SAND2013-1849P

Peridigm: A New Paradigm in Computational Peridynamics

Workshop on Nonlocal Damage and Failure

Peridynamics and Other Nonlocal Models

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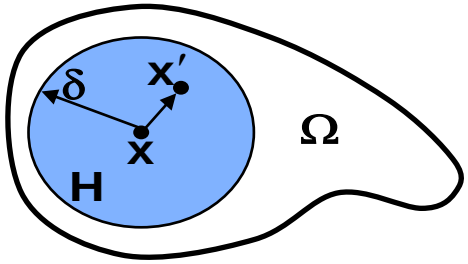
What is Peridynamics?



Point x interacts directly with all points x' within H

- **Peridynamics is a nonlocal extension of classical solid mechanics that permits discontinuous solutions**

- **Peridynamic equation of motion (integral, nonlocal)**

$$\rho\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{H} \left(\mathbf{T}[\mathbf{x},t]\langle \mathbf{x}'-\mathbf{x} \rangle - \mathbf{T}[\mathbf{x}',t]\langle \mathbf{x}-\mathbf{x}' \rangle \right) dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x},t)$$

  - Replace PDEs with integral equations
  - Utilize same equation everywhere; nothing "special" about cracks
  - No assumption of differentiable fields (admits fracture)
  - Damage incurred when deformation criteria satisfied (critical stretch, etc.)
  - No obstacle to integrating nonsmooth functions
  - Integrand is "force" function; contains constitutive model
  - Integrand = 0 for points x,x' more than δ apart (like cutoff radius in MD!)
  - PD is "continuum form of molecular dynamics"

"It can be said that all physical phenomena are nonlocal. Locality is a fiction invented by idealists."

A. Cemal Eringen

- **Impact**
  - Nonlocality
  - Larger solution space than corresponding classical PDE-based models (fracture)
  - Account for material behavior at small & large length scales **(multiscale material model)**

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Part I
Brief Overview of Peridynamics

Part II
Demonstration Computations

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Peridigm: A Computational Peridynamics Code

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Peridigm: Tutorial and Example

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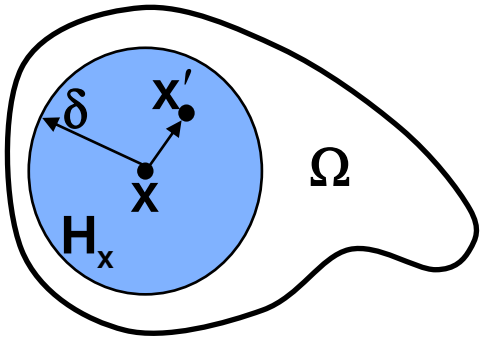
Peridynamics: The Basics

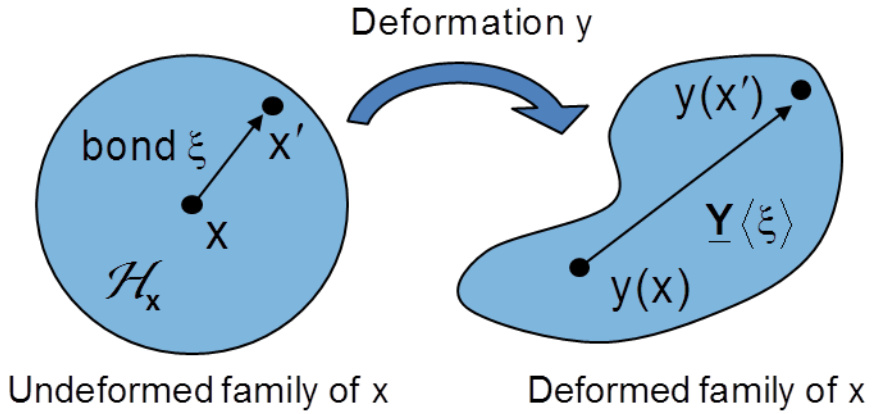
- **Horizon and family**
  - Point **x** interacts directly with all points with distance δ (***horizon***)
  - Material within distance δ of **x** is denoted H_x (***family of x***)



- **Bonds and bond forces**
  - Vector between **x** and any point in its family is called a ***bond:*** **ξ = x' – x**
  - Each bond has ***pairwise force density vector*** applied at both points: **f(x', x, t)**
  - This vector is determined jointly by collective deformation of $\mathbf{H_x}$ and collective deformation of $\mathbf{H_{x'}}$
  - Bond forces are antisymmetric: **f(x', x, t) = - f(x, x', t)**

- **Deformation state**
  - Deformation state operator **Y** maps each bond ξ into its deformed image

$$\underline{\mathbf{Y}}\langle\xi\rangle = \mathbf{y(x')} - \mathbf{y(x)}$$



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Peridynamics: The Basics

- **Bonds and states**
  - **f(x', x)** has contributions from material models at both **x** and **x'**

$$\mathbf{f}(\mathbf{x}',\mathbf{x}) = \mathbf{T}[\mathbf{x},t]\langle \mathbf{x}'-\mathbf{x}\rangle - \mathbf{T}[\mathbf{x}',t]\langle \mathbf{x}-\mathbf{x}'\rangle$$

  - $\underline{\mathbf{T}}[\mathbf{x}]$ is the ***force state*** – it maps bonds onto bond force densities
  - $\underline{\mathbf{T}}[\mathbf{x}]$ is determined by the constitutive model $\underline{\mathbf{T}} = \hat{\mathbf{T}}(\underline{\mathbf{Y}})$, where $\hat{\mathbf{T}}$ maps deformation state to force state
  - For elastic materials, $\underline{\mathbf{T}}[\mathbf{x}] = \mathbf{W}_{\underline{\mathbf{Y}}}$ (Fréchet derivative)

- **Peridynamics vs. standard equations**
  - Peridynamic operators and relationships between them are nonlocal analogues of standard theory

Relation	Peridynamic Theory	Standard Theory
Kinematics	$\underline{\mathbf{Y}}\langle \mathbf{x}'-\mathbf{x}\rangle = \mathbf{y}(\mathbf{x}')-\mathbf{y}(\mathbf{x})$	$\mathbf{F} = \frac{\partial \mathbf{y}}{\partial \mathbf{x}}(\mathbf{x})$
Linear Momentum Balance	$\rho\ddot{\mathbf{u}}(\mathbf{x}) = \int_{\mathcal{H}_\mathbf{x}} \{\underline{\mathbf{T}}[\mathbf{x},t]\langle \mathbf{x}'-\mathbf{x}\rangle - \underline{\mathbf{T}}[\mathbf{x}',t]\langle \mathbf{x}-\mathbf{x}'\rangle\} dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x})$	$\rho\ddot{\mathbf{u}}(\mathbf{x}) = \nabla\cdot\boldsymbol{\sigma}(\mathbf{x}) + \mathbf{b}(\mathbf{x})$
Constitutive Model	$\underline{\mathbf{T}} = \widehat{\mathbf{T}}(\underline{\mathbf{Y}})$	$\boldsymbol{\sigma} = \widehat{\boldsymbol{\sigma}}(\mathbf{F})$
Angular Momentum Balance	$\int_{\mathcal{H}_\mathbf{x}} \{\underline{\mathbf{Y}}\langle \mathbf{x}'-\mathbf{x}\rangle \times \underline{\mathbf{T}}\langle \mathbf{x}'-\mathbf{x}\rangle\} dV_{\mathbf{x}'} = 0$	$\boldsymbol{\sigma} = \boldsymbol{\sigma}^T$

Peridynamic Material Modeling

- **Linear Peridynamic Solid (LPS)***
- Nonlocal analog to linear isotropic elastic solid
- k is bulk modulus, μ is shear modulus

$$\rho\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{\mathbf{H}} \left(\mathbf{T}[\mathbf{x},t]\langle \mathbf{x}' - \mathbf{x} \rangle - \mathbf{T}[\mathbf{x}',t]\langle \mathbf{x} - \mathbf{x}' \rangle \right) dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x},t)$$

$$\mathbf{T}[\mathbf{x},t]\langle \mathbf{x}' - \mathbf{x} \rangle = \left(\frac{3k\theta}{m} \underline{\omega}\underline{\mathbf{x}} + \frac{15\mu}{m} \underline{\omega}\mathbf{e}^{\mathbf{d}} \right) \frac{\mathbf{x}' - \mathbf{x}}{\|\mathbf{x}' - \mathbf{x}\|}$$

- Many other peridynamic material models available: elastic-plastic, viscoelastic, etc.

- Can wrap classical material models (existing material libraries) in peridynamic "skin"

*S.A. Silling, M. Epton, O. Weckner, J. Xu, & E. Askari, Peridynamic States and Constitutive Modeling, J. Elasticity, 88, pp. 151-184, 2007.

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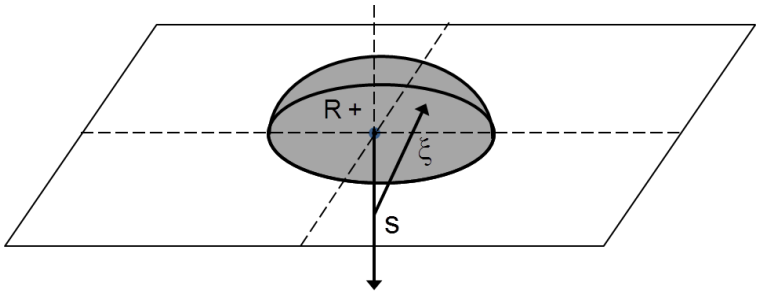
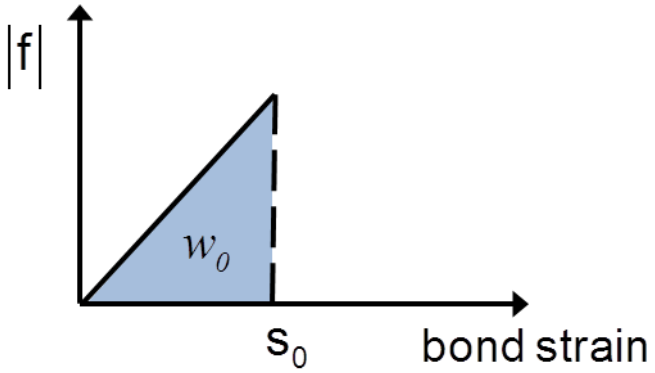
Peridynamic Fracture Modeling

- **Fracture ("Critical Stretch")**
  - Break bond if bond stretch **s** exceeds critical stretch s_0
  - If work to break bond ξ is $\mathbf{w_0(\xi)}$, then energy release rate found by summing this work per unit crack area

$$G = \int_0^{\delta} \int_{R_+} w_0(\xi) dV_\xi ds$$

  - Can then get the critical strain s_0 for bond breakage in terms of **G** (strain energy release rate), an experimentally measurable quantity





- **Fracture ("Critical Energy")***
  - Break bond if work done on bond exceeds critical value*

* J.T. Foster, S.A. Silling, W. Chen, An energy based failure criterion for use with peridynamic states, J. Multi. Comp. Engng. 9 (6): 675–687 (2011).

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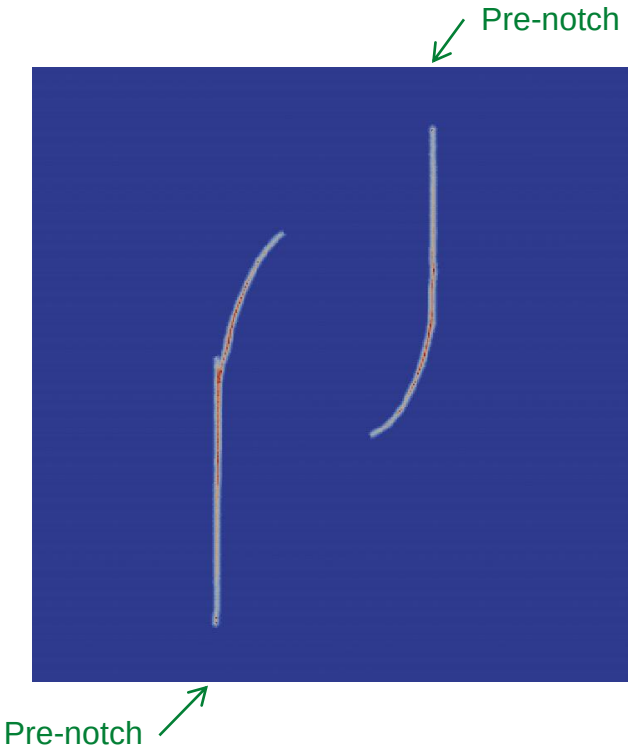
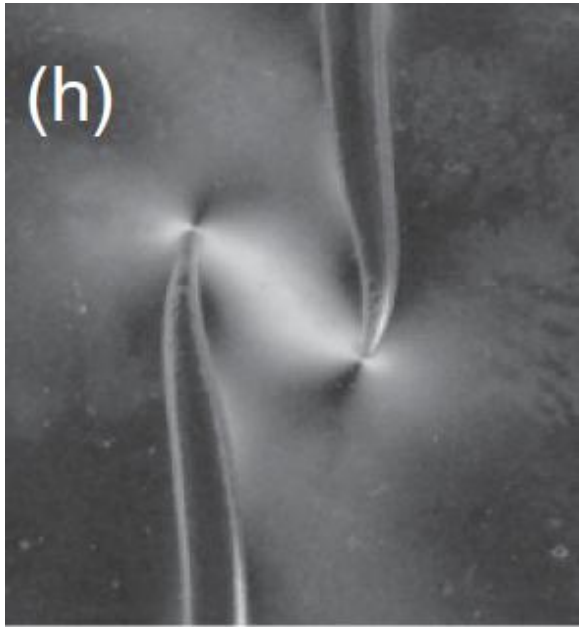
Simulation performed with PDLAMMPS code (Parks)

Two Interacting Cracks

- Offset notches thin rectangular elastic plate
- Uniaxial strain applied from sides
- Approaching cracks produce “en passant” crack pattern



Peridynamics



Physical Experiment*

* M. Fender, F. Lechenault, and K. Daniels, Universal Shapes Formed by Two Interacting Cracks, Phys. Rev. Lett. 105, 125505 (2010) .

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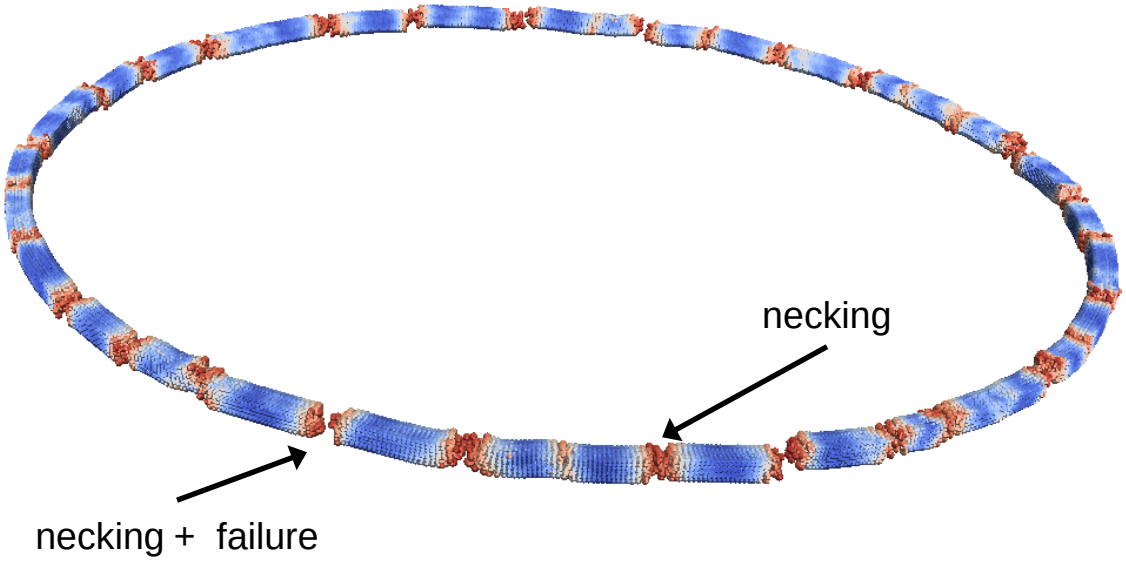
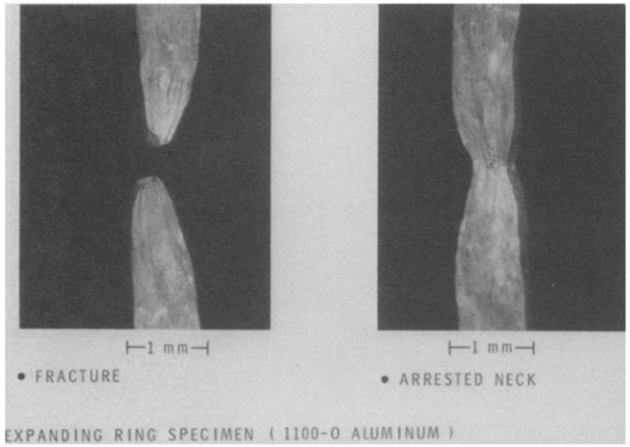
Simulation performed with Peridigm

Electromagnetically loaded ring

- 1100-0 aluminum ring (ductile)
- Motivated by ring fragmentation experiments of Grady & Benson*
- Used peridynamic elastic/plastic model**





Fracture and arrested neck region from dynamic expansion of ring*

* D. Grady, D. Benson, Fragmentation of metal rings by electromagnetic loading, Experimental Mechanics, 23(4), pp. 393-400, 1983
** J. Mitchell, A Nonlocal, Ordinary, State-Based Plasticity Model for Peridynamics, SAND2011-3166, 2011.

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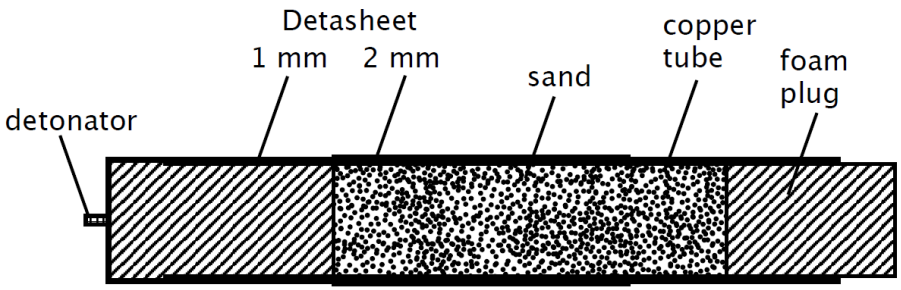
Simulation performed with Peridigm

Explosively Compressed Cylinder*

- Motived by experiments of Vogler & Lappo*
- Commonly used for consolidation of powders
- Copper cylinders filled with granular material and wrapped with Detasheet explosive
- Polyurethane foam plugs used to keep granular sample in tube.

- Geometry and Material Properties
- Copper tubes 305 mm long, ID 50.8 mm, wall thickness of 1.52 mm
- PETN based Detasheet with thicknesses of 1, 2, 4, or 6 mm were used, and a
- Detonation traveled down length of tube, compressing both tube and sand fill



Cylinder schematic

Cylinder after compression

* T.J. Vogler and K.M. Lappo, Cylindrical Compaction of Granular Ceramics: Experiments and Simulations, The 12th Hypervelocity Impact Symposium. 2012.

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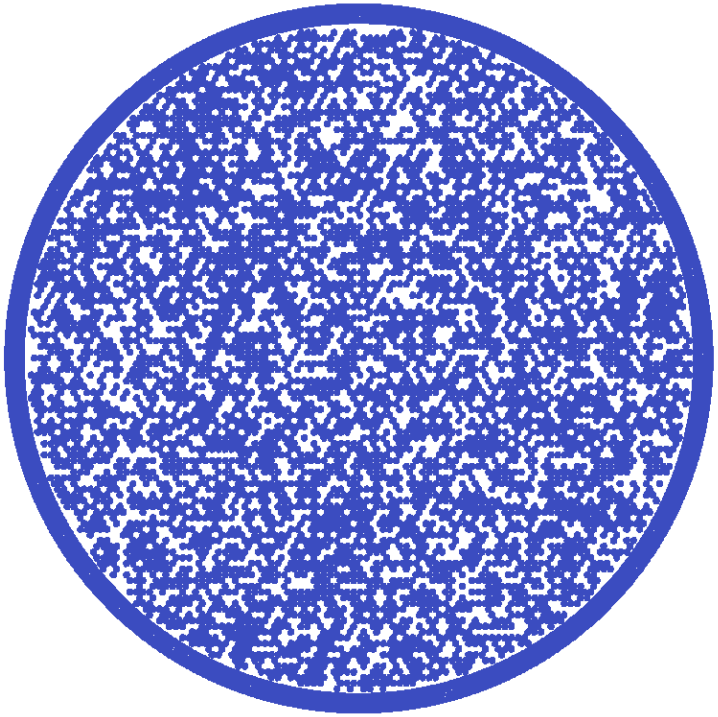
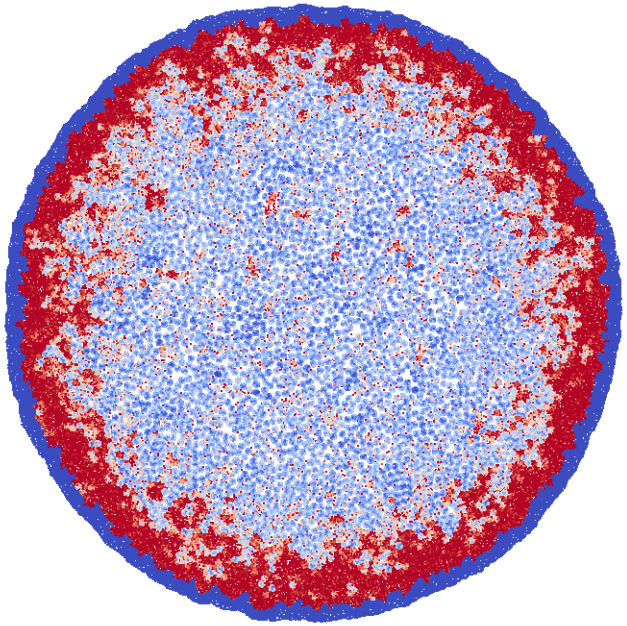
Simulation performed with Peridigm

Explosively Compressed Cylinder

- Peridigm computational results (with C. Hoffarth (ASU), D. Littlewood (SNL))
  - Color indicates damage (blue = undamaged, red = damaged)



Before



After

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Simulation performed with Peridigm

Tensile Test

- Stainless steel dogbone specimen.
- Apply displacement boundary conditions corresponding to 1% strain.
- Quasistatic solve

before

after

Color proportional to yield.

Displacement exaggerated 10×

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Peridigm

- **Peridigm** (Open Source, C++)
- Developers: Parks, Littlewood, Mitchell, Silling
- **https://software.sandia.gov/trac/peridigm**
- Intended as Sandia's primary open-source PD code
- Built upon Sandia's Trilinos Project (**trilinos.sandia.gov**)

- **Features/Capabilities**
- Massively parallel, Exodus mesh input, Multiple material blocks

- Only state-based material models
  - elastic, elastic-plastic, elastic-plastic with hardening, viscoelastic

- Explicit time integration (Velocity-Verlet)
- Implicit time integration (Newmark-beta method)
- Quasistatics
- Nonlinear (Newton/Krylov, nonlinear CG)
- Linear (preconditioned Krylov subspace methods)
- Automatic differentiation Jacobians
- DAKOTA interface for UQ/optimization/calibration, etc. (dakota.sandia.gov)

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Peridigm: Peridynamics via Agile Components

Peridigm

Software Quality Tools

- Mailing Lists
- Version Control
- Build System
- Testing (CTest)
- Project Management
- Issue Tracking
- Wiki

DAKOTA

- UQ
- Optimization
- Error Estimation
- Calibration

ParaView

- Visualization

Visualization Toolkit

- Service Tools

Trilinos

Parallelization Tools

- Data Structures (Epetra)
- Load Balancing (Zoltan)

Analysis Tools

- UQ (Stokhos)
- Optimization (MOOCHO)

Services

- Interfaces (Thyra)
- Tools (Teuchos, TriUtils)
- Field Manager (Phalanx)
- DAKOTA Interface (TriKota)

Solver Tools

- Iterative Solvers (Belos)
- Direct Solvers (Amesos)
- Nonlinear Solvers (NOX)
- Eigensolvers (Anasazi)
- Preconditioners (IFPack)
- Multilevel (ML)

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Peridynamic Codes

- **EMU** (Export controlled, F90)
  - Developer: Silling (www.sandia.gov/emu/emu.htm)
  - Research code
- **PDLAMMPS (Peridynamics-in-LAMMPS)** (Open source, C++)
  - Developers: Parks, Seleson, Plimpton, Silling, Lehoucq
  - Particular discretization of PD has computational structure of molecular dynamics (MD)
  - LAMMPS: Sandia's open-source massively parallel MD code (lammps.sandia.gov)
  - More info & user guide: www.sandia.gov/~mlparks
- **Peridigm** (Open Source, C++)
  - Developers: Parks, Littlewood, Mitchell, Silling
  - Intended as Sandia's primary open-source PD code
  - Built upon Sandia's Trilinos Project (trilinos.sandia.gov)
  - Massively parallel, Exodus mesh input, Multiple material blocks
  - Explicit, implicit time integration
  - State-based linear elastic, elastic-plasticity, viscoelastic models
  - DAKOTA interface for UQ/optimization/calibration, etc. (dakota.sandia.gov)
- **Peridynamics in Sierra/SolidMechanics** (Export controlled, C++)
  - Developer: Littlewood
  - Sandia engineering analysis code
- **Peridynamics is a capability that can be added to (almost) any analysis code!**

Peridigm Material Models

- **Linear Peridynamic Solid (LPS)***
  - Nonlocal analog to linear isotropic elastic solid
  - k is bulk modulus, μ is shear modulus

$$\rho\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{\mathbf{H}} \left(\mathbf{T}[\mathbf{x},t]\langle \mathbf{x}'-\mathbf{x}\rangle - \mathbf{T}[\mathbf{x}',t]\langle \mathbf{x}-\mathbf{x}'\rangle \right) dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x},t)$$

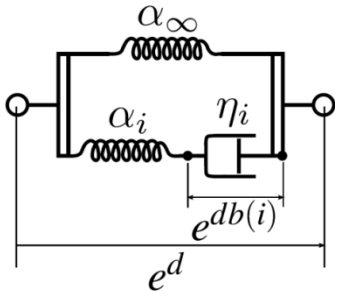
$$\mathbf{T}[\mathbf{x},t]\langle \mathbf{x}'-\mathbf{x}\rangle = \left(\frac{3k\theta}{m}\omega\underline{\mathbf{x}} + \frac{15\mu}{m}\omega\mathbf{e}^{\mathbf{d}} \right) \frac{\mathbf{x}'-\mathbf{x}}{\|\mathbf{x}'-\mathbf{x}\|}$$

- Many other peridynamic material models available:

- **Elastic-Plastic Model****
  - Nonlocal analogue to perfect plasticity model

- **Elastic-Plastic Model with Hardening (J. Foster, UTSA)**

- **Viscoelastic Model*****
  - Nonlocal analog to standard linear solid



*S.A. Silling, M. Epton, O. Weckner, J. Xu, & E. Askari, Peridynamic States and Constitutive Modeling, J. Elasticity, 88, pp. 151-184, 2007.
**J. Mitchell, A Nonlocal, Ordinary, State-Based Plasticity Model for Peridynamics, SAND2011-3166, 2011.
***J. Mitchell, A Non-local, Ordinary-State-Based Viscoelasticity Model for Peridynamics, SAND2011-8064, 2011.

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Peridigm: Structure & User Interface

- Peridigm designed to be user extensible
  - User defined material models, compute classes, etc.

- Compute class: Compute any user-defined quantity
  - Class must declare what data it needs allocated
    - Examples: per-element or per-node scalar, vector, tensor, etc.
  - Class must provide routine that computes user-defined quantity
  - User writes only serial code -- parallel communication handled "auto-magically"
- Example: Compute Acceleration (for output)

```
//! Fill the acceleration vector
int PeridigmNS::Compute_Acceleration::compute( Teuchos::RCP< std::vector<Block> > blocks ) const {
  int retval(0);

  Teuchos::RCP<Epetra_Vector> force, acceleration;
  std::vector<Block>::iterator blockIt;
  for(blockIt = blocks->begin() ; blockIt != blocks->end() ; blockIt++){
    force        = blockIt->getData(m_forceDensityFieldId, PeridigmField::STEP_NP1);
    acceleration = blockIt->getData(m_accelerationFieldId, PeridigmField::STEP_NP1);
    *acceleration = *force;
    double density = blockIt->getMaterialModel()->Density();
    // Report if any calls to Scale() failed.
    retval = retval || acceleration->Scale(1.0/density);
  }

  return retval;
}
```

- Declare "acceleration" as output field in input deck
  - Only specified fields are computed

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Peridigm: Structure & User Interface

- Peridigm material models: Create your own!

```
 //! Returns a vector of field specs that specify the variables associated with the material
 virtual Teuchos::RCP< std::vector<Field_NS::FieldSpec> > VariableSpecs() const = 0;

//! Initialize the material model.
virtual void initialize(const double dt,
                        const int numOwnedPoints,
                        const int* ownedIDs,
                        const int* neighborhoodList,
                        PeridigmNS::DataManager& dataManager) const {}


//! Evaluate the forces on the cells
virtual void computeForce(const double dt,
                          const int numOwnedPoints,
                          const int* ownedIDs,
                          const int* neighborhoodList,
                          PeridigmNS::DataManager& dataManager) const = 0;


//! Evaluate the Jacobian
virtual void computeJacobian(const double dt,
                             const int numOwnedPoints,
                             const int* ownedIDs,
                             const int* neighborhoodList,
                             PeridigmNS::DataManager& dataManager,
                             PeridigmNS::SerialMatrix& jacobian) const;


// other routines
```

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Peridigm: Recent New Features

- Surface Correction Factor (SCF): John Mitchell
  - In PD, points close to boundary have fewer bonds than points in bulk
  - This makes the material response different near the boundary
  - Must alter material response near boundary to correct for “missing” bonds
  - **This is extremely important for engineering simulations!**
  - **See John Mitchell’s talk: *On the 'DSF' and the 'Dreaded Surface Effect‘***

- Thermal stress: Dave Littlewood

- Bond-cutting planes: John Mitchell, Dave Littlewood

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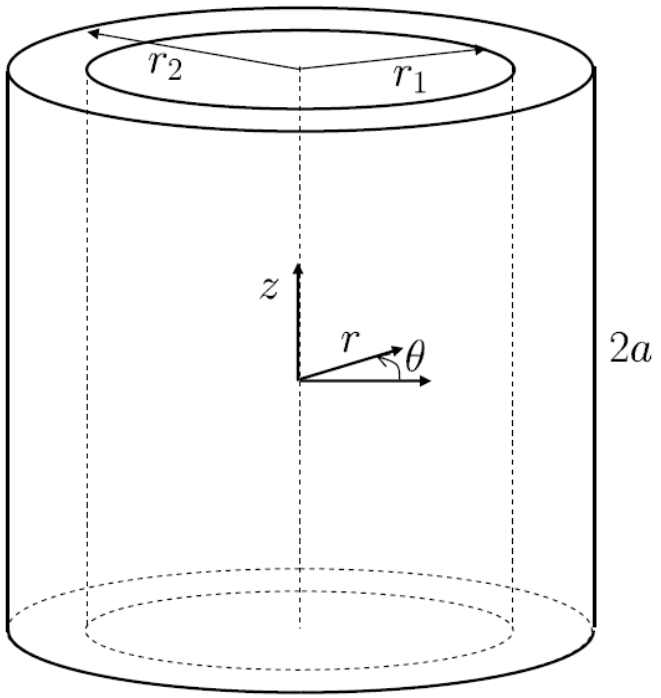
Fragmenting Cylinder

- **Fragmenting Brittle Cylinder**
  - Motivated by tube fragmentation experiments of Winter (1979), Vogler (2003)*

- **Material properties**
  - Inner radius r1 = 0.020 m
  - Outer radius r2 = 0.025 m
  - Length 2a = 0.1 m
  - Density ρ = 7800 kg/m^3
  - Bulk modulus k = 130 GPa
  - Shear modulus μ = 78 GPa
  - Yield stress Y = 500 GPa
  - Ultimate stress σ = 700 GPa
  - Elongation at failure ε = 0.02



- **Initial Velocity**
  - **$v(r) = V_{r0} - V_{r1}(a/z)^2$**
  - **$v(z) = V_{z0}(a/z)$**
  - **$v(\theta) = 0$**

  where **V_{r0} = 200 m/s, V_{r1} = 50 m/s, V_{z0} = 100 m/s**

* D. Grady, Fragmentation of Rings And Shells: The Legacy of N.F. Mott, Springer, 2006.

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Running Peridigm

- **Usage:**

```
Peridigm Input.xml
```

where Input.xml is a properly formatted input deck using Trilinos/Teuchos XML ParameterList :

```
<ParameterList>
        ... input section here...
</ParameterList>
```

- **An input deck contains these sections:**

```
<ParameterList>
  [Discretization Section]
  [Materials Section]
  [Damage Models Section]
  [Blocks Section]
  [Contact Section]
  [Boundary Conditions Section]
  [Solver Section]
  [Output Sections]
</ParameterList>
```

Running Peridigm

Refresh Example

❑ Input Deck

```
<ParameterList name="Discretization">
   <Parameter name="Type" type="string" value="PdQuickGrid" />
   <Parameter name="Horizon" type="double" value="0.00417462" />
   <Parameter name="NeighborhoodType" type="string" value="Spherical" />
   <ParameterList name="TensorProductCylinderMeshGenerator">
      <Parameter name="Type" type="string" value="PdQuickGrid" />
      <Parameter name="Inner Radius" type="double" value="0.020" />
      <Parameter name="Outer Radius" type="double" value="0.025" />
      <Parameter name="Cylinder Length" type="double" value="0.100" />
      <Parameter name="Ring Center x" type="double" value="0.0" />
      <Parameter name="Ring Center y" type="double" value="0.0" />
      <Parameter name="Z Origin" type="double" value="0.0" />
      <Parameter name="Number Points Radius" type="int" value="5" />
   </ParameterList>
</ParameterList>
```

Alternative: Read from Exodus/Genesis mesh generated by meshing tool (example: CUBUIT)

```
<ParameterList name="Materials">
       <ParameterList name="My Linear Elastic Material">
         <Parameter name="Material Model" type="string" value="Elastic"/>
         <Parameter name="Density" type="double" value="7800.0"/>
         <Parameter name="Bulk Modulus" type="double" value="130.0e9"/>
         <Parameter name="Shear Modulus" type="double" value="78.0e9"/>
       </ParameterList>
 </ParameterList>
```

Material properties

```
<ParameterList name="Damage Models">
       <ParameterList name="My Critical Stretch Damage Model">
         <Parameter name="Damage Model" type="string" value="Critical Stretch"/>
         <Parameter name="Critical Stretch" type="double" value="0.02"/>
       </ParameterList>
 </ParameterList>
```

Damage model properties

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Running Peridigm

```
<ParameterList name="Blocks">
       <ParameterList name="My Group of Blocks">
         <Parameter name="Block Names" type="string" value="block_1"/>
         <Parameter name="Material" type="string" value="My Linear Elastic Material"/>
         <Parameter name="Damage Model" type="string" value="My Critical Stretch Damage Model"/>
       </ParameterList>
 </ParameterList>

<ParameterList name="Boundary Conditions">
       <ParameterList name="Initial Velocity X">
         <Parameter name="Type" type="string" value="Initial Velocity"/>
         <Parameter name="Node Set" type="string" value="All"/>
         <Parameter name="Coordinate" type="string" value="x"/>
         <Parameter name="Value" type="string"
                                value="(200 - 50*((z/0.05)-1)^2)*cos(atan2(y,x)) + rnd(5)"/>
       </ParameterList>
       <ParameterList name="Initial Velocity Y">
         <Parameter name="Type" type="string" value="Initial Velocity"/>
         <Parameter name="Node Set" type="string" value="All"/>
         <Parameter name="Coordinate" type="string" value="y"/>
         <Parameter name="Value" type="string"
                                value="(200 - 50*((z/0.05)-1)^2)*sin(atan2(y,x)) + rnd(5)"/>
       </ParameterList>
       <ParameterList name="Initial Velocity Z">
         <Parameter name="Type" type="string" value="Initial Velocity"/>
         <Parameter name="Node Set" type="string" value="All"/>
         <Parameter name="Coordinate" type="string" value="z"/>
         <Parameter name="Value" type="string"
                                value="(100*((z/0.05)-1)) + rnd(5)"/>
       </ParameterList>
 </ParameterList>
```

Used to associate blocks of elements with specific material models

Function parser: Enter any mathematical function to specify initial velocities or boundary conditions as a function of space & time

Alternative: Specify nodesets in exodus/genesis database

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Running Peridigm

```
<ParameterList name="Solver">
       <Parameter name="Verbose" type="bool" value="false"/>
       <Parameter name="Initial Time" type="double" value="0.0"/>
       <Parameter name="Final Time" type="double" value="2.5e-4"/>
       <ParameterList name="Verlet">
         <Parameter name="Fixed dt" type="double" value="1.0e-8"/>
       </ParameterList>
 </ParameterList>

 <ParameterList name="Output">
       <Parameter name="Output File Type" type="string" value="ExodusII"/>
       <Parameter name="Output Format" type="string" value="BINARY"/>
       <Parameter name="Output Filename" type="string" value="fragmenting_cylinder"/>
       <Parameter name="Output Frequency" type="int" value="250"/>
       <Parameter name="Parallel Write" type="bool" value="true"/>
       <ParameterList name="Output Variables">
         <Parameter name="Proc_Num" type="bool" value="true"/>
         <Parameter name="Displacement" type="bool" value="true"/>
         <Parameter name="Velocity" type="bool" value="true"/>
         <Parameter name="Acceleration" type="bool" value="true"/>
         <Parameter name="Force_Density" type="bool" value="true"/>
         <Parameter name="ID" type="bool" value="true"/>
         <Parameter name="Dilatation" type="bool" value="true"/>
         <Parameter name="Damage" type="bool" value="true"/>
         <Parameter name="Weighted_Volume" type="bool" value="true"/>
       </ParameterList>
 </ParameterList>
```

Alternative: Implicit time integrator (Newmark-Beta) or quasistatic solver (damped Newton)

Output from compute class defined earlier

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Simulation performed with Peridigm

The Results…

- Fragmenting Brittle Cylinder

Before

After (brittle)

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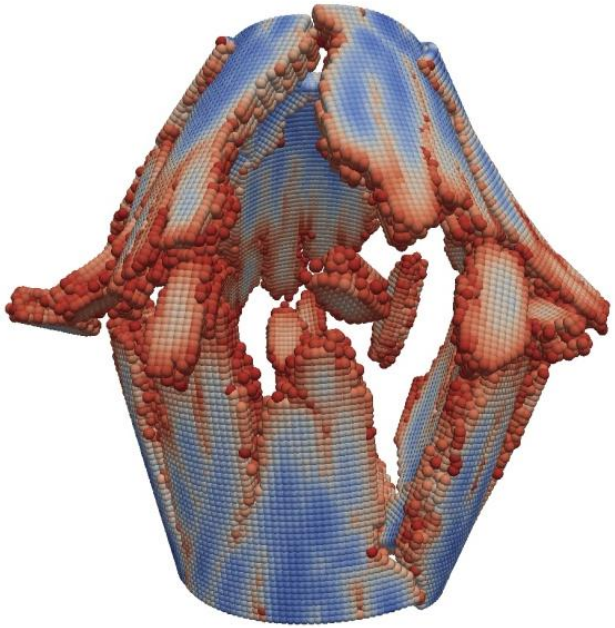
Simulation performed with Peridigm

The Results…

- Fragmenting Brittle Cylinder

Before



After (brittle)

- What about ductile failure?

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Running Peridigm

- Modify the material section and damage model

```
<ParameterList name="Materials">
       <ParameterList name="My Elastic Plastic Material">
         <Parameter name="Material Model" type="string" value="Elastic Plastic"/>
         <Parameter name="Density" type="double" value="7800.0"/>
         <Parameter name="Bulk Modulus" type="double" value="130.0e9"/>
         <Parameter name="Shear Modulus" type="double" value="78.0e9"/>
         <Parameter name="Yield Stress" type="double" value="176.0e6"/>
       </ParameterList>
 </ParameterList>
```

Change material type and parameters

```
<ParameterList name="Damage Models">
       <ParameterList name="My Critical Stretch Damage Model">
         <Parameter name="Damage Model" type="string" value="Critical Stretch"/>
         <Parameter name="Critical Stretch" type="double" value="0.12"/>
       </ParameterList>
 </ParameterList>
```

Increase critical stretch to be consistent with elongation at failure for material.

Allows material to yield plastically before failure.

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Simulation performed with Peridigm

The Results…

- Fragmenting Ductile Cylinder

Before

After (ductile)

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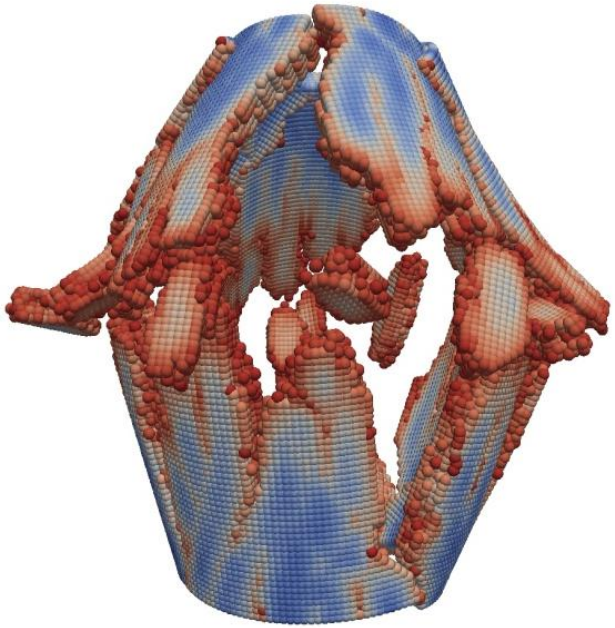
Simulation performed with Peridigm

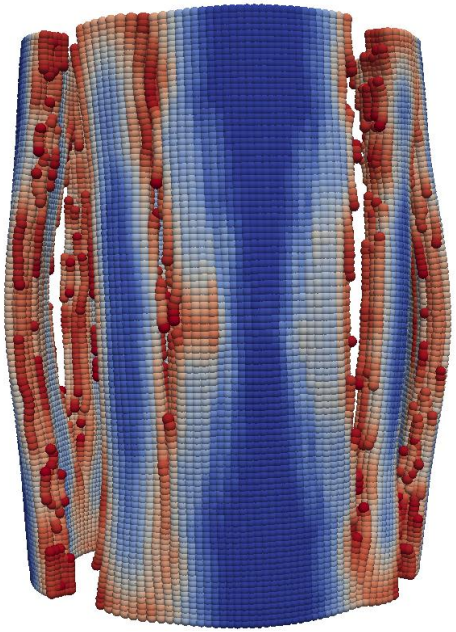
The Results…

- Fragmenting Cylinders
  - Brittle fracture characteristically different from ductile fracture

Before



After (brittle)



After (ductile)

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Summary

- Peridynamics overview
- Example computations
- Peridigm overview
- Peridigm fragmenting cylinder demonstration
  - Input deck distributed with Peridigm…
  - Other interesting examples (disk impact, tensile test)

- Peridigm
  - https://software.sandia.gov/trac/peridigm

- Contact me for more info: mlparks@sandia.gov

- Papers, etc.: www.sandia.gov/~mlparks

- **Thank you!**

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