in-lbf 200 in-lbf 300 in-lbf 400 in-lbf

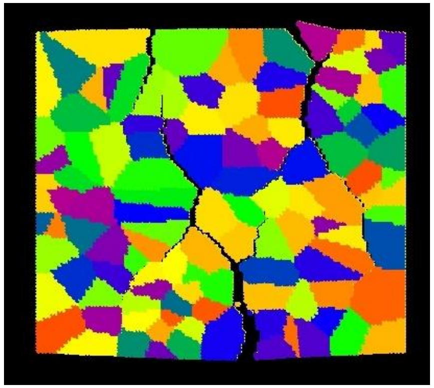




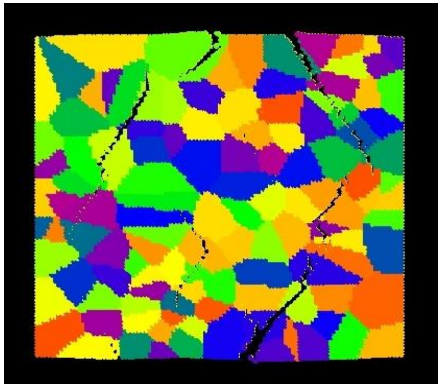


Complex materials: Random microstructure

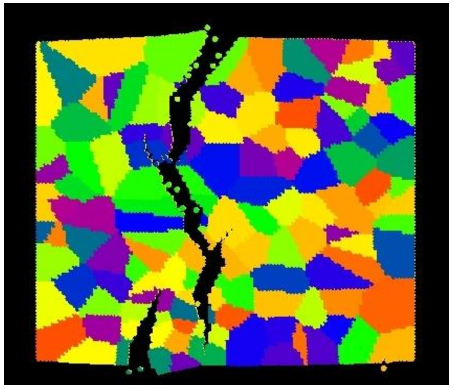
- Bonds between grains have properties that characterize the interface.



β = 0.25



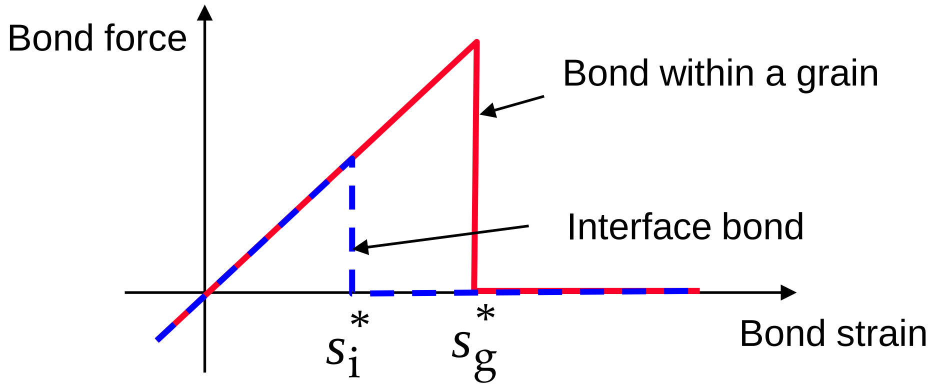
β = 1



β = 4

$$\beta = \frac{s_i^*}{s_g^*}$$

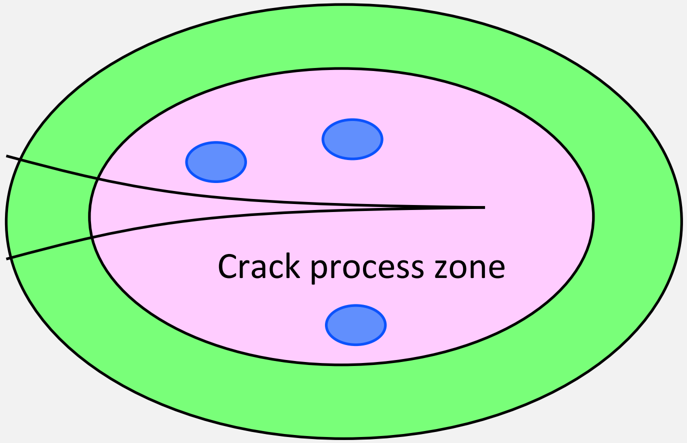
Large β favors trans-granular fracture.



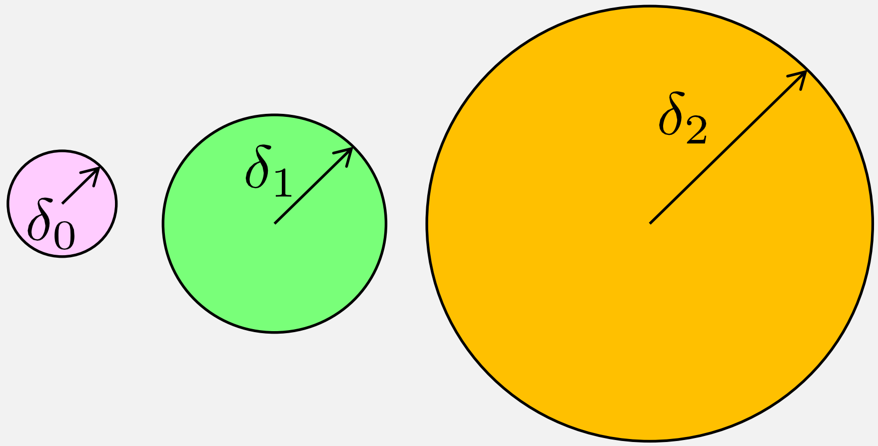
* Work by F. Bobaru & students (University of Nebraska – Lincoln)

Multiple length scales

- Challenge: Apply the most detailed physics to active areas of damage within a larger structure.



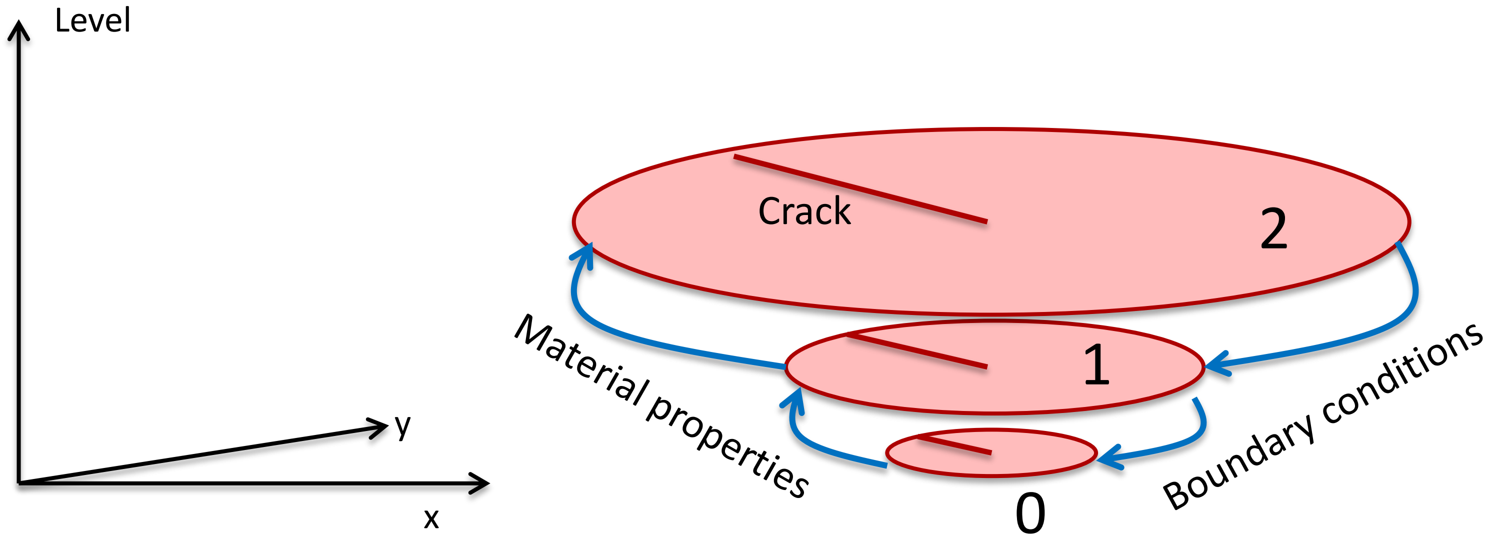
The details of damage evolution are always modeled at level 0.



Each successive level has a larger length scale (horizon).

Concurrent solution strategy

- The equation of motion is applied only <u>within</u> each level.
- Higher levels provide boundary conditions on lower levels.
- Lower levels provide coarsened material properties (including damage) to higher levels.

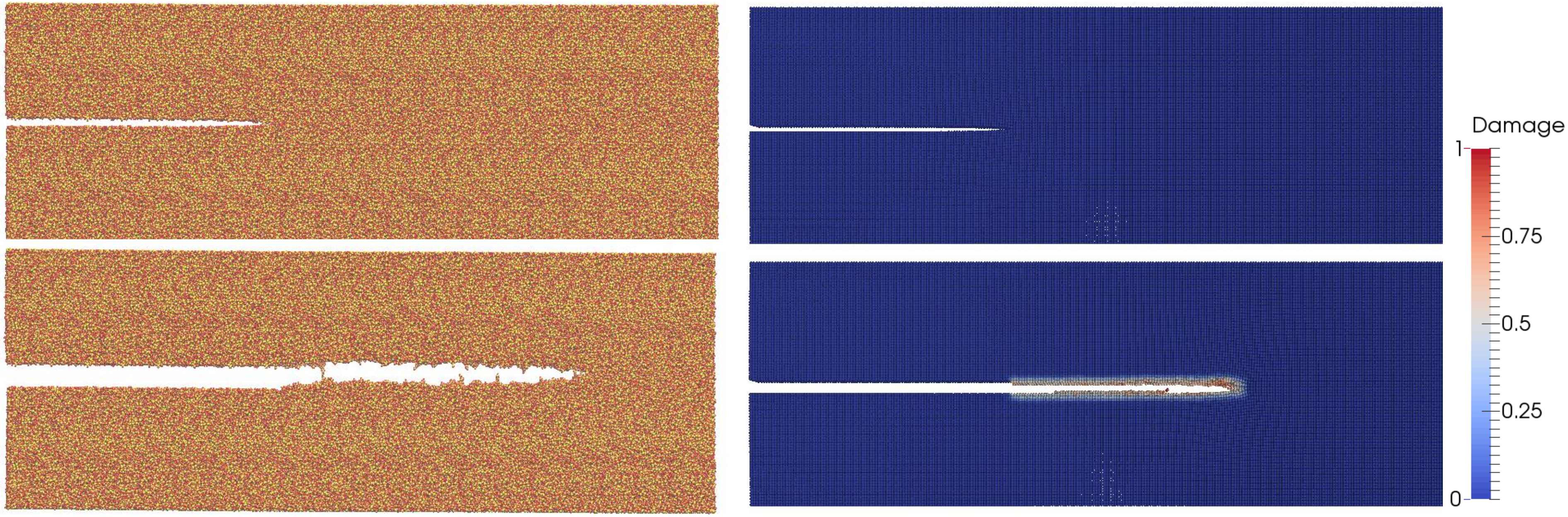


Schematic of communication between levels in a 2D body

Peridynamic fracture models from MD

- Peridynamic damage is modeled through bond breaking criteria and the suitable selection of a parameter called the horizon, which characterizes the degree of nonlocality in the model. Initial qualitative work to capture fracture properties has been promising.
- A reformulation of the peridynamic upscaling, which coarse grains the system by constrained optimization, is being evaluated in plane-strain 2D fracture geometries.

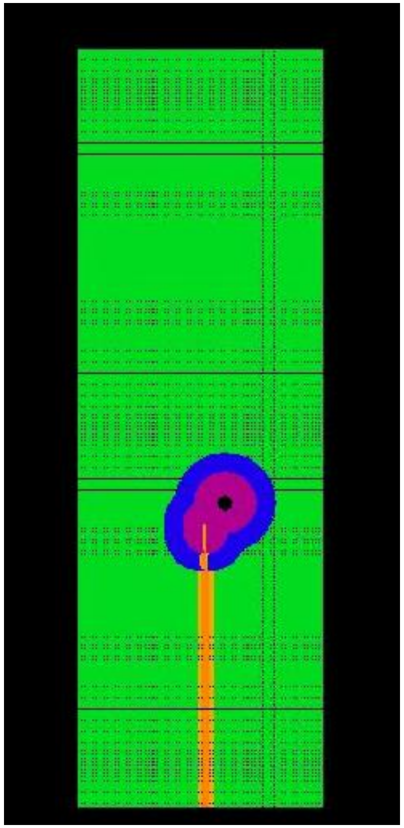
Preliminary results demonstrating qualitative agreement in glass fracture (on the left, atomistic simulation, and on the right, peridynamics modeling.)

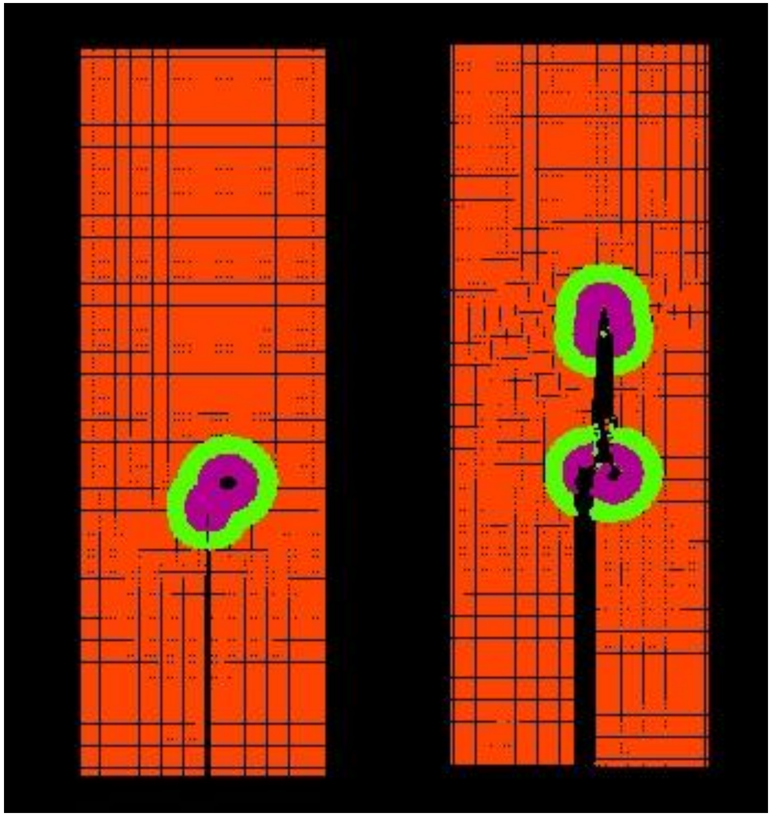


Upscaling and flaw interaction

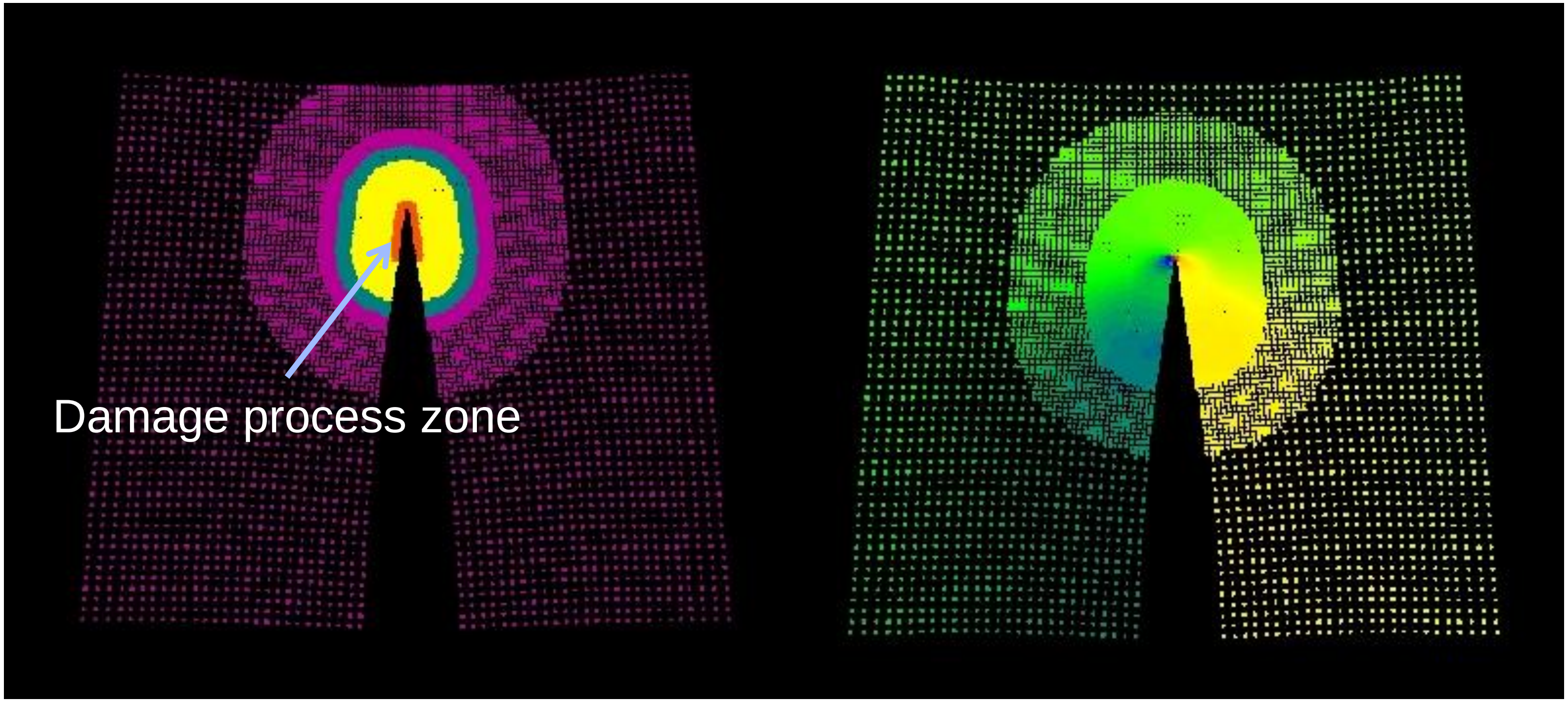
- Peridynamic multscale simulation of crack tip interaction with a void

VIDEO





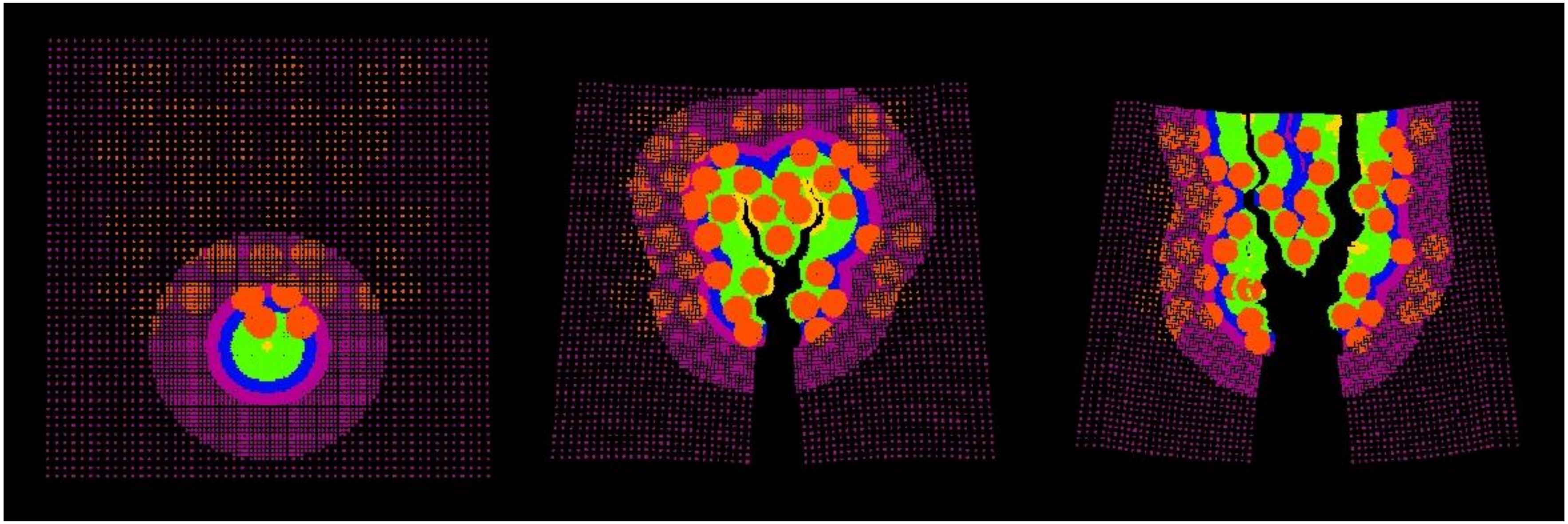
Levels move and adapt as the crack grows



v_1 velocity

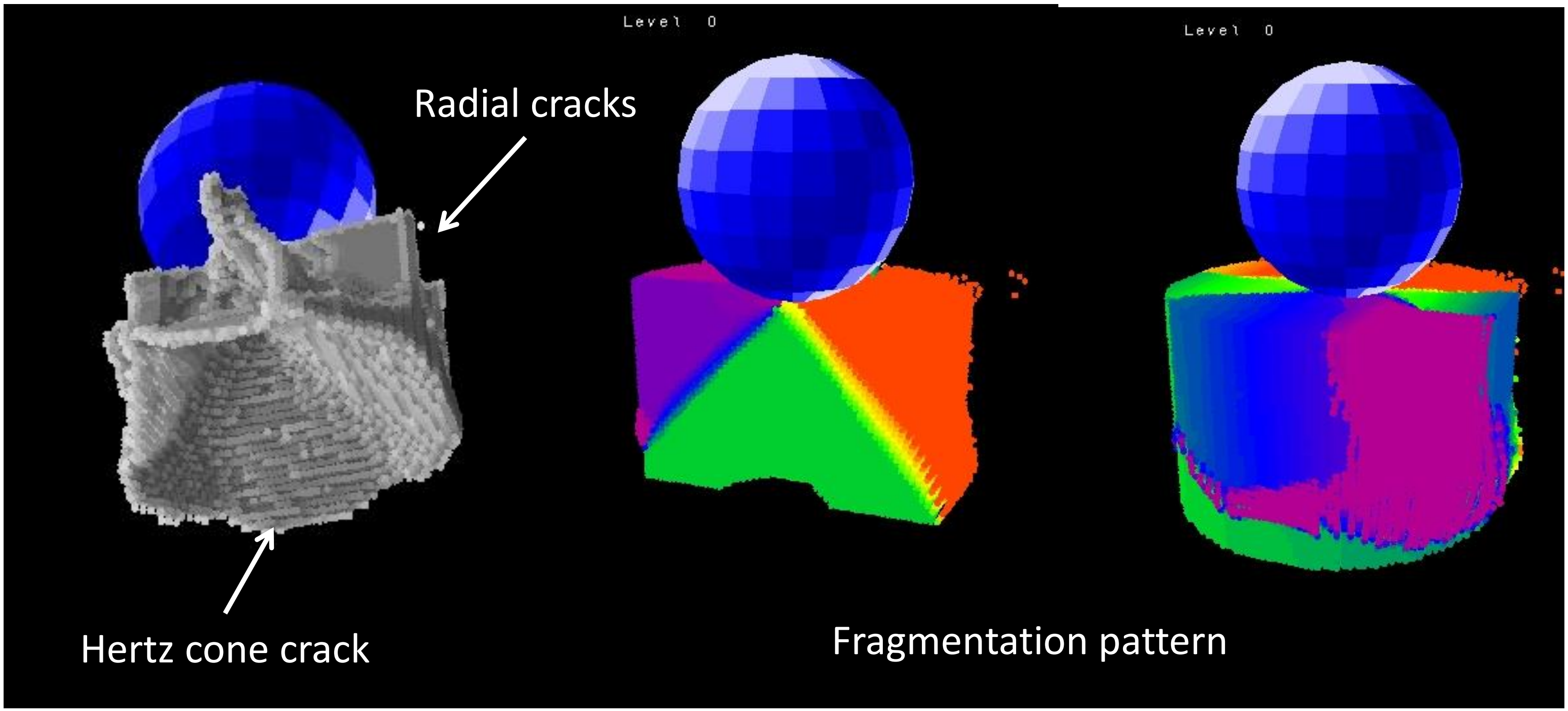
Branching in a heterogeneous medium

- Multiscale method tracks crack growth between randomly placed hard inclusions.



Multiscale simulation of damage due to contact with a rigid sphere

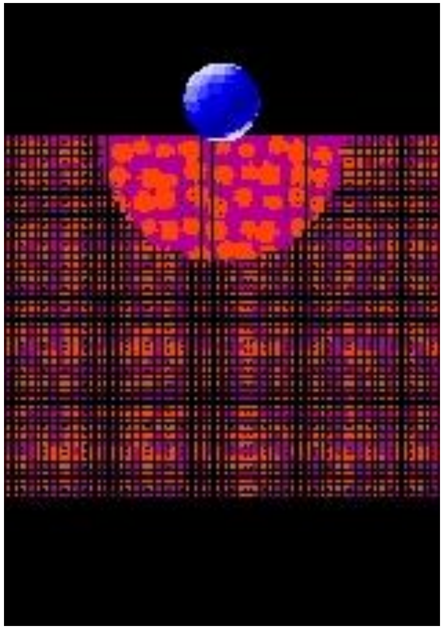
- Method reproduces the classical cone crack of contact mechanics as well as interaction with free surfaces.



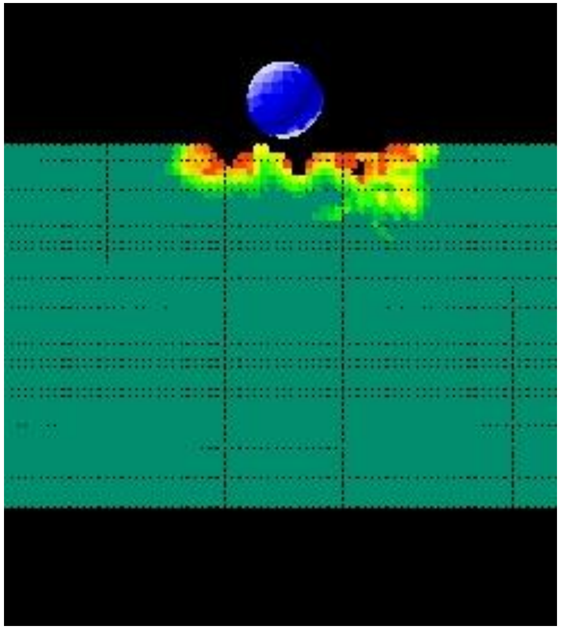
Multiscale model of damage accumulation

- Heterogeneous solid is impacted many times at random positions.
- Damage accumulates between inclusions.
- Surface appears to harden because the soft material is compacted.

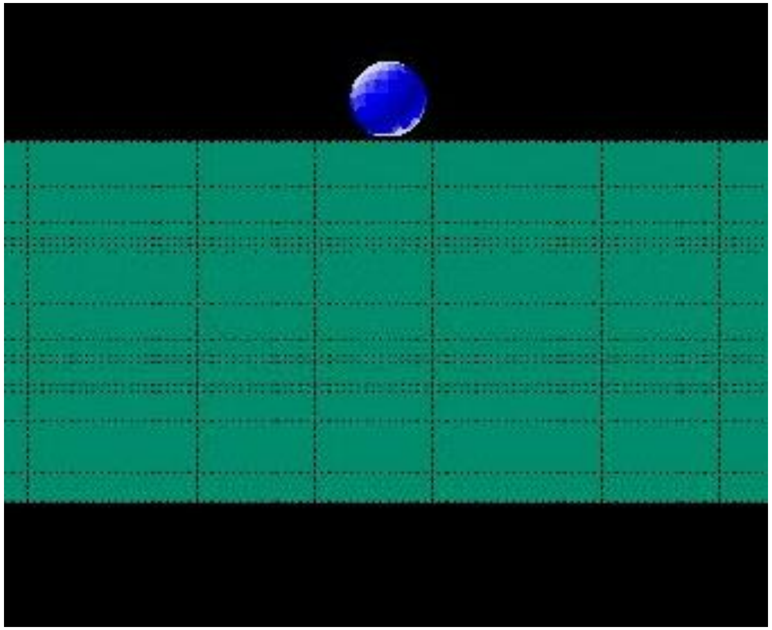
VIDEO



Heterogeneous microstructure



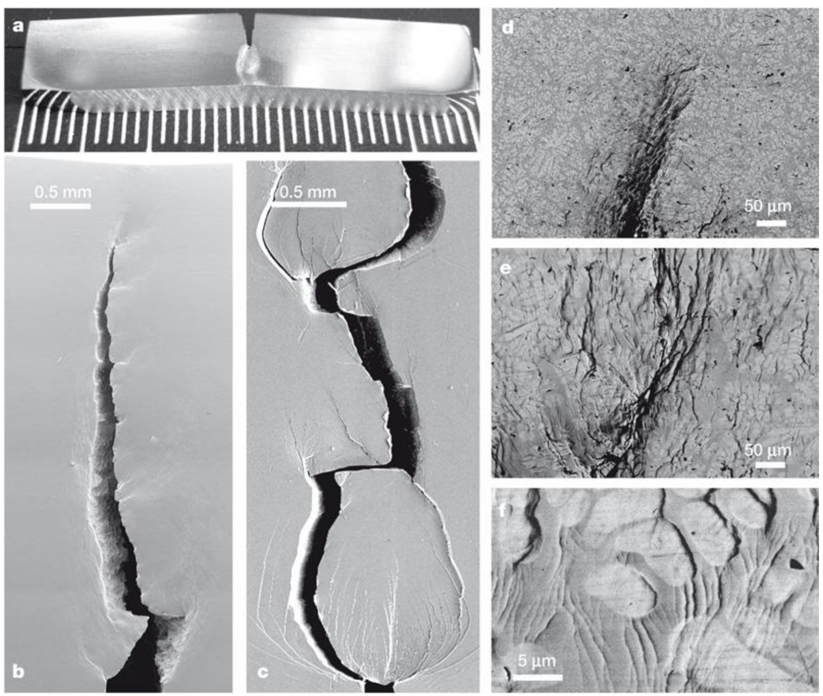
Accumulated damage



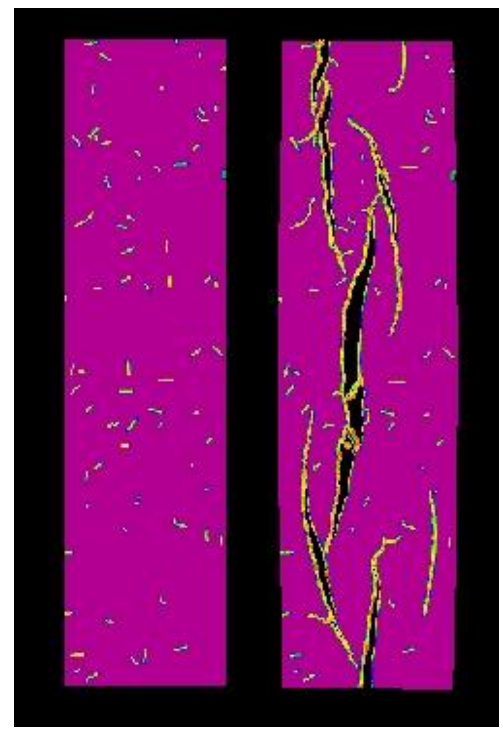
Many projectiles striking at random locations

Using peridynamics to explore nonlinear processes in brittle fracture

- LEFM is designed to hide rather than elucidate the complexity of a crack process zone.
  - Yet the details of these processes determine the fracture toughness, etc.
- PD may provide a way to predict the details of crack tip growth as well as the <u>nucleation</u> of a macroscopic crack.

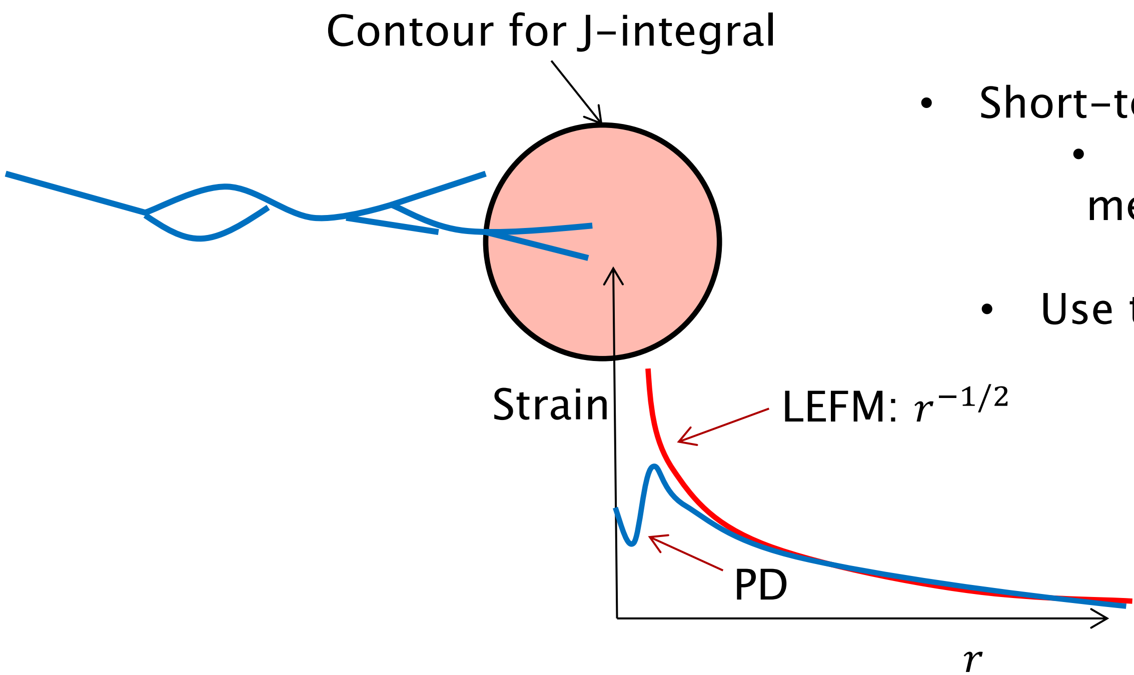


Metallic glass fracture at different length scales reveals non-ideal morphology (Hofmann et al, Nature 2008)



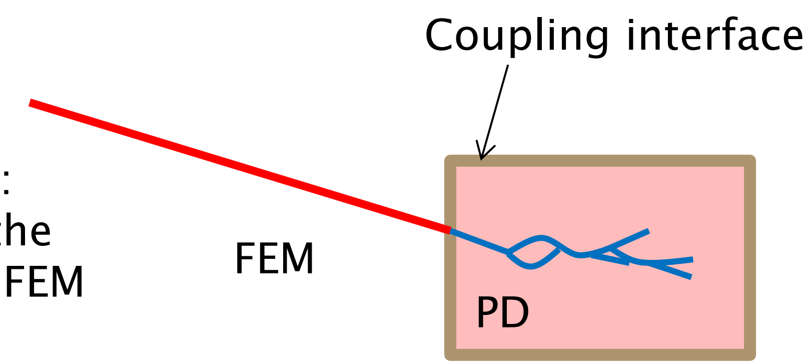
Peridynamic model of small defects merging to form a larger-scale crack

Connecting peridynamics with LEFM



- Short-term option (parameter passing):
  - Evaluate the J-integral from a mesoscale model of the nonlinear region.
  - Use this to determine K_{IC} for use in an LEFM model.

- Longer-term option (tight coupling):
  - Use a fully coupled PD model of the process zone embedded within an FEM mesh.



Key features

- Meshless method offers simple approach to complex microstructures.
- Damage and cracking happen spontaneously without additional equations of fracture mechanics.
- Multiscale method adaptively refines where damage is occurring.